

Large-scale physical and molecular conditions in structures of Cygnus-X

Dissertation
zur
Erlangung des Doktorgrades (Dr. rer. nat.)
der
Mathematisch-Naturwissenschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von
Ivalu Barlach Christensen
aus
Nuuk, Grönland

Bonn 2026

Angefertigt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen
Friedrich-Wilhelms-Universität Bonn

Gutachterin/Betreuerin:	Prof. Dr. Serena Viti
Gutachter:	Prof. Dr. Frank Bigiel
Tag der Promotion:	12.06.2026
Erscheinungsjahr:	2026

Abstract

by Ivalu Barlach Christensen
for the degree of
Doctor rerum naturalium

The physical state of the interstellar medium (ISM) is essential for understanding the intricate processes involved in massive star formation within galaxies. The nearby ($d \sim 1.5$ kpc) molecular cloud, Cygnus-X, harbors multiples sites of high-mass star-formation, allowing us to probe the various stages as stars form and how the chemistry evolve. Within the Cygnus Allscale Survey of Chemistry and Dynamical Environments (CASCADE), we aim to explore the large-scale distribution of deuterated molecules in Cygnus-X. A plethora of star-forming clumps are observed with the CASCADE survey, where clumps are believed to evolve from quiescent infrared-dark clouds to high-mass protostellar objects to hot molecular cores to ultra-compact HII regions. The most active and dense region within Cygnus-X is the DR21 filament, harboring the prominent HII region DR21 Main with the most intense outflow of the Milky Way. The degree of deuteration, R , can significantly enhance over the elemental D/H-ratio (10^{-5}) depending on physical parameters such as temperature, density, and ionization fraction. Deuterated molecules and their molecular D/H-ratios are important diagnostic tools to study the physical conditions of star-forming regions.

This thesis focuses on probing the deuterated fractions of Cygnus-X. Along the DR21 filament, the deuterated fraction of DCO^+ , DNC, and DCN exhibit morphological variations, caused by the local physical conditions. Active star-formation along the filamentary structure initiate shock chemistry in these high density region, destroying DCO^+ , and consequently decreasing $R(\text{DCO}^+)$. Furthermore, the lower density regions are exposed to FUV, in which the formation of HCO^+ is halted, consequently increasing the $R(\text{DCO}^+)$.

Finally, to further understand how deuterated fractions behave as clumps evolve, we investigate 67 clumps. Utilizing CASCADE observation of the ubiquitous H_2CO complemented with higher J -transitions with the APEX telescope, we determine the physical conditions of 67 clumps in Cygnus-X. The methodology of determining the H_2 volume density is efficient in probing the bulk of the gas within 0.2 pc of the clumps. With the physical conditions constrained, we model the chemical evolution of these clumps utilizing the plethora of molecules covered with CASCADE, including the 6 deuterated fractions: $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, $R(\text{DCN})$, $R(\text{DNC})$, and $R(\text{DCO}^+)$. We find that the latter two deuterated fractions decrease and increase, respectively, as the clumps evolve and become hotter.

Per aspera ad astra

- Latin proverb

Publications related to this thesis

This research work made for this thesis culminated in two peer-reviewed first-author publications, and one more is under preparation. They are as following:

1. The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE III. The large scale distribution of DCO^+ , DNC, and DCN in the DR21 filament

Christensen et al. 2024, *A&A*, 688, A215. DOI: [10.1051/0004-6361/202450118](https://doi.org/10.1051/0004-6361/202450118)

Contributions: Performed the data reduction, and scientific analysis, interpreted the results, and wrote the manuscript, supervised by the co-authors.

2. Formaldehyde as densitometer and thermometer in Cygnus-X, GLOSTAR pilot region, and M8: Utilizing the H_2CO ground-state transition

Christensen et al. *subm.*

Contributions: Performed the data reduction, and scientific analysis, interpreted the results, and wrote the manuscript, supervised by the co-authors.

3. The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE. Chemical Evolution in Early-Stage Cygnus-X Clumps

Christensen et al. *in prep.*

Contributions: Performed the data reduction, and scientific analysis, interpreted the results, and wrote the manuscript, supervised by the co-authors.

Other publications

Below is a list of paper, which I have contributed to, published during the period of this thesis work.

4. The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE. Overview and first results toward DR20 from the Max Planck IRAM Observatory program (MIOP)

Beuther et al. 2022, A&A, 665, A63. DOI: [10.1051/0004-6361/202244040](https://doi.org/10.1051/0004-6361/202244040)

Contributions: Part of the collaboration, and commented on the manuscript.

5. The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE II. A detailed kinematic analysis of the DR21 Main outflow

Skretas et al. 2023, A&A, 679, A66. DOI: [10.1051/0004-6361/202346825](https://doi.org/10.1051/0004-6361/202346825)

Contributions: Part of the collaboration, and commented on the manuscript.

6. High-resolution APEX/LAsMA ^{12}CO and ^{13}CO (3-2) observation of the G333 giant molecular cloud complex. II. Survival and gravitational collapse of dense gas structures under feedback

Zhou et al. 2024, A&A, 682, A128. DOI: [10.1051/0004-6361/202347377](https://doi.org/10.1051/0004-6361/202347377)

Contributions: Helped develop the script to derive the column densities of ^{12}CO and ^{13}CO with pyradex, and commented on the manuscript.

7. The effects of stellar feedback on molecular clumps in the Lagoon Nebula (M8)

Kahle et al. 2024, A&A, 687, A162. DOI: [10.1051/0004-6361/202349009](https://doi.org/10.1051/0004-6361/202349009)

Contributions: Developed the script to derive the column densities of H_2CO with pyradex+emcee, and commented on the manuscript.

8. The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE IV. Unveiling the hidden structures in DR18

Kim et al. 2025, A&A, 694, A30. DOI: [10.1051/0004-6361/202451998](https://doi.org/10.1051/0004-6361/202451998)

Contributions: Part of the collaboration, and commented on the manuscript.

9. Exploring the interplay between molecular and ionized gas in regions

Khan et al. 2025, accepted for publication. DOI: [10.1051/0004-6361/202558059](https://doi.org/10.1051/0004-6361/202558059)

Contributions: Helped develop the script to derive the column densities of H_2CO with pyradex+emcee, and commented on the manuscript.

Contents

1	Introduction	1
1.1	The interstellar medium	3
1.2	Structure of molecular clouds	4
1.2.1	Filaments	6
1.2.2	Clumps and cores	6
1.3	Understanding star formation within Cygnus-X	7
1.3.1	High-mass star formation (HMSF)	7
1.3.2	The Cygnus-X cloud complex	10
1.4	Probing molecular clouds with molecules	13
1.5	About this thesis	14
1.5.1	Motivation	14
1.5.2	Goals	15
1.5.3	Outline	15
2	Observations	17
2.1	The basic properties of a radio telescope	17
2.1.1	Telescopes used in this thesis	20
2.2	Surveys	22
2.2.1	The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE	22
2.2.2	The GLobal view of STAR Formation in the Milky Way: GLOSTAR pilot region	26
2.2.3	The M8 region	27
2.2.4	Data reduction	28
3	Physical and Chemical Processes in Star-Forming Molecular Clouds	31
3.1	Observing Molecular Clouds	31
3.1.1	Spectral line emission	31
3.1.2	Radiative Transfer	32
3.1.3	Molecular line emissions	34
3.1.4	Deriving column densities	35
3.2	Chemistry in dense molecular clouds	36
3.2.1	Gas-phase chemistry	38
3.2.2	Grain-surface chemistry	38
3.2.3	Deuterated molecules	39

3.2.4	Formaldehyde	42
4	The large scale distribution of DCO⁺, DNC and DCN in the DR21 filament	45
4.1	Context	45
4.2	Deuteration along the DR21 filament	46
4.3	Impact of Physical Conditions on Deuteration	46
4.3.1	Effects of Shocks and Photodissociation on the abundance of DCO ⁺	47
4.3.2	DNC and DCN with the gas kinetic temperature	48
4.4	Conclusions	49
5	Formaldehyde as Densitometer and Thermometer in Cygnus-X, GLOSTAR pilot region and M8	51
5.1	Context	51
5.2	Formaldehyde tracing the same gas	52
5.3	Physical conditions with pyradex+emcee	54
5.3.1	Temperatures in clumps	54
5.3.2	Volume densities in clumps	55
5.4	Physical conditions with evolutionary phases	55
5.5	Conclusion	56
6	Chemical Evolution in Early-Stage Cygnus-X Clumps: Initial Results	57
6.1	Introduction	57
6.2	Observations and results	58
6.2.1	Spectral line analysis	58
6.2.2	Column densities	60
6.3	Analysis	61
6.3.1	MUlti Stage ChemicalL codE	62
6.4	Discussion	63
6.4.1	Modeling parameters	63
6.5	Molecules with evolution	68
6.5.1	Deuterated molecules in Cygnus-X	69
6.5.2	Deuterated fractions with evolution	72
6.6	Conclusion	73
7	Conclusion and outlook	75
A	Paper I: The large scale distribution of deuterated molecules in the DR21 filament	79
B	Clumps in Cygnus-X	105
C	Paper II: Formaldehyde as a thermometer and densitometer	171
D	Formaldehyde spectra and pyradex+emcee results	195
D.1	Line profile measurements of H ₂ CO	195

E	Molecules in the clumps of Cygnus X	205
E.1	Column Densities in Clumps	205
E.2	Radial density profiles of the clumps	213
E.3	MUSCLE results	225
	Bibliography	227
	List of Figures	241
	List of Tables	247
	Acknowledgements	249

Nomenclature

Astronomical constants

$M_{\odot}$	Solar mass	$1.989 \times 10^{30} \text{ kg}$
pc	Parsec	$3.0857 \times 10^{16} \text{ m}$
AU	Astronomical Unit	$1.496 \times 10^{11} \text{ m}$

Physical constants

k_B	Boltzmann's constant	$1.381 \times 10^{-23} \text{ J K}^{-1}$
h	Planck's constant	$6.626 \times 10^{-34} \text{ J Hz}^{-1}$
c	Speed of light	$2.9979 \times 10^8 \text{ m sec}^{-1}$

Frequently used symbols

yr	Year
ν	Frequency
v	Spectral velocity
λ	Wavelength
J	Orbital angular momentum
τ	Optical depth
Ω	Solid angle
T_{ex}	Excitation temperature
T_{kin}	Kinetic temperature
T_{A}^*	Antenna temperature
T_{MB}	Main beam temperature
N or N_{tot}	Column density
n	Volume density
R	Deuterated fraction
θ	Angle

Introduction

Our universe was brought to life
That we may fall in love
Every time we open up our eyes

Sleeping at last - Sun

In Greenlandic mythology, stars are made up of the deaths of our ancestors, forever immortalized in the night sky. The Cygnus constellation is known as *Qamasut*¹ in Greenlandic culture. Within this celestial formation, seven stars are believed to represent seven hunters who met their fate in treacherous waters (Christensen, 2020). In modern astronomy, stars are born in dense and cold regions of space.

William Herschel's observation of dark patches in the night sky was a significant moment in astronomical history. In 1785, while he was observing, Herschel told his sister Caroline, "Hier ist wahrhaftig ein Loch im Himmel"². This observation led the Herschel's to speculate that these dark areas might be caused by some medium obscuring the light of distant stars, which turned out to be a pretty accurate guess (Steinicke, 2016). Later, telescopes that could pick up more than just visible light changed everything we knew about space. In 1933, Karl G. Jansky, now recognized as the father of radio astronomy, observed the first cosmic radio waves (Jansky, 1933). The 1950s saw significant growth in radio astronomy; one of the most notable findings was the identification of large molecular clouds, with the Cygnus-X region emerging as a prominent example. Molecular clouds have a density and size that permit absorption nebula, the formation of molecules, and the formation of HII regions (detailed discussion in Sect. 1.3). In 1951, Piddington and Minnett (1952) observed a diffuse, extended radio source in the Cygnus constellation, naming it Cygnus-X, recognizing it as the first "radio nebula" (check out Fig. 1.1 for Cygnus-X North, referred to as Cygnus-X in this thesis). With the advancement of telescopes, astronomers started to understand those "holes in the sky" that intrigued William Herschel. These dark regions were revealed to be vast clouds of interstellar gas and dust, now recognized as crucial sites of star formation.

The interstellar medium (ISM) undergoes a cycle of matter transformation, driven by the life cycles of stars. Low-mass stars live for billions of years, while the high-mass stars, defined as $\geq 8 M_{\odot}$, have lifespans of millions of years. These massive stars play a crucial role in cosmic evolution by enriching

¹ English: *Those who lie in wait, seal hunting in a kayak*

² English: *Here truly is a hole in the sky.*

the ISM with heavy elements. As they progress through the life cycles, and ultimately die, they generate and disperse a plethora of elements through mechanisms such as stellar winds and supernova explosions. This ongoing process of stellar birth and death progressively enhances the metallicity of the ISM over time, contributing to the chemical evolution of galaxies, and the potential for complex chemistry in future stellar and planetary systems.

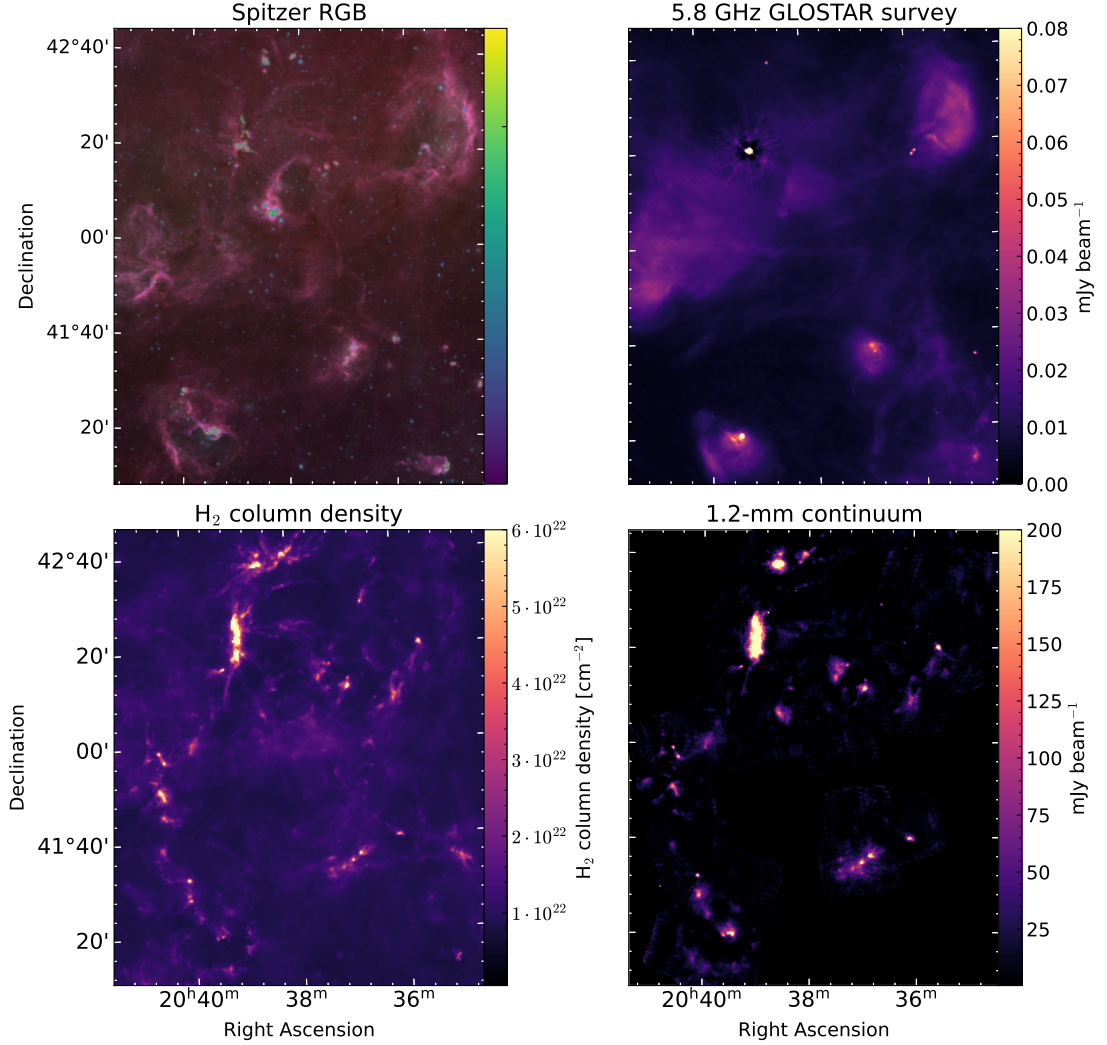


Figure 1.1: The image of Cygnus-X with different tracers of the same field-of-view. *Top left image:* The *Spitzer* IRAC three-color composite image (Beer et al., 2010). Red: 8.0 μm ; green: 4.5 μm ; blue: 3.6 μm . *Top right image:* 5.8 GHz GLOSTAR combination (Very Large Array D-configuration and Effelsberg; Brunthaler et al., 2021) with the zero-level intensities restored using the Urumqi 4.8 GHz continuum data (Dokara et al., 2023). *Bottom left:* The H₂ column density (HOBYS program; Motte et al., 2010; Bonne et al., 2023). *Bottom right:* mm-continuum image (IRAM 30-m telescope using MAMBO and MAMBO-2 cameras; Motte et al., 2007).

To understand the formation of massive stars, comprehensive studies of the mechanisms that influence the process and the role of the molecular content where stars form are required. The initial mass distribution of stars in the Milky Way follows a power-law relationship, described by $\frac{dN}{dM} = M^{-\alpha}$

with $\alpha = 2.35$ (Salpeter, 1955). This distribution implies that for every 100 solar-mass of stars formed, only one star with a mass of about $30 M_{\odot}$ is formed. Furthermore, the lifespans of high-mass stars are dramatically shorter than their low-mass counterparts; a $30 M_{\odot}$ star lives only about 1/2000th the lifetime of a solar-mass star. These factors contribute to the rarity and transient nature of high-mass stars compared to low-mass stars, making them challenging to study. Despite these obstacles, recent years have witnessed significant advancements in our understanding of massive star formation. The initial mass function (IMF) shows little variation across the Milky Way, and most massive stars preferentially form in specific physical environments rather than randomly within molecular clouds (Kroupa et al., 2013).

1.1 The interstellar medium

The ISM, far from being empty, is a complex environment permeating the space between stars in galaxies. Composed primarily of gas, dust, and cosmic rays (CRs), the ISM is dominated by molecular hydrogen (H_2 ; Herbst, 1995) and undergoes continuous cycles of matter transformation. As the universe evolved and stars began to form, the ISM became progressively enriched with heavier elements. This enrichment process facilitated the in situ formation of various molecules, including complex organic molecules (COMs; molecules with ≥ 6 atoms, with at least one atom being carbon), significantly diversifying the chemical composition of the interstellar environment (Herbst and van Dishoeck, 2009).

The baryonic matter in the ISM exhibits a wide range of physical conditions, characterized by varying volume densities and temperatures. These diverse states are categorized into several distinct phases, each with its own characteristic properties and observational techniques (see Table 1.1). The **coronal gas** phase, resulting from supernova shocks, features extremely high temperatures ($\gtrsim 3 \times 10^5$ K) and cools over approximately 20 million years through adiabatic expansion or X-ray emission. **HII regions** consist of photoionized hydrogen gas created by UV radiation from newly formed massive stars. The **warm neutral medium**, with temperatures in the thousands of Kelvin, comprises a significant portion of the ISM. In contrast, the **cold neutral medium**, at hundreds of Kelvin, is less abundant but denser. Within the cold neutral medium, **diffuse molecular gas** regions exist where H_2 densities allow for self-shielding, and even denser regions are classified as **dense molecular gas**. These phases can have sharp boundaries or exhibit continuous, overlapping transitions. Understanding these various components and their interactions is crucial for comprehending the complex dynamics and evolution of the ISM in galaxies (Draine, 2011).

The dense molecular phase of the ISM is characterized by the predominance of H_2 and a rich chemical inventory. This molecular diversity is important for astronomical observations, as each molecule interacts uniquely with light, exhibiting specific emission or absorption spectra at characteristic wavelengths. These spectral signatures serve as powerful diagnostic tools for studying the physical and chemical conditions within molecular clouds (explained in detail in Sect. 3.1). Notably, most of the total dust and gas content of the ISM is concentrated within molecular cloud structures (Heyer and Dame, 2015). Dust grains efficiently cool by absorbing far-ultraviolet (FUV) radiation from stars and re-emitting it in the infrared (IR), effectively cooling the environment (Draine and Lee, 1984; Li and Draine, 2001; Tielens, 2005). Additionally, dust grains, although not acting as a catalyst for reaction, are a great site for the condensed reservoir of atoms to react, enabling the formation of complex molecules (Taquet et al., 2012; van Dishoeck, 2014). The role of gas and dust grain on astrochemistry

Table 1.1: Physical properties of the ISM, adopted from Table 1.3 in Draine (2011).

Phase	Volume density [cm ⁻³]	Temperature [K]	Primary observational techniques
Coronal gas	4×10^{-3}	$\gtrsim 3 \times 10^5$	UV and x-ray emission; radio synchrotron emission
HII gas	$0.2 - 10^4$	10^4	Optical line emission; thermal radio continuum
Warm neutral medium	0.6	$\sim 5 \times 10^3$	H I 21-cm emission, absorption; optical, UV absorption lines
Cold neutral medium	30	100	H I 21-cm emission, absorption; optical, UV absorption lines
Diffuse H ₂	~ 100	~ 50	H I 21-cm emission, absorption; CO 2.6-mm emission; optical, UV absorption lines
Dense H ₂	$10^3 - 10^6$	10–50	CO 2.6-mm emission; dust FIR emission

Acronyms: UV: ultraviolet, FIR: far-IR.

is discussed further in Sect. 3.2.

1.2 Structure of molecular clouds

Molecular clouds, the densest component of the ISM, are predominantly located within the galactic disk and along the spiral arms of galaxies like our Milky Way (e.g. Larson, 1981; Dobbs et al., 2006; Rice et al., 2016). These vast structures (sizes ~ 10 parsecs (pc)) of cold gas and dust represent a significant fraction of the Milky Way’s mass, despite occupying only a small percentage of its volume. Molecular clouds play a crucial role in the life cycle of stars and are often referred to as stellar nurseries due to their pivotal function in star formation processes (McKee and Ostriker, 2007).

It is widely believed that stars are formed in molecular cloud through fragmentation (e.g. Larson, 1978; Miyama et al., 1984; Li et al., 2017). Clouds and the formations of stars are intrinsically hierarchical processes, characterized by the transport of gas across a vast range of spatial scales. This journey begins at the large cloud scales, typically spanning tens to hundreds of pc, and culminates in the remarkably compact inner accretion regions of forming stars, measured on sub-astronomical unit (au) scales (Pokhrel et al., 2018). These clouds are by far dominated by H₂, containing much less abundant molecules, such as CO (four magnitudes less abundant than H₂) and other complex molecules ($\sim 10^{-10} - 10^{-8}$ less abundant than H₂; Herbst, 1995). The hierarchical structure of fragmentation inside the molecular cloud is shown in Figure 1.2 adapted by Motte et al. (2018). A detailed description of star formation is presented in Sect. 1.3.1.

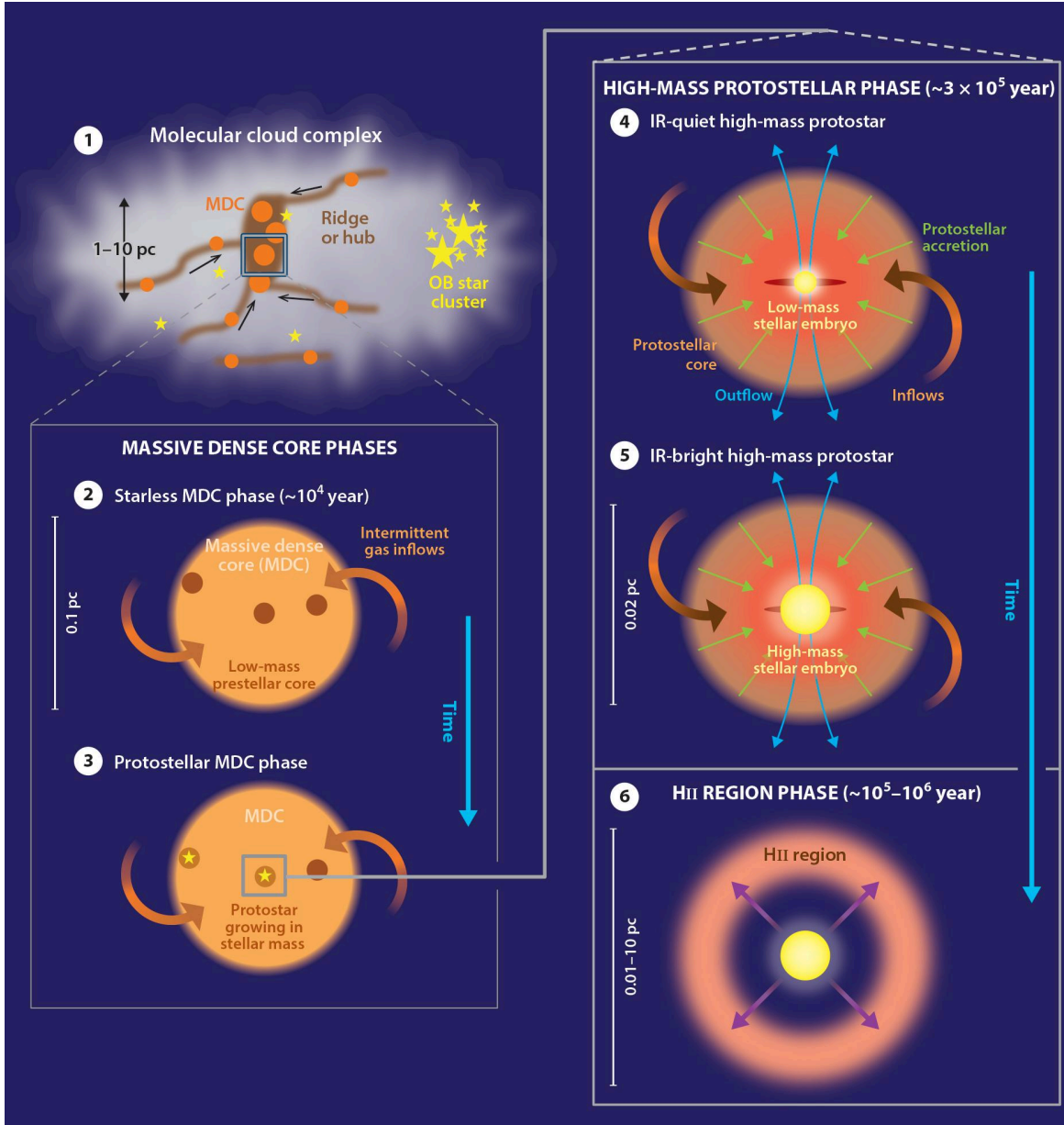


Figure 1.2: Schematic evolutionary sequence of high-mass star formation, adopted from Tigé et al. (2017), adapted by Motte et al. (2018). (1) Massive filaments and spherical clumps are hosts for massive dense cores, where high-mass stars are formed. (2) During the starless phase, the massive dense cores only harbor low-mass prestellar cores. (3) The IR-quiet massive dense cores become protostellar hosting a stellar embryo of low-mass, and as the protostellar cores collapse, the surrounding massive dense cores and filaments/spherical clumps also collapse. (4) High-mass protostars are formed as the protostellar envelopes are accreted in gravitationally driven inflows. (5) High-mass protostars become IR-bright for stellar embryos of $> 8 M_{\odot}$. (6) The accretion of the material stops when the UV of the star ionizes the protostellar envelope and an HII region develops.

1.2.1 Filaments

A filament in molecular clouds is a long, sub-pc, and thread-like structure composed of cold, dense gas and dust (Hacar et al., 2013). Recent observations, particularly from the *Herschel Space Observatory*, have revealed that these filamentary structures are ubiquitous in molecular clouds and essential components in the process of star formation (e.g., Hill et al., 2011; Kirk et al., 2013; André et al., 2014; Peretto et al., 2014; Hacar et al., 2023; Pineda et al., 2023).

The precise characteristics of filaments in molecular clouds remain a subject of considerable scientific debate and investigation. Molecular filaments exhibit a narrow distribution of widths of ~ 0.1 pc, regardless of their mass per unit length at distances $d < 500$ pc (Arzoumanian et al., 2019; André et al., 2022). Discussions are ongoing whether the scale-free width of filamentary structures truly are physical. Utilizing molecular line emission, the width of filaments differ from the 0.1 pc (e.g. ~ 0.03 pc using N_2H^+ in Orion, or ~ 0.4 pc using ^{13}CO in Taurus Hacar et al., 2018; Panopoulou et al., 2014). The reason for the difference of widths using molecular line emissions are due to the molecules tracing high densities. Thus, these molecules trace the higher densities, not reliably tracing the whole filamentary structure (Pineda et al., 2023).

Observational and theoretical studies show that molecular clouds undergo hierarchical fragmentation, initially forming filamentary structures that subsequently fragment into dense, star-forming cores (Peretto et al., 2013; Peretto et al., 2014; Hacar et al., 2018; Hacar et al., 2023; Pineda et al., 2023). High-mass stars are frequently found to form at the intersections of filaments, commonly referred to as hubs (e.g., Motte et al., 2018; Kumar et al., 2020, see Fig. 1.2). The presence of gravitationally unbound and non-star-forming regions (in e.g., Polaris) suggests that the filamentary structures are precursors of clumps and cores (André et al., 2014).

1.2.2 Clumps and cores

Dense condensations known as clumps, typically measuring ≤ 1 pc in size, are commonly observed within molecular clouds (see Fig. 1.2; Motte et al., 2018). These clumps represent localized areas of increased density within the larger cloud structure. The APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al., 2009) is a crucial resource for studying star formation within the inner Galactic plane. This $870\ \mu\text{m}$ dust survey spans 420° , revealing approximately 10 000 dense molecular clumps (Contreras et al., 2013; Urquhart et al., 2014; Csengeri et al., 2014). ATLASGAL builds a large sample spanning all major evolutionary stages, enabling direct comparisons between them and providing a coherent view of star formation activity across the inner Galactic plane (König et al., 2017; Giannetti et al., 2017; Urquhart et al., 2022).

Clumps and cores are prevalent in the Milky, but the exact formation mechanism are not known. Clouds are support by the gas thermal and non-thermal pressure (Pokhrel et al., 2018). The collapse of a cloud is most likely due to gravitational instability, turbulence, magnetic fields, and stellar feedback (Larson, 2006; Pokhrel et al., 2018). A gas cloud is Jeans stable when the outward and inward forces are equal, i.e. in hydrostatic equilibrium. A simplified way to describe the stability of a cloud is to consider the Jeans Mass (Lequeux, 2005):

$$M_{\text{Jeans}} = 1.0 M_{\odot} \times \left(\frac{T}{10\text{ K}} \right)^{1.5} \times \left(\frac{n_{\text{H}_2}}{10^4\text{ cm}^{-3}} \right)^{-0.5}, \quad (1.1)$$

where T is the temperature, and n_{H_2} is the density. Eq. (1.1) is the largest gravitationally stable mass

for a given temperature and density. In the case where either the temperature is too low or the density is too high, thermal pressure cannot support the cloud, thus resulting in collapse.

Looking into the Perseus molecular cloud, Pokhrel et al. (2018) found that at clump to core scales, the gas thermal pressure alone cannot support the fragmentation within clumps. Observations show that the observed number of cores are consistently lower than the expected number of cores, based on the Jeans mass. Compared with the large scale, i.e. cloud scales, the gas non-thermal pressure is efficient in supporting the pressure, but as the fragmentation occurs, at the cores and envelope scales, this non-thermal gas pressure becomes inefficient (Pokhrel et al., 2018).

The typical physical conditions with the evolutionary sequence of clumps are described in detail in Sect. 1.3.1.

1.3 Understanding star formation within Cygnus-X

The composition of the ISM evolves in complexity through the life cycles of stars, primarily composed of hydrogen (Payne-Gaposchkin, 1925). This process begins with nucleosynthesis within stellar cores, where atoms heavier than hydrogen are formed (Hoyle, 1946; Burbidge et al., 1957). Stars maintain stability for varying durations - millions of years for high-mass stars and billions for low-mass stars - primarily fusing hydrogen into helium. As hydrogen fuel depletes, stars expand into giants: red giants for low-mass stars or red supergiants for high-mass stars. The fate of these stars differs based on their mass. Low-mass stars end their lives by ejecting outer layers as planetary nebulae, enriching the ISM with new material for future star formation, while their cores become white dwarfs that cool indefinitely. High-mass stars, on the other hand, end dramatically in supernova explosions, dispersing heavier elements into the ISM. These explosions leave behind either neutron star, for lower-mass massive stars, or black holes, for higher-mass massive stars. This continuous cycle of stellar birth, evolution, and death progressively enriches the ISM with diverse atoms and, consequently, molecules, setting the stage for increasingly complex chemistry in subsequent generations of stars and potential planetary systems.

The formation of stars exhibits a significant distinction between low-mass and high-mass regimes. While the processes governing low-mass star formation are relatively well understood both theoretically and observationally, the formation of high-mass stars remains a challenging area of study in astrophysics.

1.3.1 High-mass star formation (HMSF)

There are two main competing models of HMSF: *competitive core accretion* and *turbulent core accretion* (McKee and Tan, 2002; McKee and Tan, 2003; Krumholz and Bonnell, 2009; Tielens, 2021). The turbulent core accretion is where the entire core condenses into a single, massive star, whereas the competitive core accretion forms fragment of cores within the cores, ultimately uniting into a single, massive star. These models differ in their initial conditions at the molecular cloud stage (Girichidis et al., 2020), where small pockets of over-densities occur, and stars are believed to form. Typical timescales for HMSF are $\sim 10^5$ yr (McKee and Tan, 2002; McKee and Tan, 2003; Mottram et al., 2011). The process of star formation within molecular clouds is a fundamental aspect of galactic evolution and is influenced by various factors such as magnetic fields, galactic dynamics, and the physical properties of giant molecular clouds.

Before the star is formed, the clumps go through evolutionary phases, characterized by their physical

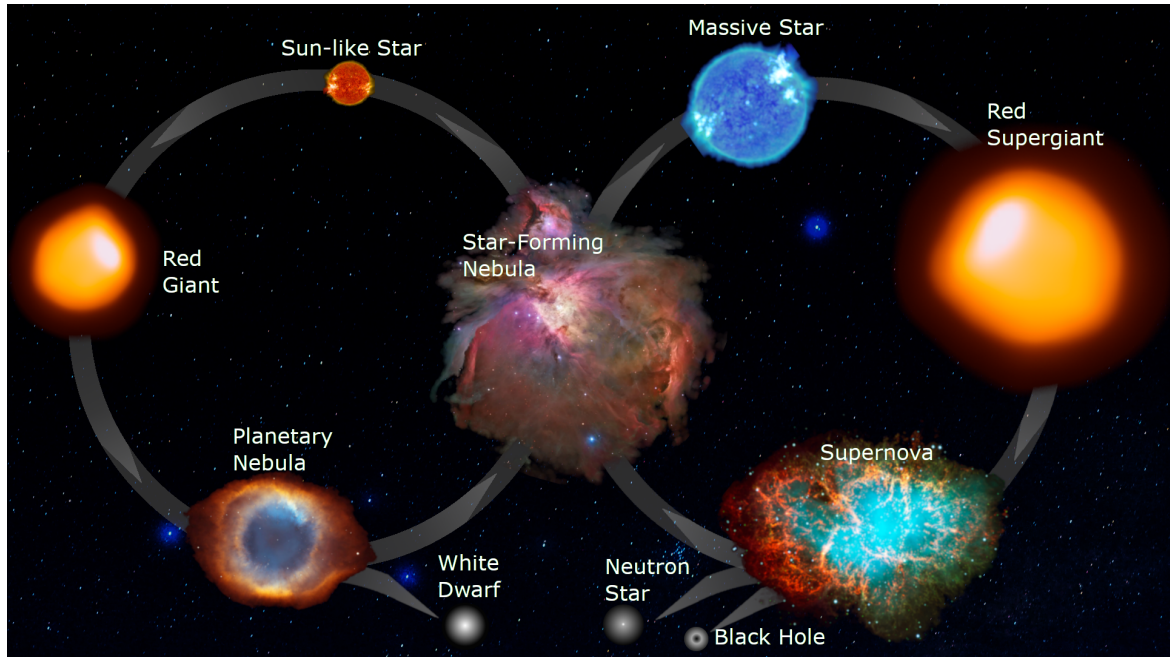


Figure 1.3: Simplified image of the low- and high-mass stellar life cycle. All stars are formed in dense molecular clouds (“Star-forming nebula”), but their evolution differ. The low-mass star (“Sun-like star”) is in a steady state of hydrogen-to-helium fusion for several billion years. As the star exhaust the hydrogen in its core, the low-mass star evolves to a “Red giant”, where it increases in size and loses its mass through stellar winds. As the low-mass star cools down, it leaves its hot core (“White dwarf”), heating up and exciting the surrounding gas and dust (“Planetary nebula”). This gas and dust will later become part of a molecular clouds, forming the next generation of stars. The high-mass star has a much shorter lifetime (millions of years), where it ends its life as a “Supernova”. Depending on the initial mass of the star, the remnant is either a “Neutron star” (lower mass massive stars) or “Black hole” (higher mass massive stars). Image made by Ivalu Barlach Christensen.

conditions based on sub-mm, IR- and radio observations. The evolutionary phases of precursor HMSF process has been divided into four stages, motivated by observational properties; infrared dark clouds (IRDC), high mass protostellar object (HMPO), ultra compact HII region, and hot molecular core (Beuther et al., 2007a; Zinnecker and Yorke, 2007; Gerner et al., 2014; Gerner et al., 2015; Urquhart et al., 2022). Although there are no strict boundaries between these phases, their general properties are described below:

IRDC: Dense, cold regions within molecular clouds, known as Infrared Dark Clouds (IRDCs), appear opaque in mid-infrared wavelengths and provide critical environments for studying the early stages of star formation, particularly for massive stars (Motte et al., 2018). IRDCs are observed as dark silhouettes against the intense mid-infrared emission of the Galactic plane, typically at wavelengths around $8\ \mu\text{m}$ using instruments such as the *Spitzer* or *Herschel* telescopes (Hernandez and Tan, 2015). These regions boast high column densities ($N > 10^{22} - 10^{23}\ \text{cm}^{-2}$) and low temperatures ($< 25\ \text{K}$), creating ideal conditions for star formation (Schneider et al., 2015; Carey et al., 1998). Studies of carbon phases (C_{II} , C_{I} , CO) in IRDCs have found evidence suggesting that these clouds form from atomic gas flows that transition into molecular gas during the cloud formation process (Beuther et al., 2014). IRDCs harbor a rich chemistry, including

molecular tracers like CO, HCO^+ , and N_2H^+ , which helps probe their density and dynamics (Rigby et al., 2024).

HMPO and HMC The subsequent phase corresponds to high-mass protostellar objects, in which the cloud collapses into fragments capable of forming high-mass binaries but not a full cluster (Motte et al., 2018). As the cloud contracts, these overdensities begin to form one or several protostars with masses of $M > 8M_\odot$. A region like this is classified as an High-Mass Protostellar Object (HMPO), where at this stage, hydrogen burning begins. The HMPOs are further categorized to two sub-groups: HMPO and Hot Molecular Core (HMC). During this evolutionary stage, the cloud accretes the surrounding gas in their immediate environment, where the densities and temperature increase, evolving with more complex density structures (Beuther et al., 2002). The HMPO are less evolved, where the environment is colder ($T = 50 - 250$ K) and usually chemically poorer. The HMC are further evolved in a hotter stage ($T = 150 - 500$ K), where the chemistry has evolved to a higher complexity (Gerner et al., 2014; Gerner et al., 2015). This stage can be observed in the mid-IR range.

UCHII This final stage, an ultra-compact HII region (UCHII), can overlap with the HMC-stage with the same temperature range ($T = 150 - 500$ K). At this stage, most of the immediate surrounding gas has been accreted, with the stellar winds from the protostar fully ionizing the environment.

Table 1.2: Physical properties of the HMSF, adopted from Motte et al. (2018); Table 1.

Source nature	IRDC fragments, clumps	HMPO clumps	MDCs, dense cores
FWHM (pc)	~ 0.5	~ 0.5	$0.1 - 0.2$
Mass ($M_\odot$)	~ 150	~ 290	~ 150
$< n_{\text{H}_2} > (\text{cm}^{-3})$	$\sim 5 \times 10^4$	$\sim 6 \times 10^4$	$\sim 2 \times 10^6$
d_{Sun} (kpc)	1.8–7.1	0.3–14	1.4

Acronyms: FWHM, full width at half maximum; HMPO, high-mass protostellar object; IRDC, infrared-dark cloud; MDC, massive dense core.

The latter three stages, HMPO, HMC, and UCHII, may overlap in the physical conditions (Gerner et al., 2014). An overview of typical size, mass, density, and distances of the evolutionary stages are summarized in Table 1.2.

The evolutionary stages are also classified observationally based on their physical properties. Urquhart et al. (2022) classified the increasing evolutionary stages as: quiescent, protostellar, young stellar object (YSO), and HII. **Quiescent** clumps appear dark at wavelengths of $70 \mu\text{m}$ or less. As **protostellar** objects take shape inside these clumps, the energy released during their growth heats up the surrounding material, causing the peak of their light emission to move towards shorter wavelengths. This heating makes the protostar visible initially at $70 \mu\text{m}$, then in the mid-infrared ($\leq 24 \mu\text{m}$), and ultimately in the near-infrared as it develops into **YSO**. High-mass stars emit a lot of UV radiation, ionizing the gas around them and forming **HII** regions that can be identified by their compact radio and mid-infrared emissions. This progressive change in the light emitted allows us to use specific far-

and mid-infrared images ($3.6\ \mu\text{m}$, $24\ \mu\text{m}$, and $70\ \mu\text{m}$) to differentiate between clumps that are quiet and those actively forming stars, and also to categorize the objects embedded within them. Urquhart et al., 2022 found that the HII phase is half the timescale of the YSO phase, whereas the statistical timescale that they found for the protostellar phase is similar to that of the HII phase. The evolutionary sequences of the clumps in the Cygnus-X complex are investigated in Chapters 5 and 6.

1.3.2 The Cygnus-X cloud complex

Cygnus-X, situated in the constellation Cygnus, is recognized as one of the richest star-forming regions in our galaxy (see Figure 1.1). Cygnus-X occupies a vast area within the Milky Way galaxy, approximately $170 \times 170\ \text{pc}$ (Reipurth and Schneider, 2008; Beerer et al., 2010), characterized by high-energy phenomena such as star formation regions, supernova remnants, and dense clouds of gas and dust. This region is massive and luminous (e.g., Kumar et al., 2007; Beerer et al., 2010) at a relatively nearby distance ($\sim 1.5\ \text{kpc}$, Rygl et al., 2012), making it an excellent hunting ground to study various phases of massive star formation (Beuther et al., 2022). The whole Cygnus-X cloud contains $\sim 3.4 \times 10^6\ M_{\odot}$, a very rich environment with OB-associations, Wolf-Rayet stars and +800 HII-regions (Schneider et al., 2010). The nearby OB-association is blasting the region with UV radiation and stellar winds, but no excess luminous protostars are found near the association suggesting that these 100s of massive stars are not influencing the formation of protostars (Kryukova et al., 2014). With the close proximity to large OB-associations, Cygnus-X is also a great site to study the feedback processes of already formed stars on the remnant ISM. Figure 1.1 shows the Cygnus-X complex in different gas and dust tracers.

Cygnus-X has undergone intense and widespread star formation over the past few million years. Its associated giant molecular cloud complex hosts objects at various stages of stellar evolution, including dense, hot cores with embedded protostars, and filaments (Schneider et al., 2006; Motte et al., 2007; Motte et al., 2010; Dib et al., 2020). Several OB associations are present in the region, a testament to the formation of stars over millions of years. Over 1000 protostars have been observed with the *Spitzer* Legacy Survey (Beer et al., 2010; Kryukova et al., 2014). These protostars in Cygnus-X concentrate in large filamentary structures (Kryukova et al., 2014), including a super-bubble driven by the stellar winds of O-type stars, and the famous Cygnus Loop supernova remnant, namely the “Diamond Ring” (Marston et al., 2004). Cygnus-X exhibits varied characteristics, and its close proximity provides us with a unique opportunity to observe and analyze these complex astronomical processes.

For these reasons, Cygnus-X is an ideal target to observe ongoing star formation. *Herschel*, *Spitzer*, and several radio telescopes have carried out surveys towards this large and close molecular cloud. Recent observations at mm- and cm wavelengths have provided extensive data on dust, ionized gas, and molecular gas emission in the region. For instance, observations have revealed the presence of compact sources, filamentary structures, and extended emission in both continuum and spectral line observations (Taylor et al., 2003; Motte et al., 2010; Molinari et al., 2010; Cao et al., 2021; Li et al., 2021; van der Walt et al., 2021; Cao et al., 2022).

Motte et al. (2007) explored the wealth of massive star-forming regions in Cygnus-X with a $3^{\circ}2$ survey at wavelength of 1.2-mm using the IRAM-30m telescope’s MAMBO and MAMBO-2 cameras, and determined that there is no sudden star-formation burst happening in the molecular cloud, but rather a dynamical ongoing star-formation across the cloud. The cloud complex is probed at column densities of $N(\text{H}_2) \sim 9 \times 10^{21} - 2 \times 10^{24}\ \text{cm}^{-2}$, with the northern region named CygX-North (which coincides with the region of Cygnus-X in this thesis) and the southern region, CygX-South. Motte

et al. (2007) observed that CygX-North and CygX-South have different concentrations of gas and found that CygX-North is 5 times more efficient in forming protostars than CygX-South.

A more recent catalog of clumps has been identified by Cao et al. (2019), covering a larger area of $5 \times 6^{\circ 2}$ towards the Cygnus-X. Only $2.2^{\circ 2}$ of the Cygnus-X region is covered by both Cao et al. (2019) and Motte et al. (2007). Using mm-wavelength continuum, Motte et al. (2007) identified compact cloud fragmentation of < 1 pc, and Cao et al. (2019) used the *Spitzer* Legacy Survey observations and 1.2-mm continuum to identify clumps with masses of $M \geq 23.3 M_{\odot}$ at 0.1 pc. Furthermore, these clumps are associated with either observational HMSF-signatures of class II methanol masers or UCHII regions.

129 dense cores at 1.2-mm wavelength are identified by Motte et al. (2007), where 66 are observed with CASCADE (see Sect. 2.2.1), and 151 massive dense cores are detected by Cao et al. (2019). 16 clumps of the Cao et al. (2019) catalog are not detected and added to the complete list of clumps. A total of 82 clumps are observed with the CASCADE survey. These clumps are focused on in Chapters 5 and 6.

DR21

The most active, dense, and massive region in Cygnus-X is the DR21 filament (Dickel et al., 1978; Wilson and Mauersberger, 1990; Jakob et al., 2007; Hennemann et al., 2012). The DR21 region, located at R.A.(J2000) = 20:39:01.6 and δ (J2000) = +42:19:38, represents a prominent astronomical site characterized by intense massive star formation activity (see Figure 1.4; Schneider et al., 2006; Schneider et al., 2010; Bonne et al., 2023). Situated within the expansive Cygnus-X molecular cloud complex, the DR21 molecular cloud a dense filamentary structure that hosts multiple dense cores along its length (Hennemann et al., 2012). The filament has width of ~ 0.13 pc with a length of ~ 3.6 pc with a mass of $M = 1048 M_{\odot}$ (Hu et al., 2021). The southern portion of the filament harbors a compact HII region, signifying ongoing star formation processes (Hennemann et al., 2012).

These diverse components within the filament emphasize the complex nature of the DR21 region and its significance in the study of massive star formation processes (Hennemann et al., 2012; Koley et al., 2021). This region is notable for its proximity to the stellar association Cygnus OB2 and contains prominent water masers, particularly near the DR21(OH) sub region. Spectroscopic observations, specifically self-absorption features in ^{12}CO emission, suggest the presence of W75N, a colder molecular cloud that may be positioned along the line of sight towards DR21 (Schneider et al., 2010). This complex interplay of structures and temperatures within the DR21 region underscores its significance as a laboratory for studying the processes of massive star formation and the evolution of molecular cloud complexes.

DR21 has previously been studied with the IRAM telescope in tracers such as CO, CS, C^{34}S , HCO^+ , H^{13}CO , N_2H^+ , H_2CO by Schneider et al. (2010). They find that a dynamic, rapid mode of star formation occurs in the filament, with the filament collapsing globally. The DR21-ridge exhibits different properties in its northern and southern parts, and clumps in the filament exhibit a gradient of evolutionary phases. (Hennemann et al., 2012). Previous JCMT studies have shown that H_2D^+ traces cold, quiescent gas (Pillai et al., 2012) near the DR21 filament. Pillai et al. (2012) observed an anti-correlation of star formation imaged using the sub-millimeter array (SMA) and the H_2D^+ in the DR21-filament. The details of observations toward Cygnus-X and DR21, that are used in this thesis, are described in Sect. 2.2.1.

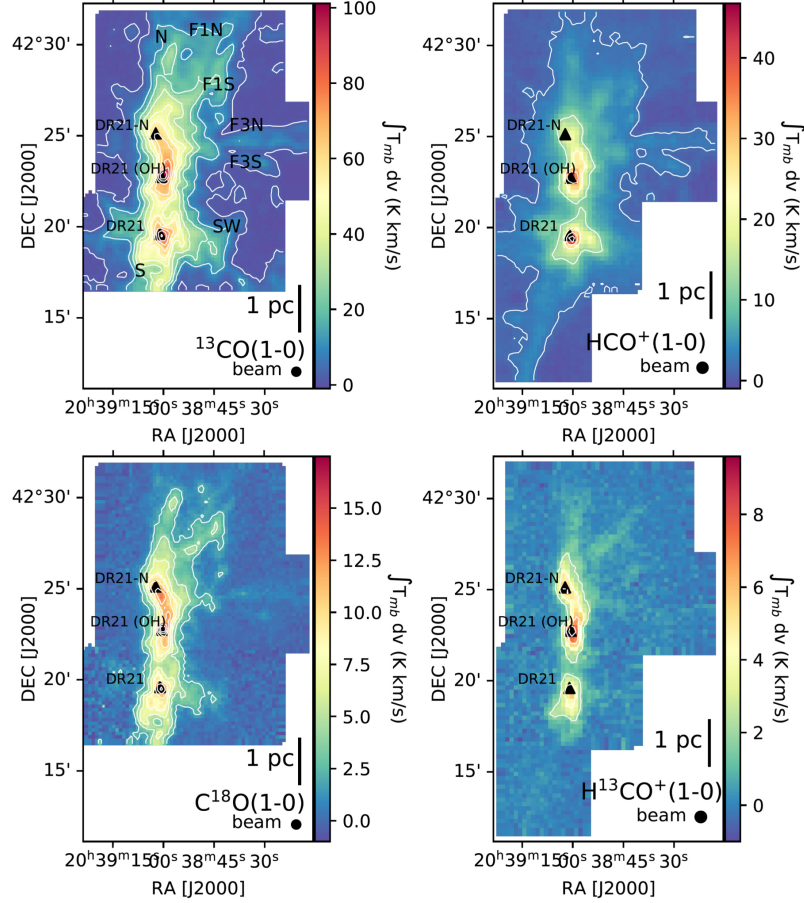


Figure 1.4: The DR21 filament adopted from Bonne et al. (2023). *Top left*: integrated brightness map of ^{13}CO (1–0) toward the DR21 cloud. Overlaid on the map are the integrated intensity contours starting at 2 K km s^{-1} with increments of 10 K km s^{-1} . The subfilaments in the cloud are indicated with their names. *Top right*: same as the top left panel, but for HCO^+ (1–0) with increments of 5 K km s^{-1} . *Bottom left*: same as the top left panel, but for C^{18}O (1–0), with contour increments of 2 K km s^{-1} . *Bottom right*: same as the top left panel, but for H^{13}CO^+ (1–0), with contour increments of 2 K km s^{-1} . The locations of the DR21 radio continuum source (Downes and Rinehart, 1966) and the DR21(OH) and DR21–N massive clumps (e.g., Motte et al., 2007) are indicated with black triangles.

1.4 Probing molecular clouds with molecules

Light, and its behavior, is our strongest tool when observing the Universe. The baryonic matter (stars, planets, galaxies) only makes up $\sim 5\%$ of the Universe. In order to explore the structures, dynamics, and evolution of the baryonic matter, understanding it is important (Yamamoto, 2017).

Baryonic matter is composed of 98% hydrogen and helium, and only 2% consists of the remaining atoms of the periodic table (see Fig. 1.5; Johnson, 2019). Despite only making up such a small part of the Universe, these heavy atoms enrich the ISM with a rich chemical world.

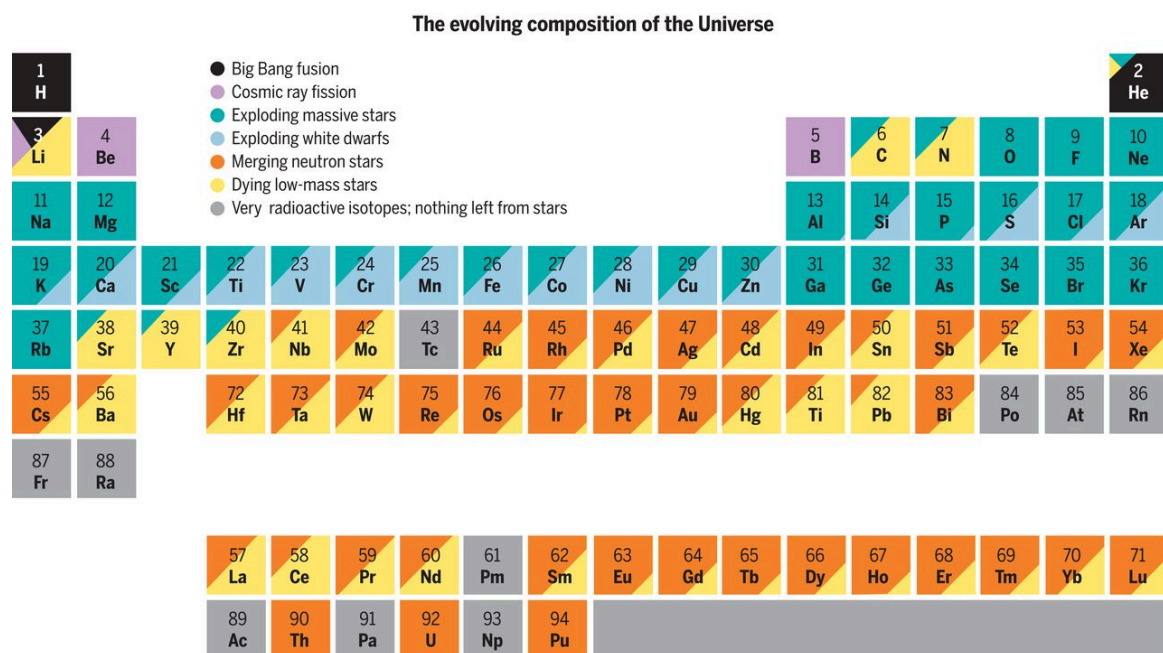


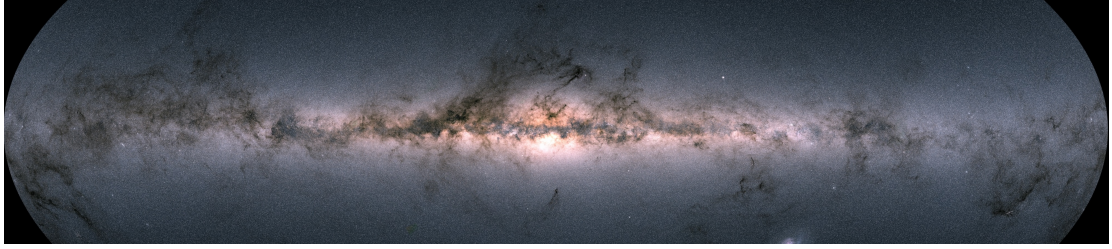
Figure 1.5: Periodic table of atoms, color-coded relevant to their nucleosynthesis sources, adopted from Johnson (2019). Black, purple, green, blue, orange, and yellow show the naturally occurring elements of our Solar System from Big Bang fusion, CR fission, exploding massive stars, exploding white dwarfs, merging neutron stars, dying low-mass stars, respectively. Gray show artificially made elements.

Molecules play a strong role in molecular clouds as coolants of the gas, but also as a strong diagnostic of the physical conditions pertaining gas. One molecule has its own unique radiation it emits, just like a person has its own unique fingerprints. The knowledge of how these radiations are emitted allows us to understand the conditions that the molecules are in (Yamamoto, 2017). Furthermore, molecules are formed from the atoms in the ISM, and interact with each other, building complex molecules, later becoming the building blocks to form stars, planets, similar to our own Solar System.

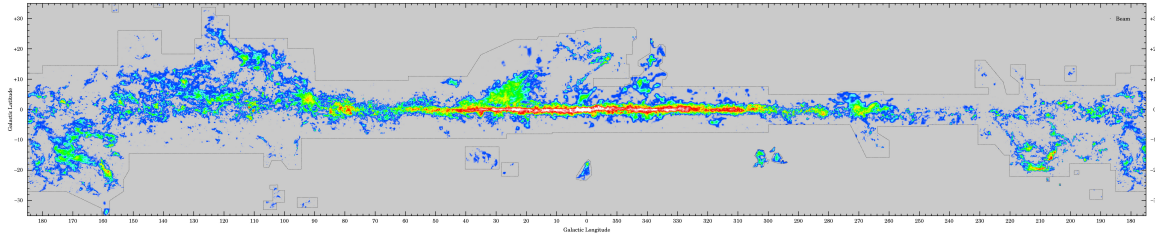
The field studying the formation, destruction, and excitation of molecules (*chemistry*) in space (*astro-*) is called “astrochemistry”. This interdisciplinary field aims characterize the chemistry utilizing the various extreme conditions in space, and vice versa, utilizing laboratories to probe the physical properties, such as temperature, radiation fields, and densities, of various interstellar environments (Dalgarno, 2008; van Dishoeck, 2018). One specific molecule emits several “colors” (specific frequencies of radiation) unique to its specific elemental composition. The intensity of the different radiation emitted by the molecule depends on the temperature of the gas and the density of the gas

collisionally exciting the molecules.

The low energy regions of molecular clouds emit in the (sub-)mm wavelength regime through their rotation transitions, which can be observed with radio telescopes. Figure 1.6 shows the Milky Way Galactic plane stellar population using the Gaia telescope in optical wavelength (Gaia Collaboration et al., 2016), and the large-scale survey of CO emission toward the same region. As can be seen in these figures, the dark spots of molecular clouds in the optical wavelengths can be seen as bright regions in CO line emission (Dame et al., 2001).



(a) The Milky Way Galactic plane observed with the Gaia telescope. The brighter regions indicated dense concentration of especially bright stars. Acknowledgment: Gaia Data Processing and Analysis Consortium (DPAC); A. Moitinho / A. F. Silva / M. Barros / C. Barata, University of Lisbon, Portugal; H. Savietto, Fork Research, Portugal. Credit: ESA/Gaia/DPAC.



(b) The Milky Way molecular clouds. The large-scale survey CO emission of the Galactic plane was observed with the CfA 1.2-m and a similar telescope in Cerro Tololo in Chile. The figure is adopted from Dame et al. (2001).

Figure 1.6: The Milky Way in optical (top) and radio wavelength (bottom).

1.5 About this thesis

In this thesis, we investigate the nearby massive and luminous region, a great HMSF region, Cygnus-X, using observations in the sub-mm wavelength.

1.5.1 Motivation

Massive stars form within dense molecular clouds, and the composition and dynamics of these clouds impact the star formation process. The interplay between various physical phenomena, including gravitational collapse, turbulence, magnetic fields, and feedback mechanisms, shapes the molecular environment and ultimately determines the efficiency and characteristics of massive star formation.

Essential components within molecular clouds are filamentary structures, narrow cylindrical bands of gas. These are believed to funnel gas and condense into star-forming clumps. The Cygnus-X region hosts intense star-forming clumps with a broad range of stellar evolutionary stages (Motte et al., 2007;

Beerer et al., 2010). This region harbors the DR21 filament, the most dense and active region within Cygnus-X (Dickel et al., 1978; Hennemann et al., 2012).

Deuterated molecules are efficiently formed in cold, dense regions. In these regions, the deuterated fraction is expected to be enhanced compared to the interstellar average. These properties make the deuterated fraction an excellent tracer of the earliest phases of star formation. Additionally, the changes in physical and chemical conditions as star-formation progresses affect the deuterated fraction, allowing them to also trace the evolution of star-formation (e.g.; Fontani et al., 2014; Gerner et al., 2015).

1.5.2 Goals

The scientific objectives of this thesis is:

- To explore deuterated molecules, and the fraction of their hydrogen counterparts, on a large scale in filamentary structures with ongoing star formation.
- To determine the physical conditions of high-mass star-forming clumps.
- To study the chemical conditions of high-mass star-forming clumps, specifically in the Cygnus-X region.
- Finally, to investigate the deuterium fractionation as star-formation progresses in clumps.

1.5.3 Outline

The next chapters describe the observational techniques, telescopes, and surveys used in this thesis (Chapter 2), and further details on astrochemistry and how to discern the physical and chemical processes in molecular clouds (Chapter 3). Chapter 4 presents a summary of the published article on large-scale deuteration in the DR21 filament. Chapter 5 presents a summary of the submitted article on deriving the physical conditions of clumps in Cygnus-X, the GLOSTAR pilot region, and the M8 region, utilizing the ground-state H_2CO transition. Chapter 6 presents the results, analysis, and discussion on the chemical modeling and deuteration in the clumps in Cygnus-X.

Observations

And when every constellation suddenly
appeared
Through telescopes and calculations,
the far was pulled so near

Sleeping at last - Overture

The formation of massive stars occur deeply embedded in their natal molecular clouds. These denser regions of molecular clouds are obscured in the optical and IR, but are optically thin in the FIR and radio wavelength emission. Due to the Earth's atmosphere (mainly water vapor), the atmosphere is opaque for FIR emission, thus for ground-based observations, the radio wavelength regime is optimal. At the highest radio frequency regime (~ 1 THz), water and oxygen absorb the incoming radiation. In the lower radio-frequency regime (~ 30 MHz), the ionosphere reflects incoming radiation. However, between the shortest and longest wavelengths of the radio wavelength regime, there are atmospheric frequency windows that allow radiation to pass through. In the sub-mm wavelength regime, atmospheric water vapor attenuates the interstellar radiation, hindering observations. Therefore, dry places (with lower atmospheric water vapor and lower pressure, resulting in narrower absorption bands of water vapor), such as high altitudes, are great sites for radio telescopes operating at mm/sub-mm wavelengths. At these wavelengths, the rotational transitions of molecules dominate the emission $\rightarrow$ thermal radiation $\rightarrow$ thus allowing astronomers to observe the cold molecular clouds.

In this chapter, the fundamental properties of telescopes are presented. The telescopes used in this thesis are introduced. The Cygnus-X survey, CASCADE, follow-up observations in these regions, as well as the surveys towards the GLOSTAR pilot region and the M8 region are presented. Lastly, the data reductions of all observations used in this thesis are described in detail.

2.1 The basic properties of a radio telescope

General references: Gulkis and de Pater (2003) and Liu and Yu (2020).

In this section, the basic properties of a telescope are presented. Radio telescopes are characterized by the amount of power they collect from astronomical source (flux density), how well they can distinguish structures on the sky (angular resolution), how effectively they convert incoming waves

into signal (effective area and efficiency), and how their output is limited by random noise. In principle, radio antennae can both receive and emit electromagnetic radiation; in radio astronomy the receiving properties are utilized. The electromagnetic radiation hitting a radio telescope induces a voltage, U . This voltage is measured and processed with the receivers, making it possible to decipher the interstellar electromagnetic radiation.

Flux density

The observable power from an astronomical source is defined as the flux density. The flux is defined as the integrated source temperature over the solid angle of the source. The unit of the flux density is Jansky ($1 \text{ Jy} = 10^{-26} \text{ W}$), in honor of Karl Jansky. The flux density is:

$$S_\nu = \frac{c^2}{2k_B \nu^2} \int \int T_B d\Omega \quad (2.1)$$

For a single dish telescope, the total power received from an astronomical source with flux density, S_ν , is:

$$P = A_{\text{eff}} \times S_\nu \times \Delta\nu, \quad (2.2)$$

where $\Delta\nu$ is the bandwidth and A_{eff} is the effective area.

Effective area and main beam efficiency

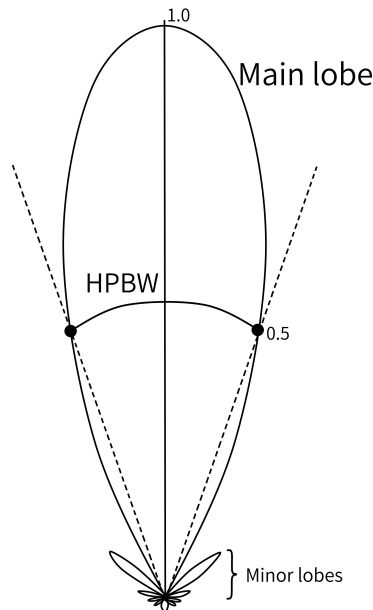


Figure 2.1: Sketch of the 2-dimensional power pattern of an antenna. The width at half-power beam of the main lobe denotes the angular resolution of the telescopes.

Although the antenna receives radiation from all directions, the receiver is not equally sensitive to radiation from all directions. The effective area is an idealized area where radiation is fully covered to obtain the same telescope gain as the actual telescope. This is related to its physical size. The main beam efficiency of the telescope is determined as the ratio of the power obtained in the main beam solid angle to that of the power obtained in the beam solid angle. The integrated area over the main beam lobe is defined as the beam solid angle, $\Omega_{\text{beam,main}}$, whereas the integration of the entire sky is defined as the beam solid angle, Ω_{beam} . Figure 2.1 shows the power pattern of an antenna in two dimensions. The power pattern of a telescope is described in lobes, where the main lobe is the dominant contribution to the power.

This effective area is also dependent on the beam and the wavelength as:

$$A_{\text{eff}} = \frac{\lambda^2}{\Omega_{\text{beam}}}. \quad (2.3)$$

The half-power at the main beam in angular units is the angular resolution of the telescope.

Angular resolution

The angular resolution is the measure of the smallest angular separation on the sky that the telescope can distinguish. The resolving power is limited by the aperture of the telescope and the observing wavelength, λ (Wilson et al., 2009). The half-power of the main beam in angular units is:

$$\theta_{\text{FWHM}} \simeq 1.1 \frac{\lambda}{D}. \quad (2.4)$$

Detailed observation in the (sub-)mm wavelength regime resolving the sub-structure within molecular clouds and star-forming region required radio telescope with large diameters.

The construction of these large antenna comes with great difficulty as the construction has to support the antenna against gravity. Since the 1970s, the largest steerable European telescope has been in action, credited to the Max-Planck-Gesellschaft (MPG), the Effelsberg 100-m telescope. Due to its enormous size, gravity deforms the main reflector of the telescope when tilted from zenith. However, homologous deformation allows the telescope to always obtain paraboloid shape, though with different parameters (Nothnagel et al., 2010).

Temperatures and noise

In radio astronomy, the signal obtained from the sky brightness is related to an antenna temperature, assuming the source is ideal, emitting as a blackbody. The Planck's law in the long wavelength (low frequency) regime low temperatures (i.e. $h\nu/k_B T$ is low) allows the Taylor approximation limited to the first term only, known as the Rayleigh-Jeans approximation. Thus, the brightness temperature of the source is proportional to the flux density of the source:

$$T_B = \frac{2k_B \nu^2 S_\nu}{c^2 \Omega_{\text{beam}}}, \quad (2.5)$$

where c is the speed of light, k_B is the Boltzmann constant, and ν is the frequency.

The total collected temperature of an antenna is the sum of all the contributing radiation; the system of the telescope, the atmosphere, the background emission of the sky and the source brightness:

$$T_a = T_{\text{sys}} + T_{\text{atm}} + T_{\text{sky}} + T_B. \quad (2.6)$$

Everything emits radiation. The antenna temperature collects all the radiation, where all but the source brightness temperature are contributing to the noise levels.

The noise of observation can be reduced greatly by increasing the integration time, τ . The ideal radiometer equation for a total power receiver relates the integration time and the bandwidth, $\Delta\nu$ as:

$$\sigma \simeq \frac{T_{\text{sys}}}{\sqrt{\Delta\nu \tau}} \quad (2.7)$$

2.1.1 Telescopes used in this thesis

Data are obtained utilizing several telescopes. In the following, the facilities used to obtain the data used in this thesis are described as well as the observations.

Atacama Pathfinder EXperiment (APEX)

The overview of APEX is based on Güsten et al. (2006) and the APEX telescope instrument overview page¹.

The Atacama Pathfinder EXperiment (APEX) is located in the Chilean High Andes on Llano de Chajnator, at an altitude of 5104 m. The APEX telescope is a modified prototype for the nearby Atacama Large Millimeter Array (ALMA) telescope with a paraboloidal main reflector with a diameter of 12-m, accommodating one Cassegrain (C) and two Nasmyth (A+B) receiver cabins.

The new FaciLity APEX Submillimetre Heterodyne (nFLASH) 230 receiver is located in the A cabin, with dual sideband and dual polarization capabilities. Each sideband and polarisation has an IF coverage spanning 4–12 GHz, recorded by two Fast Fourier Transform Spectrometer (FFTS; inner: 4–8 GHz, outer: 8–12 GHz).

The APEX telescope using the nFLASH230 receiver, is used for pointed observations towards the clumps in the Cygnus-X region, the GLOSTAR pilot region, and the M8 region to cover the $\text{H}_2\text{CO } J = 3 - 2$ transitions at 218 GHz. This project is summarized in Chapter 5.



Figure 2.2: The APEX telescope at Llano de Chajnator, Chile.

Institut de Radioastronomie Millimétrique (IRAM)

The overview of the IRAM observatories are based on the IRAM 30-m² and NOEMA³ instrument overviews, unless otherwise stated.

The IRAM institute, based in Grenoble, France, operates two observatories: a single-dish radio telescope and an interferometric array of 12 telescopes.

¹ <https://www.apex-telescope.org/ns/observing-run/observing/the-telescope/instruments/>

² <https://iram-institute.org/science-portal/30-meter-telescope/>

³ <https://iram-institute.org/science-portal/noema/>

IRAM 30-m telescope



Figure 2.3: The IRAM 30-m telescopes close to Pico Veleta, Spanish Sierra Nevada.

the E090, E150, E230, and E345 receivers, around 90, 150, 230, and 345 GHz, of which certain pairs can be observed simultaneously.

The Cygnus Allscale Survey of Chemical and Dynamical Environments (CASCADE, explained in detail in Sect. 2.2.1) utilized the IRAM telescopes. The observations using the E090 receiver as part of CASCADE are used in this thesis (Chapters 4, 5, and 6). Furthermore, the IRAM 30-m telescope was used to map the extended emission of deuterated molecules using the E230 receiver. This project is summarized in Chapter 4.

The single-dish IRAM 30-m telescope is located in the Spanish Sierra Nevada, on Pico Veleta, at an altitude of 2820 m. The IRAM 30-m telescope is one of the largest and most sensitive millimeter radio telescopes in the world, with its diameter of 30 m,. Since the commissioning of the telescope in 1984, the IRAM 30-m telescope has evolved, now equipped with continuum cameras and heterodyne receivers.

The heterodyne receiver, Eight Mixer Receiver (EMIR⁴; Carter et al., 2012), on the telescope enables dual-sideband and dual-polarization observations. It covers four frequency ranges, namely

NOrthern Extended Millimeter Array (NOEMA)

The NOrthern Extended Millimeter Array (NOEMA) is located in the French Alps on Plateau de Bure at an altitude of 2550 m. Previously known as the Plateau de Bure Interferometer (Guilloteau et al., 1992), the telescope was built in the 1980s, starting with three telescopes, and continuously expanded to the current 12 telescope array named NOEMA, and operates in the cm to mm wavelengths regime.

NOEMA observations are part of the CASCADE survey, described in Sect. 2.2.1.

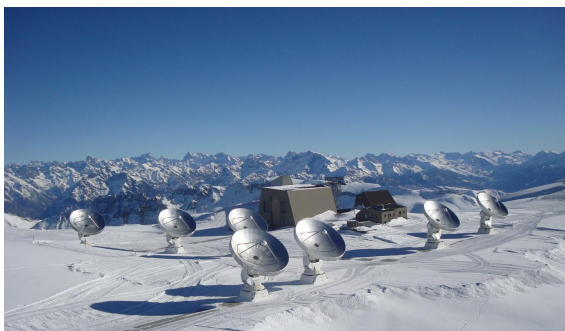


Figure 2.4: The NOEMA telescope array at Plateau de Bure. Photo credit: IRAM/André, R.

Green Bank Telescope (GBT)

The overview of the GBT observatory is based on the GBT instrument overview⁵.

The Green Bank Telescope is located in Green Bank, West Virginia, USA. With its large 100-m

⁴ <http://www.iram.es/IRAMES/mainWiki/EmirforAstronomers>

⁵ <https://greenbankobservatory.org/portal/gbt/instruments/>

effective diameter, the GBT ranks as the world’s largest fully steerable telescope and operates in the millimeter wavelength regime.

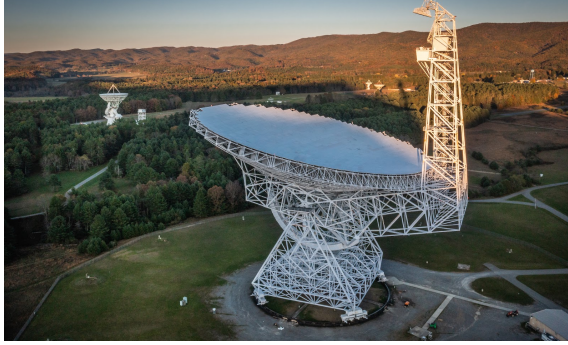


Figure 2.5: The Green Bank Telescope in West Virginia.
Photo credit: Jay Young.

MUSTANG-2, a receiver on the GBT, is a continuum camera at the GBT that observes using an “on-the-fly” (OTF) scanning method. It has a 5.8’ instantaneous field of view composed of a 338-element array of feedhorn-coupled transition-edge sensor (TES) bolometers (Dicker et al., 2014).

The continuum observations of Cygnus-X using this receiver are used in Chapter 6.

2.2 Surveys

The following sections describe the scientific objectives of the surveys used in this thesis. An overview of the surveys is shown in Table 2.1.

Table 2.1: Overview of surveys used in this thesis.

Survey	Telescope	Receiver	Mode	Project ID	PI
CASCADE	IRAM 30-m	E090	OTF	031-20	Dr. F. Wyrowski & Dr. H. Beuther
DR21	IRAM 30-m	E150 & E230	OTF	053-21	I. B. Christensen
Cygnus-X	APEX	nFLASH 230	PSW	M-0109.F-9508C-2022	I. B. Christensen
GLOSTAR	APEX	nFLASH 230	PSW	M-099.F-9519A-2017	Dr. H. Nguyen & I. B. Christensen
M8	IRAM	E090	PSW	141-21	Dr. F. Wyrowski
M8	APEX	nFLASH 230	PSW	M-0107.F-9530C-2021	Prof. K. M. Menten

2.2.1 The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE

The overview of CASCADE is based on Beuther et al. (2022), unless stated otherwise.

Cygnus-X, as described in Sect. 1.3.2, offers an ideal site for studying the various phases of star formation. The MPG and IRAM jointly initiated an observational program to study this region, namely the **Cygnus Allscale Survey of Chemistry and Dynamical Environments**. It combines large-scale observations from the IRAM 30-m telescope and small-scale surveys within the Milky Way, such as the CORE survey (Beuther et al., 2018). This combination bridges the gap between large-scale cloud

surveys in the Milky Way (and galaxies) and core-scale surveys within the Milky Way, such as the ATLASGAL survey. Since the Cygnus-X region is an active site of HMSF, this survey aims at:

- detailed studies of cloud collapse kinematics,
- detailed studies of the filaments, including analysis of gas-flow along them,
- detailed studies of deuterated molecules, including the influence of YSOs on deuteration levels and the behavior of similar deuterated molecules.

The Cygnus-X region of CASCADE was covered with 40 mosaic tiles. OTF mapping observations at 3.6 mm wavelength covered $1000''^2$ in the Cygnus-X complex using the IRAM 30-m telescope (Project ID: 031-20; PIs: F. Wyrowski and H. Beuther). The selected area is based on *Herschel* SPIRE 250 μm and PACS 70 μm continuum emission data taken from the HOBYS program (Motte et al., 2010, see Fig 2.6 for the coverage of CASCADE with the IRAM 30-m telescope.). Using the EMIR receiver and using the Fourier Transform Spectrometer 195 kHz (FTS200), the large bandwidth covers several deuterated molecules and ground-state lines of e.g. HCO^+ , HCN , HNC , and H_2CO . A bandwidth of 8 GHz per sideband (in total, a frequency coverage of 16 GHz) with EMIR E090 in both polarization was covered. The spectral channel resolution is 195 kHz (equivalent to a velocity resolution of $\sim 0.8 \text{ km s}^{-1}$) with a HPBW of $33.4''$ at 72.0 GHz.

Similarly, the small-scale structures are observed in mosaic tiles, using the NOEMA telescopes, with each mosaic tile made up of 78 individual pointings. These observations were conducted in both the C- and D-configurations. Achieving a sensitivity of $\sim 11 \text{ mJy}$ at a 150 kHz channel resolution requires ~ 9 hrs of observation time. The first studies utilizing observations with the NOEMA telescopes look into the accretion flows towards evolving H II region in DR20 (Beuther et al., 2022), the outflow nature of the biggest (in size and mass) outflow in our Milky Way, the DR21 Main outflow (Skretas et al., 2023), and the comet-like complexity of the DR18 H II region (Kim et al., 2025).

The observations of CASCADE are the foundation for this entire thesis.

Observations of the DR21 filament

The overview of the observations towards the DR21 filament is based on Christensen et al. (2024), unless stated otherwise.

The DR21 filament was observed with the IRAM 30-m telescope during five nights in 2021 July 15 - July 19 (Project ID: 053-21; PI: I. Barlach Christensen, Christensen et al., 2024). The aim was to cover the higher J -transitions of DCO^+ , DNC , and DCN . Five tiles of OTF maps, each of size $\sim 120'' \times 120''$, were carried out using the E150 and E230 receivers. The tiles are outlined in red boxes in Fig. 2.7. Each tile, consisting of two combined coverages, was observed with a scanning velocity of $3''8 \text{ s}^{-1}$. The FTS covered 8 GHz bandwidth in each sideband in both polarization. The spectral resolution is 195 kHz. Covering $\text{N}_2\text{D}^+ (2-1)$ and $\text{DNC} (2-1)$ transitions, the E150 receiver was tuned to 150.25 GHz in the upper inner sideband, corresponding to a spectral resolution of 0.38 km s^{-1} at $\sim 154 \text{ GHz}$ and angular resolution is $\theta \sim 16''$ for $\text{DNC} (2-1)$. The total frequency coverage is 132.2–140 GHz in the lower sideband and 148–155.7 GHz in the upper sideband.

Covering $\text{DCO}^+ (3-2)$, $\text{DCN} (3-2)$ and $\text{N}_2\text{D}^+ (3-2)$, the E230 receiver was tuned to 216.75 GHz in the lower outer sideband, corresponding to a spectral resolution of 0.25 km s^{-1} at $\sim 231 \text{ GHz}$ and angular resolution of $\theta \sim 12''$ for $\text{DCO}^+ (3-2)$. The total frequency coverage of 214.4–222.2 GHz for the lower sideband and 230.1–237.9 GHz for the upper sideband.

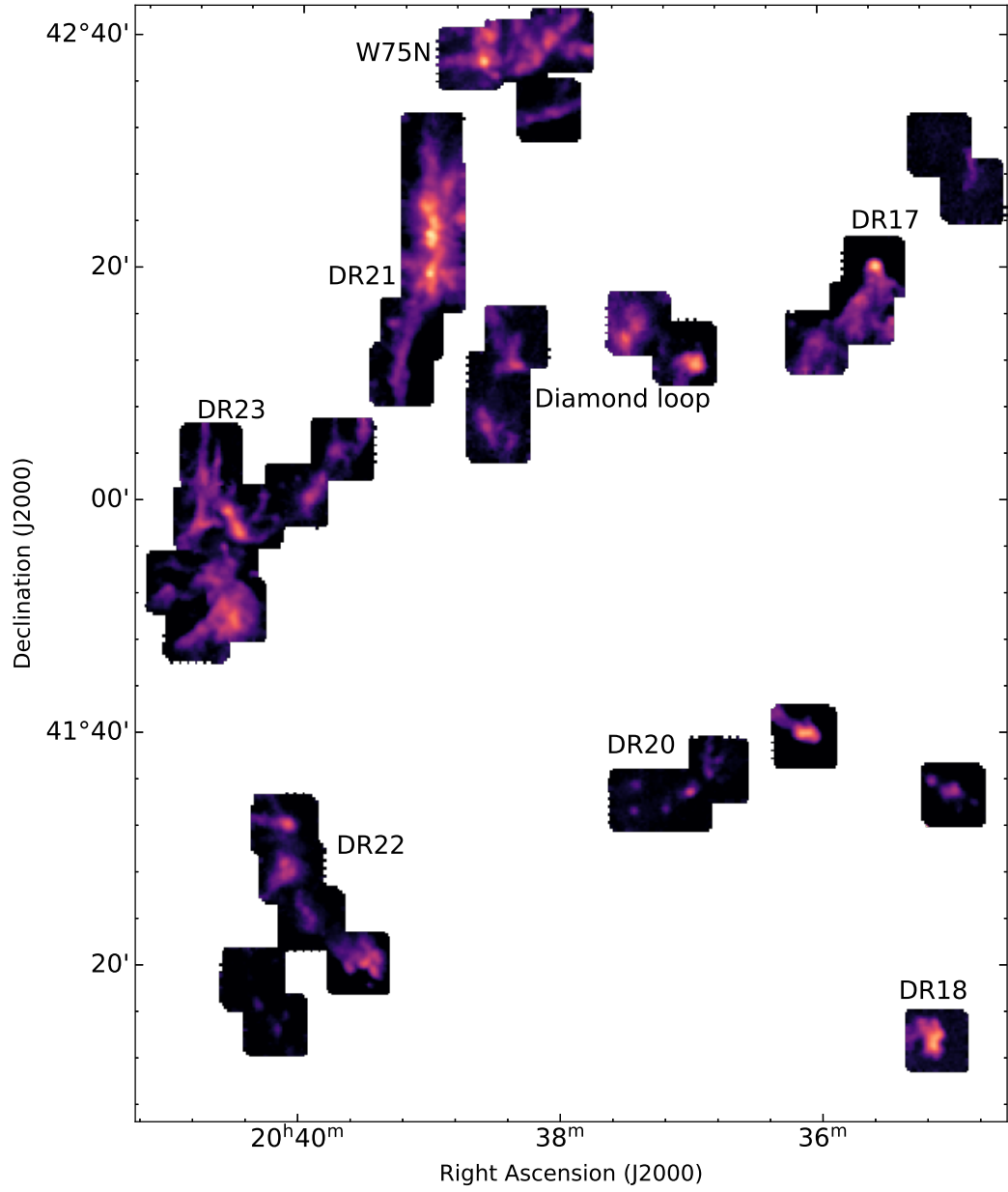


Figure 2.6: The coverage of CASCADe towards Cygnus-X. The maps show the integrated intensity of HCO⁺. Credits to Dr. Friedrich Wyrowski.

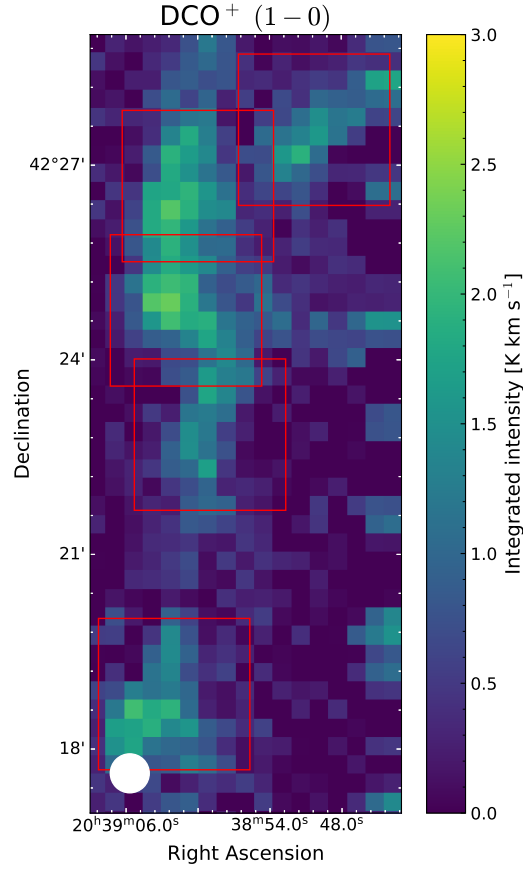


Figure 2.7: The coverage of the follow-up observations towards the DR21 filament (tiles marked in red). The background emission shows the integrated intensity of $\text{DCO}^+ J = 1 - 0$.

The spectra are smoothed to a spectral resolution of $d\nu = 0.8 \text{ km s}^{-1}$ and the maps of the higher J -transitions are convolved to the same beam size as that of $\text{DCO}^+ J = 1 - 0$ ($\theta = 34''$) to match the spectral resolution of the CASCADE survey. These observations are utilized in Chapters 4 and 6.

Observations of the clumps of CASCADE

Single-pointing observations toward the selected 72 clumps in Cygnus-X were carried during 2022 July and August (project ID: M-0109.F-9508C-2022; PI: Ivalu Barlach Christensen) with the APEX telescope. The lower sideband using the nFLASH 230 receiver was tuned to 217.538 GHz with the aim to cover three H_2CO lines ($3_{0,3} - 2_{0,2}$, $3_{2,2} - 2_{2,1}$, and $3_{2,1} - 2_{2,0}$). The observations were performed in position switching mode, with the offsets depending on the sub-regions within Cygnus-X and a fixed offset of $(+600'', 0)$ for each source in the GLOSTAR pilot region (see Sect. 2.2.2). The telescope focus and pointing were checked, depending on the day, with Mars, Jupiter, or Saturn, achieving an estimated pointing accuracy of $\sim 2''$. The frequency range coverage was 200.4 – 208.4 GHz in the lower sideband and 216.4 – 224.4 GHz in the upper sideband, with a typical integration time of 5 minutes. However, the 5 clumps in Cygnus-X DR20 have additional observations of 30 minutes each. Additional integrations were performed for clumps in which the strongest H_2CO ($3_{0,3} - 2_{0,2}$) line was

observed but the fainter H_2CO ($3_{2,2} - 2_{2,1}$) and H_2CO ($3_{2,1} - 2_{2,0}$) lines were not detected above 4σ .

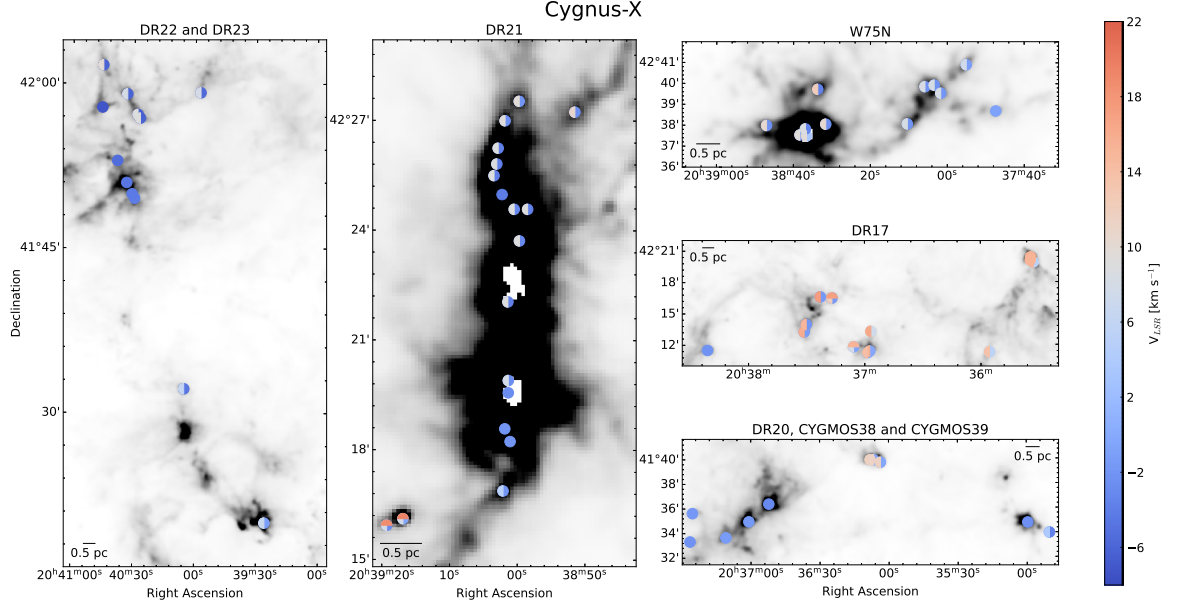


Figure 2.8: The Cygnus-X clumps on the *Herschel* 250 μm map. The clumps are colored based on the source velocity components, with multiple colors indicating more velocity components. The scalebar shows 0.5 pc at a distance of 1.5 kpc.

2.2.2 The GLObal view of STAR Formation in the Milky Way: GLOSTAR pilot region

The GLObal view on Star Formation in the Milky Way (GLOSTAR) project aims to find and characterize the unbiased statistical properties of star formation in the Galactic plane (Brunthaler et al., 2021).

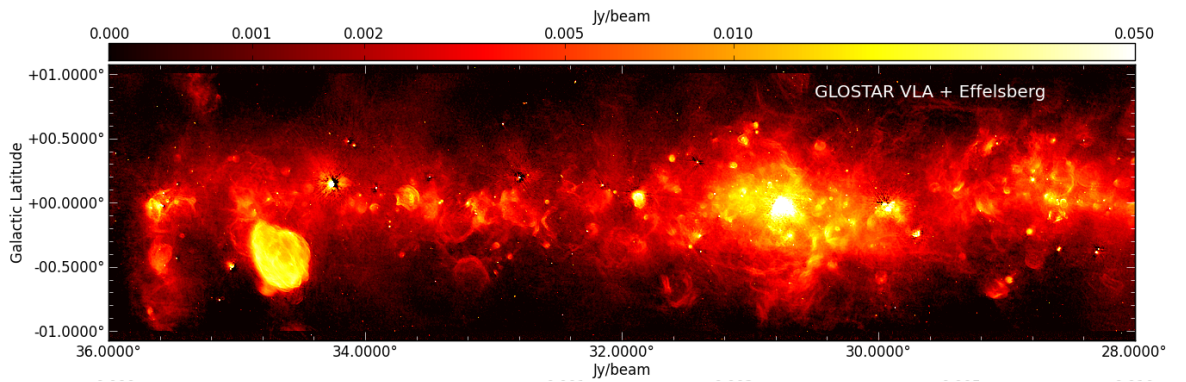


Figure 2.9: Radio continuum image of the GLOSTAR pilot region, adopted from Brunthaler et al. (2021). The continuum image is a combination of VLA D-configuration and Effelsberg 100-m telescope observations.

The GLOSTAR survey utilizes the Jansky Very Large Array (VLA; Perley et al., 2011) and the

Effelsberg 100-m telescope⁶ to conduct continuum and line observations covering the frequency range of 4–8 GHz. The “GLOSTAR pilot region” of this survey, discussed by Brunthaler et al. (2021), covers $28^\circ < l < 36^\circ$, $|b| < 1^\circ$ (see Fig. 2.9). This 16 square-degree pilot region shows a diversity of extended and compact sources, including HII region candidates, supernova remnants, and several CH₃OH masers (Medina et al., 2019; Dokara et al., 2021; Nguyen et al., 2022; Dokara et al., 2023). We observed positions in the GLOSTAR pilot region toward which H₂CO absorption was observed in that survey.

We carried out single-pointing observations toward the selected 10 clumps in the GLOSTAR pilot region during 2024 April and May (project ID: M-099.F-9519A-2017; PI: H. Nguyen and I. B. Christensen). The tuning using nFlash 230 is the same as the observations of clumps in CASCADE (described in Sect. 2.2.1).

2.2.3 The M8 region

The Lagoon Nebula, also known as Messier 8 (M8 hereafter), is a bright HII region illuminated by O- and B-stars. Located at a distance of 1.3 kpc, it is one of the nearest HII regions, characterized by a high UV flux (Damiani et al., 2017; Tiwari et al., 2019). Tothill et al. (2002) identified 37 clumps associated with the molecular cloud. A plethora of molecules are identified in the M8 photodissociation region (PDR) and 38 dense dusty clumps that surround it, some of which also show PDR signatures, while 38% are likely hosting protostellar objects (Kahle et al., 2024). Kahle et al. (2024) suggest that the remnant gas in the M8 region may be fragmenting due to the radiation pressure of the surrounding O- and B-stars.

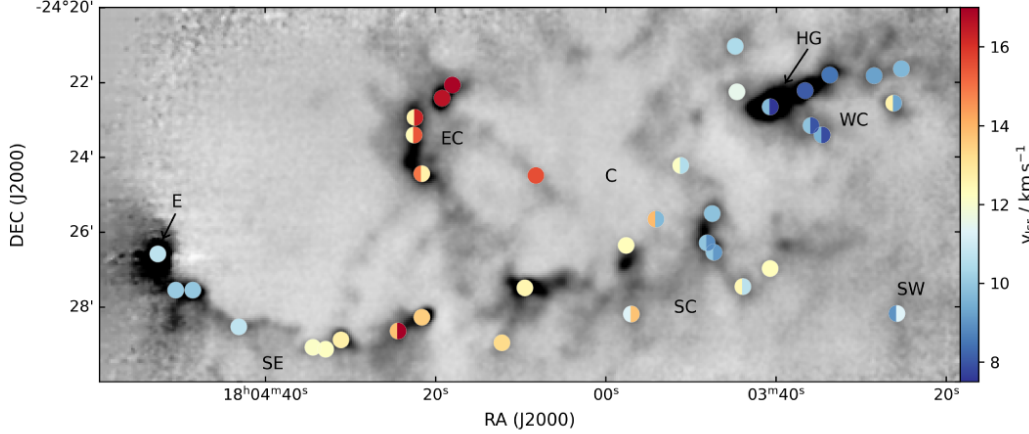


Figure 2.10: The M8 region with the line-of-sight velocities of the clumps. The background shows the grey-scale of the 870 μ m dust continuum flux. This image is adopted from Kahle et al. (2024).

The data for four H₂CO transitions from 37 clumps within the M8 region in this study were reduced by Kahle et al. (2024). Line survey toward the clumps in the M8 region were done with the IRAM 30-m telescope and the APEX telescope. The APEX pointing observations were conducted in July and October 2021 (project-ID: M-0107.F-9530C-2021; P.I.: Dr. Friedrich Wyrowski),

⁶ The 100-m telescope at Effelsberg is operated by the Max-Planck Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck Gesellschaft (MPG).

utilizing the nFLASH 230 receiver. The total frequency coverage toward each clump was 213.1 — 279.7 GHz, obtaining a typical rms of 28 mK. Complementary observation using the IRAM 30-m telescope were conducted in March and June 2022 (project-ID: 141-21; P.I.: Prof. Karl M. Menten), utilizing the E090 receiver. A total frequency coverage toward each clump was 70.3 — 116.5 GHz, obtaining typical rms of 0.17 K. After inspecting the APEX observations by Kahle et al. (2024), the central positions of WC3, SE8, and SC5 were changed by $\sim 1'$ with the IRAM 30-m telescope observations. All observations with the APEX and IRAM telescopes used the reference position of $\text{RA(J2000)}=18^{\text{h}}04^{\text{m}}40.0^{\text{s}}$, $\text{Dec(J2000)}=-24^{\circ}23'00.0''$

2.2.4 Data reduction

The data of the CASCADE, follow-up, and single-pointing observations using the IRAM 30-m and APEX telescopes were processed using the Grenoble Image and Line Data Analysis Software (GILDAS) package⁷ (Pety, 2005; Pety, 2018).

Maps of CASCADE

The data reduction of the deuterated molecules DCO^+ , DNC, and DCN, in the DR21 filament, observed with the IRAM 30-m telescope, and their main isotopologs, are described below. These maps are used in Chapter 4 and are published as Christensen et al. (2024). We utilize the Continuum and Line Analysis Single-dish Software (CLASS) program to re-grid the mapped areas. All images were re-projected to that of the spatial grid of DCO^+ using the MAP%LIKE procedure of CLASS, resulting in a spatial resolution of $34''$. T_{A}^* was converted to the main beam brightness temperature T_{MB} with a forward efficiency of $F_{\text{eff}} = 0.95$, and beam efficiency dependent on the frequency of the molecule⁸:

$$B_{\text{eff}} = 1.2 \times 0.69 \times \exp\left(-\left(\frac{4 \times \pi \times 0.07\nu [\text{MHz}]}{c [\text{km s}^{-1}]}\right)^2\right). \quad (2.8)$$

where ν is the rest frequency of the line emission and c is the speed of light.

We identified a strong narrow spike at $\nu = 76304.9$ MHz near the emission line of DNC $J = 1 - 0$, shifted -1 MHz. This is likely due to contamination from an automotive long-range radar⁹. By comparing the noise of the artefact-free spectral velocity range ($< -30 \text{ km s}^{-1}$) with that of the contaminated channels ($> 0 \text{ km s}^{-1}$), we minimize the contamination from this spike. Spectra, with an increase of 20% in the noise level of the contaminated channels to that of the artefact-free spectral velocity range, are discarded.

Similarly, the maps towards all the CASCADE regions with the IRAM 30-m telescope (shown in Fig. 2.6) are reduced utilizing the CLASS program. The antenna temperatures are converted to main beam brightness temperature using Eq. (2.8) and a forward efficiency of 0.95. These maps are gridded to their native resolution (i.e. $\theta_{\text{B}}['] = 2460/\nu[\text{GHz}]$). A spectrum for each clump is extracted for each molecule of interest with the native resolution of the molecules' frequency.

⁷ <http://www.iram.fr/IRAMFR/GILDAS>

⁸ <https://web-archives.iram.fr/ARN/feb01/node5.html>

⁹ <https://www.everythingrf.com/community/automotive-radar-frequency-bands>

H₂CO survey

The spectral line properties of the four H₂CO transitions are summarized in Table 2.2.

Table 2.2: H₂CO transitions observed with the IRAM 30-m and the APEX 12-m telescopes.

Telescope	H ₂ CO J_{K_a,K_c}	Frequency [GHz]	E_{up}/k [K]	A_{ij} [s ⁻¹]	g_{up}	n_{crit} [cm ⁻³]
IRAM 30-m	$1_{0,1} \rightarrow 0_{0,0}$	72.838	3.5	8.2(−6)	3	$2.8 \cdot 10^4$ ^a
APEX	$3_{0,3} \rightarrow 2_{0,2}$	218.222	21.0	2.8(−4)	7	$7.8 \cdot 10^5$ ^a
APEX	$3_{2,2} \rightarrow 2_{2,1}$	218.475	68.1	1.6(−4)	7	$3.2 \cdot 10^5$ ^b
APEX	$3_{2,1} \rightarrow 2_{2,0}$	218.760	68.1	1.6(−4)	7	$3.1 \cdot 10^5$ ^b

Notes. The rest frequencies, upper energies, and critical densities of the four observed transitions of H₂CO. The Einstein coefficients are written in the form of $A(-x) = A \times 10^{-x}$.

References. ^a Shirley, 2015; critical density at $T = 20$ K. ^b Order of critical density estimated based on collisional rates of Wiesenfeld and Faure, 2013, assuming optically thin conditions and considering p-H₂ as the main collider. Molecular properties were taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al., 2005).

We converted the APEX T_A^* scale to a T_{MB} scale using $\eta_{\text{eff}} = 0.95$ and a main-beam efficiency depending on the date of observations. For Cygnus-X sources, observations of Mars, Jupiter, and Saturn allow us to estimate the beam efficiencies, and we find $0.68 < \eta_{\text{MB}} < 0.86$. Based on Mars observations, we found $\eta_{\text{MB}} = 0.77$ for the GLOSTAR sources. For the M8 sources, $\eta_{\text{MB}} = 0.80$ is adopted, based on Jupiter¹⁰. An overview of the receiver tuning parameters of the observations of the three sub-samples is presented in Table 2.3.

Table 2.3: Parameters of the IRAM and APEX observations.

Sources	Telescope (Receiver)	θ_B [′′]	Tuning [GHz]	SB	η_{MB}	# pointings
Cygnus-X	IRAM (EMIR 090)	33	72.8	LSB inner	0.83	72
	APEX (nFLASH230)	29	218.5	USB	0.68 – 0.86	
GLOSTAR	IRAM (EMIR 090)	33	72.6	LSB inner	0.83	10
	APEX (nFLASH230)	29	218.5	USB	0.77	
M8	IRAM (EMIR 090)	33	Spectral line survey		0.8	37
	APEX (nFLASH230)	29	Spectral line survey		0.797	

Although the beam sizes are similar, the small difference is taken into account by adjusting source

¹⁰ The beam efficiency for the M8 sources is adopted from the publicly available line monitoring of APEX telescope receivers <https://www.apex-telescope.org/telescope/efficiency/>

size. Assuming the source size is that of the APEX beam size ($\theta_{\text{APEX}} = 29''$), the ground-state observations are corrected for beam dilution, $\eta_{\text{bf}} = \left(\frac{\theta_{\text{APEX}}}{\theta_{\text{IRAM}}} \right)^2 = 0.73$.

Physical and Chemical Processes in Star-Forming Molecular Clouds

The night sky once ruled my imagination
Now I turn the dials with careful calculation

Sleeping at last - Venus

Light is our strongest tool for observing the Universe, and understanding how light interacts with the atoms and molecules in space gives us great insight into the physical conditions out there. In this Chapter, the method of calculating column densities is presented with details on radiative transfer and molecular line emission. Furthermore, the formation and destruction of molecules, specifically deuterated molecules, are presented.

3.1 Observing Molecular Clouds

3.1.1 Spectral line emission

Atoms or molecules emit spectral lines when they release a photon during a transition from a higher energy state to a lower one. The photon emitted has a specific wavelength, which depends on the energy difference between the higher and lower states.

Atoms or molecules interact with photons through either absorption or emission. Figure 3.1 illustrates the energy transitions of an atom, which can occur by absorbing a photon (absorption) or emitting a photon (spontaneous or stimulated emission). Atoms emit photons via spontaneous emission during energy transitions triggered by collisions. In high-density environments, collisions between atoms or molecules transfer energy, causing them to transition to a lower state and emit a photon. Additionally, a photon with the exact wavelength can stimulate an atom or molecule in an excited state to emit a photon.

The energy transition mechanism in atoms and molecules arises from various factors. Atoms, consisting of a nucleus surrounded by electrons, exhibit well-defined energy levels determined by the number of electrons in their shells, which varies among different atoms. The energy state of an atom changes when its outer-shell electrons transition from the outer shell to a higher-energy state.

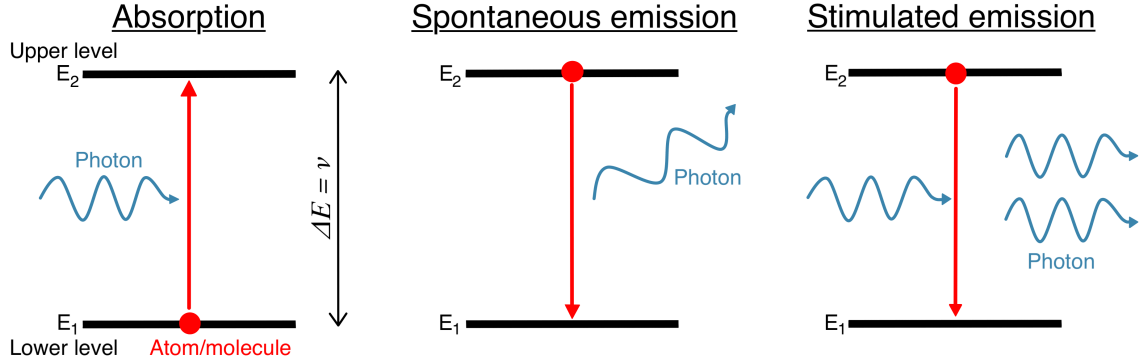


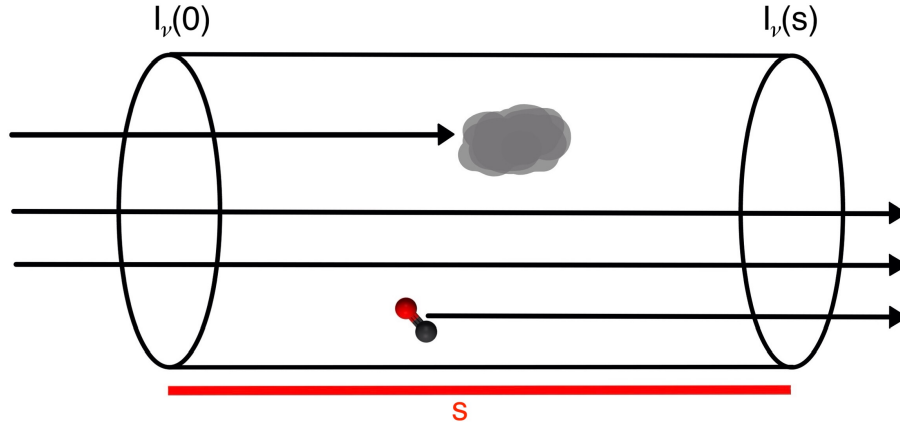
Figure 3.1: Processes of emission and absorption in atoms and molecules.

Molecules, on the other hand, undergo energy transitions through changes in their vibrational or rotational energies, as further detailed in Sect. 3.1.3.

Pressure, temperature, abundance, and Doppler shift influence the spectral lines. Pressure broadens the spectral lines due to collisions. Temperature affects the population of the energy levels, following the Boltzmann distribution (see details in Sect. 3.1.2). The Doppler shift can either red-shift the spectral line if the gas is moving away or blue-shift it if the gas is approaching.

3.1.2 Radiative Transfer

As light travels through the ISM, it interacts with atoms and molecules (consider Figure 3.2). The radiative transport equation helps us comprehend how the intensity of light changes as it travels a distance, allowing us to interpret the information we receive from the ISM. Not considering scattering,


 Figure 3.2: Sketch of light traveling through a medium s . A dust particle partially absorbs the light I traveling through the medium, and a molecular line is emitted.

the change in intensity over a distance is a result of absorption and emission:

$$dI_\nu = -I_\nu \kappa_\nu ds + j_\nu ds \quad (3.1)$$

where $-I_\nu \kappa_\nu ds$ is the absorption with κ_ν the extinction coefficient, and $j_\nu ds$ is the emission, with emission coefficient j_ν . The emission and absorption of intensity are frequency-dependent, meaning that the intensity through a medium may be opaque at certain frequencies but transparent at others.

Defining the opacity of the medium as $d\tau_\nu = \kappa_\nu ds$, Eq. (3.1) can be rewritten as:

$$dI_\nu + I_\nu d\tau_\nu = \frac{j_\nu}{\kappa_\nu} d\tau_\nu \quad (3.2)$$

The general solution for this differential equation is:

$$I_\nu(\tau_\nu) = I_\nu(0) \exp(-\tau_\nu) + \int_0^{\tau_\nu} \exp(-(\tau_\nu - \tau')) \frac{j_\nu}{\kappa_\nu} d\tau' \quad (3.3)$$

where the term $I_\nu(0) \exp(-\tau_\nu)$ is the attenuation from the background intensity and the term $\int_0^{\tau_\nu} \exp(-(\tau_\nu - \tau')) \frac{j_\nu}{\kappa_\nu} d\tau'$ is the attenuation from the emission along the path traversed.

Assuming the medium is comprised of molecules in local thermodynamic equilibrium (LTE), the level populations of the medium are discrete and can be explained with a single temperature black-body, i.e., $I_\nu = B_\nu(T_{\text{ex}})$. Assuming the radiation is uniform and the intensity is constant, i.e. $\frac{dI_\nu}{d\tau_\nu} = 0$, Eq. (3.3) can be simplified to:

$$I_\nu(\tau_\nu) = I_\nu(0) \exp(-\tau_\nu) + \int_0^{\tau_\nu} \exp(-(\tau_\nu - \tau')) B_\nu(T_{\text{ex}}) d\tau' \quad (3.4)$$

$$= I_\nu(0) \exp(-\tau_\nu) + B_\nu(T_{\text{ex}}) (1 - \exp(-\tau_\nu)) \quad \text{for constant } T_{\text{ex}} \quad (3.5)$$

Further assuming $I_\nu(0)$ is a black-body radiation of the background temperature T_{bg} , we obtain:

$$I_\nu(\tau_\nu) = B_\nu(T_{\text{bg}}) \exp(-\tau_\nu) + B_\nu(T_{\text{ex}}) (1 - \exp(-\tau_\nu)) \quad (3.6)$$

The primary focus when observing a source is its intensity. This involves observing on/off positions and measuring the background intensity contribution at a reference position where only the background, and no medium contribution, is present. Subsequently, to isolate the source intensity, the observations at the reference position are subtracted from the observations of the source of interest:

$$I_{\nu, \text{source}}(\tau_\nu) = I_\nu(\tau_\nu) - I_\nu(0) \quad (3.7)$$

$$= B_\nu(T_{\text{bg}}) \exp(-\tau_\nu) + B_\nu(T_{\text{ex}}) (1 - \exp(-\tau_\nu)) - B_\nu(T_{\text{bg}}) \quad (3.8)$$

$$= [B_\nu(T_{\text{ex}}) - B_\nu(T_{\text{bg}})] (1 - \exp(-\tau_\nu)) \quad (3.9)$$

The black body radiation distribution is given by the Planck's law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1} \quad (3.10)$$

where h is Planck's constant, c is the speed of light, k_B is the Boltzmann constant. In the sub-mm range $h\nu \ll k_B T$, where Planck's law can be simplified to the Rayleigh-Jeans' law:

$$B_\nu(T) = \frac{2\nu^2}{c^2} k_B T \quad (3.11)$$

Isolating for the brightness temperature, the observed brightness temperature of the source is:

$$T_B(\nu) = \frac{c^2}{2k_B\nu^2} I_{\nu, \text{source}}(\tau_\nu) \quad (3.12)$$

$$= \frac{c^2}{2k_B\nu^2} [B_\nu(T_{\text{ex}}) - B_\nu(T_{\text{bg}})] (1 - \exp(-\tau_\nu)) \quad (3.13)$$

$$= \frac{c^2}{2k_B\nu^2} \left[\frac{2h\nu^3}{c^2} \left(\frac{1}{\exp\left(\frac{h\nu}{k_B T_{\text{ex}}} - 1\right)} - \frac{1}{\exp\left(\frac{h\nu}{k_B T_{\text{bg}}} - 1\right)} \right) \right] (1 - \exp(-\tau_\nu)) \quad (3.14)$$

$$= [J_\nu(T_{\text{ex}}) - J_\nu(T_{\text{bg}})] (1 - \exp(-\tau_\nu)), \quad \text{where} \quad J_\nu = \frac{h\nu}{k_B} \left[\exp\left(\frac{h\nu}{k_B T} - 1\right) \right]^{-1} \quad (3.15)$$

3.1.3 Molecular line emissions

The main transitions observed in molecular clouds are rotational transitions. The emission of molecules is governed by collisions with other particles in the gas or by radiation, e.g., from nearby stars or CRs.

In the simple case of a diatomic molecule, CO, the discrete energy levels are described as:

$$E_J = \frac{h^2}{8\pi^2\mu r^2} J(J+1), \quad (3.16)$$

where h is the Planck constant, $\mu (= \frac{m_1 m_2}{m_1 + m_2})$ is the reduced mass between m_1 and m_2 separated by a distance, r . The dipole rotational transitions are only possible $\Delta J = \pm 1$ for molecular species with permanent dipole moments (Bernath, 2005). The adjacent lines of the spectrum are separated by a distance:

$$E_{J+1} - E_J = \frac{h^2}{4\pi^2\mu r^2} J + 1 \quad \text{or} \quad \nu = \frac{hJ}{4\pi^2\mu r^2}, \quad J = 1, 2, 3, \dots \quad (3.17)$$

In the case of symmetric molecules, such as H_2 with no permanent dipole moment, the lowest quadrupole transition possible $J = 2 \rightarrow 0$, corresponding to an excitation temperature of $T_{\text{ex}} \approx 500$ K (Bernath, 2005). In the typical conditions of the cold, dark molecular clouds, the lowest transition of H_2 is far above. In the case of simple diatomic molecules, CO, the first excited state $J = 1$ is efficiently possible at $T \approx 5$ K. The de-excitation to the energy state $J = 0$ emits a photon at frequency $\nu \approx 115.27$ GHz. Calculation of the transition energies becomes complex as the number of atoms in the molecule increases, as well as the symmetry of the molecules (Bernath, 2005). Generally, the higher the number of atoms, the more lines are within a frequency interval.

Consider the simple case of a molecule with just two energy levels, E_1 and E_2 . The excitation and de-excitation between these levels are equal in equilibrium, thus the ratio of population in the upper and lower energy levels is:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(-\frac{E_u - E_l}{k_B T}\right) \left(1 + \frac{n_{\text{crit}}}{n}\right)^{-1} \quad (3.18)$$

where the critical density is:

$$n_{\text{crit}} \approx \frac{A_{ul}}{\sigma v}. \quad (3.19)$$

The critical density quantifies the dominant excitation process. The Einstein coefficient, A_{ul} , is a measure of the probability of spontaneous photon emission, whilst the collisional cross section, σ , and the gas velocity, v , is a measure of the probability for the collision (e.g. Heiner et al., 2015).

In the case where the densities are much higher than the critical density of a molecule (i.e. $n_{\text{crit}} \ll n$), the population of the two levels approaches the Boltzmann distribution, simplifying Eq. (3.18) as:

$$\frac{n_u}{n_l} \approx \frac{g_u}{g_l} \exp\left(-\frac{E_u - E_l}{k_B T}\right). \quad (3.20)$$

This is the case for a system governed by collision and is in local thermodynamic equilibrium (LTE). In the same molecular cloud, with density n , LTE conditions may be possible for a molecule (with a high critical density), whilst another molecule may not be in LTE due to a lower critical density. Atoms or molecules with higher critical densities can be used to trace the higher-density regions.

In the case where the critical density is lower than the density (i.e., $n_{\text{crit}} < n$), the level populations are not governed by collisions. These regions are governed by the interaction with background radiation. Thus, Eq. (3.18) becomes:

$$\frac{n_u}{n_l} \approx \frac{g_u}{g_l} \exp\left(-\frac{E_u - E_l}{k_B T}\right) \left(\frac{n_{\text{crit}}}{n}\right)^{-1} \propto n. \quad (3.21)$$

Under these conditions, the excitation between the levels are dependent on both the density and excitation temperature.

3.1.4 Deriving column densities

The column density is a measure of the number of atoms/molecules per unit area along a line-of-sight. This quantity is determined by the rotational diagram method, assuming the levels are populated following LTE (Goldsmith and Langer, 1999; Mangum and Shirley, 2015):

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{\text{tot}}}{Q_{\text{tot}}}\right) - \frac{1}{T_{\text{exc}}} \frac{E_{\text{up}}}{k_B}, \quad (3.22)$$

where N_u and g_u is the population and degeneracy of energy level u , N_{tot} is the total population in all energy levels, and Q_{rot} the partition function, with the partition function for each molecule calculated by CDMS (Müller et al., 2005). E_{up} is the upper energy, k_B is the Boltzmann constant and T_{exc} is the excitation temperature.

Under the assumption that the source fills the beam, the upper energy level population can be simplified as (Goldsmith and Langer, 1999):

$$N_u = \frac{8\pi k_B \nu^2}{h c^3 A_{ij}} \int T_{\text{MB}} d\nu \times C, \quad (3.23)$$

where ν is the central frequency of the emission line, A_{ij} is the Einstein coefficient, and $\int T_{\text{MB}} d\nu$ is

the integrated intensity of the molecular line of interest. $C = \frac{\tau}{1 - \exp^{-\tau}}$ is the optical depth factor.

When several emission lines with different energies of the same molecule, the N_u for each emission line is obtained. Considering the N_u/g_u as the y -values, and the E_{up}/k_B as the x -values, Eq. (3.22) under LTE-assumption becomes linear, with the equivalence:

$$\underbrace{\ln\left(\frac{N_u}{g_u}\right)}_y = \underbrace{\ln\left(\frac{N_{\text{tot}}}{Q_{\text{tot}}}\right)}_b - \underbrace{\frac{1}{T_{\text{exc}}}}_a \underbrace{\frac{E_{up}}{k_B}}_x, \quad (3.24)$$

allowing a linear regression to obtain the excitation temperature from the slope $-1/T_{\text{exc}}$, and the total column density from the intercept $N_{\text{tot}}/Q_{\text{tot}}$.

3.2 Chemistry in dense molecular clouds

The journey of stellar formation begins in the molecular cloud stage, where the initial conditions of stellar nurseries for massive stars hold significant importance. The rich chemistry of the ISM has been a subject of fascination since the groundbreaking detection of CH, CN, and CH^+ molecules in 1937, marking the beginning of the field of astrochemistry (Swings and Rosenfeld, 1937; McKellar, 1940; Douglas and Herzberg, 1941). As telescope technology has advanced, particularly in the field of radio astronomy, scientists have been able to detect increasingly complex molecules in space. This progress has been remarkable, with the number of observed interstellar molecules reaching about 330¹ as of May 2025. These molecular discoveries not only enhance our understanding of the chemical composition of space but also provide crucial insights into the environments in which stars form and evolve. Building upon this molecular complexity, scientists have identified molecules composed of up to 19 atoms in the cold, ISM, and within our own solar system. These complex molecules serve as precursors to potential future stellar systems. Of particular interest are the more complex (≥ 6 atoms) organic (carbon-containing) molecules (COMs), which are frequently observed near high-mass hot cores and their low-mass counterparts, hot corinos. The famous binary hot corino system, IRAS 16293-2422, has revealed an especially rich chemical complexity (Jørgensen et al., 2011; Jørgensen et al., 2016). Figure 3.3 provides a striking example of this chemical richness, showcasing a spectrum from IRAS 16293-2422B, which illustrates the diverse molecular composition found close to these stellar nurseries. The Sagittarius (Sgr) B2 molecular cloud, located towards our Galactic center, showcases remarkable chemical richness in COMs, particularly in its star-forming regions SgrB2(N) and SgrB2(M) (Belloche et al., 2013; Busch et al., 2024).

The temperature, density, interstellar radiation field, and cosmic-ray flux all drive chemical processes in the ISM. These processes occur not only in the gas phase but also on the surfaces and within the icy mantles of dust grains (Garrod and Herbst, 2006; Garrod et al., 2008). The interplay of these factors creates a complex chemical environment that shapes the composition and evolution of the ISM, ultimately influencing star and planet formation (Caselli and Ceccarelli, 2012; Jørgensen et al., 2020).

¹ CDMS; https://cdms.astro.uni-koeln.de/classic/molecules#molecules_in_the_interstellar_medium_or_circumstellar_shells_as_of_02_2025. Accessed 10 June 2025.

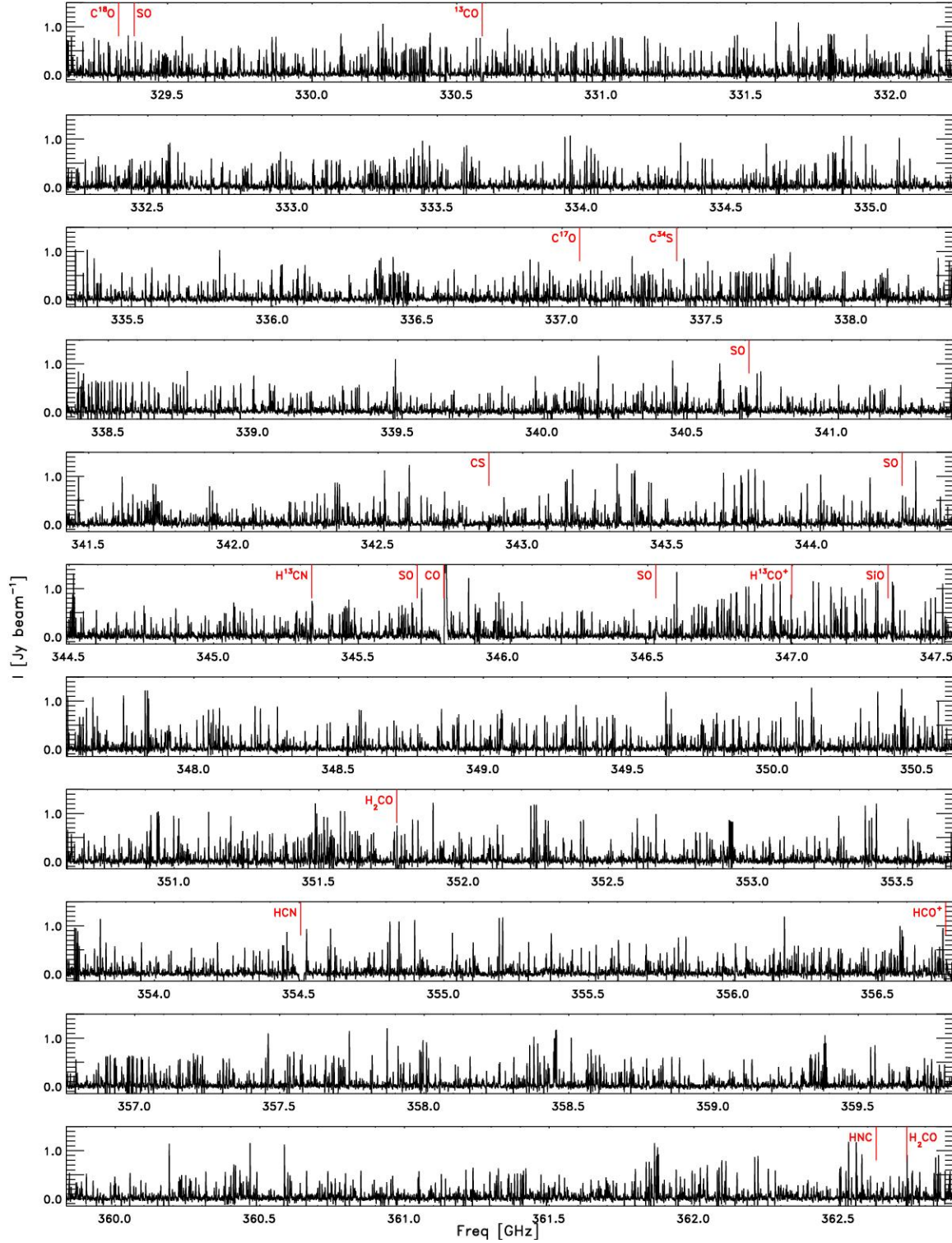


Figure 3.3: The rich spectrum 0.5'' offset from the continuum peak of low-mass star-forming region IRAS 16293-2422B by Jørgensen et al. (2016).

3.2.1 Gas-phase chemistry

The ISM has very low densities compared to Earth's atmosphere; collisions between two particles (i.e., atoms or molecules) in the ISM are rare and occur very slowly. In these regions, UV photons and CRs can penetrate the molecular clouds and ionize existing atoms, resulting in ion-molecule reactions dominating (van Dishoeck, 2018). The initial build-up of the chemistry in the ISM is through the ion-molecule reaction, with H_3^+ playing a fundamental role in initiating the complexity of molecules in the ISM (McGuire et al., 2020). When two particles (A and B) collide, they not only excite the molecule (see Sect. 3.1) but, depending on the geometry and energies, they can also facilitate the formation of new molecules. The key reactions of formation and destruction of particles are shown in Table 3.1.

Table 3.1: Gas-phase bond formation, destruction, and rearrangement.

Bond formation	{	Radiative association	$A + B$	$\rightarrow AB + \gamma$
		Associative dissociation	$A + B$	$\rightarrow AB + e^-$
Bond destruction	{	Photo-dissociation	$AB + \gamma$	$\rightarrow A + B$
		Dissociative recombination	$AB + e^-$	$\rightarrow A + B$
Bond rearrangement	{	Ion-molecule, neutral-neutral or charge-transfer		$AB + C \rightarrow AC + B$

The rate of these reactions are dependent on the temperature and density. Furthermore, photons and CRs can participate in the formation and destruction of molecules (e.g. Caselli and Ceccarelli, 2012). CRs play a crucial role in initiating the chemical reaction in the diffuse clouds, where H_2 is ionized to H_3^+ , a first critical step in ISM chemistry. Increased densities (e.g., in dense cores) shield the UV-radiation from the innermost and dense parts, allowing H_2 to be present in the interior of the clouds (Yamamoto, 2017).

In order to understand the conditions that are responsible for the observed molecules and their abundances, chemical models consider reaction rates of two-body collisions. Considering the reaction $A + B \rightarrow C + D$, the evolution of the abundance of A can be described by the respective reaction rates:

$$\frac{d[A]}{dt} = -k_{r,1}[A][B] + k_{r,2}[C][D] \quad (3.25)$$

where $[X]$ denotes the abundances of the respective particle. The reaction rate k_r , following the Arrhenius equation, is dependent on the temperature, T , as (e.g. Semenov et al., 2010):

$$k_r \approx \exp\left(\frac{E_a}{RT}\right), \quad (3.26)$$

with an activation energy, E_a , needed to be exceeded in order for the reaction to occur, and gas constant R .

3.2.2 Grain-surface chemistry

Only considering the gas-phase reactions has, historically, not been able to reproduce the observed abundances of molecules, especially those of COMs. To reproduce the observed abundances of COMs,

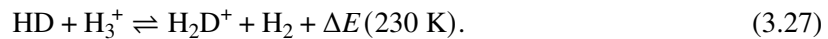
grain-surface chemistry must be taken into account (Öberg et al., 2009; Garrod, 2013; van Dishoeck, 2014).

In the earliest stages of star-formation, where the gas is cold ($T \leq 10$ K), molecules are able to accumulate on the surface of dust grains. Although the temperatures are low, the small molecules on the surface can still move. Molecules can be formed utilizing the surface of grains; the Langmuir-Hinshelwood reaction ($A_{\text{grain}} + B_{\text{grain}} \rightarrow AB_{\text{grain}}$), where two grain surface atoms/molecules react with each other to form a molecule, or the Eley-Rideal reaction ($A_{\text{grain}} + B_{\text{gas}} \rightarrow AB_{\text{grain}}$) where a gas-phase atom/molecule reacts with a dust grain particle (Herbst and van Dishoeck, 2009). Furthermore, COMs can be formed via successive hydrogenation of CO (see Fig. 3.5; e.g. Watanabe and Kouchi, 2002; Taquet et al., 2012).

These dust grain molecules reside on the surface. The complexity increases as the inventory on the surface increases, with a starting point of methanol, CH_3OH , and forming COMs such as CH_3OCH_3 and CH_3OCHO (Jørgensen et al., 2020) or polycyclic aromatic hydrocarbons (PAHs) such as C_9H_8 (Burkhardt et al., 2021). The grain surface molecules are sublimated into the gas-phase with increasing temperature (Herbst and van Dishoeck, 2009) or due to shocks (Burkhardt et al., 2019).

3.2.3 Deuterated molecules

The chemical composition of stellar birthplaces reveals crucial information about their physical properties. Deuterated molecules, in particular, serve as key probes for the coldest gas phases. Deuterium, a heavier isotope of hydrogen, originates from the birth of the Universe. Stars slowly destroy deuterium in their interiors, but it persists in the ISM, primarily in its molecular form, HD. Observations of the ISM show an atomic abundance ratio between the main hydrogen isotope and deuterium, $[\text{D}]/[\text{H}] \sim 10^{-5}$ (Oliveira et al., 2003; Cooke et al., 2018). Deuterium fractionation is the enhancement of deuterated molecules relative to their non-deuterated counterparts. Deuterium fractionation is an efficient process occurring during the early stages of star formation. This efficiency results in enhancements (up to a few percent) of molecular $[\text{D}]/[\text{H}]$ abundance ratios in dense molecular clouds and star-forming regions compared to that of the global ISM $[\text{D}]/[\text{H}]$ (Roberts and Millar, 2000a; Roberts et al., 2004). This reaction, fundamental to the deuteration process, involves the exchange of a proton with a deuteron:



This exothermic reaction proceeds effectively at low temperatures, specifically ≤ 25 K (Roberts and Millar, 2000b). The study of deuteration and its products not only enhances our understanding of the chemical processes in these cold environments but also provides a unique window into the physical conditions present during the initial phases of stellar evolution.

Low temperatures and CO freeze-out enhance deuteration in star-forming regions. As neutral molecules decrease, especially during CO freeze-out, the $[\text{H}_2\text{D}^+]/[\text{H}_3^+]$ ratio increases (e.g. Roueff et al., 2007). CO typically destroys H_2D^+ , so its depletion allows H_2D^+ to accumulate. Temperatures below 20-30 K drive the deuteration reaction forward, transferring elemental D from HD to other species through two main pathways: 1) Rapid ion-molecule reactions of H_2D^+ with neutral species, 2) Deuteration of ices by D-atoms sticking to dust grain surfaces (Roberts and Millar, 2000a; Roberts et al., 2004; Roueff et al., 2007).

Light hydrocarbons (C_nH_m) provide additional fractionation pathways, driving deuterium chemistry

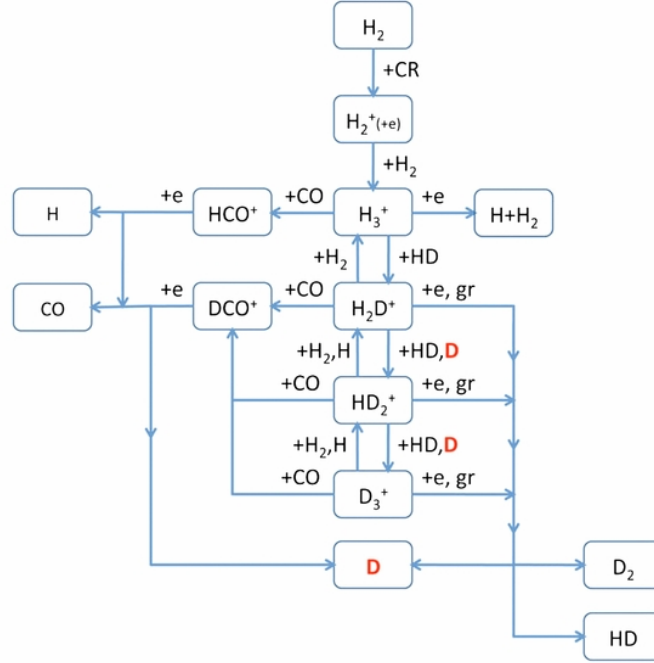
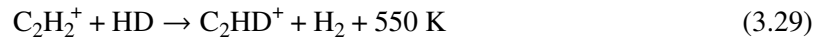


Figure 3.4: Chemical network in the gas phase leading to atomic deuterium formation, adopted by Taquet et al. (2012). The atomic deuterium is marked in red “D”.

up to temperatures of $T \sim 100$ K (e.g. Turner, 2001):



These processes collectively lead to significant deuterium enrichment in cold, dense environments, making deuterated molecules excellent probes of the conditions of early-stage star formation. Furthermore, at temperatures of ≤ 10 K and densities $\geq 10^5 \text{ cm}^{-3}$, gaseous species, such as CO and other neutrals, are frozen onto the dust grains, deuterium fractionation enhances as the reactions between CO and the ions in Eqs. (3.27), (3.28), and (3.29) (Bacmann et al., 2003; Crapsi et al., 2005; Fontani et al., 2014).

The dynamical environment of star-forming regions affects the deuterium fractionation, thus making it a powerful tool to probe the conditions of star formation. Specifically, the abundance and ratio of deuterated molecules play a significant role in determining the chemical age of high-mass star-forming regions. Fontani et al. (2011) found that the $R(\text{N}_2\text{D}^+)$ can be used as an evolutionary tracer in high-mass star-forming regions, decreasing by an order of magnitude at the onset of star formation. DNC is formed through similar gas-phase reactions as N_2D^+ , but the deuterium fractionation of DNC is able to stay relatively stable as the destruction is slow compared with $R(\text{N}_2\text{D}^+)$, and does not change significantly with the evolution (Sakai et al., 2012; Fontani et al., 2014). Lin et al. (2024) found that in starless cores, the depletion of N_2 is lower than that of CO, resulting in an enhanced $R(\text{N}_2\text{D}^+)$ compared to the depleted $R(\text{DCO}^+)$. Based on the depletion of CO, the ionization rate can be traced

with the ratio of DCO^+ and HCO^+ (Caselli et al., 1998; Caselli et al., 2002; Miettinen et al., 2011). The abundance of deuterated molecules and their ratios to non-deuterated counterparts can serve as valuable indicators of the chemical age in star-forming regions, giving insights into the evolutionary stages and timescales of star formation, particularly in high-mass star-forming environments.

DCO^+ and its main isotopologue HCO^+

DCO^+ and HCO^+ form most efficiently in the lower temperature regime ($T_{\text{kin}} < 20$ K). The following gas phase reaction (Albertsson et al., 2013) is the primary formation pathway of DCO^+ :



The formation pathway of the main isotopolog also requires CO:



When the molecular cloud is cold ($T_{\text{dust}} < 20$ K) and dense ($n > 10^4 \text{ cm}^{-3}$), CO freezes onto dust, leaving very little in the gas to react with H_2D^+ . But as the ice warms and CO evaporates, it reacts with H_3^+ , thereby using up the H_3^+ needed to form H_2D^+ . Thus, the abundance of DCO^+ is highest when the gas is really cold ($T_{\text{gas}} \leq 20$ K) and drops as it heats up (Aikawa et al., 2012).

The abundance of DCO^+ and HCO^+ decrease because H_3^+ gets used up before it can turn into H_2D^+ (Albertsson et al., 2013). A time-dependent chemical model showed that the abundance of DCO^+ varies with temperature, being higher at low temperatures (~ 30 K) (Albertsson et al., 2013). As the critical temperature of the DCO^+ formation is reached, the $R(\text{DCO}^+)$ starts to decrease, eventually matching the basic amount of interstellar $[\text{D}]/[\text{H}]$ abundance ratio ($\sim 10^{-5}$, Cooke et al., 2018). So, $R(\text{DCO}^+)$ varies with temperature in regions that are not ionized, and this variation follows that of its precursors (Herbst, 1982; Anderson et al., 1999).

Elevated temperatures driven by shocks can cause the nonthermal sublimation or sputtering of CO from dust grains. The primary pathway leading to the destruction of DCO^+ and HCO^+ is dissociative recombination:



and



A higher electron fraction accelerates the destruction of HCO^+ more rapidly than that of DCO^+ , thereby influencing the molecular isotopic ratio (Albertsson et al., 2013).

DCN and DNC and their main isotopologues, HCN and HNC

The formation of the isomers, DNC and DCN, differs in their thermal dependence. When it's colder ($T_{\text{dust}} \leq 30$ K), DNC predominantly forms because deuterium is quicker to react with the main isotopolog of the isomers, HCN and HNC. Interestingly, DCN is created in this cold range by deuterium being passed from HNC (Turner, 2001). However, when the regions warm up a bit (~ 80 K), both DNC and DCN are efficiently formed from light deuterated light hydrocarbons like CH_2D^+ (Albertsson et al., 2013). At lower gas temperatures ($T_{\text{gas}} \leq 30$ K), DCN does not form as well as DNC since it relies on CH_2D^+ , unlike DNC, which uses H_2D^+ (Turner, 2001; Roueff et al., 2007).

On the contrary, DNC does not form as well as the temperature rises because oxygen atoms become effective at destroying this molecule (Gerner et al., 2015).

HCN and HNC, which are the main isotopologs of DCN and DNC, have been shown to be useful for determining the kinetic gas temperature (Hacar et al., 2020). The ratio of $I(\text{HCN})/I(\text{HNC})$ is influenced by the selective destruction of HNC at gas temperatures $T \leq 200$ K (Hacar et al., 2020), as shown in these reactions:



and,



The change between HCN and HNC happens is effective at temperatures $T > 40$ K. When temperatures are low, HCN and HNC are produced through reactions between ions and molecules with roughly equal probability (Herbst et al., 2000; Albertsson et al., 2013).

3.2.4 Formaldehyde

Formaldehyde (H_2CO) is a pervasive molecule that is thought to be formed through the successive hydrogenation of CO on the icy mantles of grain particles (e.g. Mangum et al., 1990; Watanabe and Kouchi, 2002; Woon, 2002; Yan et al., 2019; Taquet et al., 2012, see Figure 3.5 by the latter for further details). Snyder et al. (1969) first detected H_2CO in the ISM, the first polycyclic molecule to be detected, observing the 4.8 GHz (6 cm) $1_{1,0} - 1_{1,1}$ transition between the hyperfine structure levels of its ortho-ground state. Researchers have established H_2CO as a well-known tracer of high-density environments and a wide range of temperatures in molecular clouds (Mangum and Wootten, 1993; Ao et al., 2013; Okoh et al., 2014). Downes et al. (1980) identified the presence of this molecule through absorption measurements toward numerous HII regions.

The frequency of the $1_{0,1} - 0_{0,0}$ ground-state transition of para-formaldehyde (H_2CO) at 72.8 GHz, which falls at the lower end of the receiver coverage of the 3/4 mm atmospheric window, has limited the number of observations made of this line. This line, first detected in the ISM by Akabane et al. (1974, see also Kaifu et al., 1975), has a relatively low critical density of $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$, allowing its use as a densitometer at lower densities. H_2CO is a slightly asymmetric rotor molecule, and its utility in determining volume density and kinetic gas temperature in various sources stems from the collisionally governed K -levels (e.g. Mangum and Wootten, 1993; Mangum et al., 2013; Tang et al., 2018; Tang et al., 2021). The ground-state transitions of ortho- H_2CO at 4.8- and 2-cm, corresponding to the $1_{1,0} - 1_{1,1}$ and $(2_{1,1} - 2_{1,2})$ transitions, respectively, serve as density tracers (e.g. Mangum et al., 2008; Ginsburg et al., 2011; Ginsburg et al., 2015; Gong et al., 2023). Tang et al. (2017) observed that the abundance of H_2CO remains relatively stable across different stages of star formation, where the abundance of H_2CO varies by only one order of magnitude during these different stages of evolution, with $X(\text{H}_2\text{CO}) \simeq 10^{-10}$ (Tang et al., 2018).

Previous studies have identified a significant discrepancy between gas densities derived from molecular tracers and those derived from dust observations. For example, studies using CS (Beuther et al., 2002) or higher J -transitions of H_2CO (Tang et al., 2018) have reported higher gas densities than dust-based estimates. This discrepancy can be attributed to the high critical densities of the lines used in these studies. By utilizing the ground-state transition, H_2CO ($1_{0,1} - 0_{0,0}$), researchers can now probe the bulk material of clumps with a line of lower critical density. Consequently, this ground-state transition enhances the utility of H_2CO emission lines as both a thermometer and a densitometer.

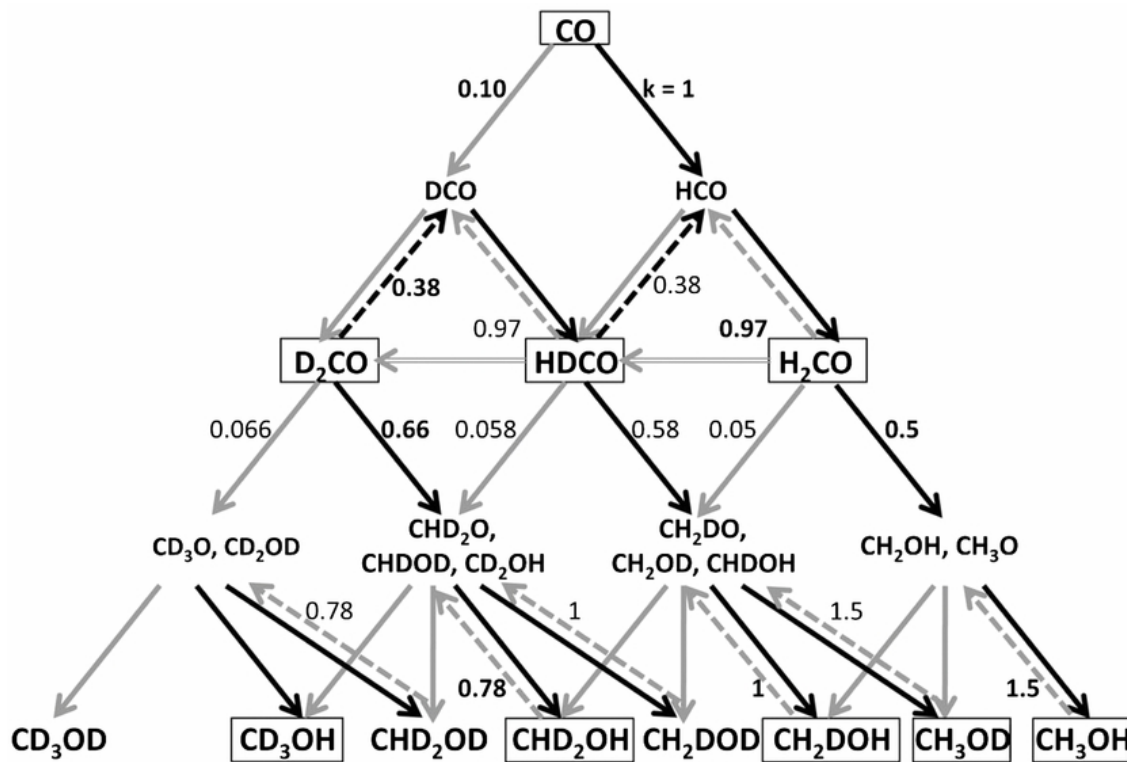


Figure 3.5: Chemical network of the successive hydrogenation forming H₂CO and CH₃OH on dust grain mantles, adopted by Taquet et al. (2012). Solid, dashed, and open arrows indicate addition, abstraction, and substitution reactions, respectively. Black arrows denote reactions involving hydrogen, while gray arrows represent reactions involving deuterium. Bold values show rates relative to the H + CO reaction, and non-bold values indicate deduced relative rates by analogy with similar reactions.

The large scale distribution of DCO^+ , DNC and DCN in the DR21 filament

The rumour of buried treasure
The starting line of an adventure
It's a glimpse of light in a mine of gold

Sleeping at last - Joy

This chapter summarizes the study of deuterated molecules in the DR21 filament, published in the article listed below, and is reproduced as Appendix A.

Christensen et al., 2024: "The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE III. The large scale distribution of DCO^+ , DNC, and DCN in the DR21 filament" in *Astronomy & Astrophysics*, Vol. 688, A215; by I. Barlach Christensen; F. Wyrowski; V. S. Veena; H. Beuther; D. Semenov; K. M. Menten; A. M. Jacob; W.-J. Kim; N. Cunningham; C. Gieser; A. Hacar; S. Li; N. Schneider; I. Skretas; and J. M. Winters.

4.1 Context

The DR21 filament, located at ~ 1.5 kpc, is an active site of HMSF. Deuterated molecules are powerful tools for investigating the gas conditions in cool, dense regions where stars form. The formation of deuterated molecules is influenced by temperature and density, with specific pathways for DCO^+ , DNC, and DCN. In the lower temperature condition (≤ 20 K), the primary molecule for the formation of deuterated molecules is H_2D^+ , while CH_2D^+ is responsible for deuteration in higher temperatures (~ 80 K). DCO^+ is formed primarily through H_2D^+ reacting with CO, whereas the formation DNC from HCND^+ via both H_2D^+ or CH_2D^+ reacting with N. In the case of DCN, it is formed through CH_2D^+ and has a less efficient pathway via DCO^+ reacting with HCN or HNC. The efficiency of DNC production is higher at lower temperatures (~ 30 K), while DCN production becomes more efficient at higher temperatures (~ 80 K).

The study, as part of CASCADE, investigates the distribution of deuteration ($R(\text{XD}) \equiv [\text{XD}]/[\text{XH}]$)

in the DR21 filament of the Cygnus-X region, focusing on the spatial characteristics and relationships with physical conditions of DCO⁺, DNC, and DCN.

4.2 Deuteration along the DR21 filament

The CASCADE program (described in Sect 2.2.4) covers the ground-state transitions of DCO⁺, DNC, and DCN, their main isotopologs (HCO⁺, HNC, and HCN) and their optically thin ¹³C-isotopologs (H¹³CO⁺, HN¹³C, and H¹³CN). The higher J -transitions of these three deuterated molecules, focusing on the higher emission regions of DCO⁺, were also observed. The main velocity of the filament is $v_{\text{LSR}} = -3 \text{ km s}^{-1}$. Integrated intensity maps were created over the velocity range from -7 km s^{-1} to $+0.5 \text{ km s}^{-1}$. The column densities are calculated following the description described in Sect. 3.1.4, where $R(D) = N(XD)/N(XH)$.

We find that significant morphological differences between these three molecules. DCO⁺ shows extended emission along the filament, with the strongest emission towards the northern region of DR21 filament. Contrary, we find that the DCN shows clumpy emission with strong peaks towards the famous DR21 Main and DR21(OH). We find that the morphology of DNC emission along the filament can be considered an “intermediate” between DCO⁺ and DCN, where the emission is more extended than DCN but also more clumpy than DCO⁺.

The fractional abundances of deuterated ($X(D) \equiv N(XD)/N(H_2)$) reveal similar values across the species. We find median abundances of $X(\text{DCO}^+) = 5.9_{1.4}^{10} \times 10^{-11}$, $X(\text{DNC}) = 6.5_{3.2}^{9.8} \times 10^{-11}$, and $X(\text{DCN}) = 6.8_{1.9}^{12} \times 10^{-11}$. The degree of deuteration was found to be approximately 1%, with $R(\text{DCO}^+) = 0.012 \pm 0.003$, $R(\text{DNC}) = 0.014 \pm 0.003$, and $R(\text{DCN}) = 0.010 \pm 0.002$. Considering only the regions where all three molecules are detected, we find that the highest deuteration is $R(\text{DNC}) = 0.014 \pm 0.003$, which is comparable to $R(\text{DCN}) = 0.010 \pm 0.002$ but a factor two higher than $R(\text{DCO}^+) = 0.006 \pm 0.001$. Although the deuteration of the three molecules are similar within a factor two, we find morphological variation of deuteration degree in the DR21 filament.

4.3 Impact of Physical Conditions on Deuteration

We investigate whether the morphological differences in the deuterated molecules are observed to be dependent on the physical conditions of the filament. Figure 4.1 shows the deuteration $R(\text{DCO}^+)$, $R(\text{DNC})$, and $R(\text{DCN})$ with the H₂ column density, dust temperature, and gas kinetic temperature. The H₂ column density and dust temperatures are based on data taken as part of the *Herschel* imaging survey of OB Young Stellar objects (HOBYS) program (Motte et al., 2010; Bonne et al., 2023).

We find varying degrees of (anti-)correlation on the physical conditions of the DR21 filament’s deuteration (see Fig. 4.1). $R(\text{DCO}^+)$ shows strong decrease at temperatures $T_{\text{dust}} \leq 20 \text{ K}$, and flattens at higher temperatures. $R(\text{DCN})$ is found to show a flat trend along the entire temperature regime, whereas $R(\text{DNC})$ shows a less significant decrease than $R(\text{DCO}^+)$.

Interestingly, we find the strongest anti-correlation between the H₂ column density with $R(\text{DCO}^+)$ ($\rho = -0.74$). This anti-correlation is likely due to local physical conditions of the DR21 filament. $R(\text{DCO}^+)$ is affected by reactions prevalent in regions with higher photodissociation and/or in shocked regions.

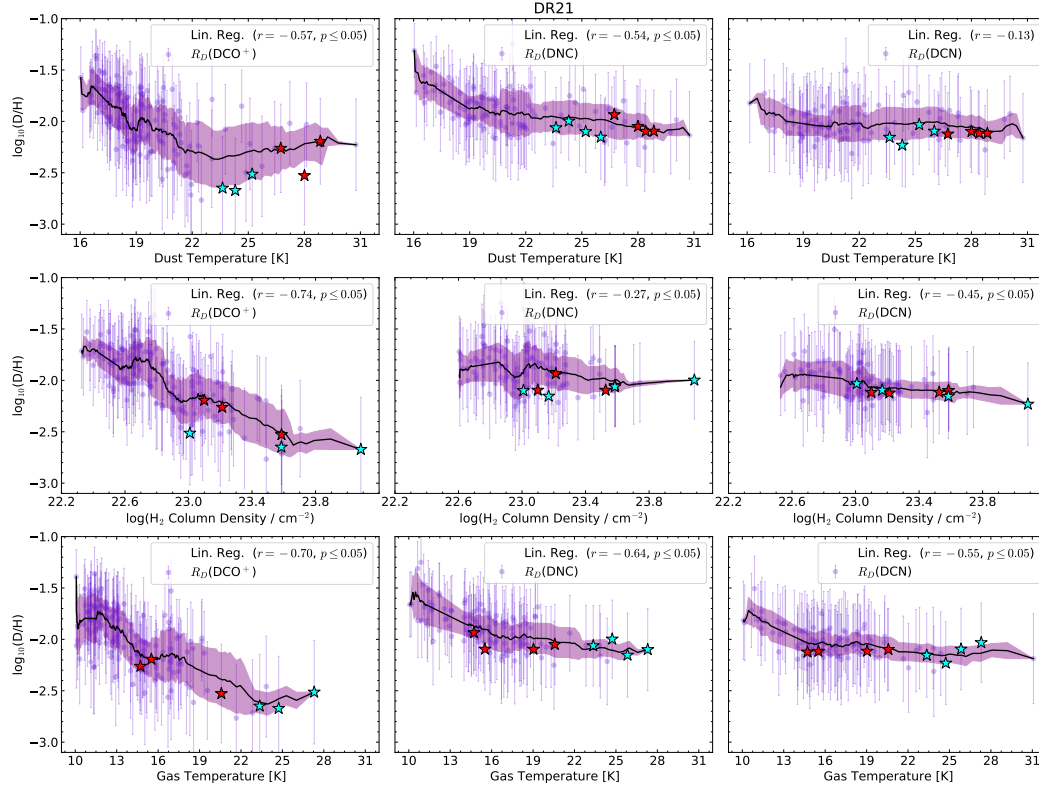


Figure 4.1: Degrees of deuteration, $R(\text{DCO}^+)$ (left column), $R(\text{DNC})$ (middle column), and $R(\text{DCN})$ (right column), with dust temperature (top row) and H_2 column densities (middle row) (Bonne et al., 2023) and kinetic gas temperature (bottom row) in the DR21 filament. Each point corresponds to the pixel-wise deuteration derived from the $J = 1 - 0$ and $J = 2 - 1$ or $J = 3 - 2$ transitions of DCO^+ , DNC , and DCN where each of the species were detected at an rms noise level $\geq 4\sigma_{\text{tot}}$. The black line shows the running mean, while the purple range marks the standard deviation. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.

4.3.1 Effects of Shocks and Photodissociation on the abundance of DCO^+

In order to understand the correlation between H_2 and $R(\text{DCO}^+)$, we look at the influence of shocks and photodissociation in the region. For this, we used their tracers, as covered by the CASCADE program, and investigated the effect of the chemistry of $R(\text{DCO}^+)$.

The DR21 filament is an active region containing several star-forming regions and harbors the most extreme outflow in the Milky Way, namely DR21 Main (Hennemann et al., 2012; Skretas et al., 2023). Utilizing the $(2-1)$ transition of SiO covered with CASCADE, a well-known tracer for shocks (e.g. Martín-Pintado et al., 1997; Kelly et al., 2017; Rybarczyk et al., 2023), we trace the regions where SiO is detected as shocked regions. In these shocked regions, where SiO is sputtered, the CO molecule is also sputtered. The CO halts the production of H_2D^+ , successively halting the production of DCO^+ . We find the presence of the SiO molecule in regions of H_2 column densities $\geq 3 \times 10^{22} \text{ cm}^{-2}$. In the regions where SiO $(2-1)$ emission is detected, we find that it corresponds with the region where $R(\text{DCO}^+)$ is consistently low (< 0.03).

To investigate photodissociation by UV radiation, we use the HCO molecule, known to form

efficiently in photodissociation regions (PDRs) via far-UV (e.g. Schilke et al., 2001; Gerin et al., 2009). In PDRs, the abundance of the rare HCO molecule becomes comparable to that of the isotopologue H^{13}CO^+ . The outer regions of the DR21 filament with lower H_2 column densities are found to be affected by the interstellar UV radiation, whereas the regions near the HII region DR21 Main and DR21(OH) are evidently associated with photodissociation from the intense star-formation (Yamagishi et al., 2018). We find in the lower H_2 column density regions, HCO^+ is destroyed at a higher rate than DCO^+ , and at higher H_2 column densities the destruction of HCO^+ decreases, resulting in an overall decrease of $R(\text{DCO}^+)$ with H_2 column density in the DR21 filament.

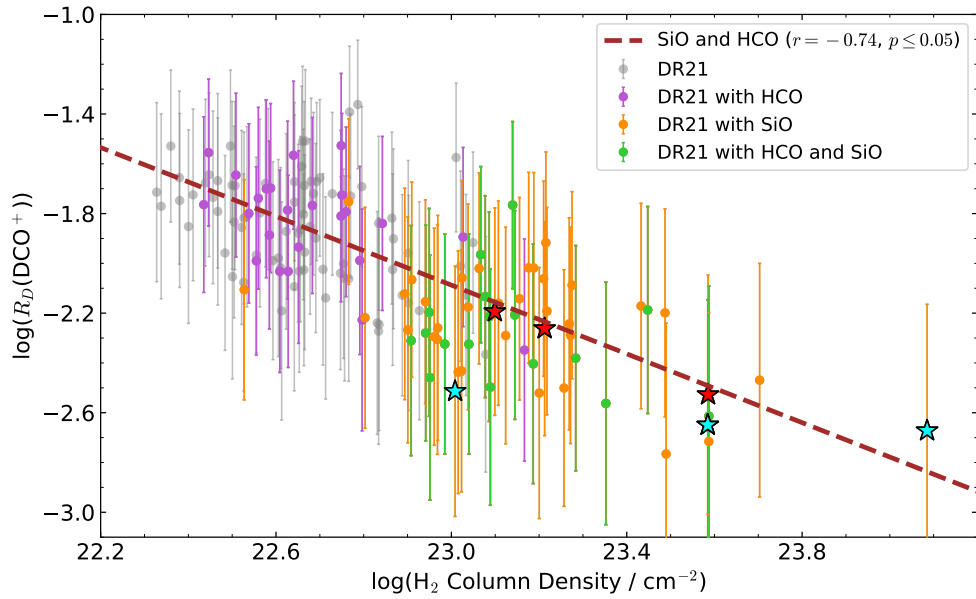


Figure 4.2: $R(\text{DCO}^+)$ with column density, where in gray are all the pixels measured in DR21, purple is $R(\text{DCO}^+)$ where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ was measured, orange is where $X(\text{SiO})$ was measured, and green is where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ and $X(\text{SiO})$ intersect. The linear fit, where SiO and HCO are detected, is shown in dashed brown. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.

The decreasing trend of $R(\text{DCO}^+)$ with H_2 column density in the DR21 filament is thus influenced by both the shocks and photodissociation by UV. Figure 4.2 shows this overall decreasing trend, marking the regions influenced by photodissociation by UV (purple), shocks (orange), and both (green).

4.3.2 DNC and DCN with the gas kinetic temperature

We find that DNC and DCN are tracing similar warmer and denser regions of the DR21 filament. This shows a temperature-dependent variation in their abundance ratio.

At dust temperatures of ≤ 30 K, DNC forms through deuterium transfer with HCN and HNC, whereas DCN mainly forms through deuterium transfer of HNC. At higher dust temperatures (~ 80 K), both DNC and DCN form efficiently through the deuterated hydrocarbon CH_2D^+ , but the efficiency of forming DNC decreases with temperature as DNC is destroyed by atomic oxygen. These differences result in distinct thermal dependencies.

Previous studies have found that the ratio of the main isotopologues HCN/HNC, and their ^{13}C

isotopologues $\text{H}^{13}\text{CN}/\text{HN}^{13}\text{C}$ have been found to serve as a proxy for kinetic gas temperatures (Hacar et al., 2020; Beuther et al., 2022; Pazukhin et al., 2022). We find that in the DR21 filament, the integrated intensity ratio of $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$ shows a moderate correlation with $I(\text{DCN})/I(\text{DNC})$, suggesting the deuterated isotopologues can trace the kinetic gas temperature. Figure 4.3 shows the correlation of the integrated intensity ratio of DCN and DNC with dust temperature. We find a linear relation of $T_{\text{dust}} = 10 \times (\text{DCN}/\text{DNC}) + 6$ is found, and with a one-to-one relation between the dust temperature and kinetic gas temperature (Hacar et al., 2020), the kinetic gas temperature can be derived using the ratio of deuterated molecules, DCN and DNC.

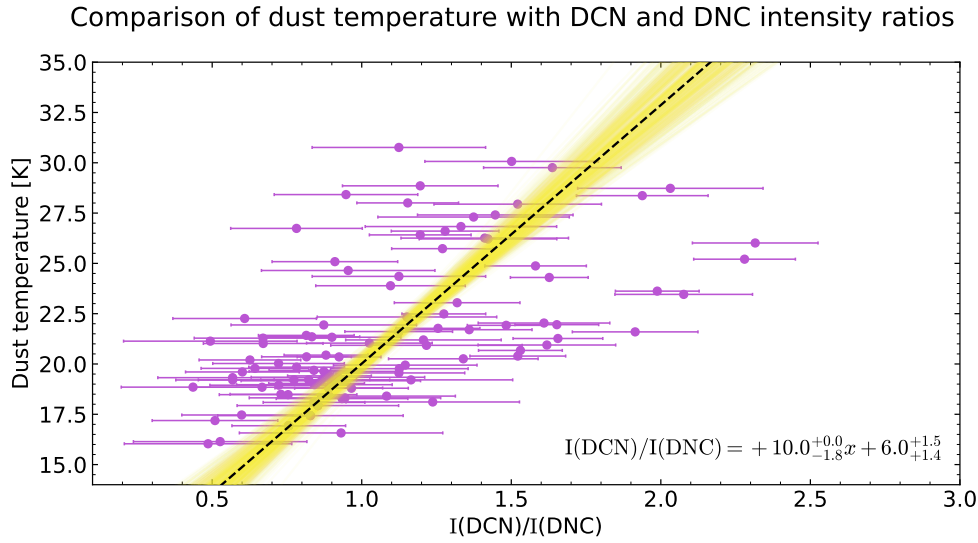


Figure 4.3: Dust temperature as a function of integrated intensity ratio of DCN and DNC with a Pearson correlation of $r = 0.58$.

4.4 Conclusions

Our observations of the DR21 filament show a high degree of deuteration ($\sim 1\%$) of $R(\text{DCO}^+)$, $R(\text{DNC})$, and $R(\text{DCN})$. We find variations of these three deuterated molecules with the physical conditions of the DR21 filament, specifically the strong anti-correlation of the $R(\text{DCO}^+)$ with H_2 column density ($\rho = -0.74$). We investigated the effects of photodissociation and shock in the DR21 filament to explain this strong decrease of $R(\text{DCO}^+)$. In the lower H_2 column density, photodissociation by UV affects the strong decrease of $R(\text{DCO}^+)$ due to the low production of the main isotopologue HCO^+ in the lower H_2 column densities. In the higher H_2 column densities, shocks affect the strong decreasing trend of $R(\text{DCO}^+)$ due to the co-sputtering of CO, thus halting the production of H_2D^+ , and successively, DCO^+ . Furthermore, we found that the integrated intensity ratio of DCN and DNC can be used to derive the kinetic gas temperature, similar to the integrated intensity ratio of the main and ^{13}C isotopologues, HCN/HNC and $\text{H}^{13}\text{CN}/\text{HN}^{13}\text{C}$. Our study emphasizes the complex interplay of physical processes affecting deuteration in the DR21 filament.

Formaldehyde as Densitometer and Thermometer in Cygnus-X, GLOSTAR pilot region and M8

We are becoming whole,
Slowly now

Sleeping at last - Slowly, Now

This chapter presents a comprehensive analysis of the physical conditions in molecular clumps within the Cygnus-X, GLOSTAR pilot, and M8 regions using multiple H₂CO transitions. We achieve a high success rate in estimating the H₂ volume density, kinetic gas temperature, and H₂CO column densities in 102 sources, and find that the obtained H₂ volume densities are consistent with those determined from 1.2-mm continuum emission. Furthermore, we find an increasing trend in the volume densities as clumps evolve in Cygnus-X and the M8 region. This work, submitted in the article listed below, is reproduced as Appendix C and summarized here.

Christensen et al. subm: "**Formaldehyde as densitometer and thermometer in Cygnus-X, GLOSTAR pilot region, and M8: Utilizing the H₂CO ground-state transition**" in *Astronomy & Astrophysics*, by I. Barlach Christensen, F. Wyrowski, H. Nguyen, T. D. Hoang, V. S. Veena, C. Gieser, H. Beuther, K. M. Menten, K. A. Kahle, Y. Gong.

5.1 Context

Formaldehyde (H₂CO) is a ubiquitous molecule believed to form through successive hydrogenation of CO on icy grain mantles (e.g. Mangum et al., 1990; Watanabe and Kouchi, 2002; Woon, 2002; Yan et al., 2019) or through the gas-phase reaction of CH₃ with atomic oxygen (e.g. Potapov and Garrod, 2024; Punanova et al., 2025) (see Sect. 3.2.4 for more details). H₂CO is a well-known tracer of high-density regions, with the $J = 3 - 2$ transition showing great capabilities of measuring a wide

range of temperatures in molecular clouds (Mangum and Wootten, 1993; Ao et al., 2013; Okoh et al., 2014). Furthermore, the fractional abundance of H_2CO remains relatively stable across different evolutionary phases of star formation, as found in the ATLASGAL Top 100 sources (Tang et al., 2017).

The relatively low critical density $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$ of the $1_{0,1} - 0_{0,0}$ ground-state transition of para- H_2CO , first detected in the ISM by Akabane et al. (1974, see also Kaifu et al., 1975), allows us to utilize this transition as a densitometer at $n \leq 10^5 \text{ cm}^{-3}$. The ortho- H_2CO transitions $J_{\text{Ka,Kc}} = 1_{1,0} - 1_{1,1}$ and $J_{\text{Ka,Kc}} = 2_{1,1} - 2_{1,2}$ have shown to be useful density tracers (e.g. Mangum et al., 2008; Ginsburg et al., 2011; Ginsburg et al., 2015; Gong et al., 2023).

Molecular line emission, such as that of NH_3 , CH_3CCH , CH_3CN , and CH_3OH , has attempted to probe the kinetic gas temperature and/or volume density with its limitations (e.g. Cummins et al., 1983; Walmsley and Ungerechts, 1983; Tafalla et al., 2004; Remijan et al., 2004; Wienen et al., 2012; Giannetti et al., 2017; Lin et al., 2022). Studies have revealed a significant discrepancy between gas densities derived from molecular tracers and those derived from the dust continuum, which can be attributed to the higher critical densities of molecular lines (e.g. Beuther et al., 2002; Tang et al., 2018).

The study aims to utilize the newly available ground-state transition of H_2CO in conjunction with the $J = 3 - 2$ transitions to investigate the capabilities of H_2CO as a densitometer and thermometer, thereby modeling the chemical ages of the clumps in Cygnus-X. We investigate closing the gap between the discrepancies observed in the volume density measurements of the clumps using dust continuum and molecular emission line observations. Further, we also aim to determine the physical conditions in clumps from various environments, spanning a wide range of evolutionary phases.

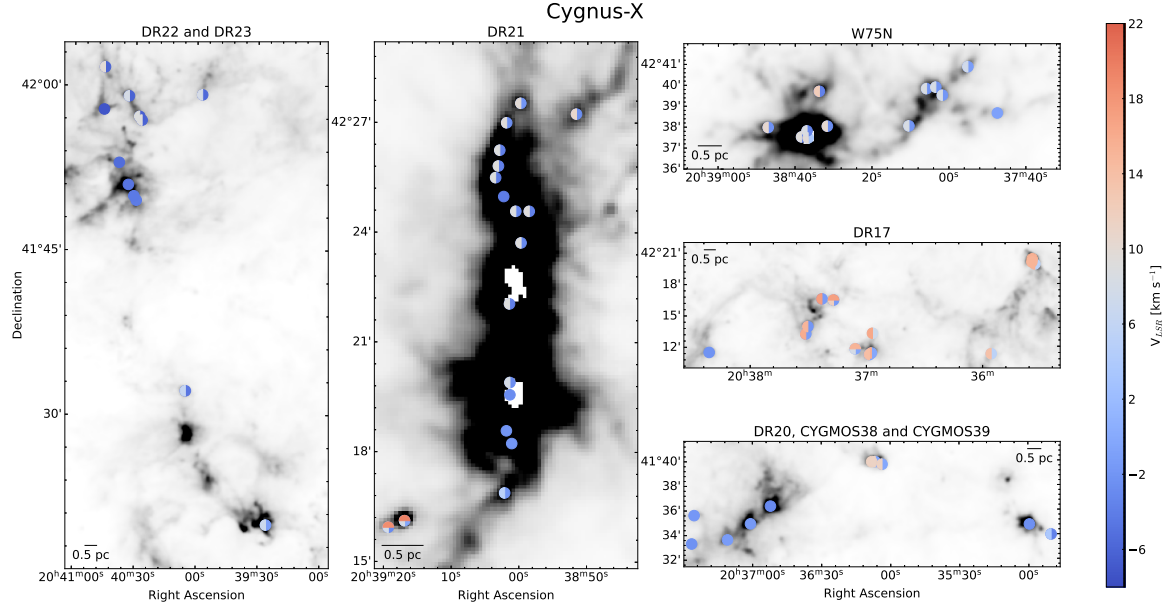
The clumps of this study focus on spanning a variety of environments and evolutionary phases. Thus, we have utilized the observations of clumps in Cygnus-X, GLOSTAR pilot region, and the M8 region (see details on observations in Sect. 2.2). Figure 5.1 shows the location of the clumps in the three source catalogs. The three source catalogs yield a total of 127 clumps: 78 in Cygnus-X, 12 in the GLOSTAR pilot region, and 37 in the M8 region.

5.2 Formaldehyde tracing the same gas

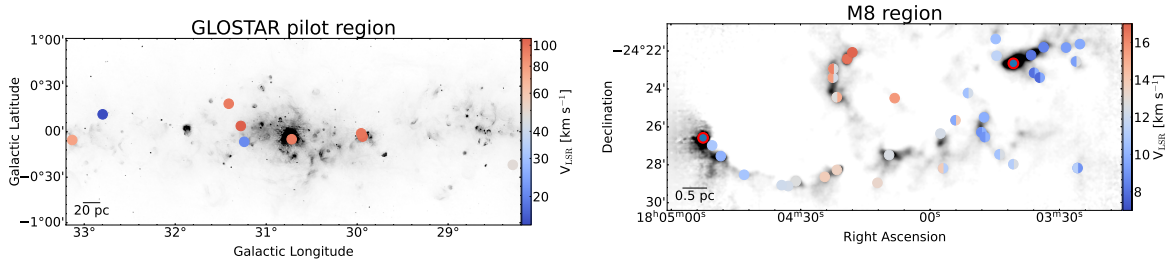
The spectra of the observed H_2CO towards all clumps are presented in Appendix D. The line profiles of the four H_2CO transitions towards all clumps are analyzed to ensure that all detected transitions for each clump are tracing the same gas prior to modeling with `pyradex+emcee`.

The detected lines are determined to trace the same gas by comparing their line profiles; similar central peak velocity, V_{LSR} , and similar linewidth, Δv . Furthermore, H_2CO ($3_{2,2} - 2_{2,1}$) and H_2CO ($3_{2,1} - 2_{2,0}$) share identical values of upper energies, E_{up} , and Einstein coefficients, A_{ij} , hence it is expected that these two transitions exhibit similar line emission profiles if these transitions originate from the same physical conditions. The last criterion for modeling the physical conditions with `pyradex+emcee` is to ensure that three or more lines are detected at $\geq 4\sigma$.

As a result, a total of 10 sources are discarded in Cygnus-X, and 13 in M8 clumps. We have $\geq 4\sigma$ detection for all clumps in the GLOSTAR pilot region.



(a) The Cygnus-X clumps on the *Herschel* 250 μm map. The clumps are colored based on the velocity components. The scalebar shows 0.5 pc at a distance of 1.5 kpc.



(b) Radio continuum image of the GLOSTAR pilot region from the VLA + Effelsberg combined 5 GHz data. The colors are the line-of-sight velocities. The scalebar shows 20 pc at a distance of 6 kpc, the median distance of the clumps.

(c) The clumps in the 870 μm filamentary structures of M8, adopted from Kahle et al., 2024. The colors are the line-of-sight velocities, where multi-color shows double velocity components. The scalebar shows 0.5 pc at a distance of 1.3 kpc.

Figure 5.1: Locations of clumps in Cygnus-X (top), the GLOSTAR pilot region (bottom left), and M8 (bottom right).

5.3 Physical conditions with pyradex+emcee

A total of 102 clumps are modeled with pyradex+emcee to obtain the physical conditions, namely volume gas density, gas kinetic temperature, and H_2CO column density. We find volume densities in the range of $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$, gas kinetic temperatures $T_{\text{gas}} = 16 - 219 \text{ K}$, and H_2CO column densities of $N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} - 1.6 \times 10^{15} \text{ cm}^{-2}$ in the Cygnus-X region, GLOSTAR pilot region, and M8 region.

5.3.1 Temperatures in clumps

Previous studies have found that the gas kinetic temperature under LTE conditions can be derived with the ratio of integrated intensities $\text{H}_2\text{CO} (3_{0,3} - 2_{0,2})$ and $\text{H}_2\text{CO} (3_{2,1} - 2_{2,0})$. The following equation shows this derivation (Mangum and Wootten, 1993; Tang et al., 2018):

$$T_{\text{LTE}} = \frac{47.1}{\ln \left(0.556 \times \frac{I(3_{0,3}-2_{0,2})}{I(3_{2,1}-2_{2,0})} \right)} \text{ K.} \quad (5.1)$$

We find a good agreement with gas kinetic temperature derived using Eq.(5.1) with that of non-LTE gas kinetic temperature modeled with pyradex+emcee for densities below $n(\text{H}_2) \leq 10^{5.5} \text{ cm}^{-3}$. This discrepancy between the LTE and non-LTE gas kinetic temperatures stems from $\text{H}_2\text{CO} (3_{2,1} - 2_{2,0})$ line intensity rapidly increasing compared to that of $\text{H}_2\text{CO} (3_{0,3} - 2_{0,2})$, which becomes more pronounced as the line ratio increases. Figure 5.2 shows a difference between the LTE and non-LTE gas kinetic temperatures increase at $n(\text{H}_2) \leq 10^{5.5} \text{ cm}^{-3}$ but remain flat at $n(\text{H}_2) < 10^{5.5} \text{ cm}^{-3}$.

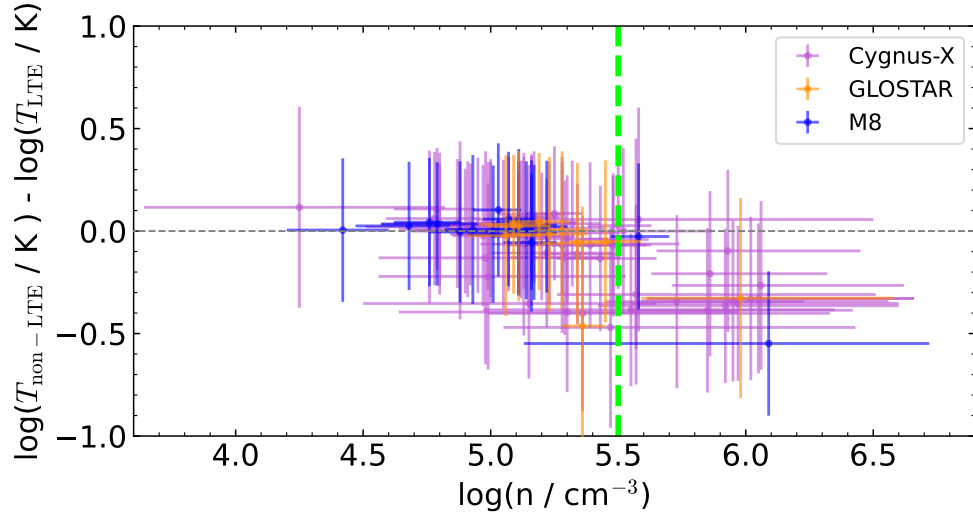


Figure 5.2: Difference between the gas kinetic temperature of sources in Cygnus-X (purple), the GLOSTAR pilot region (orange), and M8 (blue) using pyradex+emcee compared with the LTE gas kinetic temperature function presented in Tang et al., 2018. The green dashed line marks $n(\text{H}_2) = 10^{5.5} \text{ cm}^{-3}$.

5.3.2 Volume densities in clumps

Motte et al. (2007) and Tothill et al. (2002) determined the volume densities with the dust continuum in the clumps measured in Cygnus-X and the M8 region, respectively. Previous studies found discrepancies of one or two orders of magnitude between the volume densities determined using molecular emission lines and those of the dust continuum, due to the higher critical densities of the molecular line emissions (e.g. Beuther et al., 2002, using CS).

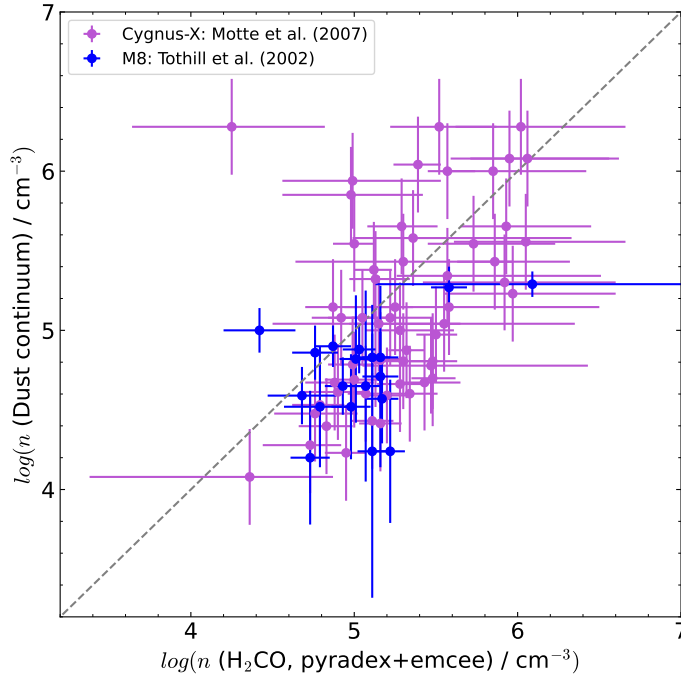


Figure 5.3: Comparison of volume densities in Cygnus-X (purple) and M8 (blue) obtained with pyradex+emcee and the 1.2-mm continuum emission by Motte et al., 2007 for Cygnus-X and Tothill et al., 2002 for M8. The grey dashed line shows $x = y$.

The lower critical density of the ground-state transition of H_2CO , in conjunction with the $\text{H}_2\text{CO } J = 3 - 2$ transitions, allows for probing the extended gas. Figure 5.3 shows a good agreement between the volume densities measured using the pyradex+emcee and those of the dust continuum by Motte et al. (2007) and Tothill et al. (2002). $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ thereby probes the bulk of the gas, obtaining volume densities $\pm 30\%$ of the volume densities measured with the dust continuum.

5.4 Physical conditions with evolutionary phases

Determining the physical conditions is essential for tracing the evolution of clumps as star formation progresses. We characterize the evolutionary phases of clumps in Cygnus-X and the M8 region using detected emission at $70 \mu\text{m}$, $24 \mu\text{m}$, and $3.6 \mu\text{m}$, obtained with the *Spitzer* telescope and AKARI (Kraemer et al., 2010; Beerer et al., 2010; Carey et al., 2009; Churchwell et al., 2009; Kahle et al., 2024) following the procedure described in Urquhart et al. (2022).

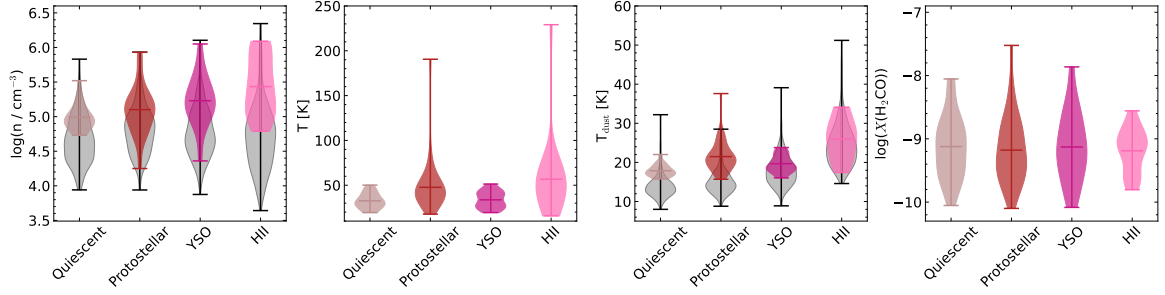


Figure 5.4: Distribution of (left to right) the H_2 volume density, gas kinetic temperature, dust temperature, and H_2CO fractional abundance with evolutionary phases of our sample. The horizontal lines within the distribution mark the mean of our sub-sample, grey distributions in the H_2 volume density and dust temperature show the mean of the ATLASGAL sample by Urquhart et al., 2022.

Figure 5.4 shows the physical conditions of clumps in Cygnus-X and M8 region distribution along their evolutionary phases: quiescent, protostellar, YSO, and HII. We find that the gas kinetic temperature and the fractional abundance of H_2CO remain rather constant along the evolutionary phases.

Interestingly, we found an increasing trend of volume densities as the clumps evolve (left-most plot in Fig. 5.4). Previous studies have observed that core scales become denser with time as gas is accreted. The clumps becoming denser indicate that the clumps are accreting gas faster than the negative feedback mechanisms. This observed trend may only be possible due to the transitions of H_2CO lines that were utilized, which allowed us to probe the bulk of the gas across all stages. Comparatively, utilizing the higher critical density transitions of H_2CO of ATLASGAL Top 100 clumps by Tang et al. (2018) do not observe this trend.

5.5 Conclusion

We utilized H_2CO ($3_{0,3} - 2_{0,2}$) transition line with the $J = 3 - 2$ H_2CO transitions to measure the H_2 volume density, gas kinetic temperature, and H_2CO column density of 102 clumps in Cygnus-X, the GLOSTAR pilot region, and the M8 region. We obtain volume densities of $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$, gas kinetic temperatures $T_{\text{gas}} = 16 - 219 \text{ K}$, and H_2CO column densities of $N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} - 1.6 \times 10^{15} \text{ cm}^{-2}$. We found that utilizing the ground-state transition probes the bulk of the gas. The H_2 volume densities obtained with the pyradex+emcee agree well with the H_2 volume densities obtained with the dust continuum.

We determine the evolutionary phases of 90 clumps in Cygnus-X and the M8 region using *Spitzer* IR observations. The clumps in the GLOSTAR pilot region are determined as HII regions. We find a significant increase in the volume density of H_2 across the evolutionary phases, suggesting that clumps become denser as they evolve on large scales. Surprisingly, we find that the dust temperature, gas kinetic temperature, and the fractional abundance of H_2CO remain constant across the evolutionary phases.

Although the purpose of this study was to determine the physical conditions for modeling chemical ages in the clumps of Cygnus-X, we find that expanding the regions to encompass various environments demonstrates the robustness of this methodology.

Chemical Evolution in Early-Stage Cygnus-X Clumps: Initial Results

You are grace, you are light
The better version of our past

Sleeping at last - Life

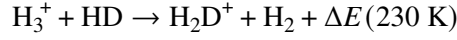
This chapter focuses on the clumps in Cygnus-X, and their chemical ages. With the CASCADE program, we covered a plethora of molecular species. We measure the column densities of several to determine the chemical age of the clumps in Cygnus-X using the Multi Stage Chemical code (MUSCLE). This work is conducted in collaboration with Dr. Caroline Gieser and Dr. Dmitry Semenov.

6.1 Introduction

The chemical evolution of high-mass star-forming regions is still poorly understood. In the earliest phases of HMSF, clumps undergo an evolution of physical conditions, from protostars accreting the surrounding gas that heats up the environment to expelling gas through outflows. Identifying molecules that can distinguish the evolutionary phases of clumps (so-called chemical clocks) is of great interest. Candidates for such are deuterated molecules, which are highly useful in constraining physical conditions such as the density, temperature, and the ionization fraction (e.g. Caselli et al., 1998; Daniel et al., 2007; Albertsson et al., 2013).

The atomic ratio of deuterium with hydrogen (D/H) in the ISM is observed to be $\sim 10^{-5}$ (Linsky, 1998; Oliveira et al., 2003; Cooke et al., 2018). Deuterium is mainly found in its molecular form in the ISM as HD, where the molecular abundance ratio of deuterated isotopologs with their main isotopologs ($\equiv X(D)/X(H)$) can reach up to a few percent, 3-4 orders of magnitudes higher than the atomic abundance ratio in the ISM. In the earliest phases of star-formation, where the natal cloud

is dense ($n > 10^5 \text{ cm}^{-3}$) and cold ($T < 30 \text{ K}$), H_2D^+ is formed rapidly through the exothermic ion-molecule reaction:



which enables a transfer of deuterium atoms to other species (Watson, 1974; Wootten, 1987).

H_2D^+ itself, being a precursor molecule for heavier deuterated molecules, and N_2D^+ , a simple N-bearing deuterated molecule, have both been suggested as tracers of the evolution of the early phases of HMSF (Emprechtinger et al., 2009; Chen et al., 2010; Fontani et al., 2011; Fontani et al., 2014). Giannetti et al. (2019) observed three massive star-forming regions and found that the abundance of $\text{o-H}_2\text{D}^+$ decreases as the cores evolve. In the same three massive cores, these authors found that the abundance of N_2D^+ is increased in the more evolved regions.

Gerner et al. (2014) and Gerner et al. (2015) studied the chemical evolution of 59 high-mass star-forming clumps. Utilizing column densities of 18 molecules, the chemical ages of these clumps were modeled, and divided into the four evolutionary: IRDC, HMPO, HMC, and UCHII (presented in detail in Chapter 1.3.1). Gerner et al. (2015) extended this study, focusing on deuterated fractions of N_2D^+ , DCO^+ , DNC , and DCN , with the evolutionary sequence of these clumps. These authors found a decreasing deuterated fraction with evolutionary phase for $R(\text{N}_2\text{D}^+)$, $R(\text{DCO}^+)$, and $R(\text{DNC})$, while $R(\text{DCN})$ is observed with an increasing trend with evolutionary phase.

In this study, we focus on the molecular conditions of 67 clumps in Cygnus-X. By applying a physical-chemical model on each of the clumps, we infer the evolutionary phases and chemical ages of these clumps. In this study, we aim to study the deuterated fraction ($R(\text{C}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, $R(\text{NH}_2\text{D})$, $R(\text{DCN})$, $R(\text{DNC})$, and $R(\text{DCO}^+)$) with evolutionary phases in Cygnus-X star-forming clumps.

6.2 Observations and results

We used the observations of the CASCADE program and its follow-up program with the IRAM 30m and APEX telescopes. The data reduction is described in detail in Sect. 2.2.4.

We retrieve the spectrum for each molecular line towards each clump in Cygnus-X. The spectra of these can be found in Appendix B. An overview of the spectroscopic properties and the respective detection rate of each molecular line is summarized in Table 6.1.

6.2.1 Spectral line analysis

We utilize the abundant molecular species HCO^+ and HNC to determine the v_{LSR} of each clump. These species are investigated as our spectral resolution does not resolve the hyperfine structures, thus enabling us to obtain a single velocity component for each clump. We manually inspect the 67 spectra of each of these clumps, and fit a Gaussian using the GILDAS Gaussian fitting procedure. With this procedure, we obtain the peak temperature (T_{MB}), integrated intensity ($\int T_{\text{MB}}$), central velocity and line width ($\Delta\nu$), with their respective errors.

We define the detection threshold as $\geq 4\sigma_{\text{tot}}$ for each emission line. We compute the total error as the calibration error ($\sigma_{\text{cal}} = 10\%$) and the integrated error propagation ($\sigma_{\text{int}} = \sigma_{\text{rms}} \times \sqrt{N_{\text{channels}}}$), as the relative uncertainty:

$$\sigma_{\text{rel,tot}}^2 = \sigma_{\text{cal}}^2 + \left(\frac{\sigma_{\text{int}}}{\int T_{\text{mb}}} \right)^2 \quad (6.1)$$

Table 6.1: Frequencies and spectroscopic properties of the transitions used to determine the column densities and utilized for the chemical modeling.

Name	Transition	Frequency [MHz]	E_{up}/k [K]	g_{up}	A_{ij} [s ⁻¹]	Catalogue	Det. rate %	Noise [mK]	Comment
¹³ CS	2-1	92494.308	6.66	10.0	1.41(-5)	CDMS	71	30	
C ₂ D	N=1-0, J=3/2-1/2, F=5/2-3/2*	72107.720	3.46	6.0	8.60(-7)	CDMS	16	39	
C ₂ D	N=1-0, J=1/2-1/2, F=3/2-3/2*	72187.708	3.46	4.0	5.34(-7)	CDMS	8	42	
C ₂ H	N=1-0, J=3/2-1/2, F=1-1*	87284.105	4.19	3.0	2.59(-7)	CDMS	86	29	
C ₂ H	N=1-0, J=3/2-1/2, F=2-1*	87316.898	4.19	5.0	1.53(-6)	CDMS	100	34	
C ₂ H	N=1-0, J=3/2-1/2, F=1-0*	87328.585	4.19	3.0	1.27(-6)	CDMS	100	35	
C ₂ H	N=1-0, J=1/2-1/2, F=1-1*	87401.989	4.20	3.0	1.27(-6)	CDMS	100	31	
C ₂ H	N=1-0, J=1/2-1/2, F=0-1*	87407.165	4.20	1.0	1.53(-6)	CDMS	98	31	
C ₂ H	N=1-0, J=1/2-1/2, F=1-0*	87446.470	4.20	3.0	2.61(-7)	CDMS	86	30	
C ₂ S	N=6-5, J=5-4	72323.789	19.21	11.0	1.60(-5)	CDMS	13	41	
C ₂ S	N=11-10, J=10-10	72783.541	46.40	21.0	2.63(-7)	CDMS	87	40	
CH ₃ CN	4(1)-3(1)	73588.799	15.98	18.0	2.05(-5)	JPL	49	42	
CH ₃ CN	4(0)-3(0)	73590.218	8.83	18.0	2.19(-5)	JPL	59	41	
CH ₃ CN	5(0)-4(0)	91987.088	13.24	22.0	4.36(-5)	JPL	54	31	
DCN	J=1-0	72414.694	3.48	9.0	1.32(-5)	CDMS	51	40	
DCN	J=3-2	217238.538	20.85	21.0	4.57(-4)	CDMS	95	30	Only in DR21
DCO ⁺	J=1-0, F=1-1	72039.350	3.46	3.0	2.29(-5)	CDMS	83	40	
DCO ⁺	J=3-2, F=3-2	216112.580	20.74	7.0	7.06(-4)	CDMS	100	20	Only in DR21
DNC	1-0	76305.727	3.66	3.0	1.60(-5)	CDMS	95	34	
DNC	2-1	152609.774	10.99	5.0	1.54(-4)	CDMS	100	20	Only in DR21
H ₂ CO	1(0,1)-0(0,0)	72837.948	3.50	3.0	8.15(-6)	CDMS	100	43	
H ₂ CO	3(0,3)-2(0,2)	218222.	21.0	7.0	2.8(-4)	CDMS	100	23	APEX
H ₂ CO	3(2,2)-2(2,1)	218475.	68.1	7.0	1.6(-4)	CDMS	83	96	APEX
H ₂ CO	3(2,1)-2(2,0)	218760	68.1	7.0	1.6(-4)	CDMS	83	90	APEX
H ¹³ CN	J=1-0	86339.921	4.14	9.0	2.23(-5)	CDMS	59	32	
H ¹³ CO ⁺	1-0	86754.288	4.16	3.0	3.85(-5)	CDMS	98	28	
HC ₃ N	J=27-26	71889.595	48.30	165.0	3.98(-5)	CDMS	33	40	
HC ¹³ CCN	J=8-7, F=8-7	72475.060	15.65	17.0	2.90(-5)	CDMS	10	42	
HCO	1(0,1)-0(0,0), J=3/2-1/2, F=2-1*	86670.760	4.18	5.0	4.69(-6)	JPL	76	29	
HCO	1(0,1)-0(0,0), J=3/2-1/2, F=1-0*	86708.360	4.16	3.0	4.60(-6)	JPL	65	31	
HCO	1(0,1)-0(0,0), J=1/2-1/2, F=1-1*	86777.460	4.18	3.0	4.61(-6)	JPL	52	30	
HCOOH	4(1,4)-3(1,3)	86546.189	13.57	9.0	6.35(-6)	CDMS	8	30	
HN ¹³ C	J=1-0	87090.850	4.18	3.0	1.87(-5)	JPL	94	32	
HNCO	4(0,4)-3(0,3)	87925.237	10.55	9.0	8.78(-6)	CDMS	68	27	
NH ₂ D	1(1,1)0s-1(0,1)0a	85926.278	20.68	27.0	2.61(-6)	CDMS	55	27	

Continued from previous page.

Name	Transition	Frequency [MHz]	E_{up}/k [K]	g_{up}	A_{ij} [s ⁻¹]	Catalogue	Det. rate %	Noise [mK]	Comment
N ₂ D ⁺	J=1-0	77109.258	3.70	27.0	2.06(-5)	CDMS	79	31	
N ₂ D ⁺	J=2-1	154217.032	11.10	45.0	1.97(-4)	CDMS	83	26	Only in DR21
N ₂ D ⁺	J=3-2	231321.857	22.20	63.0	7.14(-4)	CDMS	62	20	Only in DR21
N ₂ H ⁺	J=1-0	93173.398	4.47	27.0	3.63(-5)	CDMS	95	38	
OCS	6-5	72976.779	12.26	13.0	1.07(-6)	CDMS	22	37	
SO	2(2)-1(1)	86093.950	19.31	5.0	5.25(-6)	CDMS	88	30	
SO ₂	6(0,6)-5(1,5)	72758.243	19.15	13.0	2.77(-6)	CDMS	43	36	
SiO	J=2-1, v=0-0	86846.985	6.25	5.0	2.93(-5)	CDMS	60	31	

Notes. The frequency, upper level energy, E_{up}/k , Einstein coefficient, A_{ij} , and upper state degeneracy g_{up} , are given. The values for A_{ij} and n_{crit} are written in the form of $x(-a) = x \times 10^{-a}$. The spectroscopic information is taken, as noted, from the Cologne Database for Molecular Spectroscopy (CDMS) (Müller et al., 2005) or from the Jet Propulsion Laboratory Spectroscopic catalog database (Pickett et al., 1998). We obtain the noise levels with a spectral resolution of 0.8 km s⁻¹.

We calculate the column densities using the detected molecular line emission of each clump. The detection rates of each transition in the 67 clumps are presented in Table 6.1, including the molecular lines that are only observed with IRAM 30-m telescope towards the DR21 filament (as part of Chapter 4; DCO⁺ (3-2), N₂D⁺ (2-1), N₂D⁺ (3-2), DCN (3-2), DNC (2-1)) and the APEX telescope (as part of Chapter 5; H₂CO (3-2)).

6.2.2 Column densities

The column density is determined assuming the levels are populated following LTE (Goldsmith and Langer, 1999; Mangum and Shirley, 2015):

$$\ln \left(\frac{N_{\text{up}}}{g_{\text{up}}} \right) = \ln \left(\frac{N_{\text{tot}}}{Q_{\text{rot}}} \right) - \frac{1}{T_{\text{exc}}} \frac{E_{\text{up}}}{k_{\text{B}}}. \quad (6.2)$$

where N_{up} and g_{up} are the column density and statistical weight of a given upper energy level u , N_{tot} is the total column density in all energy levels, and Q_{rot} the partition function taken from CDMS (Müller et al., 2005) or the JPL spectroscopy database (Pickett et al., 1998). E_{up} is the upper energy, k_{B} is the Boltzmann constant and T_{exc} is the excitation temperature. In this work, we assume $T_{\text{exc}} = T_{\text{kin}}$, where T_{kin} is derived from H₂CO using pyradex+emcee (Chapter 5).

Under the assumption that the source fills the beam, the upper energy level column density can be simplified as (Goldsmith and Langer, 1999):

$$N_{\text{up}} = \frac{8\pi k_{\text{B}} \nu^2}{h c^3 A_{ij}} \int T_{\text{MB}} d\nu \times C, \quad (6.3)$$

where ν is the central frequency of the emission line, A_{ij} is the Einstein coefficient, and $\int T_{\text{MB}} d\nu$ is the integrated intensity of the molecular line of interest. $C = \frac{\tau}{1 - \exp(-\tau)}$ is the optical depth factor. Under

the assumption of optically thin line emission, we assume $C \simeq 1$.

The method of calculating the column densities assumed that the levels are in LTE. This does not hold when the molecules of interest are optically thick. As we are interested in the D/H-fractionation, the column density of the main isotopologs (HCN, HNC, HCO^+ , N_2H^+) cannot be calculated following this method. To combat this, optically thin isotopologs are used. For HCN, HNC and HCO^+ , the ^{13}C -isotopologs are used, following the method described in Sec. 3.1.4. To obtain the total column densities of the main isotopologs, we assume isotopic ratio $^{12}\text{C}/^{13}\text{C} = 7.5D_{\text{GC}} + 7.6 = 68.2$. These are calculated by the galactic isotopic ratio gradient found in Giannetti et al. (2014), multiplying this isotopic ratio by the obtained column densities of the optical thin isotopologs. The opacity of N_2H^+ is obtained from the fitting of HFS components with CLASS, and we follow Eq. (17) of Goldsmith and Langer (1999) to determine the column density. We adopt the column densities of NH_3 in Cygnus-X clumps from Wienen et al. (2012).

For each species, we consider all detected transitions and their respective errors to calculate the total column density. The total error of the column density accounts for the respective uncertainty $\sigma_{\text{rel,tot}}$ of each transition and the error of the gas kinetic temperature. In these clumps, the temperatures range as $T_{\text{kin}} = 18 - 79$ K with uncertainties in the range of $\pm 2 - 27$ K. The column densities obtained of the 24 molecules analyzed in this study are presented in Tables E.1, E.2, E.3, and E.4.

The cumulative distribution of the S-bearing (C_2S , CS, OCS, SO, SO_2), C-bearing (C_2H), O-bearing (H_2CO , HCO, HCO^+ , HCOOH , SiO), D-bearing (C_2D , DCN, DCO^+ , DNC, N_2D^+ , NH_2D), and N-bearing (CH_3CN , HC_3N , HC_5N , HCN, HNC, HNCO, N_2H^+ , NH_3) molecules' column densities.

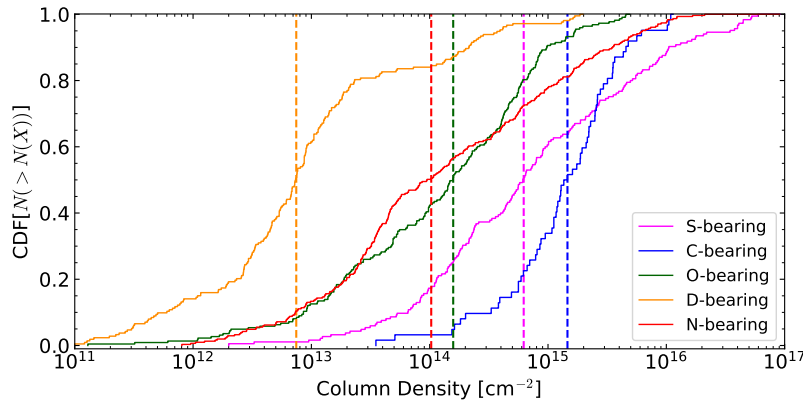


Figure 6.1: Cumulative distribution function (CDF) of S-bearing (magenta), C-bearing (blue), O-bearing (green), D-bearing (orange), and N-bearing (red) in Cygnus-X clumps. The horizontal dashed lines mark the mean column densities.

6.3 Analysis

Using the column densities and the physical conditions of clumps in the Cygnus-X region covered by CASCADE, we model the physicochemical conditions toward individual clumps to estimate the chemical age.

6.3.1 Multi Stage Chemical code

We use the Multi Stage Cloud code (MUSCLE) chemical model to estimate a chemical timescale for each Cygnus-X clump. Each clump is described by a 1D physical structure and the chemical network ALCHEMIC (Semenov et al., 2010), including a dedicated deuteration network (Albertsson et al., 2013). MUSCLE then computes abundances of 1260 molecular species using 35800 reactions as a function of time.

In Gerner et al. (2014) and Gerner et al. (2015), MUSCLE was used to create average abundances of clumps for four evolutionary phases during HMSF. These four evolutionary phases are infrared dark cloud (IRDC), high-mass protostellar object (HMPO), hot molecular core (HMC) and, finally, the ultra-compact HII (UCHII) region. This sequence is classified from an observational point of view (e.g., Beuther et al., 2007b; Zinnecker and Yorke, 2007) and covers the initial starless phase (IRDCs) up to the final UCHII region phase during HMSF. MUSCLE has also been applied to model the chemical timescales of protostars on smaller core scales (Feng et al., 2016; Gieser et al., 2019; Gieser et al., 2021; Gieser et al., 2022).

Physical Model

In MUSCLE, only the chemical model is time-dependent, while the physical structure is assumed to be static and described by 40 radial grid points. In order to consider the evolution of physical parameters, we run MUSCLE with the aforementioned four evolutionary phases taken from the Gerner et al. (2015) models.

The physical structure of each of these evolutionary phases are assumed to be spherically symmetric, with a fixed inner and outer radius, r_{in} and r_{out} . Assuming that the gas and dust are in thermal equilibrium, the radial temperature profile, with a constant inner temperature T_{in} , is described by:

$$T_r = T_{\text{in}} \quad \text{for } r \leq r_{\text{in}} \quad (6.4)$$

$$T_r = T_{\text{in}} \left(\frac{r}{r_{\text{in}}} \right)^{-q} \quad \text{for } r_{\text{in}} < r \leq r_{\text{out}} \quad (6.5)$$

The outer temperature was determined by the modeling of H₂CO (Christensen et al. subm.). For the inner and outer radius, as well as temperature power-law index $q = 0.4$, we use the best-fit models taken from Gerner et al. (2015). The radial density profile of each clump, with a fixed inner density ρ_{in} , is described by:

$$\rho_r = \rho_{\text{in}} \quad \text{for } r \leq r_{\text{in}} \quad (6.6)$$

$$\rho_r = \rho_{\text{in}} \left(\frac{r}{r_{\text{in}}} \right)^{-p} \quad \text{for } r_{\text{in}} < r \leq r_{\text{out}} \quad (6.7)$$

with the density power-law index, p . We derive p for each clump based on the MUSTANG continuum data in Appendix E.2. The inner radius, marking the onset of density plateau, is set to 12700 AU for the HMPO, 103 AU for the HMC and 1140 AU for the UCHII region phase (Table A.5, A.6, and A.7 in Gerner et al., 2015).

The clumps are assumed to be further embedded in a cloud with a extinction magnitude of $A_v = 100$ mag at the outer radius, which ensures that each clump in the clouds is shielded from the interstellar radiation field. In all of the evolutionary phases, a constant CR ionization rate is assumed. We

modeled each clump three times with a separate ionization rate, $\zeta = 1.8 \times 10^{-17} \text{ s}^{-1}$, $\zeta = 1.8 \times 10^{-16} \text{ s}^{-1}$, and $\zeta = 1.8 \times 10^{-15} \text{ s}^{-1}$ (Indriolo et al., 2015). Since the sources of whichever phase is at the highest an embedded protostar, no strong UV-radiation contribution from the source is assumed, thus we neglect X-ray ionization from the protostar. Furthermore, the model assumes that the Strömgren zone is negligibly small ($< 0.1 \text{ pc}$).

Astrochemical Model

In MUSCLE, the time-dependent gas-grain chemical model ALCHEMIC is utilized with an extended deuterium network by Albertsson et al. (2013). The chemical models are calculated up to 10^6 yr with 100 logarithmic time steps. The model assumes that the molecules at low temperature stick to grains with a 100% probability, excluding the H_2 molecules. The release of grain-molecules is through thermal desorption, cosmic-ray photoionization rate (CRP) and CRP-induced UV-photodissociation. An overview of the grain properties and radiation field parameters is shown in Table 6.2, adopted from Table 4 in Gieser et al. (2021)

We model each clump three times, each with a different ionization rate. Each model run MUSCLE with three different initial chemical abundances, following the evolutionary sequence with models of the HMPO, HMC, and UCHII phase. The initial chemical abundances of each evolutionary phase is the best-fit molecular abundance of the previous evolutionary phase, e.g. the HMPO model uses the best-fit molecular abundances of the IRDC model by Gerner et al. (2015).

Within each model, the modeled radial abundances profiles are converted into column densities within the same beam size as the observations as a function of time. The model column densities are compared to the observed column densities to determine the evolutionary phase and chemical timescale of the best-fit models based on their lowest χ^2 . The total chemical timescale of a clump is the sum of the best-fit timescale from the MUSCLE model and the sum of chemical timescales from all previous phases (Tables A.4, A.5, and A.5 in Gerner et al., 2015, with $\tau_{\text{IRDC}} = 16\,500 \text{ yr}$, $\tau_{\text{HMPO}} = 32\,000 \text{ yr}$, and $\tau_{\text{HMC}} = 35\,000 \text{ yr}$).

6.4 Discussion

We generated 201 models for the 67 clumps in the Cygnus-X region, using three ionization rates for each clump. We accept the model associated with the ionization rate that yields the lowest χ^2 as the one representing the highest likely chemical age for that specific clump. The distribution of evolutionary phase is shown in Fig. 6.2. Of the 67 clumps in Cygnus-X, 55 clumps are in the HMPO phase, three in the HMC phase, and 9 in the UCHII phase.

6.4.1 Modeling parameters

Here, we investigate how the input parameters and modeling results vary with the modeled evolutionary phases.

The top row of Fig. 6.3 shows the distribution of the independent observed parameters across the evolutionary phases; temperature within 0.1 pc ($T_{0.1\text{pc}}$), the density index (p_{obs}), the total number of molecules in the input ($\#N_{\text{tot}}$), and the ratio of continuum peak intensity and integrated intensity ($S_{\text{peak}}/S_{\text{int}}$), as observed by Motte et al. (2007). The bottom row of Fig. 6.3 shows the distribution of the model parameters across the evolutionary phases; χ^2 , the success rate in reproducing the observed

Table 6.2: MUSCLE input parameters, table adopted from Gieser et al. (2021).

Parameter	Value
Radiation field:	
CR ionization rate ζ_{CR}	$1.8(-17), 1.8(-16)^{(a)}, 1.8(-15) \text{ s}^{-1}$
Extinction A_v at r_{out}	10^{mag}
UV photodesorption yield	$1(-05)^{(b,c)}$
Grain properties:	
Grain radius r_g	$0.1 \mu\text{m}^{(d)}$
Dust density d	$3 \text{ g cm}^{-3(d)}$
Gas-to-dust mass ratio	$150^{(e)}$
Surface diffusivity $E_{\text{Diff}}/E_{\text{Bind}}$	$0.4^{(f)}$
Mantle composition	Olivine $^{(d)}$
Initial Chemical Abundances	
HMPO model	Best-fit IRDC phase $^{(g)}$
Inner radius r_{in}	12 700 au
Outer radius r_{out}	0.5 pc
Temperature T_{in} at r_{in}	113 K
Temperature power-law index q	0.0 (isothermal)
Density n_{in} at r_{in}	$1.4(5) \text{ cm}^{-3}$
Density power-law index p	1.5
Phase lifetime τ_{IRDC}	16 500 yr
HMC model	Best fit HMPO phase $^{(g)}$
Inner radius r_{in}	103 au
Outer radius r_{out}	0.5 pc
Temperature T_{in} at r_{in}	75.8 K
Temperature power-law index q	0.4
Density n_{in} at r_{in}	$1.5(9) \text{ cm}^{-3}$
Density power-law index p	1.8
Phase lifetime τ_{HMPO}	32 000 yr
UCHII model	Best-fit HMC phase $^{(g)}$
Inner radius r_{in}	1 140 au
Outer radius r_{out}	0.5 pc
Temperature T_{in} at r_{in}	162.9 K
Temperature power-law index q	0.4
Density n_{in} at r_{in}	$1.3(8) \text{ cm}^{-3}$
Density power-law index p	2.0
Phase lifetime τ_{HMC}	35 000 yr

Notes. $a(b) = a \times 10^b$.

References. $^{(a)}$ Indriolo et al. (2015); $^{(b)}$ Cruz-Diaz et al. (2016); $^{(c)}$ Bertin et al. (2016); $^{(d)}$ Gerin (2013); $^{(e)}$ Draine (2011); $^{(f)}$ Cuppen et al. (2017); $^{(g)}$ Table A.4–A.6 in Gerner et al. (2015).

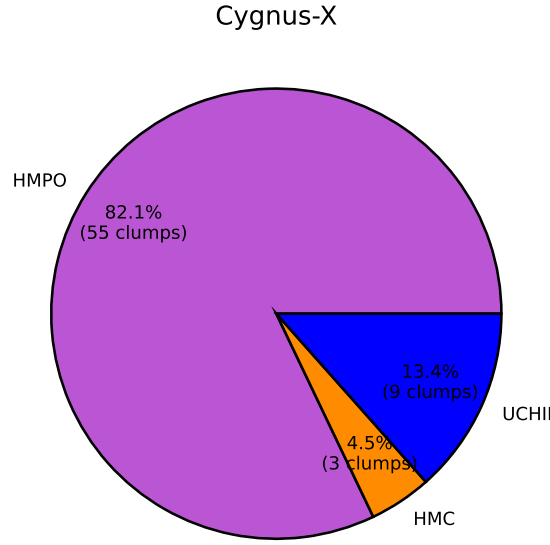


Figure 6.2: Distribution of the modeled evolutionary phases of the clumps in Cygnus-X.

column densities with the model ($\#N_{\text{best fit}}/\#N_{\text{tot}}$), the mass within 0.5 pc ($M_{0.5\text{pc}}$), and the chemical age.

In case of the independent observed parameters, $T_{0.1\text{pc}}$ and p_{obs} , they increase as the clumps evolve, suggesting the clumps become hotter and more centrally dense. The ratio between the continuum peak intensity, and the integrated intensity is a proxy for the density index. We find that $S_{\text{peak}}/S_{\text{int}}$ peaks at the hot molecular core phase, which does not agree with p_{obs} . Furthermore, we find that $\#N_{\text{tot}}$ is not biased towards a specific evolutionary phase.

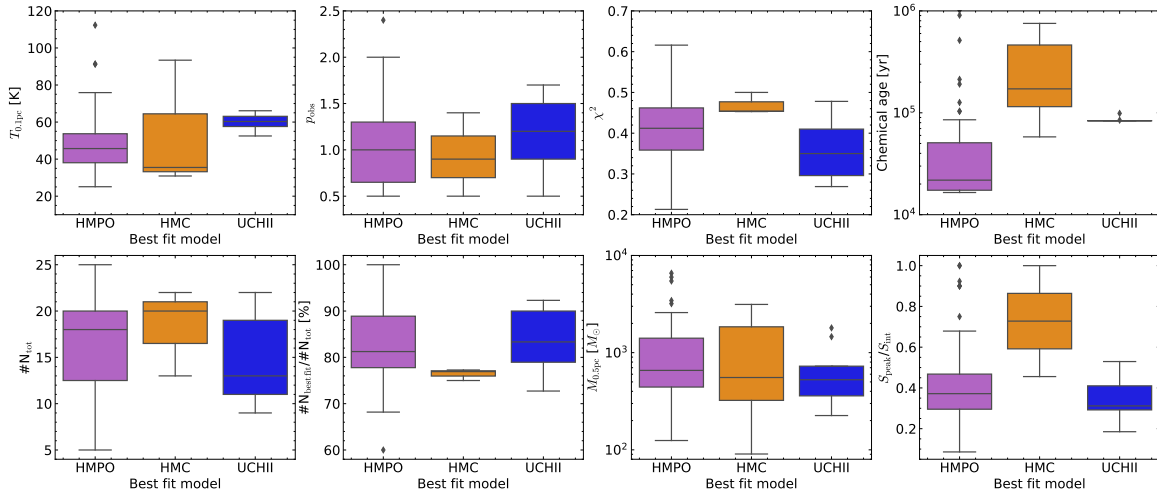


Figure 6.3: Distribution of model parameters across the evolutionary phases.

The density index measures how gas distributes inside a clump. In the early phases, gas spreads

widely without a central peak, giving the clump a low density index. As the clump evolves, gas accretes toward the center, raising the central density and producing a higher density index. This means that the density index and the evolutionary phase and the chemical age of clumps are positively correlated (e.g. Zinnecker and Yorke, 2007; Lin et al., 2022; Coletta et al., 2025). We find that we have a high success rate in reproducing the observed molecular column densities in all stages. We find that the $M_{0.5\text{pc}}$ of these clumps are consistent across across the evolutionary faces. As the clumps evolve, they accrete gas while feedback mechanisms grow more efficient, expelling gas from the central region. Consequently, the central clump maintains a roughly constant mass even though its density increases.

The total number of molecules investigated in each clump is 25. This does not mean that the column densities of all 25 molecules are measured in all clumps. The MUSCLE models reproduce the observed column densities with an average success rate of 77%, showing no bias toward any of the three evolutionary phases. Figure 6.4 shows the success and fail rate in reproducing the observed column densities. Note that CS, HCO^+ , HCN, HNC, and HC_3N column densities are derived from the ^{13}C isotopolog, thus not derived in all clumps. Our results show that the models poorly reproduce the column densities of S-bearing molecules. The S-bearing molecules not being reproduced well with the MUSCLE modeling presents a well-known challenge of modeling sulfur-chemistry (e.g. Druard and Wakelam, 2012; Miranzo-Pastor et al., 2025). Similarly using the MUSCLE models, Gerner et al. (2014) could not reproduce the sulfur-bearing molecules in clumps.

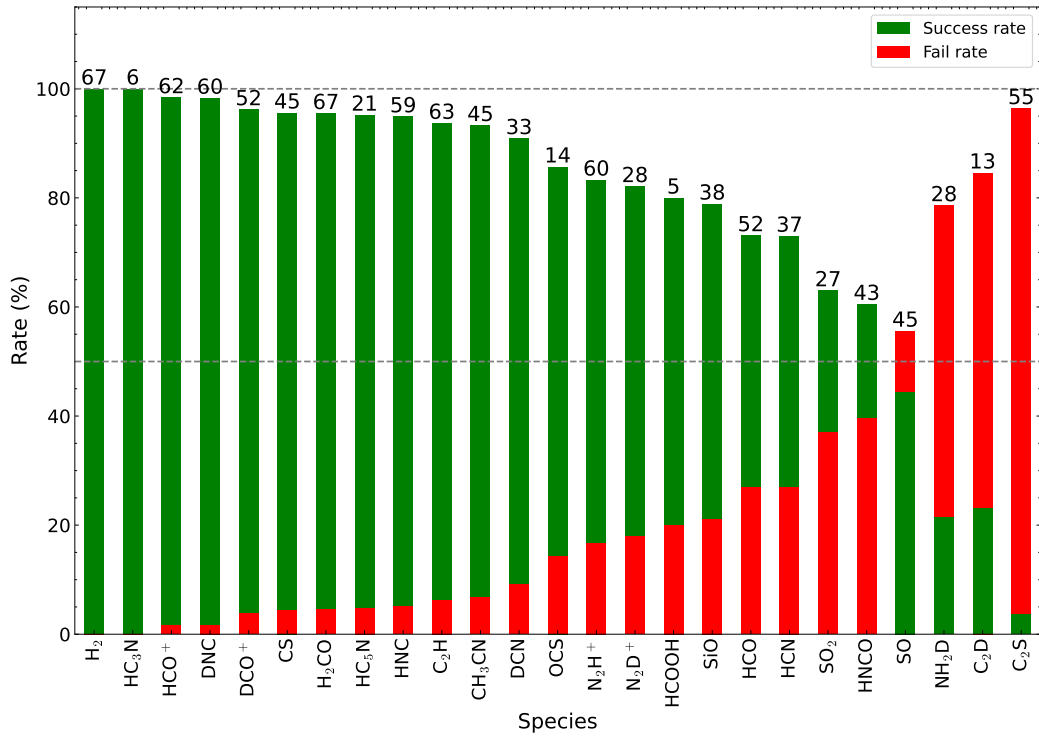


Figure 6.4: Rate of success (green) and fail (red) in reproducing the observed molecular column densities with the MUSCLE modeling. The number on top denotes the total number of clumps of which the molecule was detected.

Despite detecting NH_2D in 28 clumps, our models reproduce its molecular column density very poorly. Recent studies have expanded the reaction pathways of NH_2D and future work would include new pathways and reaction rates by Sipilä et al. (2015). We do not reproduce the column density of HCN, derived from the ^{13}C isotopolog. We find that the HCN molecular column densities are not reproduced in the HMPO stage.

Chemical age The bottom left most plot of Fig. 6.3 shows the distribution of the chemical ages across evolutionary phases. We find that the mean chemical age of HMPO is $\sim 81\,000$ years with a an error of factor $\sim 2 - 3$. This is comparable to what Gerner et al. (2014) found for the HMPO phase ($\sim 71\,000$ years). We find a very high chemical lifetime for the HMC stage of $\sim 328\,000$ years. This is an order of magnitude higher than the best-fit age of HMC found by Gerner et al. (2014). The mean chemical lifetime of the UCH_{II} phase in the Cygnus-X region is $\sim 85\,000$ years. This results in a mean total chemical lifetime across the evolutionary phases of $\sim 500\,000$ years. This total age across the evolutionary sequence is a factor 4 longer than the total age of the evolutionary sequence with Gerner et al. (2014).

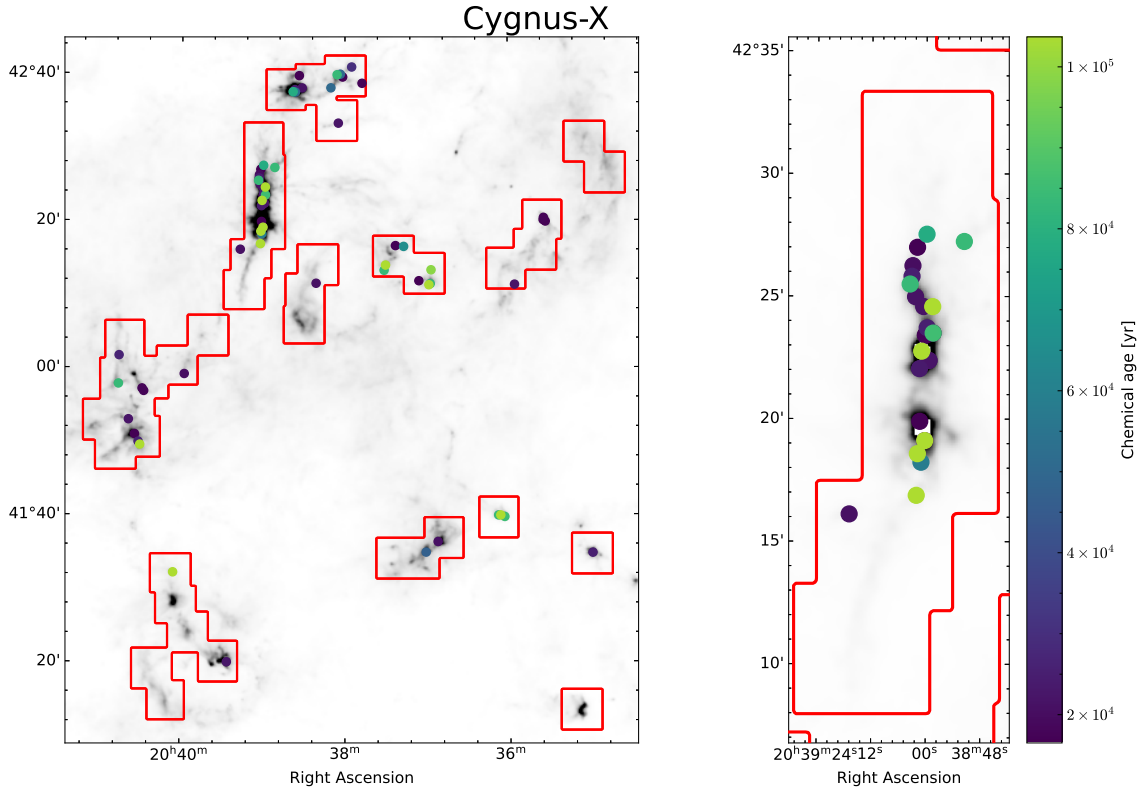


Figure 6.5: Spatial distribution of the chemical age in clumps. On the left is the entire Cygnus-X region, with the red outlining the CASCADE coverage. On the right is the DR21 filament.

Figure 6.5 shows the spatial distribution of the chemical ages of the Cygnus-X clumps. Overall, we find a spread of ages across the entire Cygnus-X region covered with CASCADE survey. The GLOSTAR survey towards galactic H_{II} regions covered the Cygnus-X region. The CASCADE survey

covers four of these H_{II} regions identified by Khan et al. (2024). In our source sample, two clumps coincide with identified H_{II} regions; N10 in DR20 is classified as an UCH_{II} with the MUSCLE modeling, and N58 in DR22 is classified as an HMPO. We do not cover the famous DR21 H_{II} region, namely N46 in the Motte et al. (2007) catalog. Additionally, an H_{II} region was observed in the DR22 region. This clump was not identified in the Motte et al. (2007) catalog due to the spatial coverage of the survey.

The right side of Fig 6.5 shows the chemical age distribution of clumps in the DR21 filament. Hennemann et al. (2012) found a gradient of evolutionary phase along the DR21 filament with clumps in the northern region younger than the clumps in the southern region near DR21(OH). With the MUSCLE modeling, we do not find this gradient of evolutionary phases. We find younger clumps near the DR21 Main and towards the northern region of DR21 filament, while the intersection of the DR21 filament and the F3 sub-filament (Schneider et al., 2010, see also Chapter 4) harbors older clumps.

We classified the evolutionary phases of the clumps using the emission of 70 μm , 24 μm , and 3.6 μm (see Chapter 5). The clumps are classified in four evolutionary phases: quiescent, protostellar, YSO, and H_{II}. With the MUSCLE modeling, we obtain best fit models in three evolutionary classifications. Table 6.3 shows the comparison between the two classifications. We find that no H_{II} classified with the μm -emissions are classified as later stage HMC or UCH_{II} with the MUSCLE modeling.

Table 6.3: Number of clumps' evolutionary phase classified with SED or the MUSCLE model.

H _{II}	9	0	0
YSO	12	1	5
Protostellar	15	1	2
Quiescent	17	1	2
	HMPO	HMC	UCH _{II}

The evolutionary phases using the μm continuum emission average over all emission lines whereas the MUSCLE modeling takes into account the separate molecular column densities, which are affected by local conditions as the clump evolves. The following section investigates how the molecular column densities behave with the evolution of the clumps. Furthermore, we focus on deuterated molecules as potential chemical clocks.

6.5 Molecules with evolution

We classified the evolutionary phases of the clumps using 25 molecules and additionally the H₂ molecule, as discussed in Sect. 6.4.1. Figure 6.6 shows the relative detection rates for each molecule across the three evolutionary phases.

We find high detection rates of deuterated molecules in Cygnus-X clumps across the evolutionary phases. The abundances of all the molecules across all evolutionary phases range between 10^{-13} to 10^{-6} .

We find that the abundances across the evolutionary phases remain within one order of magnitude, except for NH₂D, SiO, SO, SO₂, OCS, HNCO, HCO, and CH₃CN. These molecules specifically have a lower reproduction rate in the MUSCLE modeling. We find that C₂D, HC₃N, and HCOOH are not detected in the HMC stage (see Fig. 6.6), with the latter two only detected in the HMPO phase. This is

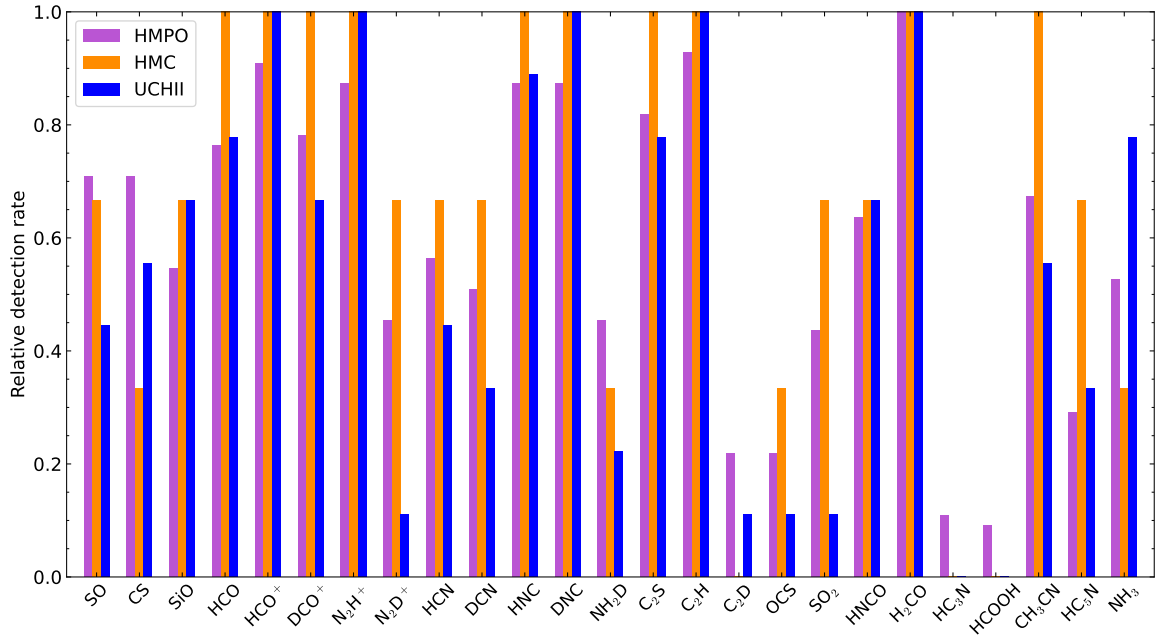


Figure 6.6: Relative detection rates of all 25 molecules in clumps in HMPO, HMC, and UCHII evolutionary phase.

likely not due to the chemical conditions of the clumps, but might be due to the low number of clumps classified in this phase.

NH_2D , N_2D^+ , DCN , DNC , and DCO^+ are detected in $\geq 42\%$ of the clumps. C_2D is detected in 19% of the clumps across all evolutionary phases. The following section focuses on the fraction to their respective main isotopologs of these 6 deuterated molecules.

6.5.1 Deuterated molecules in Cygnus-X

We investigate deuterated fraction in the entire Cygnus-X region and the duration in the sub-regions covered with CASCADE. We obtain the deuterated fraction of $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, $R(\text{DCN})$, $R(\text{DNC})$, $R(\text{DCO}^+)$ over the entire Cygnus-X region and the sub-regions covered with CASCADE (summarized in Fig. 6.7). We find the highest deuteration fraction with $R(\text{C}_2\text{D})$ ($= 0.159 \pm 0.065$), averaged over 10 clumps. Conversely, we find that the average deuteration fraction is lowest with $R(\text{DCO}^+)$ (0.008 ± 0.004), averaged over 45 clumps.

C_2D The lightest deuterated carbon molecule, C_2D , is proposed to predominantly form through an exothermic ion–molecule reaction between C_2H_2^+ and HD under elevated temperature conditions (Combes et al., 1985; Herbst et al., 1987).

We observe a wide range of $R(\text{C}_2\text{D})$ values, spanning 0.037 to 0.333, despite a relatively low detection rate of approximately 15% across the clumps. The corresponding temperatures lie between 22 and 65 K. Among the deuterated species analyzed in this study, $R(\text{C}_2\text{D})$ exhibits the highest average value ($= 0.159 \pm 0.065$), which significantly exceeds the ratios reported near the Mon R2 UCHII region

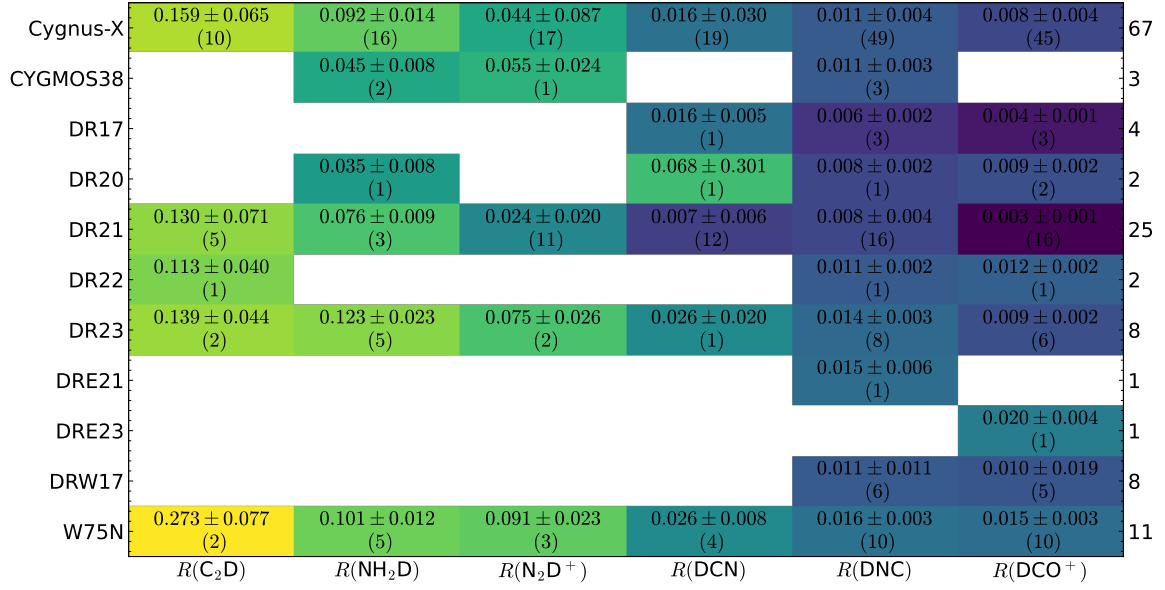


Figure 6.7: Heatmap table of the deuterated molecules in the regions covered with CASCADE with the total number of clumps in each regions shown in left. The parenthesis denotes the number of clumps the deuterated fraction was measured in, and the right y-axis denoted the total number of clumps in the region.

(0.02 – 0.08) (Treviño-Morales et al., 2014). In comparison, the Orion molecular cloud and TMC-1 display lower $R(\text{C}_2\text{D})$ ratios of 0.02-0.03 and 0.01-0.02, respectively (Herbst et al., 1987).

NH_2D Models struggle to reproduce the observed $R(\text{NH}_2\text{D})$ values, even though NH_2D forms on gas–grain surfaces and consists of comparatively simple atoms (Sipilä et al., 2015; Harju et al., 2024). The spin states of H_2 in H_2D^+ and H_3^+ further influence the formation pathways of both NH_3 and NH_2D .

We measure $R(\text{NH}_2\text{D})$ values ranging from 0.017 to 0.291, with an average of 0.092 ± 0.014 . Pazukhin et al. (2023) reported $R(\text{NH}_2\text{D})$ values between 0.02 and 0.4 in massive star-forming regions (SFRs), while Petrashkevich et al. (2024) observed notably higher ratios, from 0.30 to 0.81, in the low-mass SFR L1688, both detected toward the continuum peaks. In contrast, Treviño-Morales et al. (2014) found substantially lower $R(\text{NH}_2\text{D})$ values near the UCH_{II} region Mon R2, measuring $= 0.39 \times 10^{-3}$ at the ionization front and $= 0.6 \times 10^{-3}$ at a secondary continuum peak located $40''$ from the main Mon R2 continuum peak.

N_2D^+ N_2D^+ forms through low-temperature ion–molecule reactions between N_2 and H_2D^+ . At elevated temperatures, the sublimation of CO from dust grains promotes the destruction of N_2D^+ through reactions with CO. Nevertheless, $R(\text{N}_2\text{D}^+)$ deuteration remains efficient in dense regions (Riaz and Thi, 2022).

$R(\text{N}_2\text{D}^+)$ exhibits a high deuteration fraction in low-mass cores, with reported values of $R(\text{N}_2\text{D}^+) = 0.26^{+0.15}_{-0.14}$ in the prestellar core L1544 and 0.26 – 0.73 in the low-mass cores of L1688 (Redaelli et al., 2019; Petrashkevich et al., 2024). In contrast, proto-brown dwarfs show a much lower average deuteration level, with $R(\text{N}_2\text{D}^+) = 0.02 \pm 0.008$ (Riaz and Thi, 2022). Across the Cygnus-X region,

we detect N_2D^+ in approximately 25% of the clumps, where $R(\text{N}_2\text{D}^+)$ ranges from 0.011 to 0.113. Similarly, Yang et al. (2024) reported a low detection rate of N_2D^+ in massive starless clumps.

DCN DCN forms efficiently at elevated temperatures of ~ 80 K through reactions involving the light hydrocarbon ion CH_2D^+ . Owing to its higher critical density relative to other deuterated species, DCN serves as a valuable tracer of denser regions (e.g., Riaz and Thi, 2022; Christensen et al., 2024).

We detect DCN emission in 19 of the 67 clumps across Cygnus-X, primarily concentrated in DR21 and W75N. These two regions lie in close proximity and host clusters of early B-type stars (Schneider et al., 2023). The measured $R(\text{DCN})$ averages $= 0.016 \pm 0.03$, with individual values ranging from 0.001 to 0.068. These ratios are consistent with those observed in massive star-forming regions, where $R(\text{DCN})$ varies between 0.004 – 0.045 and 0.001 – 0.02 (Yang et al., 2024; Pazukhin et al., 2023, respectively). The associated gas temperatures of $T_{\text{gas}} = 18 - 66$ K in our sources align with the 20 – 40 K range reported for the massive clumps studied by Pazukhin et al. (2023).

DNC DNC forms efficiently at elevated temperatures through reactions involving light hydrocarbons, similar to DCN. However, unlike DCN, DNC can also form at lower temperatures via deuteron transfer to HCN and HNC (Turner, 2001). At higher temperatures, atomic oxygen contributes to the destruction of DNC.

The average $R(\text{DNC})$ is 0.011 ± 0.004 , exhibiting the smallest variation among all six measured deuteration fractions. The $R(\text{DNC})$ values correspond closely to those observed in massive clumps (Pazukhin et al., 2023; Yang et al., 2024). In the UCHII region of Mon R2, $R(\text{DNC})$ increases by a factor of two near the ionization front and by a factor of three at the offset continuum peak compared with the average values observed in the Cygnus-X clumps (Treviño-Morales et al., 2014).

DCO⁺ DCO⁺ primarily forms in the gas phase through reactions between H_2D^+ and CO. In warmer environments ($T_{\text{gas}} = 30 - 80$ K), a secondary formation pathway involves reactions of the light hydrocarbon ion CH_2D^+ with atomic oxygen (Pagani et al., 2011; Favre et al., 2015).

We measure the lowest $R(\text{DCO}^+)$ value of $= 0.008 \pm 0.004$ across the Cygnus-X region, with the highest deuteration fraction observed in W75N ($= 0.015 \pm 0.003$). High-mass star-forming regions exhibit a wide range of $R(\text{DCO}^+)$ values, spanning 0.0004 – 0.02 in 59 high-mass clumps (Gerner et al., 2015) and 0.011 – 0.040 in massive starless clump candidates (Yang et al., 2024). In contrast, the low-mass prestellar core L1544 shows an average $R(\text{DCO}^+)$ of $= 0.035^{+0.015}_{-0.012}$ (Redaelli et al., 2019), while a higher mean value of $= 0.18 \pm 0.19$ is reported in 18 Class 0/I brown dwarfs (Riaz and Thi, 2022). Despite the diversity of environments, variations in local density and temperature remain the primary distinguishing factors. The temperature range of the Cygnus-X clumps in this study aligns with those reported in the aforementioned regions. Overall, we find $R(\text{DCO}^+)$ values between 0.001 and 0.028 across all clumps.

Previous studies suggest that local physical conditions may reflect the evolutionary stage of high-mass clumps. In our analysis, $R(\text{C}_2\text{D})$ and $R(\text{NH}_2\text{D})$ exhibit the largest variations across the sample, whereas $R(\text{DCO}^+)$ and $R(\text{DNC})$ show the smallest.

6.5.2 Deuterated fractions with evolution

We examine the deuteration levels of six molecular species across different evolutionary phases (Fig. 6.8). The derived deuterated fractions of $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, and $R(\text{DCN})$ are based on measurements in < 20 clumps. The detection rates of DCN, N_2D^+ , and NH_2D are comparatively low, likely due to the high critical density required for DCN excitation and the dependence of N_2D^+ and NH_2D formation on the dense gas tracer N_2 .

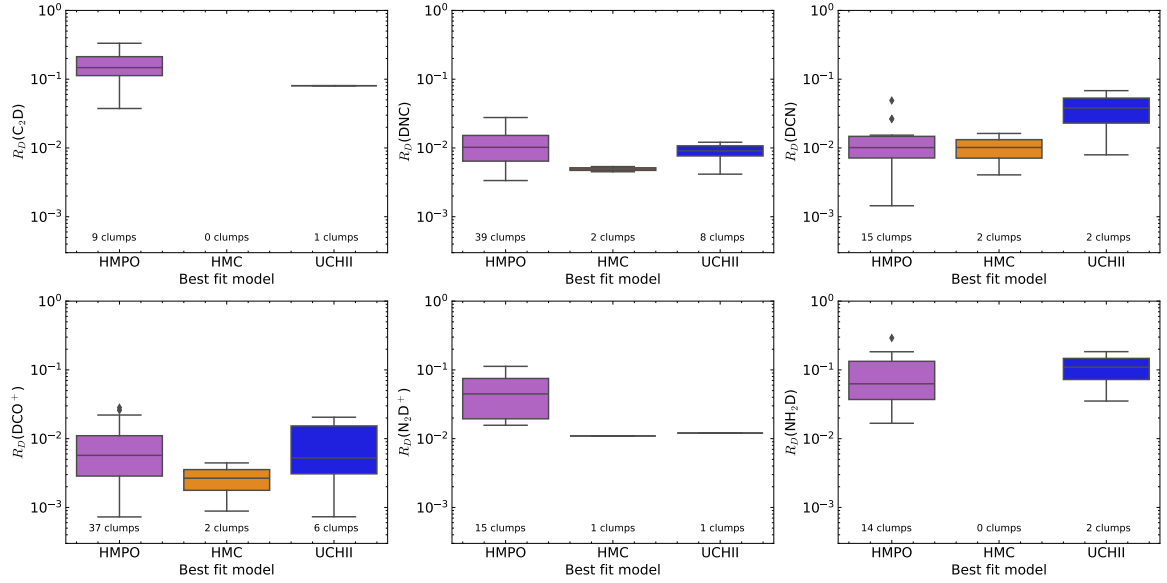


Figure 6.8: Spread of deuterated fraction in the evolutionary phases modeled with MUSCLE. The number of clumps of which the deuterated fraction is measured is written below each range. The grey boxes in $R(\text{DNC})$, $R(\text{DCN})$, $R(\text{DCO}^+)$, and $R(\text{N}_2\text{D}^+)$ are the deuterated fractions from Gerner et al. (2015).

We observe a slight increase in $R(\text{DCN})$ across the evolutionary phases of the clumps. As the clumps evolve, their temperatures rise (as discussed in Sect. 6.4.1), enhancing the efficiency of DCN formation (e.g., Turner, 2001). In the DR21 filament (Chapter 4), DCN emission and $R(\text{DCN})$ are concentrated in regions with higher temperatures and densities.

In contrast to the increasing $R(\text{DCN})$ trend observed in the Cygnus-X clumps, Gerner et al. (2015) reported a slight decrease in $R(\text{DCN})$ at more evolved clumps. $R(\text{DNC})$ decreases with evolutionary stage in both 59 high-mass star-forming clumps and 18 massive clumps (Gerner et al., 2015; Sakai et al., 2012, respectively). In dense cores, the behavior of $R(\text{DNC})$ appears intermediate between that of $R(\text{N}_2\text{D}^+)$, which declines with evolution, and $R(\text{NH}_2\text{D})$, which remains relatively constant across evolutionary stages (Fontani et al., 2011; Fontani et al., 2014; Emprechtinger et al., 2009; Fontani et al., 2015). Although early chemical models predict that $R(\text{NH}_2\text{D})$ should decrease with increasing temperature (Trofimova et al., 2024), this trend is not supported by observational studies (Fontani et al., 2015; Emprechtinger et al., 2009) or by our results. In contrast, we observe a modest increase in the median $R(\text{NH}_2\text{D})$ from 0.063 in the HMPO phase to 0.110 in the UCHII phase. The latter value is comparable to that found in Class 0 protostellar cores, where $R(\text{NH}_2\text{D})$ remains consistently above 0.15 (Emprechtinger et al., 2009).

Similar to the discrepancy observed between the $R(\text{DCN})$ trends in the Cygnus-X clumps and those

reported for 59 high-mass star-forming clumps, we find that $R(\text{DCO}^+)$ increases in more evolved clumps, whereas Gerner et al. (2015) reported a decreasing trend (see Fig. 6.8). DCO^+ forms efficiently at low temperatures under conditions where CO is frozen out (e.g., Caselli et al., 1998) and is destroyed once CO sublimates back into the gas phase. Since the temperature rises with evolutionary stage in our sample, a decline in $R(\text{DCO}^+)$ would be expected. However, we instead observe an increase in $R(\text{DCO}^+)$ in the more evolved clumps.

Previous studies have extensively examined the potential of deuterated molecules as chemical clocks. Treviño-Morales et al. (2014) proposed that $R(\text{DCN})$, $R(\text{DNC})$, and $R(\text{C}_2\text{D})$ warrant further investigation as possible tracers of chemical evolution. In contrast, the authors argued that $R(\text{N}_2\text{D}^+)$ and $R(\text{DCO}^+)$ are unsuitable as evolutionary indicators in high-mass star-forming regions, since their deuterated fractions reach steady-state abundances on relatively short timescales.

6.6 Conclusion

This chapter presents the chemical modeling of 67 clumps in Cygnus-X. The main findings are summarized below:

1. Detection rate of molecules We detect a high abundance of molecular species within the clumps. Our analysis focuses on 25 molecules, including six deuterated species, encompassing 40 transitions. The number of detected molecules per clump ranges from a minimum of 5 to a maximum of 25.

2. Column densities in clumps We derive the column densities of the detected molecules in each clump using the temperatures and H_2 column densities obtained in Chapter 5. The average molecular abundances relative to H_2 range from approximately 10^{-13} for deuterated species to 10^{-6} for the main isotopologs.

3. Astrochemical modeling of clumps We derive the density index from high-resolution MUSTANG observations of each clump. We observationally constrain the physical model of the clumps using the H_2 column density and gas kinetic temperature determined with H_2CO , together with the density index obtained from the MUSTANG data. We assume that the physical structures follow the IRDC, HMPO, HMC, and UCH_{II} outlined by Gerner et al. (2014) and Gerner et al. (2015).

We model the chemical structure of each clump in conjunction with its physical structure using the extended deuterium network developed by Albertsson et al. (2013). For each clump, we perform three simulations, each adopting a different ionization rate.

4. Evolution in clumps We classify the evolutionary phases of the clumps, identifying 55 in the HMPO phase, 3 in the HMC phase, and 9 in the UCH_{II} phase. We determine chemical ages ranging from 1.6×10^4 to 1.0×10^6 yr. The results show increasing temperature and a slight rise in the density index as the clumps evolve.

Our chemical modeling reproduces more than 60% of the observed molecular column densities. Molecules that are not well reproduced include shock-related species, known to be difficult to model, and NH_2D . Future work will extend the astrochemical network by incorporating the updated reaction rates for NH_2D provided by Sipilä et al. (2015).

5. Deuteration fraction with evolution We measure the deuterated fractions of $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, $R(\text{DCN})$, $R(\text{DNC})$, and $R(\text{DCO}^+)$, and find that the detection rates of these species vary significantly across the clumps. $R(\text{DNC})$ is detected in 73% of the clumps, whereas $R(\text{C}_2\text{D})$ is detected in only 15%, indicating that different deuterated species trace distinct physical or chemical conditions within the region. The highest deuteration degree occurs for $R(\text{C}_2\text{D})$ ($= 0.159 \pm 0.065$) over the Cygnus-X region, while the lowest is found for $R(\text{DCO}^+)$ ($= 0.008 \pm 0.004$), highlighting strong molecule-dependent variations in deuterium enrichment. $R(\text{DNC})$ exhibit decreasing deuteration as the clumps evolve, consistent with the progressive warm-up and chemical processing that reduce deuterium fractionation at later evolutionary stages. We find, in contrast to previous studies, that $R(\text{DCO}^+)$ increases at later evolutionary stages, indicating behavior that is inconsistent with earlier results.

In Chapter 4, the deuterated fraction $R(\text{DCO}^+)$ was found to be affected by both shock and ionization, both phenomena effectively decreasing this deuterated fraction. In this study, we model the evolutionary sequence of the clumps, varying the cosmic-ray ionization rate, ζ , whilst the model does not account for shocks. Further studies investigating tracers of these phenomena could shed light into the behavior of $R(\text{DCO}^+)$ with the evolutionary phases.

Conclusion and outlook

With shortness of breath, I'll explain the
infinite
How rare and beautiful it truly is that we
exist

Sleeping at last - Saturn

The processes governing the formation of high-mass stars remain poorly constrained. Deuterated fractions ($R \equiv X(D)/H(D)$) are sensitive to local physical conditions and have been proposed as tracers of ionization, temperature, density, and the evolutionary stages of star-forming regions (Caselli et al., 1998; Emprechtinger et al., 2009; Fontani et al., 2011; Sakai et al., 2012; Gerner et al., 2014; Fontani et al., 2014; Gerner et al., 2015; Fontani et al., 2015; Yang et al., 2024).

This thesis focuses on Cygnus-X, a nearby molecular cloud complex characterized by extensive and intense star formation. The region hosts objects spanning various evolutionary stages, including dense clumps, embedded protostars, and filamentary structures. The Max Planck Gesellschaft (MPG) and the Institut de Radioastronomie Millimétrique (IRAM) jointly initiated the **Cygnus Allscale Survey of Chemistry and Dynamical Environments (CASCADE)** to investigate the physical and chemical conditions within Cygnus-X. Using the IRAM 30-m telescope and the NOEMA array, the program conducted spectral line surveys targeting regions of high column density across the cloud complex. Observations covered 12 sub-regions within Cygnus-X, including the well-known DR21 filament, which contains the prominent DR21 Main core and the DR21 OH maser.

The DR21 filament represents the densest and most active region within the Cygnus-X complex. In Chapter 4, we analyze the deuterated molecules DCO^+ , DNC, and DCN based on CASCADE observations of their ground-state transitions, including those of the main and ^{13}C isotopologs. To extend the analysis to higher excitation levels, we complemented these data with additional IRAM 30-m telescope observations covering higher J -transitions of the same molecules. From these observations, we derived the deuterated fraction along the DR21 filament. The analysis yields median abundances of $X(\text{DCO}^+) = 5.9_{1.4}^{10} \times 10^{-11}$, $X(\text{DNC}) = 6.5_{3.2}^{9.8} \times 10^{-11}$, and $X(\text{DCN}) = 6.8_{1.9}^{12} \times 10^{-11}$.

We observe apparent morphological differences among the three deuterated fractions, which we attribute to variations in the physical conditions along the DR21 filament. In regions where all three deuterated molecules are detected, we measure the highest deuteration fraction for $R(\text{DNC}) = 0.014 \pm 0.003$, comparable to $R(\text{DCN}) = 0.010 \pm 0.002$.

In contrast, we find the lowest deuteration fraction for DCO^+ , with $R(\text{DCO}^+) = 0.006 \pm 0.001$, a factor of two lower than both $R(\text{DNC})$ and $R(\text{DCN})$. We also find varying degrees of (anti-)correlation between $R(\text{DCO}^+)$, $R(\text{DNC})$, and $R(\text{DCN})$ and the H_2 column density, dust temperature, and gas kinetic temperature. The strongest anti-correlation occurs between $R(\text{DCO}^+)$ and the H_2 column density, with a Pearson correlation coefficient of $\rho = -0.74$.

The DR21 filament is one of the most active regions within the Cygnus-X complex, hosting multiple star-forming sites along its length and exhibiting some of the most extreme molecular outflows detected in the region (Hennemann et al., 2012; Skretas et al., 2023). To probe these shock processes, we employed SiO, a well-established shock diagnostic. Since SiO co-sublimates with CO, it also contributes to the depletion or destruction of DCO^+ , thereby affecting local $R(\text{DCO}^+)$. The analysis reveals that regions with $N(\text{H}_2) \geq 3 \times 10^{22} \text{ cm}^{-2}$ exhibit elevated SiO abundances, suggesting that shock chemistry is active in the dense regions of the filament. Beyond these dense ridges, the filament is surrounded by lower column-density gas that appears to be inflowing toward the main structure. This lower-density material is likely exposed to FUV radiation, leading to photochemical reactions characteristic of PDRs. To trace such processes, we used the HCO molecule, which efficiently forms under FUV irradiation (e.g. Schilke et al., 2001). In regions of $N(\text{H}_2) \leq 3 \times 10^{22} \text{ cm}^{-2}$, $N(\text{HCO})/N(\text{HCO}^+) \geq 1$ and $X(\text{HCO}) \geq 10^{-10}$, indicate ongoing FUV chemistry (Kim et al., 2020). As the H_2 column density increases, $N(\text{HCO})/N(\text{HCO}^+)$ decreases, consequently decreasing $R(\text{DCO}^+)$. These findings suggest that a combination of the ongoing FUV chemistry and shock chemistry results in the overall anti-correlation of $R(\text{DCO}^+)$ with increasing H_2 column density in the DR21 filament.

The intensity ratio between the main isotopologs HCN and HNC, as well as their ^{13}C isotopologs, has been proposed as a diagnostic of the gas kinetic temperature for $T_{\text{kin}} \leq 40 \text{ K}$ (Hacar et al., 2020; Pazukhin et al., 2022). We find that the integrated intensity ratio of the deuterated isotopologs, $I(\text{DCN})/I(\text{DNC})$, increases with dust temperature, thereby extending the utility of these ratios as temperature tracers. Although the deuterated molecules are less abundant than their main and ^{13}C counterparts, they can serve as valuable probes of gas kinetic temperature in regions where the primary isotopologs are optically thick.

Cygnus-X represents a prominent high-mass star-forming region (HMSFR). The CASCADE survey covers 82 star-forming clumps identified by Motte et al. (2007) and Cao et al. (2019). In Chapter 5, we investigate the physical conditions by analyzing the ground-state transition of H_2CO observed in the CASCADE survey, complemented by $\text{H}_2\text{CO } J = 3 - 2$ observations with the APEX telescope toward 72 clumps. We extended the methodology for deriving physical conditions using `pyradex+emcee` to diverse environments, including the GLOSTAR pilot region and the M8 region, resulting in a total of 127 clumps.

Overall, we find a high detection rate in all four transitions of H_2CO . $\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})$ and $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ are detected in all Cygnus-X and GLOSTAR pilot region clumps, while $\text{H}_2\text{CO } (3_{2,2} - 2_{2,1})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ have a high detection rate ($> 83\%$). $\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})$ and $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ are detected at a lower rate, though still high (94%), and much lower detection of $\text{H}_2\text{CO } (3_{2,2} - 2_{2,1})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ (48% and 64%, respectively) in the clumps of the M8 region. We ensure all four detected H_2CO transitions trace the same gas by ensuring that the peak velocities v_{LSR} and linewidths Δv are similar. H_2CO is detected and traces similar gas in 102 clumps in Cygnus-X, the GLOSTAR pilot region, and the M8 region.

For all 102 clumps in these regions, we derived H_2 volume densities of $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$, gas kinetic temperatures of $T_{\text{gas}} = 16 - 219 \text{ K}$, and H_2CO column densities of

$N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} - 1.6 \times 10^{15} \text{ cm}^{-2}$. The H_2 volume densities derived from the ground-state transition of H_2CO enabled us to trace the bulk molecular gas as indicated by the dust continuum emission. We classified the evolutionary phases of 90 clumps in Cygnus-X and the M8 region based on IR observations. The clumps in Cygnus-X are $\sim 30\%$ in the quiescent phase, $\sim 29\%$ protostellar, $\sim 27\%$ YSO, and $\sim 14\%$ in the H_{II} phase, and the clumps in the M8 region are mainly in the protostellar phase ($\sim 92\%$) and 8% in the H_{II} phase. Those in the GLOSTAR pilot region are identified as H_{II} regions. These observations reinforce that the H_2 volume density significantly increased as the clumps evolved.

Previous studies have suggested that the integrated intensity ratio of H_2CO ($3_{0,3} - 2_{0,2}$) and H_2CO ($3_{2,1} - 2_{2,0}$) probes the LTE gas kinetic temperature (Tang et al., 2018). The obtained non-LTE gas kinetic temperature by `pyradex+emcee` agrees with the LTE gas kinetic temperatures in these regions at $n(\text{H}_2) \leq 10^{5.5} \text{ cm}^{-3}$.

Utilizing the obtained H_2 volume density, gas kinetic temperature, we determine the column densities of 25 molecules here in including formaldehyde and six deuterated molecules (C_2D , NH_2D , N_2D^+ , DCN , DNC , and DCO^+), including NH_3 by Wienen et al. (2012), to model the chemical age of the 67 clumps using the 1D time-dependent astrochemical model, MUSCLE (Chapter 6). Temperatures and H_2 volume densities in the clumps of Cygnus-X range between $18 - 79 \text{ K}$ and $1.9 \times 10^4 - 1.1 \times 10^6 \text{ cm}^{-3}$, respectively. The average molecular abundances relative to H_2 range from approximately 10^{-13} for deuterated species to 10^{-6} for the main isotopologs. With the physical conditions (i.e., H_2 volume density and gas kinetic temperature) constrained and the density index of each clump additionally determined, we defined the 1D structure of these clumps. We assume that the physical structures follow the IRDC, HMPO, HMC, and UCH_{II} outlined by Gerner et al. (2014) and Gerner et al. (2015).

We classify the clumps' evolutionary phases, identifying 55 in the HMPO phase, 3 in the HMC phase, and 9 in the UCH_{II} phase. We determine chemical ages ranging from 1.6×10^4 to $1.0 \times 10^6 \text{ yr}$. The column densities produced with the MUSCLE model reproduce the observed column densities, with a relative success rate of $\sim 77\%$. The observed molecular column densities most commonly not reproduced by the model were molecules common in shocked gas (e.g., SiO , HNCO , SO_2), and NH_2D .

The Cygnus-X clumps show the highest deuteration with $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, and $R(\text{N}_2\text{D}^+)$, although detected in fewer ($\leq 25\%$) clumps in the 67 clumps ($4\% - 15\%$). Similarly, $R(\text{DCN})$ is detected in few clumps ($\sim 28\%$) but similar to $R(\text{DNC})$ and $R(\text{DCO}^+)$, the deuterated fractions are $\leq 1\%$. The general trend is that $R(\text{C}_2\text{D})$, $R(\text{NH}_2\text{D})$, $R(\text{N}_2\text{D}^+)$, and $R(\text{DCN})$ are observed less in the 12 sub-regions in Cygnus-X, while exhibiting a higher degree of deuteration. $R(\text{DNC})$ exhibit decreasing deuteration as the clumps evolve, consistent with the progressive warm-up and chemical processing that reduce deuterium fractionation at later evolutionary stages. We find, in contrast to previous studies, that $R(\text{DCO}^+)$ increases at later evolutionary stages, indicating behavior that is inconsistent with earlier results.

In summary, the Cygnus-X molecular cloud is a great hunting ground for studying the various stages of stellar evolution. Furthermore, the CASCADE survey provides excellent observations to study the chemical evolution in many clumps formed in the same region.

Outlook

The large-scale observations with the IRAM 30-m telescope used in this thesis toward column densities in the Cygnus-X region, equivalent to small-scale observations with the NOEMA telescope, have

been conducted (presented in Sect. 2.2). As part of the CASCADE survey, the region surrounding high-mass, such as the accretion flows near HII region (Beuther et al., 2022), the outflow near the famous DR21 Main (Skretas et al., 2023), and the cometary-shaped HII region affected by a B2-star in the DR18 cavity (Kim et al., 2025). Suggestions to expand the work in this thesis, utilizing the high-resolution NOEMA observation, are as follows:

- Following the work of Chapter 4, the incredible capabilities of combining the NOEMA and the IRAM 30-m telescopes, the CASCADE survey allows for observations of high-resolution extended emissions of deuterated molecules ($\theta \sim 3''.5 \times 2''.5$). The CASCADE program has covered the deuterated molecules, such as C_2D , DCO^+ , DNC , and DCN , with velocity resolution of $v = 0.8 \text{ km s}^{-1}$ (Beuther et al., 2022), of which the DR21 filament has been observed. With the distance in mind, scales of $\sim 3700 \text{ AU}$ are probed, allowing morphological comparison of deuterated fractions as well as the detected cores. Furthermore, the higher angular resolution allows, and with the advent of the James Webb Space Telescope, the relative roles of gas-phase, dust-grain, CO freeze-out, and desorption mechanisms can be disentangled.
- Following the investigations of clumps in Chapters 5 and 6, fragmentation within clumps to cores in high-mass star-forming of Cygnus-X would be of great interest, to infer the efficiency from cloud to clump to core scales (Pokhrel et al., 2018). The numerous clumps observed with the CASCADE survey enable a robust statistical study on sources under the same initial conditions. Furthermore, the nearby OB-association, where newly formed high-mass stars have high FUV radiation, ionization can be studied further and its effect on core scales.
- Similar to (Zhou et al., 2023; Zhou et al., 2024; Zhou et al., 2025) surveying the gas kinematics of G333 molecular cloud, the gas kinematics at different scales utilizing the observation of the large- and small-scales of the CASCADE survey. The gas kinematics of G333 were done using ^{13}CO to trace the gas; the CASCADE does not observe this line. Although the CO-isotopologs are not covered with the CASCADE survey, the dense gas in the sub-regions with CASCADE at high spectral resolution can be observed with HCO^+ , HNC , HCN , and the densest with N_2H^+ (e.g. Fehér et al., 2025). Investigating this allows us to probe the gravitational collapse motion in Cygnus-X.

With this said, the Cygnus-X molecular cloud is one of many molecular clouds of the Milky Way. These investigations of high-mass star-forming regions, and how the environments affect the deuterated fractions, can be expanded to a similar nearby high-mass star-forming molecular cloud, Orion A, the intense M8 region, hosting intense HII regions and high UV flux, or the intense Central Molecular Zone (Brinkmann et al., 2020; Tiwari et al., 2019; Battersby et al., 2025). Furthermore, high-resolution investigation of deuterated fractions can be expanded with the observational programs such as “PROtostars to DIskS: Global Evolution” with NOEMA (Semenov et al., 2024) or “CORE: Fragmentation and disk formation in high-mass star formation (Beuther et al., 2018).

Paper I: The large scale distribution of deuterated molecules in the DR21 filament

The pdf of Christensen et al., [2024](#), which is summarized in Chapter [4](#), is reproduced in its original form below.

The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE

III. The large scale distribution of DCO⁺, DNC, and DCN in the DR21 filament

I. Barlach Christensen^{1,*}, F. Wyrowski¹, V. S. Veena^{1,3}, H. Beuther², D. Semenov², K. M. Menten¹,
A. M. Jacob^{1,4}, W.-J. Kim³, N. Cunningham⁸, C. Gieser⁵, A. Hacar⁷, S. Li², N. Schneider³,
I. Skretas¹, and J. M. Winters⁶

¹ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
e-mail: ibarlach@mpi-fr-bonn.mpg.de

² Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

³ Physikalisches Institut der Universität zu Köln, Zùlpicher Str. 77, 50937 Köln, Germany

⁴ William H. Miller III Department of Physics & Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA

⁵ Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany

⁶ Institut de Radioastronomie Milliétrique (IRAM), 300 rue de la Piscine, Domaine Universitaire, 38406 St-Martin-d'Hères, France

⁷ Department of Astrophysics, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria

⁸ SKA Observatory, Jodrell Bank, Lower Withington, Macclesfield SK11 9FT, UK

Received 25 March 2024 / Accepted 5 June 2024

ABSTRACT

Context. Deuterated molecules and their molecular D/H-ratios ($R_D(D)$) are important diagnostic tools with which to study the physical conditions of star-forming regions. The degree of deuteration, $R_D(D)$, can be significantly enhanced over the elemental D/H-ratio depending on physical parameters such as temperature, density, and the ionization fraction.

Aims. Within the Cygnus Allscale Survey of Chemistry and Dynamical Environments (CASCADE), we aim to explore the large-scale distribution of deuterated molecules in the nearby ($d \sim 1.5$ kpc) Cygnus-X region, a giant molecular cloud complex that hosts multiple sites of high-mass star formation. We focus on the analysis of large-scale structures of deuterated molecules in the filamentary region hosting the prominent HII region DR21 and DR21(OH), a molecular hot core that is in an earlier evolutionary state.

Methods. The DR21 filament has been imaged using the IRAM 30-m telescope in a variety of deuterated molecules and transitions. Here, we discuss the HCO⁺, HNC, and HCN molecules and their deuterated isotopologs DCO⁺, DNC, and DCN, and their observed line emissions at 3.6, 2, and 1.3 mm.

Results. The spatial distributions of integrated line emissions from DCO⁺, DNC, and DCN reveal morphological differences. Notably, DCO⁺ displays the most extended emission, characterized by several prominent peaks. Likewise, DNC exhibits multiple peaks, although its emission appears less extended compared to DCO⁺. In contrast to the extended emission of DCO⁺ and DNC, DCN appears the least extended, with distinct peaks. Focusing only on the regions where all three molecules are observed, the mean deuteration ratios for each species, R_D , are 0.01 for both DNC and DCN, and = 0.005 for DCO⁺, respectively. Anticorrelations are found with deuterated molecules and dust temperature or $N(H_2)$.

Conclusions. The strongest anticorrelation is found with $R_D(DCO^+)$ and $N(H_2)$, with a Pearson correlation coefficient of $\rho = -0.74$. We analyzed the SiO emission as a tracer for shocks and the $N(HCO)/N(H^{13}CO^+)$ as a tracer for increased photodissociation by ultraviolet radiation. It is suggested that the anticorrelation of $R_D(DCO^+)$ and $N(H_2)$ is a result of a combination of an increased photodissociation degree and shocks. A strong positive correlation between the ratio of integrated intensities of DCN and DNC with their ¹³C-isotopologs is found in high-column-density regions. The positive relationship between the ratios implies that the D-isotopolog of the isomers could potentially serve as a tracer for the kinetic gas temperature.

Key words. methods: observational – ISM: clouds – ISM: molecules – ISM: individual objects: DR21

1. Introduction

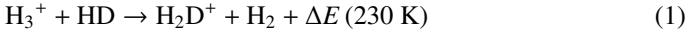
While an overall understanding has emerged that star formation occurs in cool, dense molecular clouds, the physical and chemical conditions during the formation of high-mass stars are still poorly understood. The chemistry of these clouds evolves

* Member of the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne.

in complexity, heavily depending on the underlying and evolving physical conditions (see, for example, McKee & Tan 2002, 2003; Girichidis et al. 2020; Tielens 2021). Conversely, the presence of molecules, primarily CO, and also dust grains affects the physical conditions and the evolution of the clouds, as these coolants are important to allow their contraction (Hocuk et al. 2014).

In the interstellar medium (ISM), the elemental abundance ratio of deuterium to hydrogen (D/H) is observed to be approximately 10^{-5} (Linsky 1998; Oliveira et al. 2003,

Cooke et al. 2018). The earliest phases of star formation begin when the cloud is cold ($T < 30$ K) and dense ($n > 10^5$ cm $^{-3}$) (e.g. Fontani et al. 2011). During this phase, deuterium chemistry begins via an ion–molecule reaction involving H_3^+ and HD:



enabling the transfer of deuterium from its main reservoir, HD, to other species (Watson 1974; Wootten 1987). Additionally, depending on the spin-state of H_3^+ , and consequently of the formed H_2D^+ , the reverse reaction in Eq. (1) is enhanced (Flower et al. 2006). During the freeze-out onto dust grains, the number of heavy neutral molecules in the gas phase, such as CO, decreases. This decreases the destruction of H_2D^+ (Pillai et al. 2012; Sabatini et al. 2020). Therefore, low temperatures lead to an accumulation of H_2D^+ . Reaction (1) is the first formation route for heavier deuterated molecules, leading to a higher molecular XD/XH ratio ($\equiv R_D(\text{XD})$, with XD and XH the abundance of the deuterated and H-isotopolog, respectively) that can reach up to a few percent (Roberts & Millar 2000a; Roberts et al. 2004) in dense, molecular clouds. Simple gas phase chemistry predicts equilibrium values of $R_D(\text{XD})$ for simple molecules to be on the order of several times 10 % for $R_D(\text{DCO}^+)$ (Roberts & Millar 2000b). At higher temperatures ($T \sim 30$ –80 K), deuteration mainly occurs through the light hydrocarbons, that is, CH_2D^+ and C_2HD^+ (Millar et al. 1989; Albertsson et al. 2013). Furthermore, deuterated molecules can also be formed on dust grain mantles where D-atoms react with ice. As the temperature drops below ~ 20 K, the flow of atomic D onto dust grains increases, and consequently the rate of grain-surface reactions with H and D increases (Albertsson et al. 2013). This can result in high XD-XH ratios in complex organic molecules (COMs; C-bearing molecules containing more than six atoms) of up to a few times 10% in extreme cases, leading even to multiply deuterated COMs (Parise et al. 2002). By studying the deuterated molecules and their main isotopologs, we can gain an insight into the physical conditions in early-stage star formation, such as the gas density, temperature, and ionization fraction (Herbst 1982; Caselli et al. 1998; Favre et al. 2015; Gerner et al. 2015).

In this paper, three deuterated molecules are of particular interest: DCO^+ , DNC, and DCN. DCO^+ is efficiently formed through H_2D^+ reacting with CO in the low-temperature regime (Albertsson et al. 2013). An additional formation pathway for DCO^+ in the higher-temperature regime ($T > 50$ K) is thought to occur from the light hydrocarbon, CH_2D^+ (Favre et al. 2015). The column density ratio, $R_D(\text{DCO}^+)$, also depends on the ionization fraction (Caselli et al. 1998), whereby a decreasing ratio can suggest a higher ionization fraction (Favre et al. 2015). DNC and DCN show dissimilar behavior in their formation pathways. DNC is formed from HCND^+ , via H_2D^+ , reacting with CN or HCN in the lower temperature regime (~ 20 –30 K) or through CH_2D^+ reacting with N in the higher temperature regime (Turner 2001; Albertsson et al. 2013). On the other hand, DCN is formed primarily ($\sim 66\%$) through CH_2D^+ via CHD or CH_2D reacting with N in conditions typical of translucent and dark clouds (Turner 2001). A significant, but less efficient formation pathway of DCN is through DCO^+ reacting with HCN or HNC forming HDCN^+ or DCNH^+ , respectively. This reaction becomes more efficient with increasing temperature, forming both DNC and DCN (Albertsson et al. 2013). Furthermore, the formation of DNC from HCN is more efficient than the formation of DCN from HNC (Turner 2001). The abundances of both precursors H_2D^+ and CH_2D^+ are temperature-dependent (Albertsson et al. 2013), which leads to the increasingly efficient production of

DCN with temperature. This means that the formation of DNC is more efficient at lower temperatures (~ 30 K) than that of DCN. As the temperature increases, the efficiency with which DCN is formed increases, surpassing the production of DNC at higher temperatures (~ 80 K).

Gerner et al. (2015) investigated the behavior of deuterated molecules' abundances in high-mass star-forming regions, which they divided into four different evolutionary stages; namely, infrared dark clouds (IRDC), high-mass protostellar objects (HMPO), hot molecular cores (HMC), and ultra-compact HII-regions (UCHII), evolving as $\text{IRDC} \rightarrow \text{HMPO} \rightarrow \text{HMC} \rightarrow \text{UCHII}$. They show that the column densities, N , of DCO^+ and DNC decrease with progressing evolutionary stage of a clump, whereas $N(\text{DCN})$ peaks in the HMC-stage (Gerner et al. 2015). In addition, they find that the $R_D(\text{DNC})$ and $R_D(\text{DCN})$ deuteration ratios show a range of values, with an average of 0.02 and 0.005, respectively (Gerner et al. 2015). In the same sources, $R_D(\text{DCO}^+)$ was measured to be an order of magnitude lower, with an average ratio of 0.0025 (Gerner et al. 2015). Toward two dark cloud sources, L134N and TMC-1, $R_D(\text{DCO}^+)$ was found to be 0.18 and 0.02, respectively (Tin   et al. 2000). More recent observations toward the distant HII-region W51 star-forming region showed a core, on the same spatial scales, with a comparable ratio of 0.02 (Vastel et al. 2017).

The prominent nearby giant molecular cloud or star formation complex Cygnus-X is a prime target for studying the early stages of massive star formation. It has a rich environment that contains recent and ongoing star formation activities. These are OB associations, Wolf-Rayet stars, numerous HII-regions, and dense molecular star-forming clumps (Schneider et al. 2006; Motte et al. 2007; Reipurth & Schneider 2008). The most active and dense region within the Cygnus-X region is a filament that contains, near its southern end, the compact HII-region DR21 Main (Downes & Rinehart 1966; Immer et al. 2014; Schneider et al. 2010; Hennemann et al. 2012), which has a rich molecular envelope with a photodissociation interface (Ossenkopf et al. 2010). The filament is proposed to be the result of interacting HI flows and molecular clouds (Schneider et al. 2023; Bonne et al. 2023). The DR21 region is located at a distance of 1.5 kpc (Rygl et al. 2012), and its dense filamentary structure, also called the “DR21 ridge”, harbors several dense cores with a gradient of evolutionary stages (Hennemann et al. 2012). Further north, a famous active OH, H_2O , and CH_3OH maser source, the dense protocluster or hot molecular core DR21(OH) (Mangum et al. 1992) is found and a colder region of infalling gas is located in the northernmost part of the ridge (Schneider et al. 2010; Hennemann et al. 2012; Koley et al. 2021). Previous studies of H_2D^+ north of DR21(OH) using the James Clerk Maxwell Telescope (JCMT) have shown the emission to probe a large-scale cold, quiescent gas component (Pillai et al. 2012), hinting also at the presence of cold gas pockets nearby, only slightly offset from the DR21 filament.

The Cygnus-X Allscale Survey of Chemistry And Dynamical Environments (CASCADE; Beuther et al. 2022) is a large-scale survey of the Cygnus-X region carried out with the Northern Extended Millimeter Array (NOEMA) and the Institut de Radioastronomie Millim  trique (IRAM) 30-m telescope as a Max Planck Institute and IRAM Observatory large-program (MIOP). The objective is to connect star formation properties at large scales probed with the IRAM 30-m telescope to small-scale dense cores observed by the NOEMA interferometer. In its lower frequency range of 70–80 GHz, the project covers the ground state level transitions of several key deuterated species, DCO^+ , DNC, and DCN (see Table 1). Higher rotational transitions of the

Table 1. Frequencies and spectroscopic properties of the deuterated molecules and their corresponding ^{13}C -isotopologs presented in this study alongside the spectral line properties obtained by averaging over the entire DR21 filament are presented.

Species	Transition	Frequency (MHz)	E_{up}/k (K)	A_{ij} (s^{-1})	g_{up}	n_{crit} (cm^{-3})	Database	T_{MB} (K)	ν_{Peak} (km s^{-1})	FWHM (km s^{-1})
DCO^+	$J = 1-0$	72039.312	3.46	2.2(-5)	3	4.5(4)	CDMS	0.08 ± 0.01	-2.7 ± 0.8	3.0 ± 0.1
DCO^+	$J = 3-2$	216112.582	20.74	7.1(-4)	7	1.0(6)	CDMS	0.14 ± 0.01	-3.2 ± 0.8	3.4 ± 0.1
H^{13}CO^+	$J = 1-0$	86754.288	4.16	3.9(-5)	3	4.5(4)	CDMS	0.21 ± 0.01	-3.0 ± 0.8	3.4 ± 0.0
DNC	$J = 1-0$	76305.727	3.66	1.6(-5)	3	1.1(5)	CDMS	0.06 ± 0.01	-3.0 ± 0.8	3.2 ± 0.1
DNC	$J = 2-1$	152609.774	10.99	1.5(-4)	5	1.0(6)	CDMS	0.18 ± 0.01	-2.7 ± 0.8	3.6 ± 0.1
HN^{13}C	$J = 1-0$	87090.850	4.18	1.9(-5)	3	1.1(5)	CDMS	0.07 ± 0.01	-3.0 ± 0.8	3.4 ± 0.1
DCN	$J = 1-0,$ $F = 2-1^{(*)}$	72414.694	3.48	1.3(-5)	5	3.0(5)	JPL	0.05 ± 0.01	-3.1 ± 0.8	4.1 ± 0.1
DCN	$J = 3-2$	217238.538	20.85	4.6(-4)	21	1.0(7)	CDMS	0.11 ± 0.01	-3.8 ± 0.8	4.1 ± 0.1
H^{13}CN	$J = 1-0,$ $F = 2-1^{(*)}$	86339.921	4.14	2.2(-5)	5	3.0(5)	JPL	0.11 ± 0.01	-3.8 ± 0.8	4.1 ± 0.1

Notes. The frequency, upper level energy, E_{up}/k , Einstein coefficient, A_{ij} , and upper state degeneracy g_{up} , are given. The critical density, n_{crit} , at $T_{\text{kin}} = 20$ K, are also listed (Shirley 2015). The rightmost three column give the peak intensity, T_{MB} , central LSR velocity and FWHM of Gaussian fits to a spectrum representing an average of the emission in the covered area in the DR21 region. The values for A_{ij} and n_{crit} are written in the form of $x(-a) = x \times 10^{-a}$. The spectroscopic information is taken, as noted, from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2001) or from the Jet Propulsion Laboratory Spectroscopic catalogue database (Pickett et al. 1998). $(*)$ Denotes the spectroscopic properties of the strongest HFS component.

deuterated species in the 1.3-mm and 2-mm wavelength bands were performed with follow-up observations once again using the IRAM 30-m telescope to constrain the line excitation temperatures that were used to determine reliable molecular column densities.

The paper is organized as follows: in Sect. 2, we present the observations and the data reduction; in Sect. 3 we show the integrated intensities and averaged spectra of deuterated molecules in the DR21 filament, and describe the calculation of molecular column densities. In Sects. 4 and 5, we analyze and discuss the molecular D/H ratios and their behavior with the dust temperature and H_2 column density. Finally, in Sect. 6, we present our conclusions.

2. Observations

We carried out on-the-fly (OTF) mapping observations (Project ID: 145-19 and 031-20; PIs: F. Wyrowski and H. Beuther) at 4 millimeter (mm) wavelength using the IRAM 30-m telescope. To obtain a large bandwidth, covering all of the deuterated molecules of interest, the mappings were performed using the Eight Mixer Receiver (EMIR)¹ (Carter et al. 2012) and using the Fourier Transform Spectrometer backend with 195 kHz channel spacing (FTS200). A bandwidth of 8 GHz per sideband (in total, a frequency coverage of 16 GHz) with EMIR E90 in both polarization was covered. At 72 GHz, the spectral channel resolution of 195 kHz is equivalent to a velocity resolution of 0.73 km s^{-1} (smoothed to a spectral resolution of $d\nu = 0.8 \text{ km s}^{-1}$) and the half power beam width (HPBW) of the IRAM 30-m telescope is $34''$ ².

Observations of the DR21 filament were carried out on May 21 and 22, 2020. The regions with the highest H_2 column densities (Motte et al. 2010) were covered in 6 tiles. Figure 1

shows the DR21 coverage of CASCADE in dashed red lines. Each tile, of size $\sim 306'' \times 306''$, is observed with the OTF mapping technique, in two scanning directions, in right ascension (RA) and in declination (Dec) with a scanning frequency of $\sim 17''5 \text{ s}^{-1}$ and a dump time of ~ 0.5 s. This results in an over-sampling of the beam by a factor >3 . For each mapping, two temperature load calibration observations, each of 60s duration, were done. In order to avoid edge effects, tiles slightly overlap along the filament.

2.1. Follow-up observations with IRAM 30-m telescope

To complement the lower J -transitions of some of our target molecules (see Table 1), we performed OTF mapping observations using the IRAM 30-m telescope over five nights from July 15 to July 19, 2021 (Project ID: 053-21; PI: I. Barlach Christensen). The OTF maps were carried out with the EMIR E150 and E230 modules in five tiles, each of size of $\sim 120'' \times 120''$, outlined by the orange boxes in Fig. 1. For each mapping (with two coverages combined in one tile), the scanning velocities were $5''5 \text{ s}^{-1}$ and $3''8 \text{ s}^{-1}$ for 2-mm and 1.3-mm, respectively. The HPBW is $17''$ at 145 GHz and $11''$ at 230 GHz.

The FTS covered 8 GHz bandwidth in each sideband in both polarization. To obtain a spectral resolution that is comparable to the ground-state transition observations, the FTS backend was used at 195 kHz resolution, which corresponds to 0.38 km s^{-1} at 154 GHz and 0.25 km s^{-1} at 231 GHz. The spectra are smoothed to a spectral resolution of $d\nu = 0.8 \text{ km s}^{-1}$. For the E150 observations, the receiver was tuned to 150.25 GHz in the upper inner sideband, to cover the N_2D^+ (2–1) and DNC (2–1) transitions. The frequency coverage in the 2-mm wavelength band is 132.2–140 GHz in the lower sideband and 148–155.7 GHz in the upper sideband. For the E230 observations, the receiver was tuned to 216.75 GHz in the lower outer sideband, to cover the DCO^+ (3–2), DCN (3–2) and N_2D^+ (3–2) transitions. The total E230 frequency coverage is 214.4–222.2 GHz for the lower sideband and 230.1–237.9 GHz for the upper sideband.

¹ <http://www.iram.es/IRAMES/mainWiki/EmirforAstronomers>

² This telescope's HPBW (in arcseconds) is well represented by $2460/\nu$ (GHz); see <https://publicwiki.iram.es/Iram30mEfficiencies>

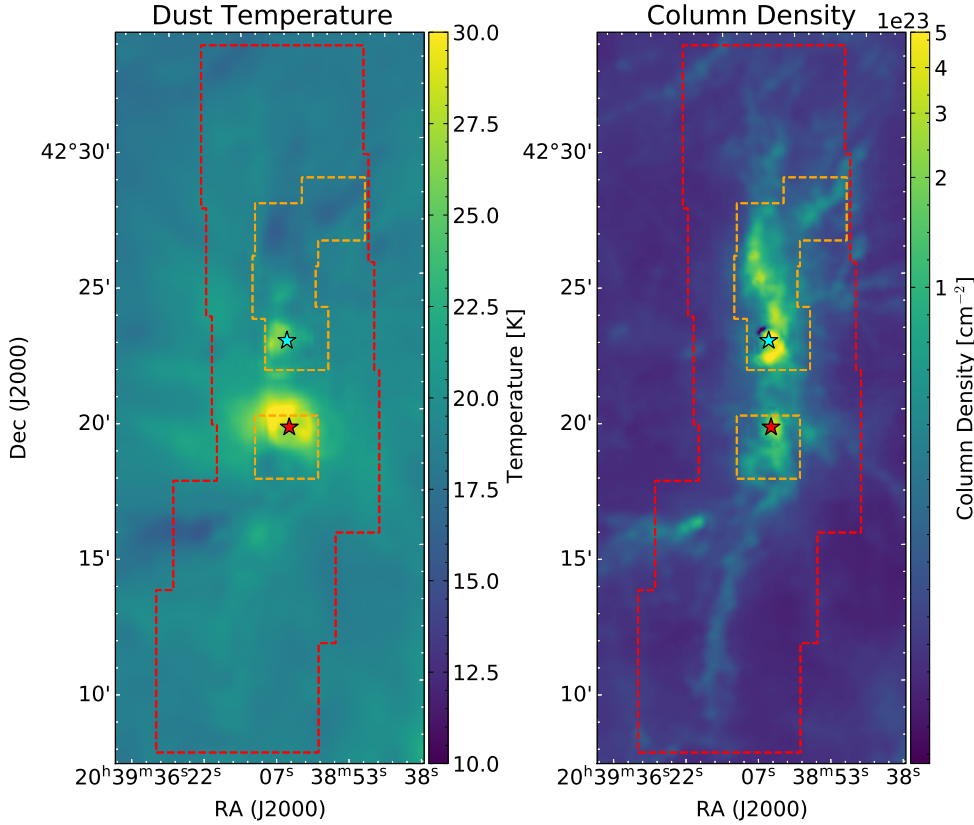


Fig. 1. Maps of dust temperature (left) and H_2 column density (right) of the DR21 filament taken determined by the HOBYS program (Motte et al. 2010). The stars in both maps indicate the positions of DR21 Main (red) and DR21(OH) (blue). The dashed red and orange lines show the coverage of CASCADE and follow-up observations, respectively.

The angular resolution of the higher J -transition observations of DCO^+ , DCN and DNC (for example $\theta \sim 12''$ for DCO^+ (3–2), and $\theta \sim 16''$ for DNC (2–1)) is higher than that of the ground-state transitions (for example, $\theta \sim 34''$ for DCO^+ (1–0)). For comparison purposes, the maps of the higher J -transitions are convolved to a common beam size, namely that of the ground-state transitions ($\theta = 34''$). However, for the maps shown, the native resolution of the respective lines was retained.

2.2. Data processing

The data of both the CASCADE and follow-up observations of the DR21 filament were processed using the Grenoble Image and Line Data Analysis Software (GILDAS) package³ (Pety 2005, 2018). Using the Continuum and Line Analysis Single-dish Software (CLASS) program, we regridded the obtained spectra over the mapped areas. Using the MAP%LIKE procedure of CLASS, all images were reprojected to the spatial grid of DCO^+ , which has a resolution of $34''$. For computing the column densities, the scale was converted from T_A^* to main beam brightness temperature T_{MB} , using a forward efficiency of $F_{\text{eff}} = 0.95$ and a beam efficiency⁴ depending on the frequency of the molecule:

$$B_{\text{eff}} = 1.2 \times 0.69 \times \exp \left(- \left(\frac{4 \times \pi \times 0.07 \nu \text{ [MHz]}}{c \text{ [km s}^{-1}\text{]}} \right)^2 \right), \quad (2)$$

where ν is the rest frequency of the line emission and c is the speed of light. This ensures that each line can be resolved and has the same velocity resolution, as the line widths are typically $\text{FWHM} \sim 3\text{--}4 \text{ km s}^{-1}$ (see Table 1).

³ <http://www.iram.fr/IRAMFR/GILDAS>

⁴ <https://web-archives.iram.fr/ARN/feb01/node5.html>

During the observations, we identified a strong narrow spike at 76304.9 MHz with a frequency shifted by -1 MHz from the emission line of DNC ($\nu = 76305.727 \text{ MHz}$). We suspect this spike to be contamination from an automotive long range radar. In order to minimize the contamination caused by this spike, we compared the noise in the artifact free spectral velocity range ($< -30 \text{ km s}^{-1}$ from the central line) with the contaminated channels ($> 0 \text{ km s}^{-1}$). If the noise level with the artifact increased by 20%, the spectrum is discarded.

2.3. Ancillary data

Figure 1 presents the dust temperature and H_2 column density (Bonne et al. 2023) maps of the DR21 filament first discussed by Hennemann et al. (2012), which are based on data taken as part of the Herschel imaging survey of OB Young Stellar objects (HOBYS) program (Motte et al. 2010).

The CASCADE mapping area is outlined by dashed red lines in both the maps. The H_2 column density maps are derived by Bonne et al. (2023) based on convolved dust brightness temperature distributions at three different wavelengths: $500 \mu\text{m}$, $360 \mu\text{m}$, and $250 \mu\text{m}$. The dust temperature was determined from the $160 \mu\text{m}/250 \mu\text{m}$ flux density ratio. The resulting H_2 column density and dust temperature maps are obtained at an angular resolution of approximately $\sim 18''$. For further analysis, both the H_2 column density map and dust temperature maps are convolved to the angular resolution of the present CASCADE study, which is $\theta \sim 34''$.

3. Results

Using data from the CASCADE survey, we investigate in detail the deuteration along the DR21 filament. For this we consider

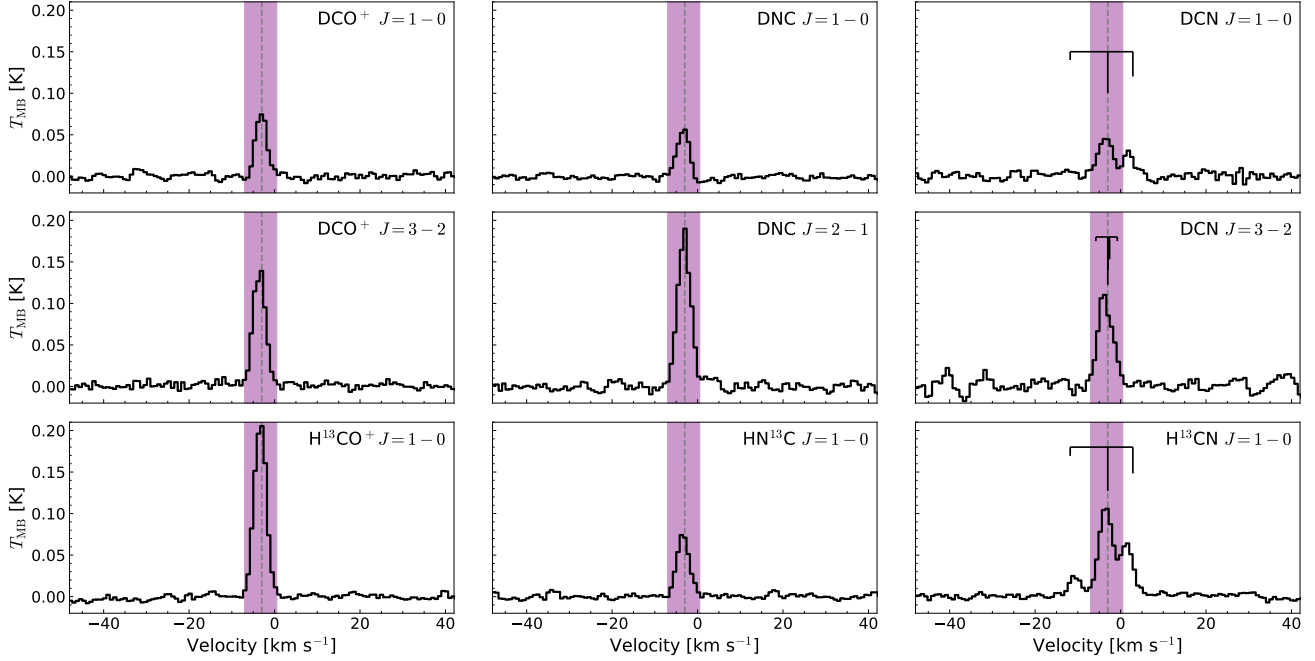


Fig. 2. Average spectra of DCO⁺, DNC, and DCN, and their ¹³C-isotopologs in the DR21 filament. The black line shows the spectra averaged over the entire mapped region of the DR21 filament for different molecules with the purple region showing the velocity range used for determining integrated intensities. The dashed gray line denotes the main velocity of the filament, $v_{\text{LSR}} = -3 \text{ km s}^{-1}$. The velocities of the un- or only marginally blended HFS components of DCN and H¹³CN are marked in black, with the relative intensity of the hyperfine components marked by the length. The LSR velocity scale of the DCN and H¹³CN $J = 1-0$ spectra corresponds to the strongest HFS component $F = 2-1$.

three molecular species that are abundant in the ISM: HCO⁺, HNC, and HCN and their corresponding deuterated species. As mentioned in Sect. 1, the three species, and their deuteration, provide an insight into distinct physical conditions. In general, HCO⁺, HNC, and HCN lines are likely to be optically thick in dense molecular clouds; hence, to estimate the column densities of these hydrogen-bearing species and to estimate the degree of deuterium fractionation, we utilized lines of their optically thin isotopologs; that is, H¹³CO⁺, HN¹³C and H¹³CN. Furthermore, we assume the deuterated isotopologs are optically thin. Table 1 summarizes the observed molecules and their transitions. Figure 2 shows spectra of the deuterated species and ¹³C-isotopologs averaged over the entire DR21 filament. For most of the lines, the hyperfine splitting structure (HFS) was too small and/or not resolved at the resolution of 0.8 km s^{-1} , except for the HCN ($1-0$) ¹³C and D-isotopolog lines. The line parameters used during the analysis account for the unresolved HFSs. In the case of the ground-state transition of HCN, H¹³CN and DCN, the integration is done only focusing on the central and strongest line. The emission from this main HFS component is extracted over the same velocity range as that of the DCO⁺ and DNC lines. The HFS components of the HCN, H¹³CN and DCN lines are not considered to ensure that the extracted line emission stems from the $v_{\text{LSR}} = -3 \text{ km s}^{-1}$ component. In contrast, the higher velocity DCN HFS component can be affected by a secondary DR21 velocity component at $v_{\text{LSR}} = 9 \text{ km s}^{-1}$ (Dickel et al. 1978; Nyman 1983). The resultant line parameters of the deuterated and ¹³C isotopologs are presented in Table 1.

3.1. Integrated intensity maps of the DR21 filament

To study the spatial distribution of the deuterated molecules in DR21, we created velocity-integrated intensity maps (see Fig. 3) over the velocity range from -7 km s^{-1} to $+0.5 \text{ km s}^{-1}$ (purple shaded region in Fig. 2). This integration velocity range was

chosen around the peak velocity $v_{\text{peak}} \pm 3.5 \text{ km s}^{-1}$, determined from a fit to a spectrum that represents an average of the emission in the covered area in the DR21 region (see Table 1). As v_{peak} has a value -3 km s^{-1} for both DCO⁺ and DNC lines and -3.5 km s^{-1} for the DCN lines, the selected velocity interval from -7 km s^{-1} to $+0.5 \text{ km s}^{-1}$ ensures that the chosen integration ranges are consistent for all the targeted species. Emission maps of the ground-state transition of the deuterated species and their ¹³C-isotopologs are shown in Fig. 3. The ground rotational transitions of deuterated molecules (i.e., DCO⁺, DCN, and DNC) show enhanced emission along the DR21 filament. For comparison, we also created the intensity maps of the corresponding hydrogenated species shown in Fig. A.1. We note that for species like H¹³CN and DCN, that show HFS, the velocity range over which we integrate includes contributions from the other HFS lines as well (see Fig. 2). As a result, the column densities subsequently derived for these species from the main HFS component will be overestimated.

3.2. Noise estimation

For each spectrum per pixel, a baseline was fitted with CLASS by applying a 1st order polynomial fit to an emission-free velocity window in the spectrum near the line of interest. The emission-free range was determined by visual inspection, aiming for a baseline subtraction in a velocity range of $\sim 20 \text{ km s}^{-1}$.

We obtain a root mean square (rms) of $\sim 80-100 \text{ mK}$ with spectral resolution at 0.8 km s^{-1} for the deuterated and the ¹³C-isotopologs covered with the CASCADE program. With the follow-up observations, we obtain a rms of $\sim 130 \text{ mK}$ with the same spectral resolution for the deuterated species.

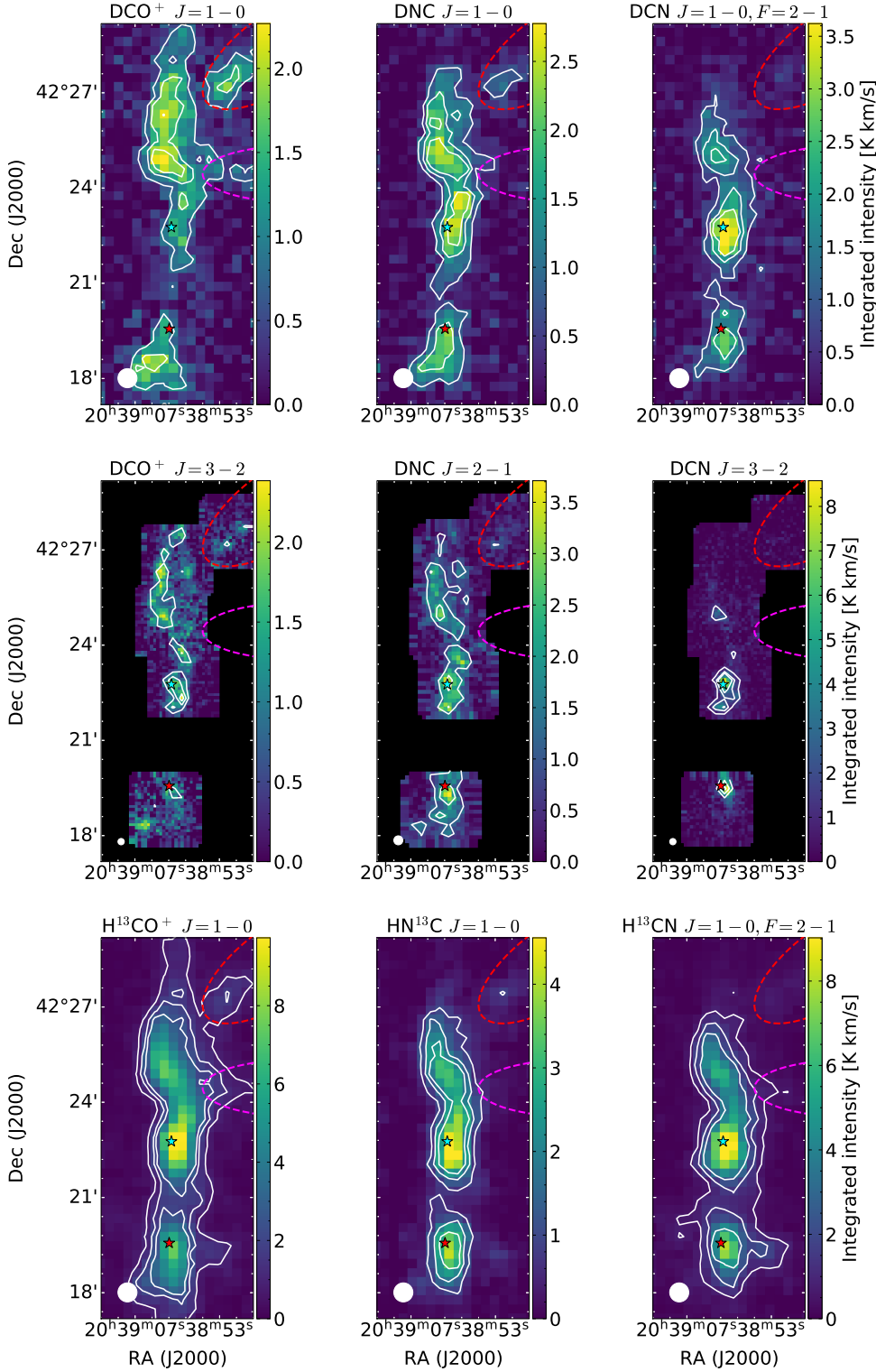


Fig. 3. Velocity-integrated intensity maps of deuterated and ^{13}C -isotopologs. Top and middle rows: Ground-state emission of DCO^+ , DNC , and DCN observed with the CASCADE-program and follow-up mapping with the IRAM 30-m telescope. Bottom row: Maps for ^{13}C -isotopologs. The intensities in the maps are integrated over the velocity range -7 km s^{-1} to $+0.5 \text{ km s}^{-1}$. HPBW are displayed by the filled white circles in the lower left corner of each panel. For example, the HPBW beam-size is $34''$ for the map showing DNC ($2-1$), $16''$ for DCO^+ ($3-2$) and $11''$ for DCN ($3-2$). The white contours are showing levels of 4σ , 8σ and 12σ . The stars mark DR21 Main (red) and DR21(OH) (blue). The locations of the F1 and F3 sub-filament (Schneider et al. 2010) are indicated by dashed red and magenta curves, respectively.

The noise in the integrated maps depends on the number of channels over which the molecular line of interest is integrated. The resulting noise map for the integrated intensity maps of each target line was calculated as $\sigma_{\text{tot}} = \sigma_{\text{channel}} \times \sqrt{N_{\text{channels}}}$. The number of channels, $N_{\text{channels}} = \Delta\nu/\delta\nu$, where $\Delta\nu$ is the line-width and $\delta\nu$ is the spectral resolution. In subsequent sections, the analysis discussed is based on the regions with a signal $\geq 4\sigma_{\text{tot}}$ for each pixel.

3.3. Column densities and kinetic gas temperature

Molecular column densities were calculated from the integrated intensities. The method assumes that the emission is optically thin and also assumes a common excitation temperature for each pixel in all transitions considered. We assume that all the lines considered are emitted under the conditions of local thermal equilibrium (LTE), which means that $T_{\text{exc}} = T_{\text{rot}} = T_{\text{kin}}$: any

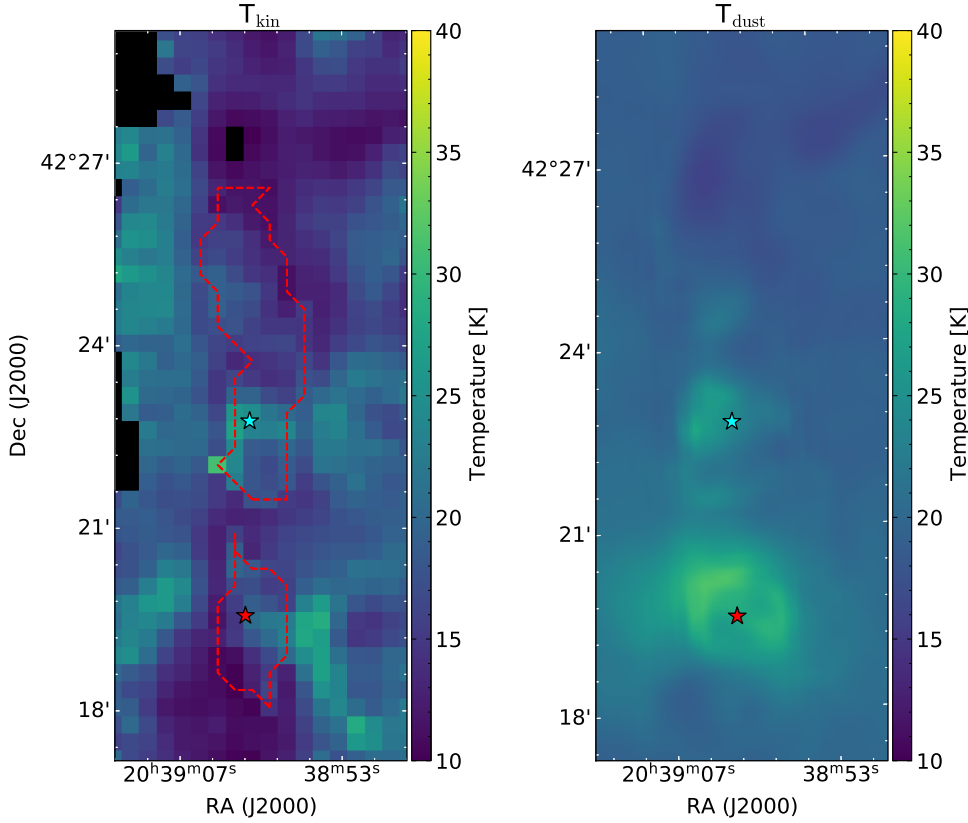


Fig. 4. Kinetic gas temperature calculated using the integrated intensity ratio of HCN and HNC for the lower column densities and H^{13}CN and HN^{13}C for the higher column densities (left) and dust temperature in the same region for comparison (right). The red contour shows the column density of $N(\text{H}_2) \geq 1 \times 10^{23} \text{ cm}^{-2}$. The stars show DR21 Main (red) and DR21(OH) (blue). The right panel shows the comparison of dust temperature in that same region.

line's excitation temperature is equal to a molecular rotation temperature, and both are equal to the kinetic gas temperature. Under LTE, the column densities can be calculated via the Boltzmann equation (Goldsmith & Langer 1999):

$$\ln\left(\frac{N_{\text{up}}}{g_{\text{up}}}\right) = \ln\left(\frac{N_{\text{tot}}}{Q_{\text{rot}}}\right) - \frac{1}{T_{\text{rot}}} \frac{E_{\text{up}}}{k_{\text{B}}}, \quad (3)$$

where N_{up} and g_{up} are the population and degeneracy of a transition's upper energy level, N_{tot} is the total population in all the energy levels, and Q_{rot} is the rotational partition function of each molecule taken from the CDMS or the JPL spectroscopy database. E_{up} is the upper level energy, and k_{B} is the Boltzmann constant, and T_{rot} is the rotation temperature. The parameters used for each molecule are presented in Table 1. We calculated N_{up} for each transition using the integrated intensity maps presented in Fig 3. Only those pixels with emission above 4σ are considered for the analysis. The upper level population of a transition, N_{up} , was calculated using the expression

$$N_{\text{up}} = \frac{8\pi k_{\text{B}} \nu^2}{h c^3 A_{ij}} \int T_{\text{mb}} dv. \quad (4)$$

Here, ν is the line's frequency, h is the Planck constant, c is the speed of light and A_{ij} is the Einstein coefficient (see Table 1). For the high densities of the dense clouds (see Table 1 for the critical densities of target molecules), the excitation temperature closely follows the kinetic gas temperature so that LTE can be assumed. Assuming a depth of the width of the filament ($d = 0.34 \text{ pc}$; Hennemann et al. 2012), the column densities, where the deuterated molecules are detected, are at $N(\text{H}_2) \geq 3 \times 10^{23} \text{ cm}^{-2}$, and the volume densities are $n(\text{H}_2) \geq 3 \times 10^5 \text{ cm}^{-3}$.

While Eq. (3) solves for the temperature based on the observation of multiple molecule transitions, not all positions in the

map have two detected transitions. Therefore, the kinetic gas temperature can be determined using several methods. Hacar et al. (2020) presented a correlation between the kinetic gas temperature and the integrated intensity ratio of HCN and HNC:

$$T_{\text{kin}}[\text{K}] = 10 \times \left[\frac{I(\text{HCN})}{I(\text{HNC})} \right] \text{ if } 1 \leq \left(\frac{I(\text{HCN})}{I(\text{HNC})} \right) \leq 4 \quad (5)$$

$$T_{\text{kin}}[\text{K}] = 3 \times \left[\frac{I(\text{HCN})}{I(\text{HNC})} - 4 \right] + 40 \text{ if } \left(\frac{I(\text{HCN})}{I(\text{HNC})} \right) > 4. \quad (6)$$

Due to the different destruction pathways of these isomers, at higher temperatures, HNC is destroyed more effectively, which thus increases the ratio as the temperature increases, in combination with opacity effects. The gas kinetic temperature is obtained using this method is used to calculate the column density maps of the deuterated molecules and the main isotopologs.

Using the HCN (1–0) and HNC (1–0) intensity maps (see Fig. A.1) and the above equations, we generated a kinetic temperature map of DR21, shown in Fig. 4. For pixels with molecular hydrogen column densities $N(\text{H}_2) \geq 1 \times 10^{23} \text{ cm}^{-2}$, HCN and HNC could be optically thick (Beuther et al. 2022). The optical depth of H^{13}CO^+ , HN^{13}C and H^{13}CN can be seen in Appendix B. The kinetic temperatures of these pixels were calculated using the intensity ratio of their optically thin isotopologs H^{13}CN and HN^{13}C (Beuther et al. 2022; Pazukhin et al. 2022). The obtained kinetic temperatures range from 10 to 31 K with a mean value of 17 K (see Fig. 4). Owing to the large beam size of our observations, we do not resolve the complex structures in DR21. Hence, the physical properties determined only represent an average value. Using Eq. (3), we generated column density maps of the deuterated molecules as well as their hydrogenated species. The column densities were determined pixel-wise using all transitions detected and fit with the

Python package `scipy.optimize.curve_fit`. The excitation temperature was determined when two transitions were detected; otherwise, the T_{kin} derived from HCN/HNC was adopted. The column density maps of DCO⁺, DNC, DCN, HCO⁺, HNC, and HCN are presented in Fig. C.1. The respective errors obtained during the fitting are presented in Fig. C.2. Column densities of the main isotopologs were calculated from their optically thin ¹³C-isotopologs, assuming that the ¹³C/¹²C isotopic ratio is constant within the cloud complex. With a Galactocentric distance, D_{GC} , of 8 kpc for Cygnus-X, and using the carbon isotope gradient versus Galactocentric distance relation $^{12}\text{C}/^{13}\text{C} = 7.5D_{\text{GC}} + 7.6$ (Wilson & Rood 1994), we find $^{12}\text{C}/^{13}\text{C} = 68$, which we assume in the following analysis. The gradient recently determined by Jacob et al. (2020) and Yan et al. (2023), delivers a value of 60, which is similar to the value of 68 adopted for the analysis in this work. In the analysis that follows, we assume no local variation in the isotopic ratio by, for example, isotopic fractionation, selective destruction of ¹²C versus ¹³C, or ion-molecule exchange reactions (Wilson & Rood 1994; Giannetti et al. 2014; Jacob et al. 2020; Yan et al. 2023).

3.4. Correlations of integrated intensity maps

The number of pixels above $4\sigma_{\text{tot}}$ in the DCO⁺, DNC, and DCN of $J = 1-0$ emission maps are 148, 115, and 103, respectively. Compared with the other species, DCO⁺ shows the most extended emission distribution. It is clumpy, with several peaks detected toward the northern half of the filament. The brightest clump is located 2:1 north of DR21(OH). Clumpy DCO⁺ emission is also present in the southern region. The southern peak is at an offset $\sim 1/2$ southeast of DR21 Main. Apart from the emission along the main filament, an additional bright clump is seen northwest of the main peak and west of the DR21-filament. The emission coincides with the low density, low kinetic gas and dust temperature infalling gas, named the F1 sub-filament by Schneider et al. (2010). Furthermore, DCO⁺ (1–0) emission is detected toward the most massive F3 sub-filament (magenta region marked in Fig. 3), which is linked to DR21(OH) (Schneider et al. 2010). The morphology of the DCO⁺ (3–2) emission is similar to that of its ground state transition. However, the peak is $\sim 32''$ southwest of DR21(OH).

Similar to DCO⁺, the emission of DNC is also filamentary and shows several peaks. The emission is not as extended as the DCO⁺ emission toward the north. The F1 sub-filament, marked in red in Fig. 3, is also not as bright in DNC as it is in DCO⁺. The strongest emission is observed from an $\approx 1'$ sized N–S elongated structure that has DR21(OH) at its southern end. A similar-sized region is seen in the south of the filament with DR21 Main at its northern end. The map of the DNC (2–1) emission resembles that of the DNC ground-state transition, and the brightest emission also is found close to DR21(OH).

Conversely, DCN (1–0) shows less extended emission with a strong peak toward DR21(OH). Likewise, DCN (3–2) is only detected toward the bright peaks of DCN (1–0). Weaker and relatively compact emission is seen surrounding DR21 Main. Emission toward the F1 sub-filament is not detected in DCN. The DCN (3–2) emission distribution is more compact than that of the (1–0) line and stronger (factor ~ 2). Its two peaks are found toward DR21(OH) and DR21 Main.

To quantify the morphological similarities between DCO⁺, DNC and DCN. The cross-correlation, ρ , of the distributions of the integrated intensities of pairs of molecules was calculated,

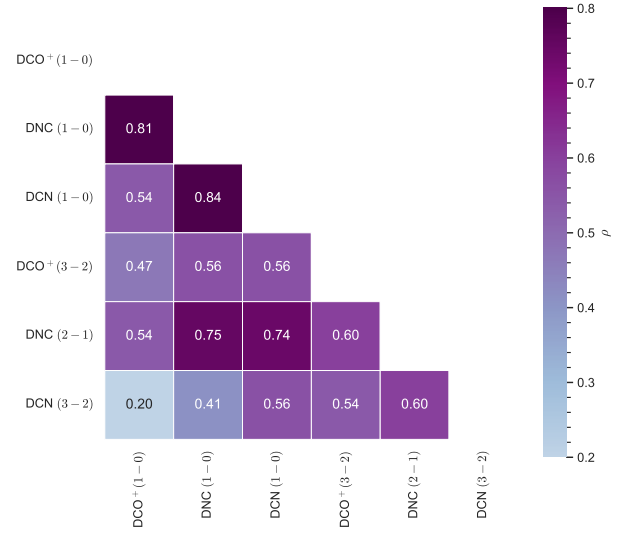


Fig. 5. Cross-correlations of integrated intensity maps of DCO⁺ (1–0), DNC (1–0), DCN (1–0), DCO⁺ (3–2), DNC (2–1), and DCN (3–2).

pixel by pixel, as (Guzmán et al. 2018; Li et al. 2022)

$$\rho_{12} = \frac{\sum_{i,j} I_{1,ij} I_{2,ij} w_{ij}}{(\sum_{i,j} I_{1,ij}^2 w_{ij} \sum_{i,j} I_{2,ij}^2 w_{ij})^{1/2}}. \quad (7)$$

Here, $I_{1,ij}$ and $I_{2,ij}$ are the integrated intensities of molecules one and two in pixel (i, j) . w_{ij} is the weight of the line emission detection. If emission from either molecule one or two is detected above $4\sigma_{\text{tot}}$ in pixel (i, j) , $w_{ij} = 1$. If neither molecules is detected in pixel (i, j) , $w_{ij} = 0$ and is not accounted for in the cross-correlation. The cross-correlation values are summarized in Fig. 5. This analysis confirms the result of visual inspection of Fig. 3, that the morphology of DNC can be considered as “intermediary” between those of DCO⁺ and DCN. For example, the cross-correlation of DCO⁺ (1–0) and DCN (1–0) is 0.54 whereas DNC (1–0) shows a stronger correlation with DCO⁺ (1–0) and DCN (1–0) of $\rho = 0.81$ and 0.84 , respectively.

DCO⁺ (1–0) seems to originate from gas with different physical conditions than DNC (1–0) and DCN (1–0). Figure 6 shows the cumulative distributions of dust temperature and H₂ column densities sampled in the pixels where $R_{\text{D}}(\text{DCO}^+)$ (purple), $R_{\text{D}}(\text{DNC})$ (orange), and $R_{\text{D}}(\text{DCN})$ is detected ($\geq 4\sigma_{\text{tot}}$). A simple Kolmogorov-Smirnov (KS) test indicates a similar distribution for DNC (1–0) and DCN (1–0) ($p < 0.05$). The mean dust temperature, where DCO⁺ (1–0) is detected, is $T_{\text{dust}} = 19$ K and $N(\text{H}_2) = 5.9 \times 10^{22} \text{ cm}^{-2}$. The dust temperature and column density is higher. For DNC (1–0), $T_{\text{dust}} = 20.6$ K and $N(\text{H}_2) = 1.0 \times 10^{23} \text{ cm}^{-2}$ and for DCN (1–0) $T_{\text{dust}} = 21.3$ K and $N(\text{H}_2) = 1.1 \times 10^{23} \text{ cm}^{-2}$. The mean values are marked in Fig. 6 with the respective color of the deuterated molecule.

Emission lines from all three deuterated molecules are observed at positions with column densities of $N(\text{H}_2) > 3 \times 10^{22} \text{ cm}^{-2}$. The DCO⁺ (1–0) and DNC (1–0) integrated maps show extended emission features spatially coinciding well with that of the filamentary structure seen in the H₂ column density map.

The morphological similarities and differences observed between the three molecules suggest local variations in the formation and excitation of their transitions. These variations

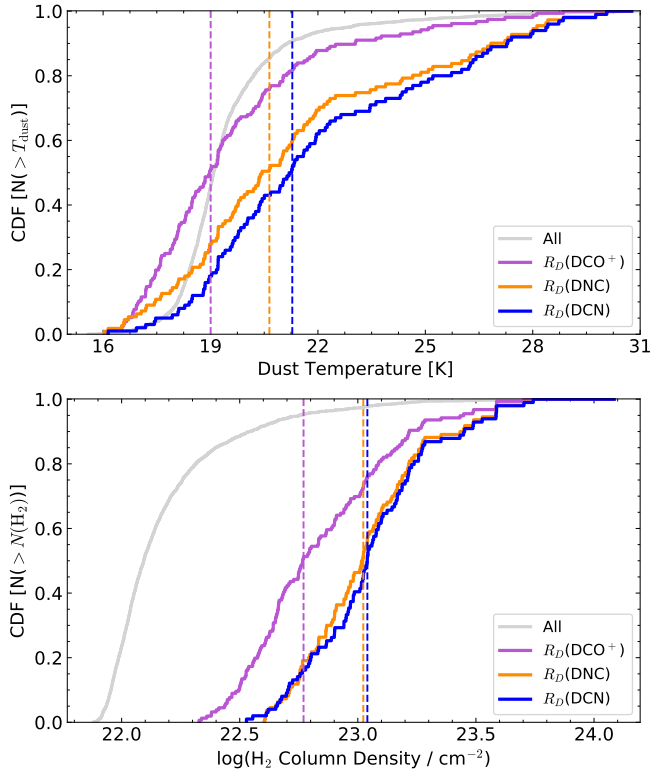


Fig. 6. Cumulative distribution function (CDF) of dust temperature and H_2 column density where DCO^+ (purple), DNC (orange), or DCN (blue) is detected in the DR21 filament. The dust temperatures and H_2 column density maps are taken from Bonne et al. (2023). The horizontal dashed lines mark the mean dust temperature or column density of the sampled distributions, colorized with the respective detected molecular ratio.

could be influenced by the local density and temperatures of the emitting gas. The dependencies of each molecule with the column density and the dust temperatures are analyzed further in Sect. 4.2.

4. Analysis

In the following sections, we investigate deuteration across the DR21 filament.

4.1. Fractional abundances of DCO^+ , DNC , and DCN

The fractional abundance is defined as $X(XD) = N(XD)/N(H_2)$ where $N(XD)$ is the column density of a deuterated molecular species. The molecular hydrogen column densities, $N(H_2)$, were adopted from the high-resolution HOBYS column densities described in Sect. 3 and convolved to an angular resolution of $34''$. In order to estimate the fraction of deuteration in DR21, we use pixel-by-pixel column density estimates, obtained in the manner described in Sect. 3.3, of the deuterated species presented in Table 1.

Figure 7 shows the abundance maps of $X(DCO^+)$, $X(DNC)$ and $X(DCN)$. The abundances of these species are similar, with median values of $X(DCO^+) = 5.9^{10}_{1.4} \times 10^{-11}$, $X(DNC) = 6.5^{9.8}_{3.2} \times 10^{-11}$ and $X(DCN) = 6.8^{12}_{1.9} \times 10^{-11}$. Though the median abundances of these three molecular species are indistinguishable within the interquartile range, their spatial distributions are different. DCO^+ shows reduced abundances toward DR21(OH) and DR21 Main. $X(DCO^+)$ increases toward the north region

Table 2. Abundances of DCO^+ , DNC , and DCN toward DR21, TMC-1, L134N, IRAS 16293–2422 (LM) and G210.82–19.47N (G210).

	DR21	TMC-1	L134N	LM	G210
$X(DCO^+)$	5.9	4.4 ^(a)	9.0 ^(a)	1.5 ^(b)	0.37 ^(c)
$X(DNC)$	6.5	71 ^(a)	41 ^(a)	0.5 ^(b)	0.13 ^(c)
$X(DCN)$	6.8	3.7 ^(a)	27 ^(a)	2.5 ^(b)	–

Notes. The abundances are written in the form of x , where $= x \times 10^{-11}$. ^(a)Turner (2001) for TMC-1 and L134N. ^(b)van Dishoeck et al. (1995) for IRAS 16293–2422, ^(c)Tatematsu et al. (2020) for G210.82–19.47N.

of DR21 and southeast region of DR21 Main. On the contrary, $X(DCN)$ exhibits a minor rise toward DR21(OH), while maintaining a relatively constant abundance throughout the DR21 filament.

Table 2 summarizes the abundances of deuterated species in DR21 compared with values determined for various other sources. This includes the extensively studied Taurus Molecular Cloud 1 (TMC-1), which is a quiescent dark cloud containing starless cores (Pratap et al. 1997), as well as another dark cloud, L134N (Dickens et al. 2000), which shares similar temperature ($T_{dust} < 15$ K, Gratier et al. 2016) and density ($n(H_2) \sim 10^6$ cm⁻³, Turner 2001) characteristics to the DR21 filament. However, the primary distinction between these dark clouds lies in their chemical composition: the TMC-1 position is that of the clouds’ cyanopolyne peak, whose chemistry is rich in carbon-chain molecules, while L134N is abundant in smaller molecules and oxygen-bearing species (Dickens et al. 2000, and references therein). G210.82–19.47N is a solar-mass star-forming core (Tatematsu et al. 2020) and IRAS 16293–2422 is a low-mass class 0 binary protostar with a rich molecular inventory surrounding a hot corino (Girart et al. 2014; Murillo et al. 2018; Kahle et al. 2023).

Compared to DR21, the abundances of most of the deuterated species studied here, are significantly higher in the dark clouds, but also in the translucent clouds. Both dark clouds have $X(DCO^+)$ that is comparable to that of DR21, but higher $X(DNC)$, whereas $X(DCN)$ is comparable in DR21 and TMC-1, but much lower than in L134N. The generally higher degrees of deuteration observed in TMC-1 and L134N relative to DR21 is a consequence of the lower gas temperatures ($T_{kin} = 10$ K) that characterize these regions (Turner 2001), which, as is discussed in Sect. 1, facilitates the deuterium enrichment.

In the low-mass star-forming regions IRAS 16293–2422 and G210.82–19.47N, the abundances are approximately an order of magnitude lower than the abundances measured in the DR21 filament. It is important to point out that accurate abundances rely on a reliable reference for $N(H_2)$. The challenge of comparing abundances is compounded by the absence of a singular approach to determining column densities of H_2 .

To summarize: we find similar abundances (indistinguishable within the interquartile range) only for DCO^+ in the DR21 filament as for the dark clouds and even for IRAS 16293–2422. Both TMC-1 and L134N have lower dust temperatures compared to the DR21 filament. The molecular cloud TMC-1 lacks, contrary to DR21, newly formed OB stars and also has a high extinction, resulting in an absence of ultraviolet (UV) radiation inside of it. Our findings for the DR21 filament indicate that, in terms of the abundances of deuterated molecules, it comprises

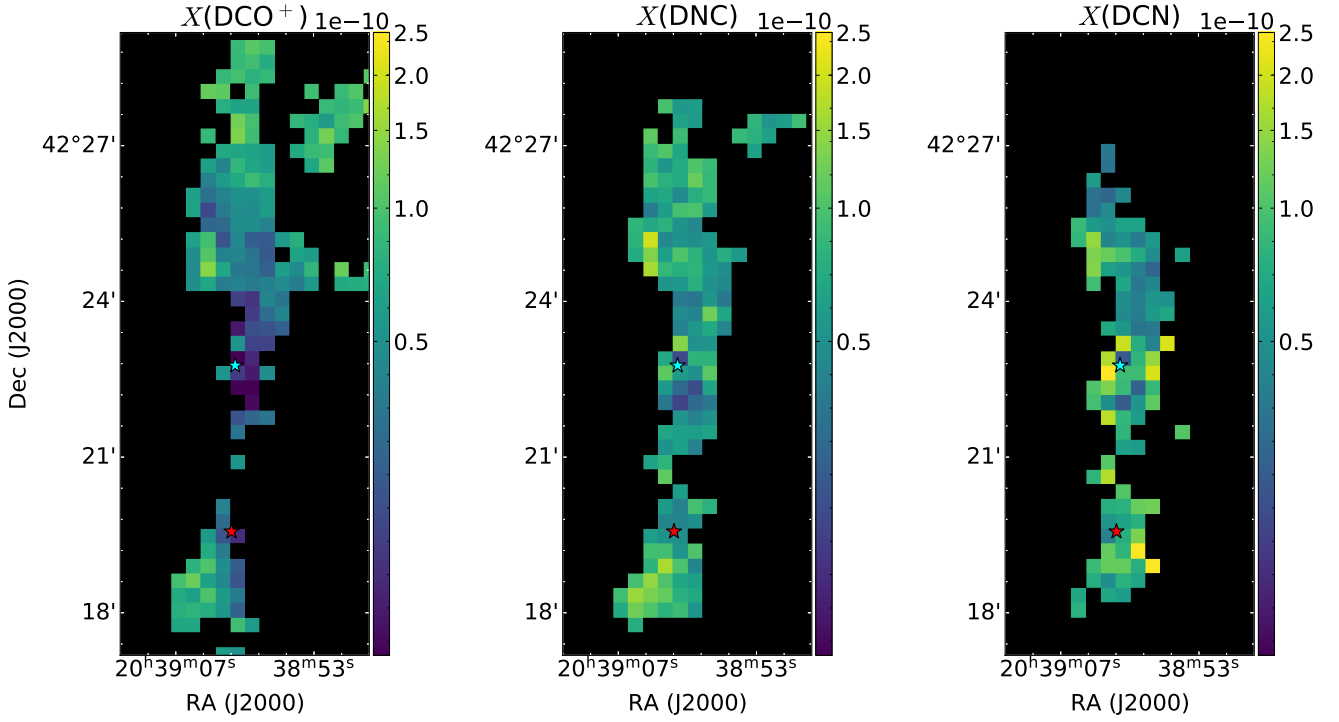


Fig. 7. Abundance maps of $X(\text{DCO}^+)$, $X(\text{DNC})$ and $X(\text{DCN})$. The stars mark the positions of DR21 Main (red) and DR21(OH) (blue).

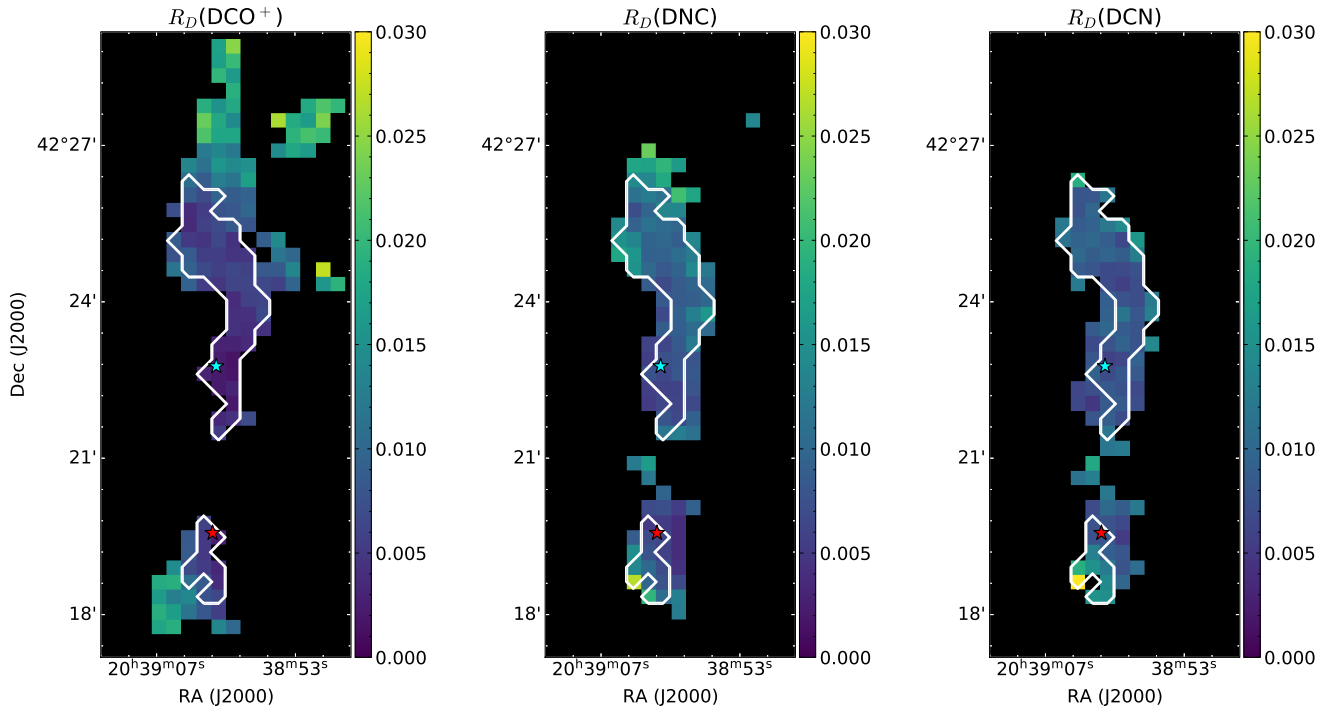


Fig. 8. Left to right: $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$, and $R_D(\text{DCN})$ in the DR21 filament. The stars show DR21 Main (red) and DR21(OH) (blue). The white contours show the pixels, for which R_D could be determined for all three species.

an intermediate stage between the low-mass star-forming regions and the large-scale structure of dark clouds.

4.2. Deuteration degree in the DR21 filament

In this section, we estimate the degree of deuteration (or simply deuteration) in the DR21 filament. Deuteration is defined as

$R_D(\text{D}) = N(\text{XD})/N(\text{XH})$, where $N(\text{XD})$ and $N(\text{XH})$ are the column densities of the D-bearing isotopolog and the H-bearing (main) isotopolog, respectively. The column density maps and the respective relative error maps are shown in Figs. C.1 and C.2. The distributions of $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$, and $R_D(\text{DCN})$ are presented in Fig. 8. For further analysis, the pixel-by-pixel R_D values obtained from these maps were used.

Table 3. Mean deuteration fraction of each molecule and the range of deuteration in the DR21-filament (where detected $\geq 4\sigma_{\text{tot}}$ level) and the overlapping region, where all three $J = 1-0$ -transitions of the deuterated molecules are observed.

D/H	Entire DR21		Overlapping Mean
	Mean	Range	
$R_D(\text{DCO}^+)$	0.012 ± 0.003	0.002–0.043	0.006 ± 0.001
$R_D(\text{DNC})$	0.014 ± 0.003	0.006–0.056	0.014 ± 0.003
$R_D(\text{DCN})$	0.010 ± 0.002	0.005–0.031	0.010 ± 0.002

The deuteration in all three species shows smooth distributions, with average values of 0.012 ± 0.003 , 0.014 ± 0.003 and $= 0.010 \pm 0.002$, for $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$, and $R_D(\text{DCN})$, respectively. Thus the overall degree of deuteration in the DR21 filament is $\sim 1\%$. Similarly, Yang et al. (2024) finds comparable deuteration between $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$, and $R_D(\text{DCN})$ toward the deuterated peaks, despite different detection rates. While significant amounts of $R_D(\text{DCO}^+)$ are measured across the entire filament spanning $N(\text{H}_2)$ between $2.1 \times 10^{22} \text{ cm}^{-2}$ and $1.2 \times 10^{24} \text{ cm}^{-2}$, deuteration is particularly enriched in regions of lower H_2 column densities. This is consistent with the increase in $X(\text{DCO}^+)$ toward dark clouds and translucent clouds.

The median H_2 column density for which DCO^+ is detected, is $N(\text{H}_2) = 5.9 \times 10^{22} \text{ cm}^{-2}$, whereas DNC and DCN are detected at higher H_2 column densities ($N(\text{H}_2) = 1.1 \times 10^{23} \text{ cm}^{-2}$). This further illustrates that DCO^+ samples regions that are less dense in comparison to that probed by DCN and DNC (see also Fig. 6), as a consequence of the lower critical densities (see Table 1). Taniguchi et al. (2024) found that at lower $N(\text{DCN})/N(\text{DCO}^+)$ ($\sim 4-7$, comparable to what we find in DR21, see Fig. D.1) favor models with higher densities.

In the overlapping region (see Fig. 8), where all three deuterated molecules are detected, the highest deuteration is seen for DNC with $R_D(\text{DNC}) = 0.014 \pm 0.003$, which is comparable to $R_D(\text{DCN}) = 0.010 \pm 0.002$. In contrast, $R_D(\text{DCO}^+)$ is a factor ~ 2 lower ($= 0.006 \pm 0.001$) in this region (summarized in Table 3). The overlapping region, in which emission from all three molecules is detected has elevated column densities. Neither $R_D(\text{DNC})$ nor $R_D(\text{DCN})$ are detected in the region that shows the highest $R_D(\text{DCO}^+)$. This region coincides with lower dust temperatures and higher H_2 column densities (see the northern region in Fig. 1 for reference).

To understand the differences in morphology, we compare the spatial variations in deuteration with the distributions of dust temperatures, molecular hydrogen column densities and kinetic gas temperatures along the DR21 filament. The resulting comparisons are presented in Fig. 9. The surroundings of DR21 Main and DR21(OH) are marked in their respective colors from Fig. 3. The surroundings of DR21 Main and DR21(OH) in this work are $34'' \times 34''$, corresponding to 4 pixels, based on the spatial resolution comparable to the surroundings examined by Koley et al. (2021). The molecular D/H-ratios show clear differences in their correlations with the dust temperature and H_2 column density.

Figure 10 presents an overview of the Pearson correlation coefficients between $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$, and $R_D(\text{DCN})$, and T_{dust} , $N(\text{H}_2)$ and T_{kin} . We note the strongest anticorrelations ($|r| \geq 0.70$) between $R_D(\text{DCO}^+)$ with H_2 column density and kinetic gas temperature. At $T_{\text{dust}} \leq 22 \text{ K}$, the trend for $R_D(\text{DCO}^+)$ strongly decreases, whereas at $T_{\text{dust}} \geq 22 \text{ K}$, the dependence of $R_D(\text{DCO}^+)$ on T_{dust} flattens. Similar to the dependence on T_{dust} , $R_D(\text{DCO}^+)$ shows a decreasing trend at $T_{\text{kin}} \leq 22 \text{ K}$, which

flattens out beyond $T_{\text{kin}} = 22 \text{ K}$. However, the limited number of data points present in this regime prevents us from making definitive conclusions about this correlation. Both $R_D(\text{DNC})$ and $R_D(\text{DCN})$ display moderate to weak anticorrelations with T_{dust} and $N(\text{H}_2)$ and T_{kin} , where the trends with $R_D(\text{DCN})$ are particularly flatter (see the right-hand panel Fig. 9). This is unsurprising because the DCN emission is detected toward a more compact region and hence shows a smaller range of deuteration.

Gerner et al. (2015) conducted a similar study on deuteration in these species for 59 high mass star-forming regions. These authors determined that luminosity (as a proxy for temperature) and H_2 column density did not show a significant correlation with any of the three ratios. On average Gerner et al. (2015) reported a deuteration of 0.0025 for $R_D(\text{DCO}^+)$, 0.005 for $R_D(\text{DNC})$ and 0.02 for $R_D(\text{DCN})$. These estimates are a factor of ~ 4 and ~ 2 lower than our estimates of $R_D(\text{DCO}^+)$ and $R_D(\text{DNC})$ while that for $R_D(\text{DCN})$ is a factor ~ 2 higher than our estimates in DR21. Unlike the high mass star-forming regions studied by Gerner et al. (2015), the DR21 filament shows a stronger anticorrelation with H_2 column density and $R_D(\text{DCO}^+)$. However, we note that there are key differences between both studies; we compute R_D using mapping observations whereas Gerner et al. (2015) performed pointed observations toward their sample of star forming regions. Hence, the D/H-ratios derived by these authors probe only the average properties of the targets studied. Moreover, these authors computed the column densities of these deuterated species using fixed values for the $T_{\text{exc}} (= T_{\text{rot}})$ based on their evolutionary stages⁵. Among these evolutionary stages, the IRDCs have temperatures most similar to DR21 among these evolutionary stages, $T_{\text{kin}} = 15 \text{ K}$. The typical values for $R_D(\text{DCO}^+)$, $R_D(\text{DNC})$ and $R_D(\text{DCN})$ derived by Gerner et al. (2015) for the subset of sources classified as IRDCs in their sample are 0.007, 0.008 and 0.015, respectively. These values are comparable to the mean values of the DR21 filament within the errors. Hennemann et al. (2012) investigated the evolutionary stages along the DR21 filament, where they found an increase in evolutionary gradient from the northern region of DR21 toward the DR21(OH). The deuteration fraction along the filament follows a trend of higher deuteration toward the younger region, but a detailed analysis will be done in a forthcoming paper.

5. Discussion

The analysis presented thus far reveals that the strongest dependencies found are between the different physical parameters and $R_D(\text{DCO}^+)$, while much weaker correlations were found for $R_D(\text{DNC})$ and $R_D(\text{DCN})$. Therefore, in the following sections, we explore the impact of the physical conditions, if any, on the chemistry of these species.

5.1. Impact of physical conditions on $R_D(\text{DCO}^+)$.

We investigate the influence of different physical parameters and, in particular, $N(\text{H}_2)$ on the $R_D(\text{DCO}^+)$. We summarize here the underlying chemistry for the formation of DCO^+ .

The formation of DCO^+ and HCO^+ are most efficient in the lower temperature regime ($T_{\text{kin}} < 20 \text{ K}$). The primary formation pathway of DCO^+ is the following gas phase reaction (Albertsson et al. 2013):



⁵ $T = 15 \text{ K}$ for IRDCs, $T = 50 \text{ K}$ for HMPOs, $T = 100 \text{ K}$ for HMCs and $T = 100 \text{ K}$ for UCHII.

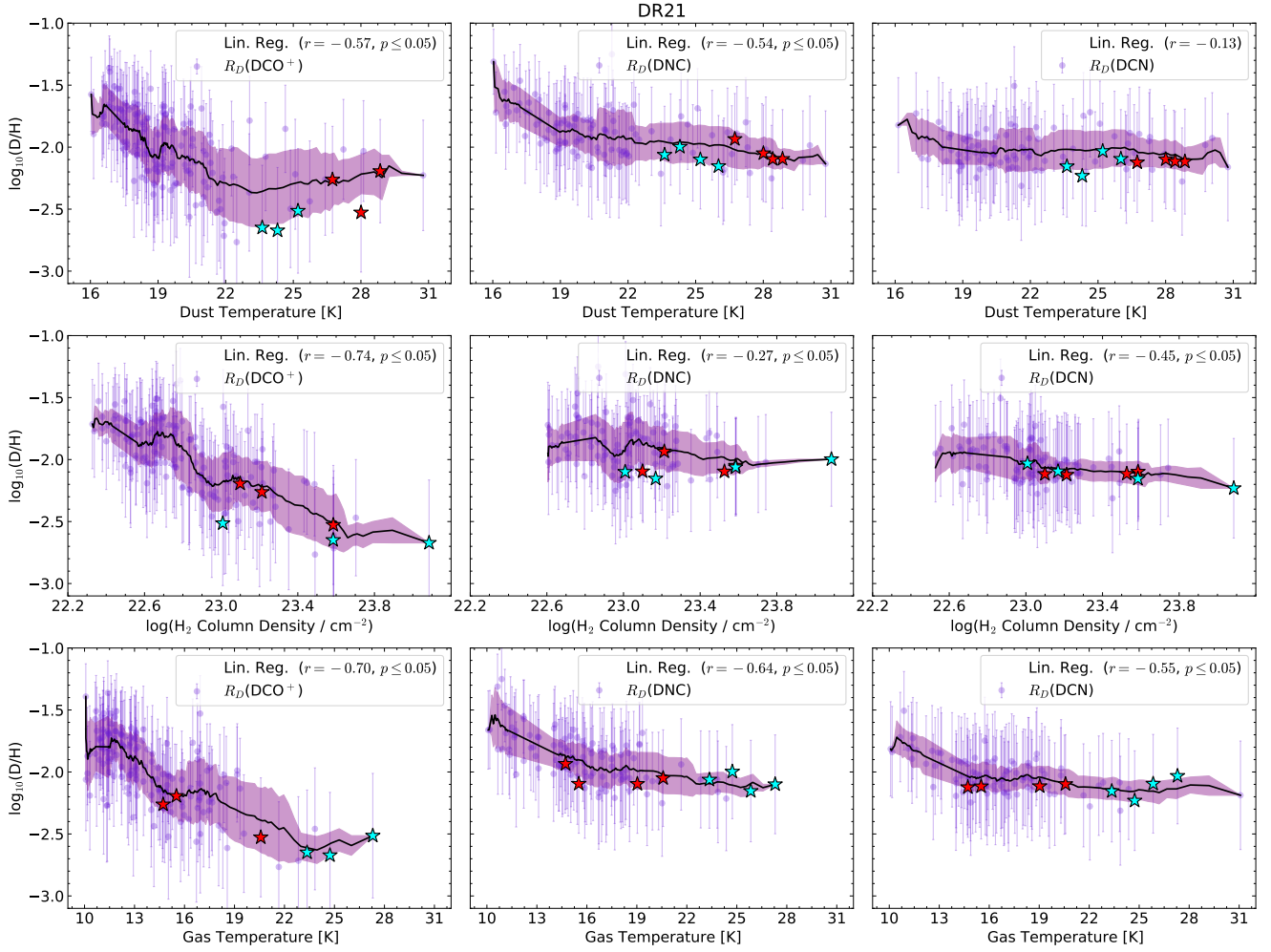


Fig. 9. Degrees of deuteration, $R_D(\text{DCO}^+)$ (left column), $R_D(\text{DNC})$ (middle column), and $R_D(\text{DCN})$ (right column), with dust temperature (top row) and H_2 column densities (middle row; [Bonne et al. 2023](#)) and kinetic gas temperature (bottom row) in the DR21 filament. Each point corresponds to the pixel-wise deuteration derived from the $J = 1-0$ and $J = 2-1$ or $J = 3-2$ transitions of DCO^+ , DNC , and DCN where each of the species were detected at an rms noise level $\geq 4\sigma_{\text{tot}}$. The black line shows the running mean, while the purple ranges marks the standard deviation. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.

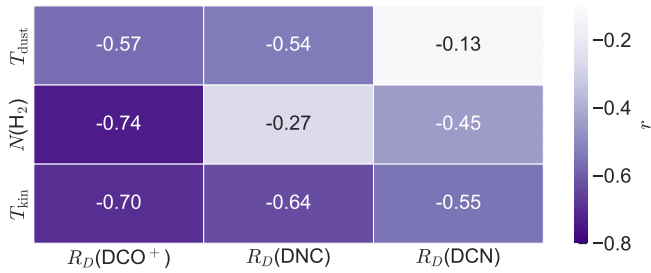


Fig. 10. Overview of the Pearson correlation coefficients (r) estimated for cross-correlations between DCO^+ , DNC , and DCN , and T_{dust} , $N(\text{H}_2)$ and T_{kin} .

The formation pathway of the main isotopolog also requires CO:



In the low temperature ($T_{\text{dust}} < 20 \text{ K}$) and high density regime ($n > 10^4 \text{ cm}^{-3}$), where CO is frozen onto the dust grains, the sparse amounts of CO available in the gas phase reacts with H_2D^+ . As CO is sublimated from the ices, CO reacts with

H_3^+ , depleting the reservoir to form H_2D^+ from H_3^+ . Consequently, $R_D(\text{DCO}^+)$ peaks in $T_{\text{gas}} \leq 20 \text{ K}$ and decreases with increasing temperature ([Aikawa et al. 2012](#)). The formation of DCO^+ and HCO^+ decreases as H_3^+ is destroyed before forming H_2D^+ ([Albertsson et al. 2013](#)). Using a time-dependent chemical model, [Albertsson et al. \(2013\)](#) showed a thermal dependence of DCO^+ in the lower temperature regime ($\sim 30 \text{ K}$). Once the critical temperature for DCO^+ formation is reached, the $R_D(\text{DCO}^+)$ begins to decrease to the elemental abundance of D/H -ratio ($\sim 10^{-5}$) ([Cooke et al. 2018](#)). A simple thermal dependence of $R_D(\text{DCO}^+)$ in low ionization fraction regions, following the temperature dependence of its precursors, has been established ([Herbst 1982; Anderson et al. 1999](#)).

Elevated temperatures driven by shocks can cause the non-thermal sublimation or sputtering of CO from dust grains. As a result, shocks can also suppress the formation of DCO^+ , discussed in depth in Sect. 5.1.1. Within the DR21 filament, an environment teeming with varied degrees of star formation activity along its structure ([Schneider et al. 2010; Hennemann et al. 2012](#)), regions like DR21 Main and DR21(OH) stand out, as is discussed in Sect. 3. The HII region in DR21 Main, from which the prominent bipolar-shaped outflow originates, drives

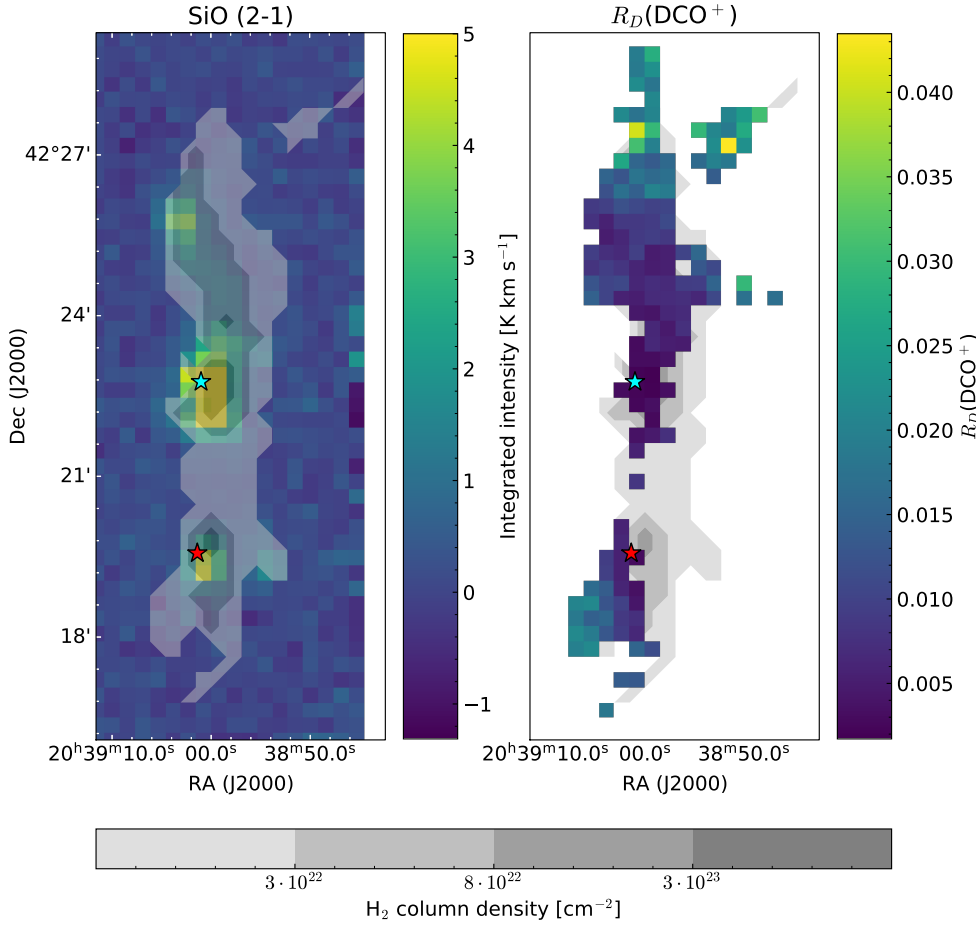


Fig. 11. Distribution of SiO (2–1) integrated intensity (left panel) and $R_D(\text{DCO}^+)$ (right panel) the DR21 filament. The gray scale shows the $N(\text{H}_2)$ column densities, where darker regions indicate higher column densities. The stars show DR21 Main (red) and DR21(OH) (blue).

shock chemistry in its surroundings (see, for example, Skretas et al. 2023). The latter region, DR21(OH), where the lowest $R_D(\text{DCO}^+)$ value is observed, also exhibits clear signatures of shock chemistry (see Godard et al. 2012). Therefore, the shocks present in the vicinity of these HII regions may play a vital role in the chemistry of $R_D(\text{DCO}^+)$.

For a complete understanding of the chemistry of DCO^+ in DR21, one must, in addition to the environment specific effects suppress its formation, also take into account the relevant destruction pathways. The primary pathway leading to the destruction of DCO^+ and HCO^+ is dissociative recombination:



and



As a result, a higher electron fraction accelerates the destruction of HCO^+ more rapidly than that of DCO^+ , thereby influencing the molecular isotopic ratio (Albertsson et al. 2013).

In the following sections, we discuss in more detail the influence of shocks and photodissociation on the chemistry of $R_D(\text{DCO}^+)$ within the DR21 filament.

5.1.1. Effect of shocks

In this section, we investigate the impact of shocks on the chemistry of $R_D(\text{DCO}^+)$. As was discussed above, the release of CO into the gas phase readily destroys H_3^+ and, in turn, suppresses

the formation of H_2D^+ and DCO^+ (see Eqs. (8) and (9)). The dominant pathway leading to the desorption of CO from dust grains at lower temperatures is via nonthermal desorption driven by shocks.

Multiple sources of shocks are found in DR21, for example outflows, star-forming regions, and cloud-cloud interactions. The DR21 filament harbors one of the most extreme outflow, by mass and size, in our Milky Way namely DR21 Main (Skretas et al. 2023). Furthermore, the DR21 filament was proposed to be the result of cloud-cloud collisions (Dickel et al. 1978; Dobashi et al. 2019). Recent observations of ionized carbon (Schneider et al. 2023; Bonne et al. 2023) have refined this scenario, revealing this region to be more complex with several molecular clouds and their HI envelopes interacting.

A commonly used molecular tracer of shocks is SiO, formed by the nonthermal sputtering of Si from dust which reacts with gas phase O (Martín-Pintado et al. 1997). The specific use of SiO as a shock tracer has been demonstrated through observations and models. Observations show an increase in SiO abundances from quiescent, previously shocked, regions to dense, active regions as the center of our Milky Way (Amo-Baladrón et al. 2011; Rybarczyk et al. 2023). Theoretical models by Kelly et al. (2017) show the abundance of SiO to increase significantly (often by an order of magnitude) in regions where it encounters both slow and fast shocks. In various environments, these studies demonstrate that the presence or enhancement of the SiO molecule serves as an indicator of shock chemistry.

Given that CO is sputtered from the dust grain mantles alongside SiO, the detection of significant amounts of SiO in the gas phase indirectly traces the source of H_2D^+ suppression.

While it is nontrivial to infer the properties of the shocks in DR21, such as shock velocity and shock age, through abundance measurements of SiO, we compare the spatial extent of SiO emission in DR21 to decipher the role of shocks in $R_D(\text{DCO}^+)$ chemistry.

Figure 11 shows the spatial distribution of the integrated intensity map of SiO (2–1), obtained with CASCADE, and $R_D(\text{DCO}^+)$, alongside $N(\text{H}_2)$ between $3 \times 10^{22} \text{ cm}^{-2}$ and $1 \times 10^{24} \text{ cm}^{-2}$ overlaid in gray scale. The increased SiO (2–1) emission suggests that it coincides with the regions of decreased $R_D(\text{DCO}^+)$. The regions with the highest values of $N(\text{H}_2)$ ($>8 \times 10^{22} \text{ cm}^{-2}$) correspond to that of the massive dense cores, DR21 Main and DR21(OH) (see Fig. 11) which coincides with the regions where the SiO (2–1) emission is the strongest. More importantly, from this comparison it is clear that the regions where the SiO (2–1) emission dominates is also spatially coincident with the regions where we estimate the lowest values for $R_D(\text{DCO}^+)$. This lends credence to our hypothesis that shocks in the vicinity of DR21 Main and DR21(OH) play an important role in regulating the chemistry and hence the deuteration present in DCO^+ . In addition, the attenuation of cosmic-rays in dense region such as DR21(Main) and DR21(OH) might diminish the abundance of H_3^+ , thus decreasing the HCO^+ and DCO^+ abundances in these regions. Testing the importance of cosmic-rays in regulating the $R_D(\text{DCO}^+)$, however, is beyond the scope of this paper.

In the top two panels of Fig. 12, we examine variations in SiO abundance with $N(\text{H}_2)$. We find a similar trend as for APEX Telescope LArge Survey of Galaxy (ATLASGAL; Schuller et al. 2009) sources SiO measurements by Csengeri et al. (2016), and the SiO $J = 1-0$ survey toward massive SFRs (Kim et al. 2023). These authors find that the embedded HII regions show a higher abundance compared with that of younger sources, where the shock conditions change with the massive clumps or with the age of the clump. Similarly, we find abundances of SiO in the DR21 filament as in the shocked ATLASGAL sources and SFRs at similar H_2 column densities.

We find that the regions toward which we detect SiO (2–1) emission at rms noise levels $\geq 4\sigma$ correspond those regions with consistently low values of $R_D(\text{DCO}^+)$ (< 0.03). The second panel in Fig. 12 shows a decreasing trend of $R_D(\text{DCO}^+)$ with the abundance of SiO. However, this decrease occurs due to H_2 column density, as the SiO abundance is independent of the H_2 column density in the DR21 filament. The Pearson correlation coefficient of $R_D(\text{DCO}^+)$ with H_2 column density and T_{dust} , where SiO is detected, is $r = -0.51$ and $r = -0.54$, respectively. While a definitive conclusion regarding the state of shocked gas in DR21 cannot be reached, the spatial correlation between the shock tracer and the decreased $R_D(\text{DCO}^+)$ strongly suggests that the shocks are influencing the chemistry of $R_D(\text{DCO}^+)$.

5.1.2. Effects of photodissociation by ultraviolet radiation

In this section, we investigate the impact of photodissociation on the chemistry of $R_D(\text{DCO}^+)$. The interface in the ISM, in which the chemistry is primarily influenced by UV photons, is known as a photodissociation region (PDR; Hollenbach & Tielens 1997). At the forefront of a PDR, H_2 molecules undergo photodissociation. As the H_2 column density increases (toward regions with higher extinction), the low column density ($N(\text{H}) \leq 2 \times 10^{20} \text{ cm}^{-2}$), ionized medium transitions to the molecular, high density ($N(\text{H}) \geq 2 \times 10^{22} \text{ cm}^{-2}$) medium. Despite only having modest abundances in the ISM, HCO is efficiently formed in

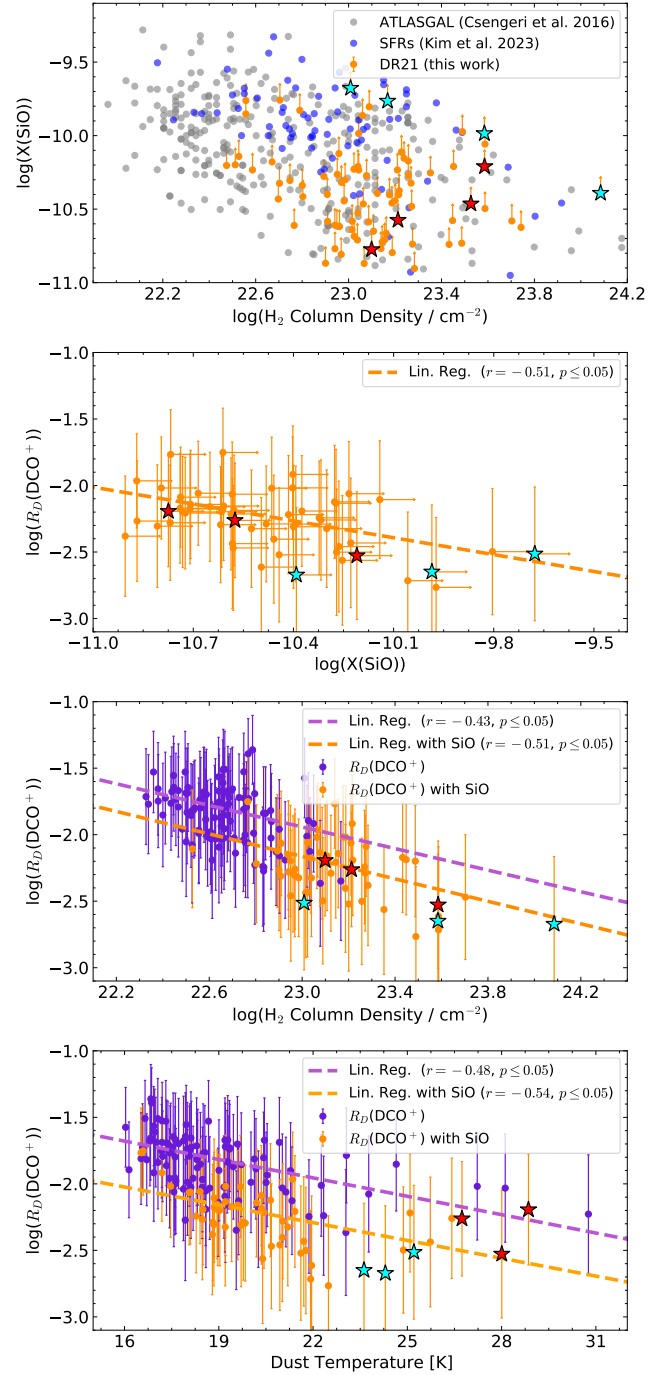


Fig. 12. Abundance of SiO with H_2 column density in the DR21 filament and ATLASGAL sources (Csengeri et al. 2016) and SFRs (Kim et al. 2023), and $R_D(\text{DCO}^+)$ with the abundance of SiO in the DR21 filament (first and second row, respectively). The third row and fourth row show the H_2 column density and the dust temperature with $R_D(\text{DCO}^+)$, respectively, where purple shows non-detection of SiO and orange shows the pixels where SiO was detected $\geq 4\sigma$. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.

PDRs via FUV (Schilke et al. 2001; Gerin et al. 2009):



and



where the abundance of this rare molecular species becomes comparable with that of H^{13}CO^+ . Furthermore, a high abundance of HCO in the gas phase can be attained by releasing HCO from grain mantles before larger molecules form there; for example, H_2CO , CH_3OH and other COMs (Gerin et al. 2009). This early release of HCO to the gas phase can occur in regions with lower $N(\text{H}_2)$ that are exposed FUV radiation. Photodissociation is an obvious process associated with the well-studied HII-region DR21 Main and DR21(OH). The outer parts of DR21 dominantly affected by the interstellar UV radiation (Yamagishi et al. 2018).

The column density ratio of HCO and H^{13}CO^+ and the abundance of the latter, have been found to be increased in HII regions when compared to regions devoid of HII regions or showing minimal signs of star formation activity (Schilke et al. 2001; Gerin et al. 2009; Kim et al. 2020). $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+) \geq 1$ and $X(\text{HCO}) \geq 10^{-10}$ reflects high degrees of photodissociation, and is indicative of ongoing FUV chemistry (Gerin et al. 2009; Kim et al. 2020).

In Fig. 13, we investigate the variation in FUV radiation fields by examining the column density ratio of $N(\text{HCO})$ and $N(\text{H}^{13}\text{CO}^+)$ in the DR21 filament. The emission maps and column densities of HCO are described in depth in Appendix A. In all panels of Fig. 13, the surroundings of DR21(OH) is marked with a blue star. Unfortunately, we did not detect HCO, H^{13}CO^+ , and DCO^+ in any of the surroundings of DR21 Main, and we only detected one pixel with the three molecules simultaneously detected in the vicinity of DR21(OH). The upper panel of Fig. 13 shows a decreasing trend of the $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ ratio with H_2 column density in the DR21 filament compared with values of this ratio determined for molecular clumps found in ATLASGAL, taken from (Kim et al. 2020). The observed trend is mainly driven by the decreasing abundance of HCO as a function of increasing H_2 column density. The middle panel of Fig. 13 shows no variation in $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ with dust temperature neither in DR21 nor the ATLASGAL clumps. No correlation between $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ and T_{dust} implies that thermal desorption does not play a role in the formation of HCO (Kim et al. 2020).

The lower panel of Fig. 13 shows a correlation between $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ and $R_D(\text{DCO}^+)$ with a Pearson correlation coefficient of $r = 0.77$. This increasing trend of $R_D(\text{DCO}^+)$ with $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ starts at the point at which the abundances of DCO^+ and HCO start to decrease; that is, where FUV driven chemistry commences (Gerin et al. 2009; Kim et al. 2020). These conditions can be found as the photodissociation degree decreases. As the H_2 column density increases, H_2 self-shielding becomes effective resulting in the decrease in the HCO^+ destruction (see Eq. (11)). The decreasing trend of $R_D(\text{DCO}^+)$ with $N(\text{H}_2)$ is caused by the decrease in the HCO^+ destruction.

To summarize the discussion on the influence of shocks and ionization, the two physical processes affect $R_D(\text{DCO}^+)$ in different ways. HCO^+ is destroyed faster than DCO^+ through dissociative recombination. The regions of $R_D(\text{DCO}^+)$ with column density, where HCO and/or SiO are present, are marked with green in Fig. 14. We find a Pearson correlation coefficient $r = -0.79$ of $R_D(\text{DCO}^+)$ with H_2 column density where HCO is detected in Sect. 5.1.2. These are found at the lower H_2 column densities. On the contrary, at higher H_2 column densities, where SiO is detected, we find a Pearson correlation coefficient $r = -0.51$ of $R_D(\text{DCO}^+)$ with H_2 column density in Sect. 5.1.1. As CO reacts with H_3^+ , the production of H_2D^+ is halted, successively decreasing the formation of DCO^+ . This suggests that FUV-chemistry affects the lower column densities and shock-chemistry affects the higher column densities

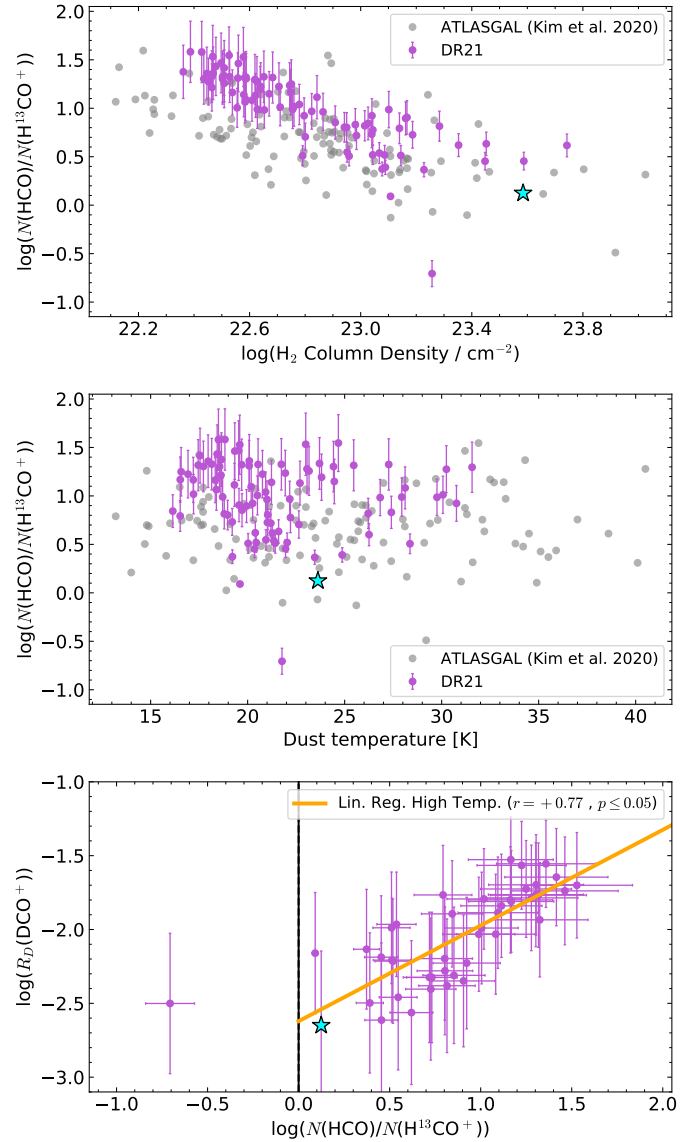


Fig. 13. $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ vs. $N(\text{H}_2)$ (top panel) and dust temperature (middle panel). The bottom panel shows the correlation of $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ with $R_D(\text{DCO}^+)$. The purple points represent pixels in the DR21 filament above 4σ and the gray point shows the ATLASGAL sources from Kim et al. (2020). The black vertical line represents the indicator of ongoing FUV chemistry ≥ 1 (Gerin et al. 2009; Kim et al. 2020). The blue star mark the surroundings of DR21(OH), where HCO, H^{13}CO^+ and DCO^+ are detected.

in DR21, overall resulting in the strong decrease in $R_D(\text{DCO}^+)$ ($r = 0.74$).

5.2. Impact of physical conditions on DNC and DCN

In Sect. 4.2, it is observed that DNC and DCN are indicative of different physical conditions compared to DCO^+ . Specifically, they are detected in warmer and denser regions within the DR21 filament. Figure 6 illustrates that these isomers trace similar gas distributions. In this section, we aim to investigate the influence of temperature on the ratio of DNC to DCN.

Figure 9 shows that $R_D(\text{DNC})$ and $R_D(\text{DCN})$ have distinct dependencies on T_{dust} . The formation pathways of these isomers have significant differences in their thermal dependence.

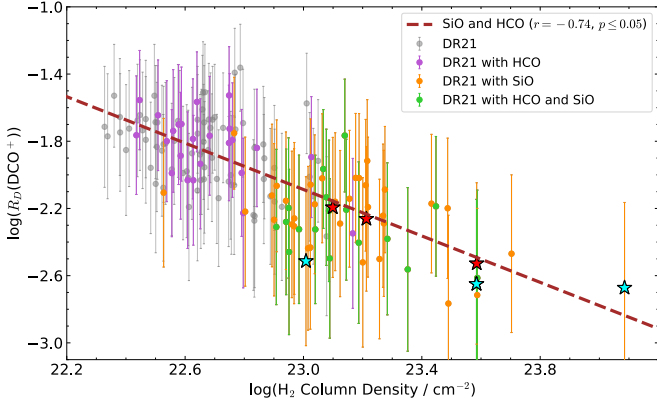


Fig. 14. $R_D(\text{DCO}^+)$ with column density, where in gray are all the pixels measured in DR21, purple is $R_D(\text{DCO}^+)$ where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ was measured, orange is where $X(\text{SiO})$ was measured, and green is where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ and $X(\text{SiO})$ intersect. The linear fit, where SiO and HCO are detected, is shown in dashed brown. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.

In the lower temperature regime ($T_{\text{dust}} \leq 30$ K), DNC is predominantly formed at a higher rate through deuterium reacting with the primary isotopologs, HCN and HNC. Surprisingly, in this temperature range, DCN formation occurs through the deuterium transfer of HNC (Turner 2001). Conversely, DNC and DCN efficiently form with deuterated light hydrocarbons, such as CH_2D^+ , at higher temperatures (~ 80 K; Albertsson et al. 2013). At lower gas temperatures ($T_{\text{gas}} \leq 30$ K), DCN exhibits lower formation efficiency, as it is formed through CH_2D^+ , compared to DNC, formed through H_2D^+ (Turner 2001; Roueff et al. 2007). As for DNC, its formation efficiency decreases with increasing temperature since the O-atom becomes more effective in destroying this isomer (Gerner et al. 2015). However, the current study does not explore these higher temperatures as the maximum dust temperature and kinetic gas temperature measured were ≤ 31 K.

HCN and HNC, the primary isotopologs of these isomers, have demonstrated an ability to trace the kinetic gas temperature (see Sect. 3.3). The ratio of $I(\text{HCN})/I(\text{HNC})$ at gas temperatures $T \leq 200$ K is controlled by the selective destruction of HNC (Hacar et al. 2020):



and,



The inter-conversion between HCN and HNC becomes efficient at $T > 40$ K. At low temperatures, HCN and HNC are formed through ion-molecule chemistry with almost equal probability (Herbst et al. 2000; Albertsson et al. 2013). A similar effect may occur for DCN and DNC, where an increase in T_{kin} is necessary to initiate the conversion of DNC to DCN through reactions with free atomic D in the gas.

Figure 15 shows the intensity ratio comparisons of $I(\text{DCN})/I(\text{DNC})$ with $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$. In the optically thin regime of these ratios, $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$ is a proxy for the kinetic gas temperature (Beuther et al. 2022; Pazukhin et al. 2022). The optical depth of each molecule is presented in Fig. B.1, which is consistent with the optically thin assumption. The intensities were used to ensure independent ratio comparison, as the column densities are inherently dependent

Comparison between H^{13}CN and HN^{13}C with DCN and DNC intensity ratios

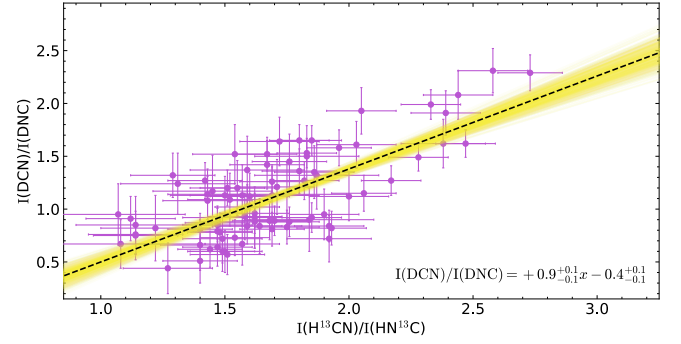


Fig. 15. Integrated intensity ratio of DCN and DNC with the ratio of H^{13}CN and HN^{13}C of optically thin region (orange), as a proxy for the kinetic gas temperature following Hacar et al. (2020) with a Pearson correlation of $r = 0.72$.

Comparison of dust temperature with DCN and DNC intensity ratios

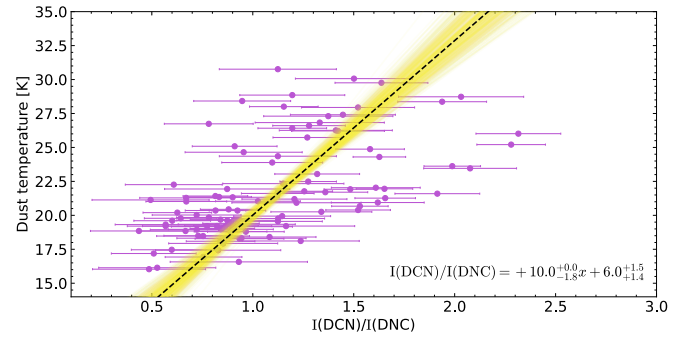


Fig. 16. Dust temperature as a function of integrated intensity ratio of DCN and DNC with a Pearson correlation of $r = 0.58$.

on the temperature calculated using $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$. The D-isotopologs $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$ with a slope $a = +0.9^{+0.1}_{-0.1}$ and intercept of $b = -0.4^{+0.1}_{-0.1}$. The temperature indicator represented by $I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C})$ exhibits a moderate correlation with $I(\text{DCN})/I(\text{DNC})$, implying that $I(\text{DCN})/I(\text{DNC})$ is also a potential tracer of kinetic gas temperature.

Figure 16 shows a plot of dust temperature as a function of $I(\text{DCN})/I(\text{DNC})$, which displays a moderate correlation between the dust temperature and the velocity-integrated intensity ratio of DCN and DNC. We find a slope $a = +10$ and intercept of $b = +6$ between the dust temperature and $I(\text{DCN})/I(\text{DNC})$. This correlation implies a kinetic gas temperature of $T_{\text{dust}} = 10 \times (\text{DCN}/\text{DNC}) + 6$. Hacar et al. (2020) reported a one-to-one correlation between dust temperature and the kinetic temperature derived from the intensity ratio of HCN to HNC. By applying the same approach to obtain kinetic gas temperature (Eq. (5)), but using the intensity ratio of DCN to DNC instead and multiplying it by ten, we establish a one-to-one relationship between the kinetic gas temperature (T_{kin}) derived from DCN/DNC and the dust temperature in DR21.

6. Conclusions

In this paper, we have investigated the distribution of deuterated molecules in DR21 as part of the Cygnus-X Allscale Survey of Chemistry And Dynamical Environment. Using the IRAM 30-m telescope, observations of the ground-state of DCO^+ , DNC,

and DCN at 3–4 mm and follow-up observations of higher J -transitions at 2 and 1.3 mm wavelengths were carried out. The main results are summarized below:

1. The emission maps of DCO⁺, DNC, and DCN show clear morphological differences along the DR21 filament. DCO⁺ shows the most extended emission along the DR21 ridge, with several peaks along its structure. DNC is also observed to have several peaks but less extended emission than DCO⁺. DCN shows relatively compact emission toward the DR21 Main and DR21(OH) star-forming clumps. The morphological differences of these three molecules suggest local variations in physical parameters.
2. The column densities derived from the optically thin lines from DCO⁺, DNC, and DCN, as well H¹³CO⁺, HN¹³C, and H¹³CN, together with the Herschel-based H₂ column density, indicate similar mean abundances of the deuterated molecules, on the order of $X(D) \sim 6\text{--}9 \times 10^{-11}$. All three molecules are observed toward higher H₂ column densities.
3. The deuteration degrees, R_D , of all three species have similar values, between 0.010 and 0.014. $R_D(\text{DCO}^+)$ and $R_D(\text{DNC})$ shows a strong anticorrelation with dust temperature ($r < -0.5$) and all three shows strong anticorrelation with kinetic gas temperature, the highest value of which ($r = -0.70$) is found for $R_D(\text{DCO}^+)$.
The three ratios between the deuterated molecules, $N(\text{DCO}^+)/N(\text{DNC})$ and $N(\text{DCO}^+)/N(\text{DCN})$, show anticorrelations with the dust temperatures in the regime in which CO is not yet sublimated ($T_{\text{dust}} \leq 22$ K). On the contrary, $N(\text{DCN})/N(\text{DNC})$ shows an increasing correlation at $T_{\text{dust}} \leq 22$ K. After the onset of thermal CO-sublimation, all three ratios are constant with dust temperature.
4. $R_D(\text{DCO}^+)$ decreases with H₂ column density. We attempted to explain this decrease with ionization and shocks. At lower column densities, FUV chemistry, as traced by $N(\text{HCO}^+)/N(\text{H}^{13}\text{CO}^+)$, is likely causing the rapid decrease by effectively destroying HCO⁺ faster than DCO⁺. $R_D(\text{DCO}^+)$ decreases with an increasing column density of SiO, a well-known shock tracer. Ionization, shocks, and the initial ortho-to-para H₂ ratio, although the latter is not quantified, appear to have an effect on the decrease in $R_D(\text{DCO}^+)$. The relative influence of the degree of ionization or shocks affecting the decreasing $R_D(\text{DCO}^+)$ is hard to discern solely based on the molecular content, as DR21 is a dynamic and complex filament with a powerful HII-region, a substantial outflow, several star-forming regions in different evolutionary stages, and cloud-cloud interactions.
5. The DCN/DNC-ratio was investigated as a possible kinetic gas temperature tracer. At higher $N(\text{H}_2)$, with the HN¹³C and H¹³CN lines being optically thin, a strong correlation is found. The obtained correlation is $I(\text{DCN})/I(\text{DNC}) = 0.9 \times I(\text{H}^{13}\text{CN})/I(\text{HN}^{13}\text{C}) - 0.4$.

Acknowledgements. The authors would like to thank the anonymous referee for their suggestions and constructive comments that improved the overall quality of the manuscript. The authors are also grateful to the staff at the Pico Veleta observatories for their support of these observations. I.B.C. is a member of the International Max-Planck Research School at the universities of Bonn and Cologne (IMPRS). This work is based on observations carried out under project number 145-19, 031-20 and 053-21 with the IRAM 30m telescope. I.R.A.M. is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain). D.S. acknowledges support from the European Research Council under the Horizon 2020 Framework Program via the ERC Advanced Grant Origins 83 24 28. N.S. acknowledges support from the FEEDBACK-plus project that is supported by the BMWI via DLR, Projekt Number 50OR2217. N.C. acknowledges funding from the European Research Council (ERC) via the ERC Synergy Grant ECO-GAL (grant 855130), from the French Agence Nationale de la Recherche (ANR) through the project COSMHIC (ANR-20-CE31-0009).

References

- Aikawa, Y., Wakelam, V., Hersant, F., Garrod, R. T., & Herbst, E. 2012, *ApJ*, **760**, 40
- Albertsson, T., Semenov, D. A., Vasyunin, A. I., Henning, T., & Herbst, E. 2013, *ApJS*, **207**, 27
- Amo-Baladrón, M. A., Martín-Pintado, J., & Martín, S. 2011, *A&A*, **526**, A54
- Anderson, I. M., Caselli, P., Haikala, L. K., & Harju, J. 1999, *A&A*, **347**, 983
- Beuther, H., Wyrowski, F., Menten, K. M., et al. 2022, *A&A*, **665**, A63 (Paper I)
- Bonne, L., Bontemps, S., Schneider, N., et al. 2023, *ApJ*, **951**, 39
- Carter, M., Lazareff, B., Maier, D., et al. 2012, *A&A*, **538**, A89
- Caselli, P., Walmsley, C. M., Terzieva, R., & Herbst, E. 1998, *ApJ*, **499**, 234
- Cooke, R. J., Pettini, M., & Steidel, C. C. 2018, *ApJ*, **855**, 102
- Csengeri, T., Leurini, S., Wyrowski, F., et al. 2016, *A&A*, **586**, A149
- Dickel, J. R., Dickel, H. R., & Wilson, W. J. 1978, *ApJ*, **223**, 840
- Dickens, J. E., Irvine, W. M., Snell, R. L., et al. 2000, *ApJ*, **542**, 870
- Dobashi, K., Shimoikura, T., Katakura, S., Nakamura, F., & Shimajiri, Y. 2019, *PASJ*, **71**, S12
- Downes, D., & Rinehart, R. 1966, *ApJ*, **144**, 937
- Favre, C., Bergin, E. A., Cleaves, L. I., et al. 2015, *ApJ*, **802**, L23
- Flower, D. R., Pineau des Forêts, G., & Walmsley, C. M. 2006, *A&A*, **449**, 621
- Fontani, F., Palau, A., Caselli, P., et al. 2011, *A&A*, **529**, A7
- Gerin, M., Goicoechea, J. R., Pety, J., & Hily-Blant, P. 2009, *A&A*, **494**, 977
- Gerner, T., Shirley, Y. L., Beuther, H., et al. 2015, *A&A*, **579**, A80
- Giannetti, A., Wyrowski, F., Brand, J., et al. 2014, *A&A*, **570**, A65
- Girart, J. M., Estalella, R., Palau, A., Torrelles, J. M., & Rao, R. 2014, *ApJ*, **780**, L11
- Girichidis, P., Offner, S. S. R., Kritsuk, A. G., et al. 2020, *Space Sci. Rev.*, **216**, 68
- Godard, B., Falgarone, E., Gerin, M., et al. 2012, *A&A*, **540**, A87
- Goldsmith, P. F., & Langer, W. D. 1999, *ApJ*, **517**, 209
- Gratier, P., Majumdar, L., Ohishi, M., et al. 2016, *ApJS*, **225**, 25
- Guzmán, A. E., Guzmán, V. V., Garay, G., Bronfman, L., & Hechenleitner, F. 2018, *ApJS*, **236**, 45
- Hacar, A., Bosman, A. D., & van Dishoeck, E. F. 2020, *A&A*, **635**, A4
- Hennemann, M., Motte, F., Schneider, N., et al. 2012, *A&A*, **543**, A3
- Herbst, E. 1982, *A&A*, **111**, 76
- Herbst, E., Terzieva, R., & Talbi, D. 2000, *MNRAS*, **311**, 869
- Hocuk, S., Cazaux, S., & Spaans, M. 2014, *MNRAS*, **438**, L56
- Hollenbach, D. J., & Tielens, A. G. G. M. 1997, *ARA&A*, **35**, 179
- Immer, K., Cyganowski, C., Reid, M. J., & Menten, K. M. 2014, *A&A*, **563**, A39
- Jacob, A. M., Menten, K. M., Wiesemeyer, H., et al. 2020, *A&A*, **640**, A125
- Kahle, K. A., Hernández-Gómez, A., Wyrowski, F., & Menten, K. M. 2023, *A&A*, **673**, A143
- Kelly, G., Viti, S., García-Burillo, S., et al. 2017, *A&A*, **597**, A11
- Kim, W. J., Wyrowski, F., Urquhart, J. S., et al. 2020, *A&A*, **644**, A160
- Kim, W. J., Urquhart, J. S., Veena, V. S., et al. 2023, *A&A*, **679**, A123
- Koley, A., Roy, N., Menten, K. M., et al. 2021, *MNRAS*, **501**, 4825
- Li, S., Sanhueza, P., Lu, X., et al. 2022, *ApJ*, **939**, 102
- Linsky, J. L. 1998, *Space Sci. Rev.*, **84**, 285
- Mangum, J. G., Wootten, A., & Mundy, L. G. 1992, *ApJ*, **388**, 467
- Martín-Pintado, J., de Vicente, P., Fuente, A., & Planesas, P. 1997, *ApJ*, **482**, L45
- McKee, C. F., & Tan, J. C. 2002, *Nature*, **416**, 59
- McKee, C. F., & Tan, J. C. 2003, *ApJ*, **585**, 850
- Millar, T. J., Bennett, A., & Herbst, E. 1989, *ApJ*, **340**, 906
- Motte, F., Bontemps, S., Schilke, P., et al. 2007, *A&A*, **476**, 1243
- Motte, F., Zavagno, A., Bontemps, S., et al. 2010, *A&A*, **518**, L77
- Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, *A&A*, **370**, L49
- Murillo, N. M., van Dishoeck, E. F., van der Wiel, M. H. D., et al. 2018, *A&A*, **617**, A120
- Nyman, L. A. 1983, *A&A*, **120**, 307
- Oliveira, C. M., Hébrard, G., Howk, J. C., et al. 2003, *ApJ*, **587**, 235
- Ossenkopf, V., Röllig, M., Simon, R., et al. 2010, *A&A*, **518**, A79
- Parise, B., Ceccarelli, C., Tielens, A. G. G. M., et al. 2002, *A&A*, **393**, L49
- Pazukhin, A. G., Zinchenko, I. I., Trofimova, E. A., & Henkel, C. 2022, *Astron. Rep.*, **66**, 1302
- Pety, J. 2005, in *SF2A-2005: Semaine de l'Astrophysique Française*, eds. F. Casoli, T. Contini, J. M. Hameury, & L. Paganì (EdP Sciences), 721
- Pety, J. 2018, in *Submillimetre Single-dish Data Reduction and Array Combination Techniques*, 11
- Pickett, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, *J. Quant. Spectrosc. Radiat. Transf.*, **60**, 883
- Pillai, T., Caselli, P., Kauffmann, J., et al. 2012, *ApJ*, **751**, 135
- Pratap, P., Dickens, J. E., Snell, R. L., et al. 1997, *ApJ*, **486**, 862
- Reipurth, B., & Schneider, N. 2008, in *Handbook of Star Forming Regions, Volume I*, 4, ed. B. Reipurth (San Francisco : ASP), 36
- Roberts, H., & Millar, T. J. 2000a, *A&A*, **364**, 780

- Roberts, H., & Millar, T. J. 2000b, [A&A](#), **361**, 388
- Roberts, H., Herbst, E., & Millar, T. J. 2004, [A&A](#), **424**, 905
- Roueff, E., Parise, B., & Herbst, E. 2007, [A&A](#), **464**, 245
- Rybarczyk, D. R., Stanimirović, S., & Gusdorf, A. 2023, [ApJ](#), **950**, 52
- Rygl, K. L. J., Brunthaler, A., Sanna, A., et al. 2012, [A&A](#), **539**, A79
- Sabatini, G., Bovino, S., Giannetti, A., et al. 2020, [A&A](#), **644**, A34
- Schilke, P., Pineau des Forêts, G., Walmsley, C. M., & Martín-Pintado, J. 2001, [A&A](#), **372**, 291
- Schneider, N., Bontemps, S., Simon, R., et al. 2006, [A&A](#), **458**, 855
- Schneider, N., Csengeri, T., Bontemps, S., et al. 2010, [A&A](#), **520**, A49
- Schneider, N., Bonne, L., Bontemps, S., et al. 2023, [Nat. Astron.](#), **7**, 546
- Schuller, F., Menten, K. M., Contreras, Y., et al. 2009, [A&A](#), **504**, 415
- Shirley, Y. L. 2015, [PASP](#), **127**, 299
- Skretas, I. M., Karska, A., Wyrowski, F., et al. 2023, [A&A](#), **679**, A66 (Paper II)
- Taniguchi, K., Rayalacheruvu, P., Yonetsu, T., et al. 2024, [ApJ](#), **963**, 12
- Tatematsu, K., Liu, T., Kim, G., et al. 2020, [ApJ](#), **895**, 119
- Tielens, A. 2021, [Molecular Astrophysics](#) (Cambridge University Press)
- Tiné, S., Roueff, E., Falgarone, E., Gerin, M., & Pineau des Forêts, G. 2000, [A&A](#), **356**, 1039
- Turner, B. E. 2001, [ApJS](#), **136**, 579
- van Dishoeck, E. F., Blake, G. A., Jansen, D. J., & Groesbeck, T. D. 1995, [ApJ](#), **447**, 760
- Vastel, C., Mookerjee, B., Pety, J., & Gerin, M. 2017, [A&A](#), **597**, A45
- Watson, W. D. 1974, [ApJ](#), **188**, 35
- Wilson, T. L., & Rood, R. 1994, [ARA&A](#), **32**, 191
- Wootten, A. 1987, in [Astrochemistry](#), eds. M. S. Vardya, & S. P. Tarafdar, [IAU Symp.](#), **120**, 311
- Yamagishi, M., Nishimura, A., Fujita, S., et al. 2018, [ApJS](#), **235**, 9
- Yan, Y. T., Henkel, C., Kobayashi, C., et al. 2023, [A&A](#), **670**, A98
- Yang, K., Wang, J., Qiu, K., & Zhang, T. 2024, [ApJS](#), **270**, 35

Appendix A: CASCADE emission maps

Velocity-integrated intensity maps of the strong and extended emission of the main isotopologs HCN and HNC can be seen in two leftmost panels of Fig. A.1. The emission in both species peak toward DR21 Main and DR21(OH). The intensity ratio between these two molecules is used for kinetic temperature determinations, as is described in Sect. 3.3.

The three right panels show the integrated intensity distributions of the three HCO HFS components of this molecule's $N_{K_a, K_c} = 1_{0,1} - 0_{0,0}$ rotational line. These are the $J = 3/2 - 1/2, F = 2 - 1, J = 3/2 - 1/2, F = 1 - 0$ and $J = 1/2 - 1/2, F = 1 - 1$ lines. Spectroscopic information for the HCO HFS lines is presented in Table A.1.

Spectroscopic information for the SiO (2 – 1) lines is presented in Table A.1. SiO (2–1) is covered as part of the CASCADE program. The integrated intensity map of SiO (2–1) is shown in Fig. 11.

Appendix B: Optical depth

The ^{12}C -bearing main isotopolog lines of the molecules studied by us are optically thick and even the opacities of the ^{13}C -bearing isotopologs are expected to be non-negligible. The determination of the optical depth of the lines from each molecule relies on the ratio of its ^{12}C -bearing isotopolog to its ^{13}C -bearing one. Under the assumption that the beam filling factor, f , of each pixel is equal for both lines, the ratio of the main beam brightness temperature of a line from the main isotopolog, $T_{\text{MB}}^{12\text{C}}$, to that of the less common ^{13}C -bearing isotopolog, $T_{\text{MB}}^{13\text{C}}$, is given by

$$\frac{T_{\text{MB}}^{12\text{C}}}{T_{\text{MB}}^{13\text{C}}}(v) = \frac{(T_{\text{ex}}^{12\text{C}} - T_{\text{bg}})(1 - \exp(-\tau_v^{12\text{C}}))}{(T_{\text{ex}}^{13\text{C}} - T_{\text{bg}})(1 - \exp(-\tau_v^{13\text{C}}))}, \quad (\text{B.1})$$

where T_{bg} is the temperature of the cosmic microwave background (2.73 K). Further assuming that the frequencies and the excitation temperatures, T_{ex} , of both lines are the same, results in an isotopic ratio of 68 for Cygnus-X (see Sect. 3.3) and the ^{13}C line being optically thin (so that $(1 - \exp(-\tau_v^{13\text{C}})) \approx \tau_v^{13\text{C}}$). This simplifies to

$$0 \approx \frac{1 - \exp(-68\tau_v^{13\text{C}})}{\tau_v^{13\text{C}}} - \frac{T_{\text{MB}}^{12\text{C}}}{T_{\text{MB}}^{13\text{C}}}(v). \quad (\text{B.2})$$

From the roots of this equation, we can determine $\tau_v^{13\text{C}}$ using the Python package `scipy.optimize.newton_krylov`. Fig. B.1 presents the pixel-by-pixel opacity map of the DR21 filament.

Appendix C: Column density maps

The distribution of the column densities derived in Sec. 3.3 is shown in Fig. C.1. The column densities were determined using the `scipy.optimize.curve_fit`, in which each fitting of Eq. 3 results in the best fit of N_u/g_u and the respective fit error. The column density maps for DCO^+ , DNC, and DCN, and the respective main isotopologs HCO^+ , HNC, and HCN are presented in Fig. C.1, with the relative error maps presented in Fig. C.2. The column density for the main isotopologs were calculated using the optically thin ^{13}C -isotopologs and assuming $^{12}\text{C}/^{13}\text{C} = 68$.

Appendix D: $N(\text{XD})/N(\text{YD})$

The dust temperature, H_2 column density and kinetic gas temperature dependence of the $N(\text{XD})/N(\text{YD})$ ratios are presented in Fig. D.1. The comparison of column density ratios with T_{dust} are presented in the left plots. Blue data points with T_{dust} below 22 K exhibit considerable temperature dependencies; $r = -0.61$ for $\log(N(\text{DCO}^+)/N(\text{DCN}))$ and $r = -0.56$ for $\log(N(\text{DCO}^+)/N(\text{DNC}))$. A negligible dependence on $\log(N(\text{DCN})/N(\text{DNC}))$ with temperature was found ($r = +0.46$). On the contrary, all three ratios show no correlation with dust temperature in the higher temperature regime ($22 \text{ K} \leq T_{\text{dust}} \leq 31 \text{ K}$). The Pearson correlation coefficients of the higher temperatures are $r = +0.14$ for $\log(N(\text{DCO}^+)/N(\text{DCN}))$, $r = +0.45$ for $\log(N(\text{DCO}^+)/N(\text{DNC}))$, and $r = +0.28$ for $\log(N(\text{DCN})/N(\text{DNC}))$ with $p > 0.05$.

The $N(\text{XD})/N(\text{YD})$ trends with H_2 column density are $r = -0.55$ for $\log(N(\text{DCO}^+)/N(\text{DCN}))$, $r = -0.69$ for $\log(N(\text{DCO}^+)/N(\text{DNC}))$ and $r = +0.12$ for $\log(N(\text{DCN})/N(\text{DNC}))$. This strong dependence is also reflected in the $R_D(\text{DCO}^+)$ and $R_D(\text{DNC})$ ratio seen in the top left and middle of Fig. 9, respectively. The strong anticorrelation of $R_D(\text{DCO}^+)$ is discussed further in Sect. 5.1.

$\log(N(\text{DCO}^+)/N(\text{DNC}))$ and $\log(N(\text{DCN})/N(\text{DNC}))$ show strong correlations with kinetic gas temperature. An anticorrelation with $\log(N(\text{DCO}^+)/N(\text{DNC}))$ is found, $r = -0.63$ and a negligible $r = -0.48$ with $\log(N(\text{DCO}^+)/N(\text{DCN}))$. On the contrary, a positive correlation is found between $\log(N(\text{DCN})/N(\text{DNC}))$ with a Pearson correlation coefficient of $r = +0.66$. It should be noted that the kinetic gas temperature was used to determine the column densities. This reflects on the formation pathway dependencies on temperature, in which the production of DCO^+ is highest at the lowest temperature, less for DNC, and least for DCN.

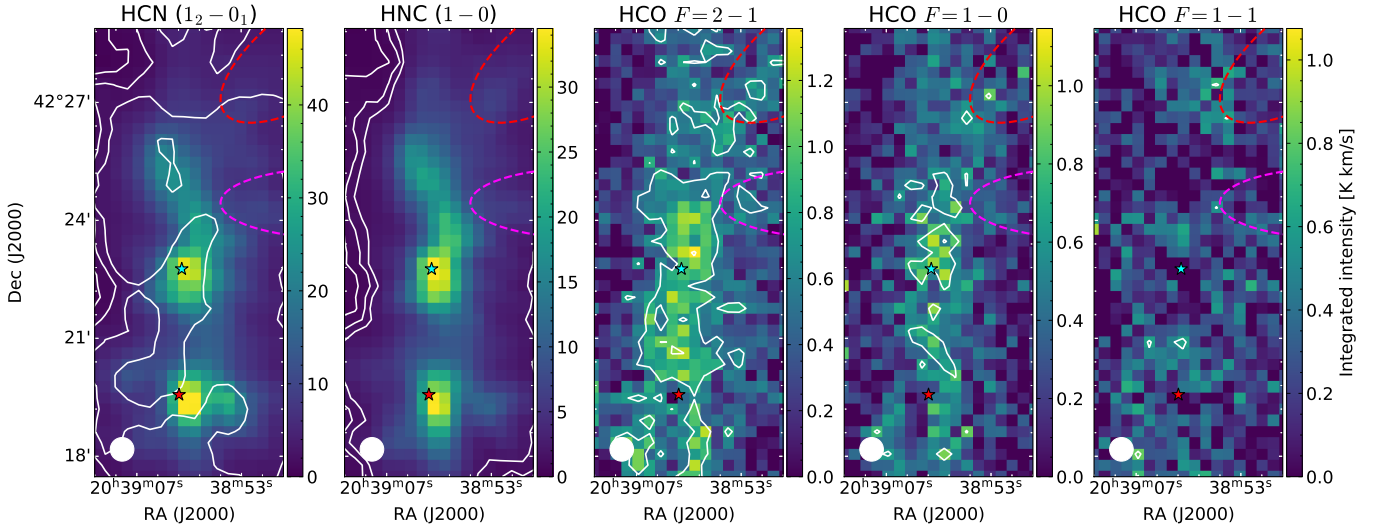


Fig. A.1: Ground-state emission of HCN, HNC, and HCO observed with the CASCADE program. The white contours show the 4σ , 8σ , and 12σ levels. The stars show DR21 Main (red) and DR21(OH) (blue), with the F1 and F3 sub-filaments marked in dashed red and magenta curves.

Table A.1: Spectroscopic information for the HCO and SiO lines covered by CASCADE.

Species	Transition	Frequency [MHz]	E_{up}/k [K]	A_{ij} [s ⁻¹]	g_{up}	Database
HCO	$N_{K_a, K_c} = 1_{0,1} - 0_{0,0}, J = 3/2 - 1/2, F = 2 - 1$	86670.76	4.18	4.67(-06)	5	JPL
HCO	$N_{K_a, K_c} = 1_{0,1} - 0_{0,0}, J = 3/2 - 1/2, F = 1 - 0$	86708.36	4.16	4.60(-06)	3	JPL
HCO	$N_{K_a, K_c} = 1_{0,1} - 0_{0,0}, J = 1/2 - 1/2, F = 1 - 1$	86777.46	4.18	4.60(-06)	3	JPL
SiO, v=0-10	2 - 1	86846.985	6.25	2.93(-05)	5	CDMS

Notes. The frequency, upper energy (E_{up}/k), Einstein coefficient (A_{ij}) and upper state degeneracy (g_{up}) are marked. The values for A_{ij} are written in the form of $x(-a) = x \times 10^{-a}$. The molecular are properties are from the JPL (Pickett et al. 1998) and CDMS (Müller et al. 2001) spectroscopic catalogues, as noted.

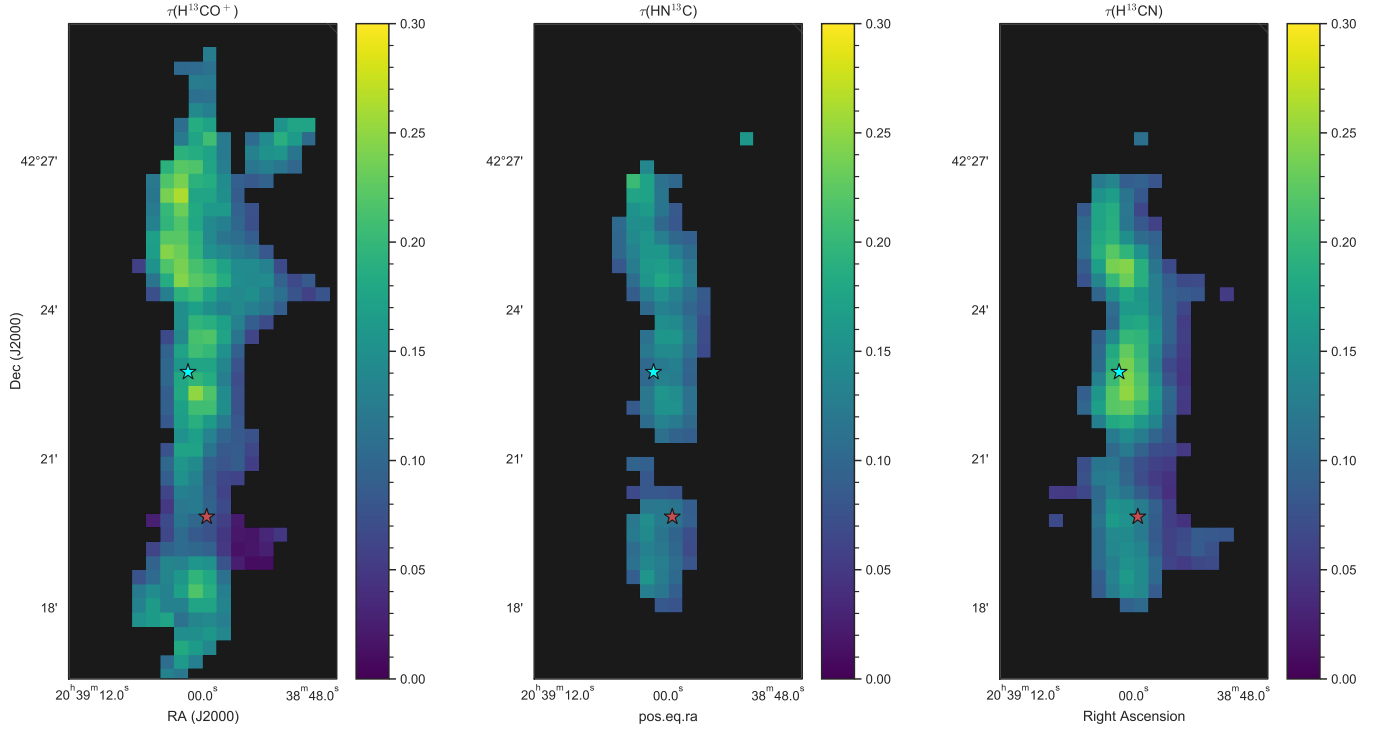


Fig. B.1: Left to right: Opacity maps of H^{13}CO^+ , HN^{13}C and H^{13}CN . The stars mark the positions of DR21 Main (red) and DR21(OH) (blue).

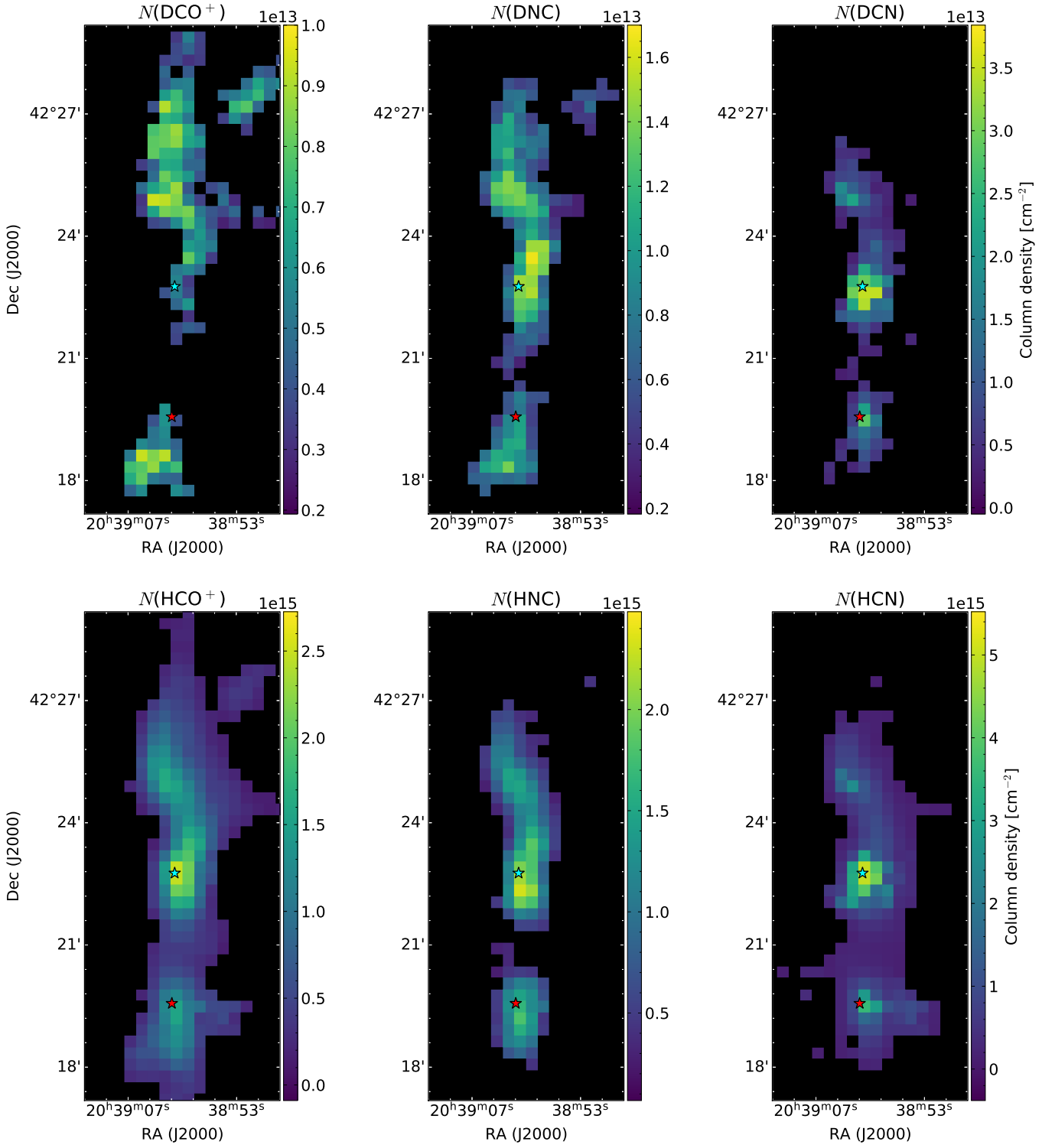


Fig. C.1: Top panel, left to right: Column density distribution maps of DCO^+ , DNC , and DCN and their main isotopologs HCO^+ , HNC , and HCN (bottom panel). The stars mark the positions of DR21 Main (red) and DR21(OH) (blue).

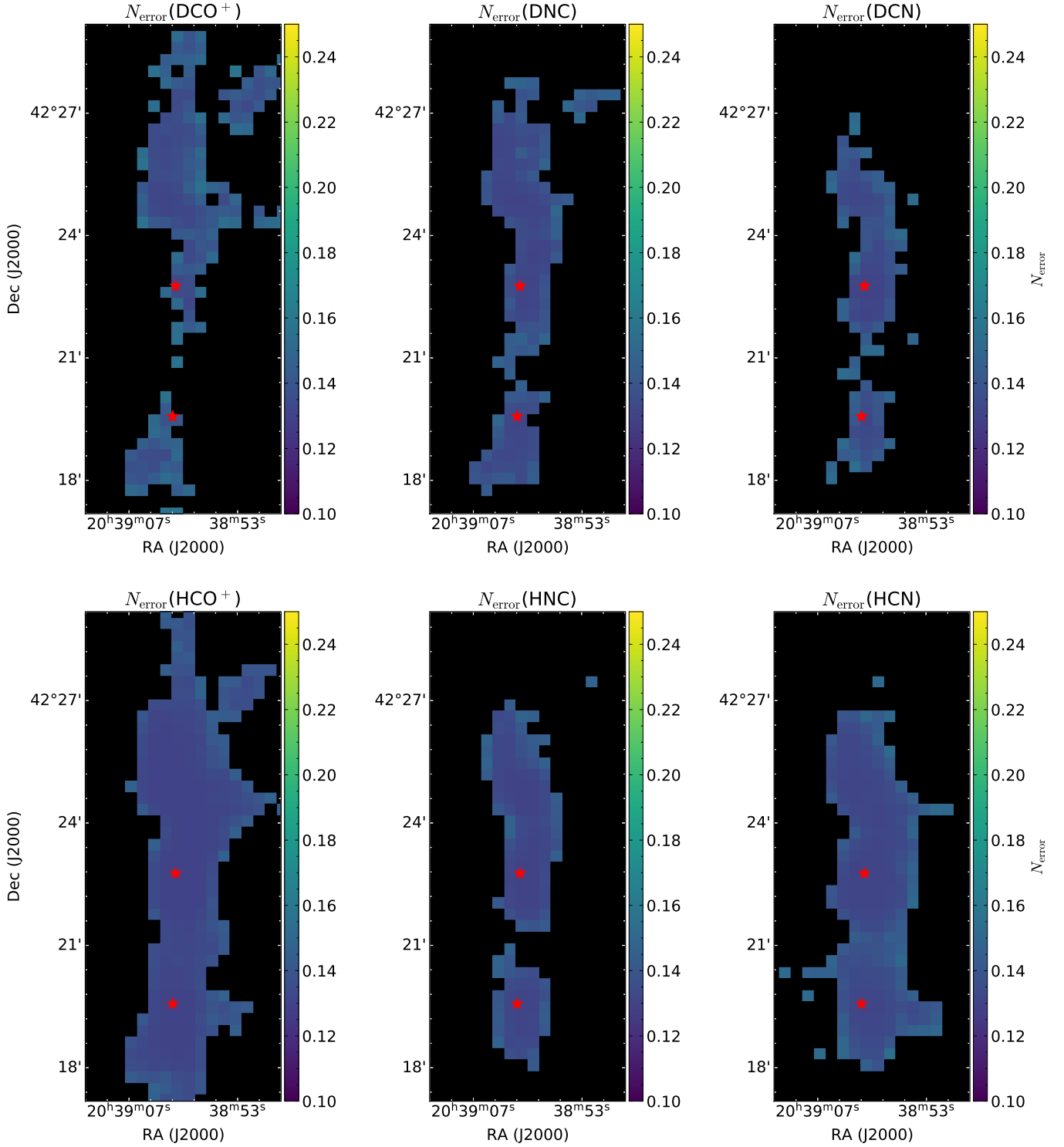


Fig. C.2: Top panel, left to right: Relative column density error distributions for DCO^+ , DNC , and DCN and their main isotopologs HCO^+ , HNC , and HCN (bottom panel). The stars mark the positions of DR21 Main (red) and DR21(OH) (blue).

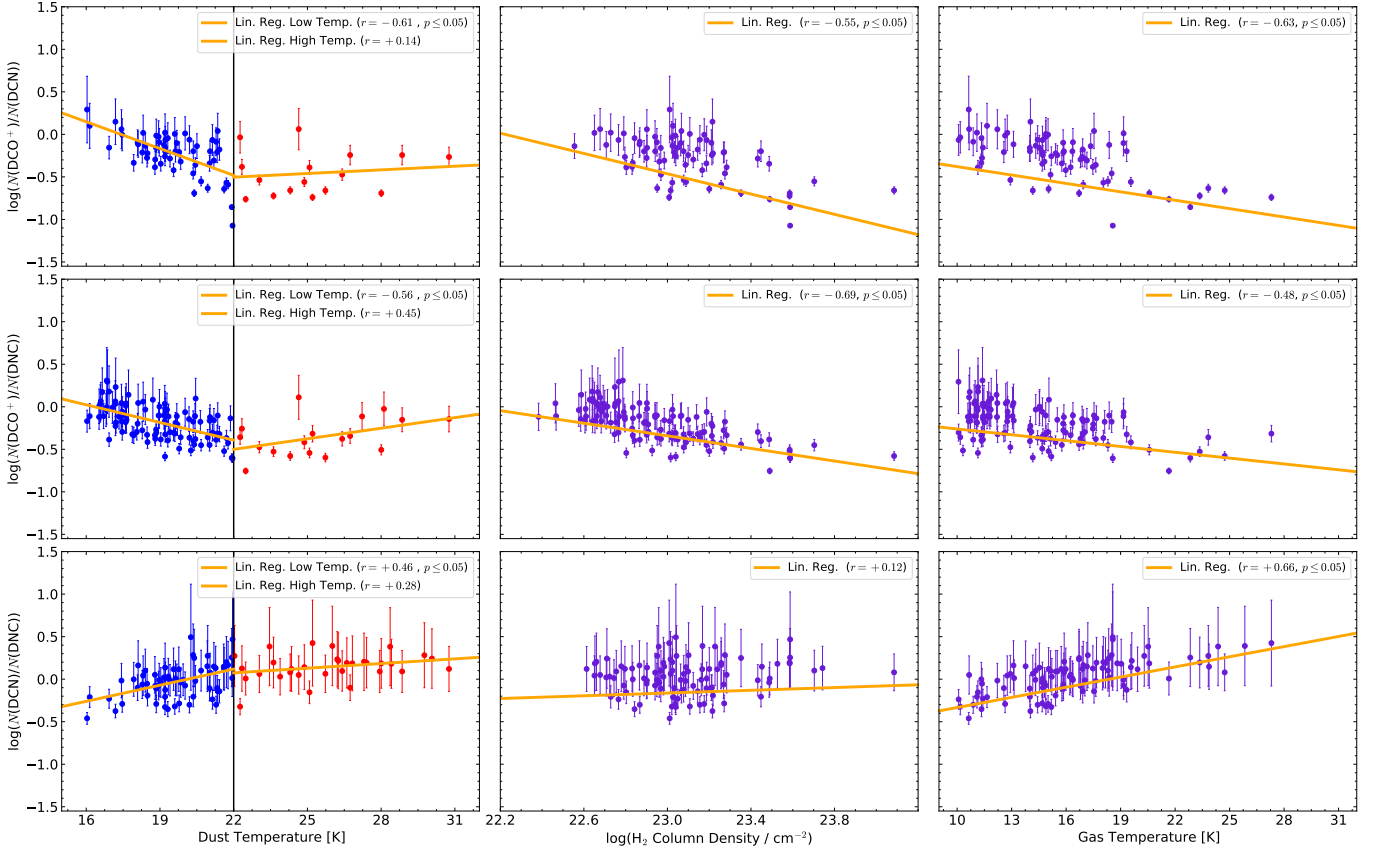


Fig. D.1: Deuterated molecular ratios with respect to the dust temperature (left) and column density (center) and kinetic gas temperature (right) of $N(\text{DCO}^+)/N(\text{DCN})$ (top), $N(\text{DCO}^+)/N(\text{DNC})$ (middle) and $N(\text{DCN})/N(\text{DNC})$ (bottom). An onset of CO sublimation from grains is expected from $T_{\text{dust}} \sim 22$ K, with blue data points showing the CO freeze-out regime.

Clumps in Cygnus-X

Motte et al. (2007) and Cao et al. (2019) identified several star-forming clumps in Cygnus-X. Motte et al. (2007) mapped the Cygnus-X region at wavelength of 1.2-mm using the MAMBO and MAMBO-2 cameras on IRAM-30m. The cloud complex is probed at densities of $N_{\text{H}_2} \sim 9 \times 10^{21} - 2 \times 10^{24} \text{ cm}^{-2}$. The clumps are identified by analyzing compact cloud fragmentation ($< 1 \text{ pc}$) using MAMBO-2, where a 2-D Gaussian fit identifies the compact fragments above a 5σ -level with Gaussclumps and improves the extraction to avoid biased Gaussian fits. 129 dense cores using the IRAM-30m telescope at 1.2-mm wavelength band are detected, where 66 of these are within the CASCADE. The clumps in the Cao et al., 2019 catalog are identified using the 8 and $24 \mu\text{m}$ images from the Spitzer Legacy Survey of the Cygnus-X region, the mosaics from 70, 160, 250, 350 and $500 \mu\text{m}$ from Herschel telescope and 1.2 mm with the IRAM 30-m telescope. The clump extraction focuses on regions where the $N_{\text{H}_2} \geq 3.5 \times 10^{22} \text{ cm}^{-2}$, ensuring that the cores have masses of $M \geq 23.3 M_{\odot}$ at 0.1 pc. Furthermore, a lower limit of $M \geq 35 M_{\odot}$, associated with either observational HMSF-signature of Class II methanol masers or UCHII regions, is set. This results in 151 massive dense cores detected, where 60 are detected with CASCADE. 16 clumps of Cao et al., 2019 are not identified in the Motte et al., 2007 catalog and added to the complete list of clumps. A total of 82 individual clumps are identified by Motte et al., 2007 and Cao et al., 2019 covered by the CASCADE observations.

A total of 72 clumps are targeted for follow-up observations with the APEX telescope (Chapter 5). These 72 clumps were chosen as they have at least one of DCO^+ , DNC, DCN, or NH_2D detected. Of these 72 clumps, we determined the physical conditions of 67 clumps and analyzed them further in Chapter 6. The line profiles, including the central position, are summarized below. The line profiles of H_2CO are presented in Appendix C.

The spectra for the molecules listed in Chapter 6 are shown below. The spectra for H_2CO ($1_{0,1} - 0_{0,0}$), H_2CO ($3_{0,3} - 2_{0,2}$), H_2CO ($3_{2,2} - 2_{2,1}$), and H_2CO ($3_{2,1} - 2_{2,0}$) are shown in Appendix D.1.

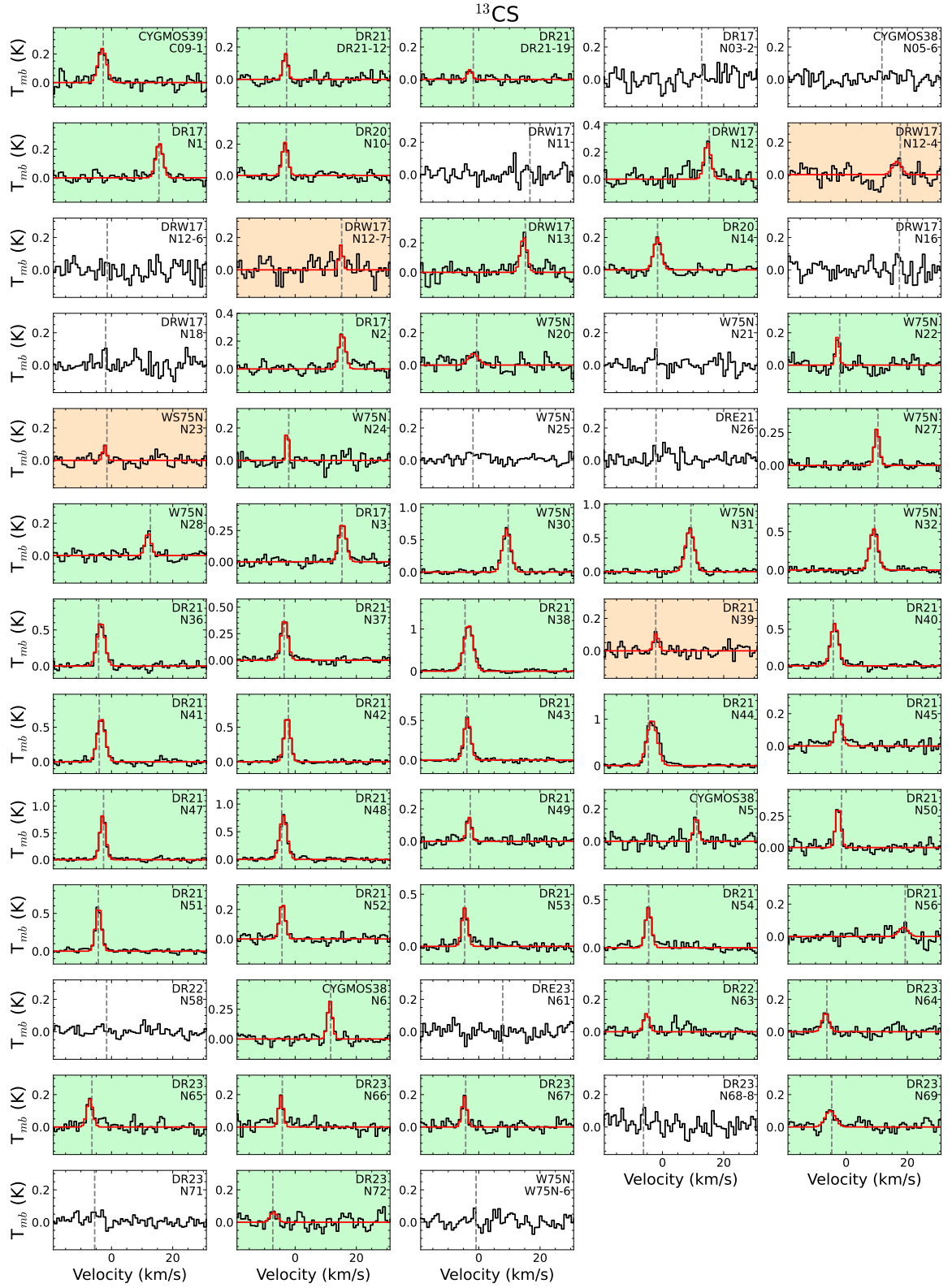


Figure B.1: Spectra of ^{13}CS $J = 2 - 1$ towards the Cygnus-X sources. The green background indicated detection ($> 4\sigma$) and white background indicates no detection.

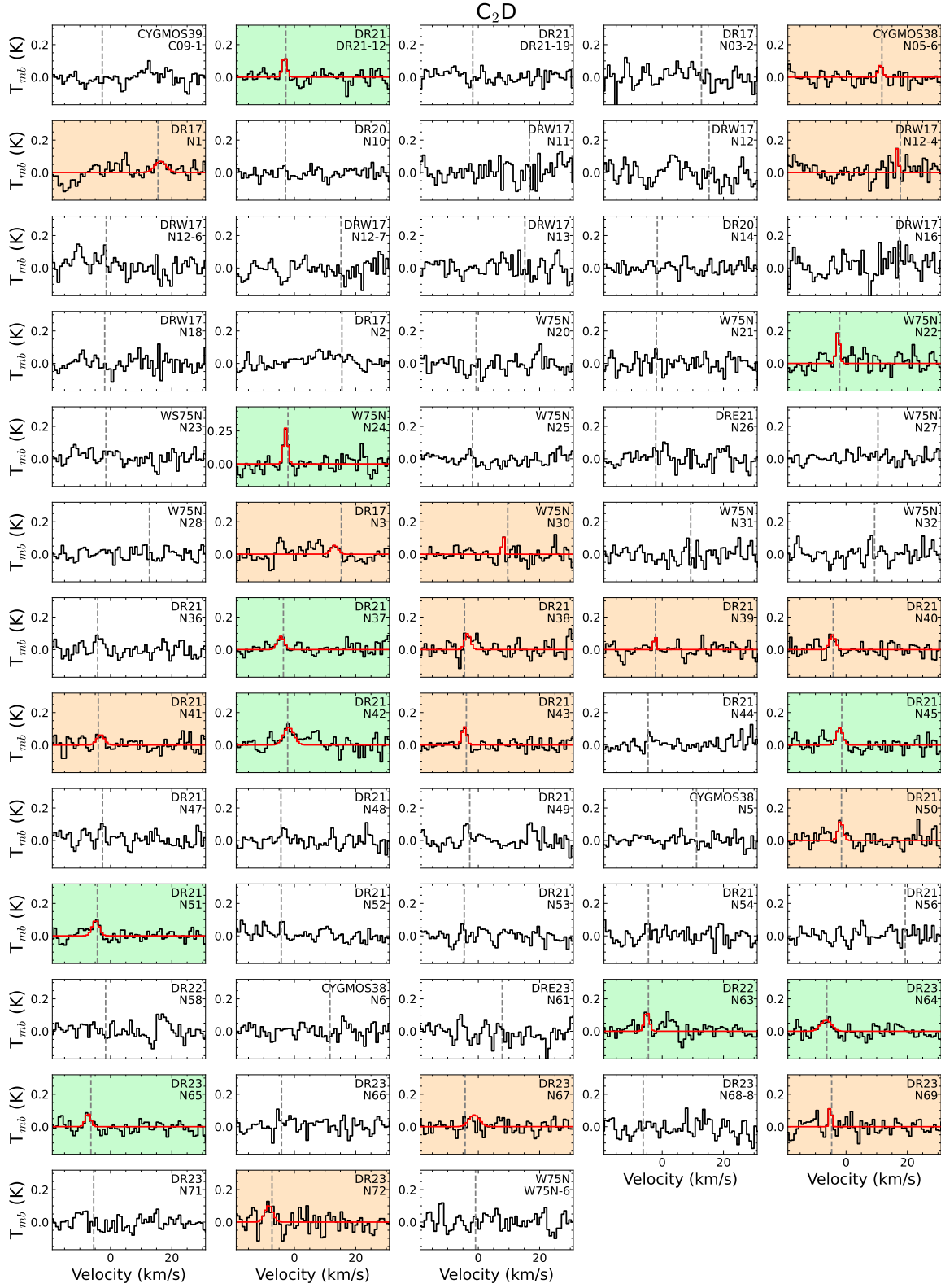


Figure B.2: Same as Fig. B.1 for C_2D $N = 1 - 0$, $J = 3/2 - 1/2$, $F = 5/2 - 3/2^*$ towards the Cygnus-X sources.

Appendix B Clumps in Cygnus-X

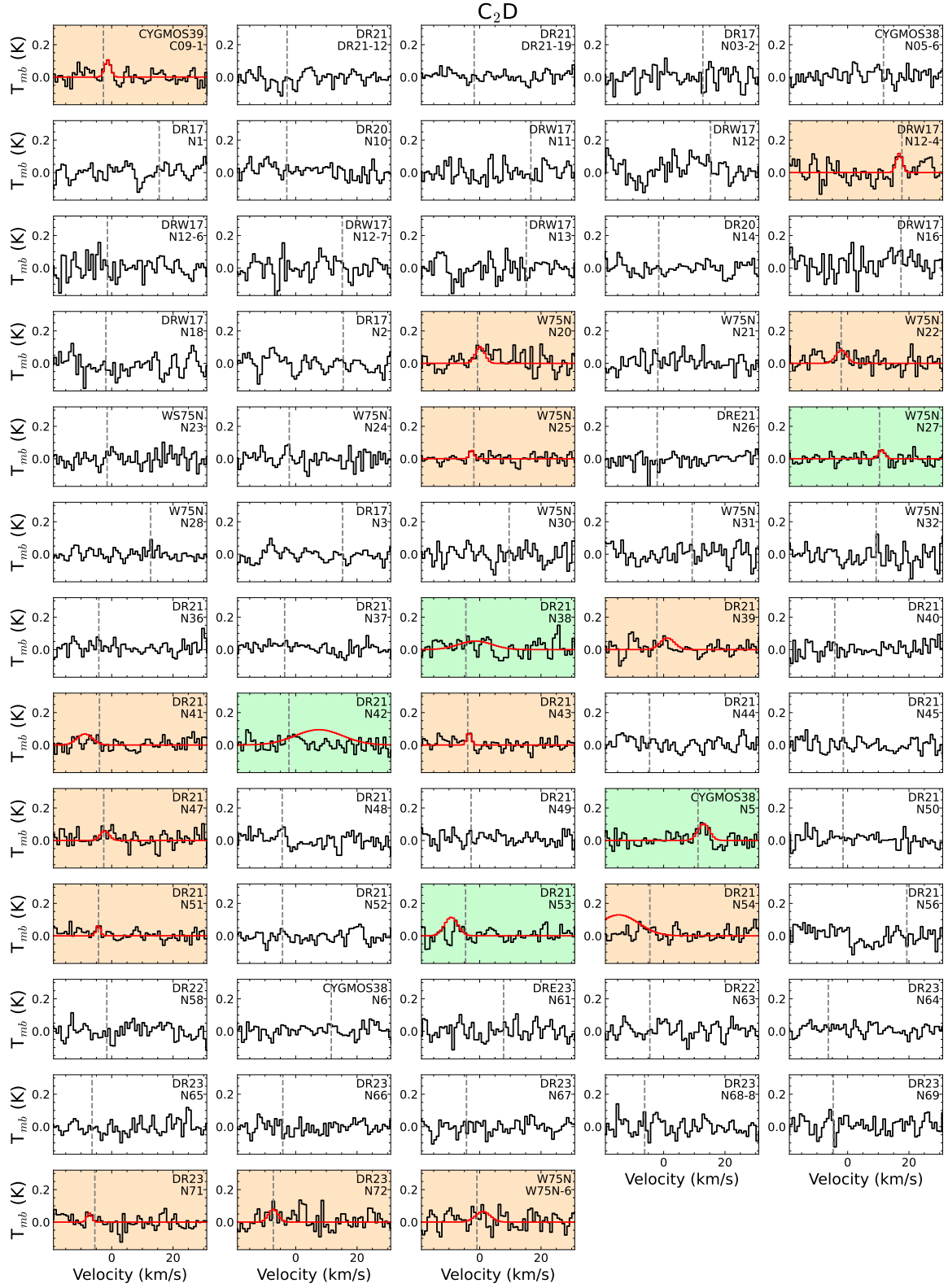
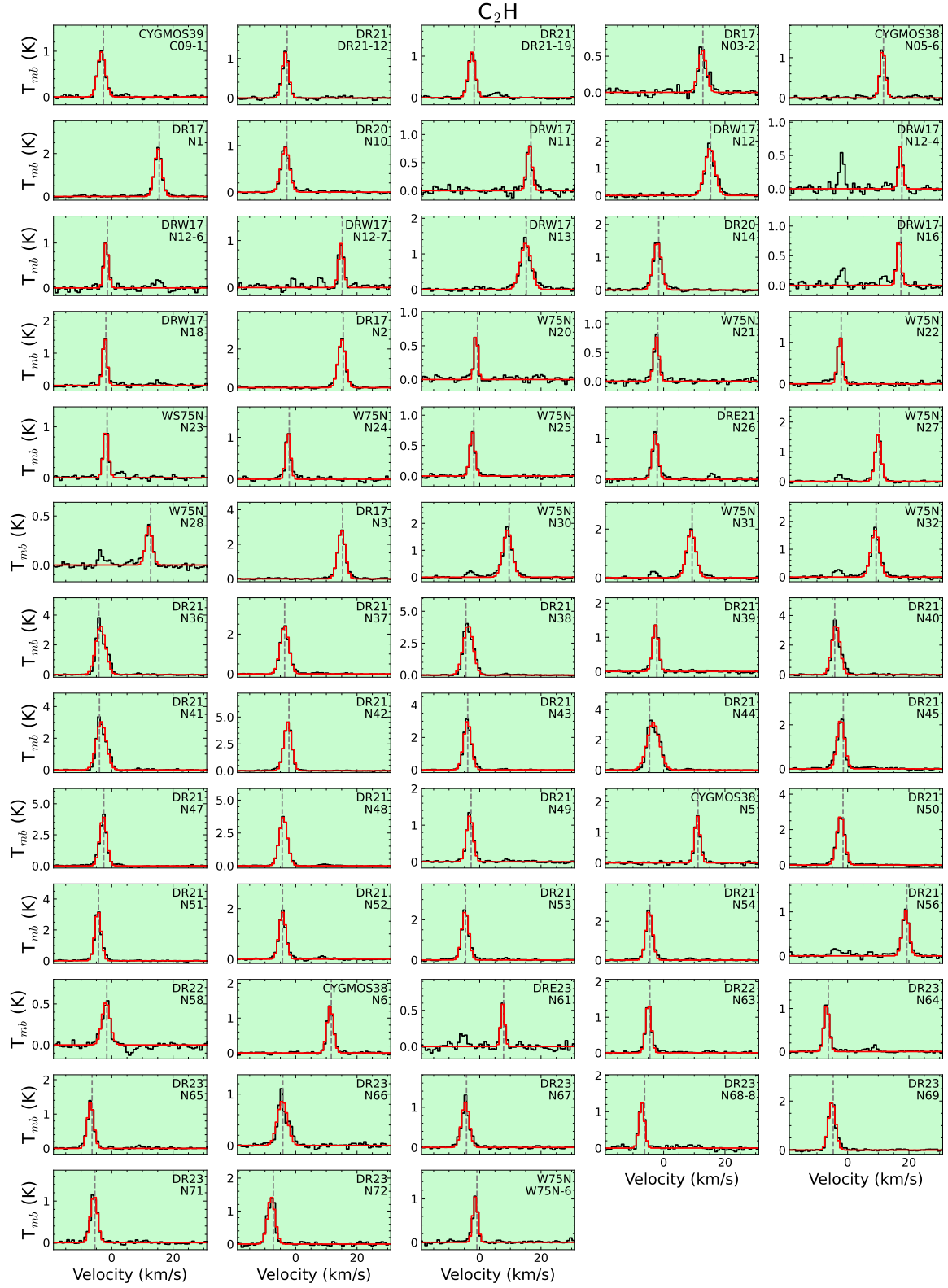


Figure B.3: Same as Fig. B.1 for C_2D $N=1-0$, $J=1/2-1/2$, $F=3/2-3/2^*$ towards the Cygnus-X sources.



Figure B.4: Same as Fig. B.1 for C_2H $N = 1 - 0, J = 3/2 - 1/2, F = 1 - 1^*$ towards the Cygnus-X sources.


 Figure B.5: Same as Fig. B.1 for C_2H $N = 1 - 0$, $J = 3/2 - 1/2$, $F = 2 - 1^*$ towards the Cygnus-X sources.

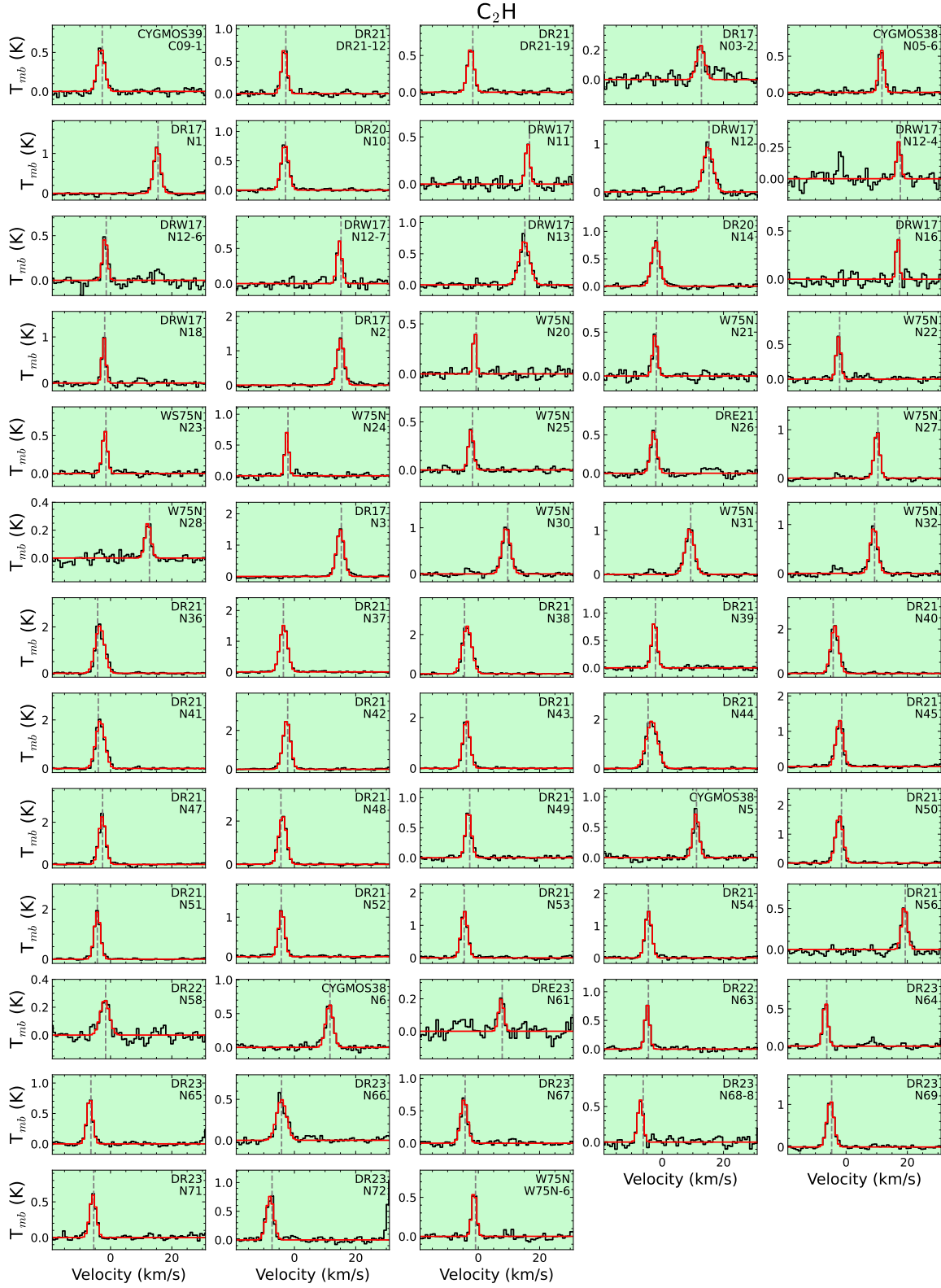
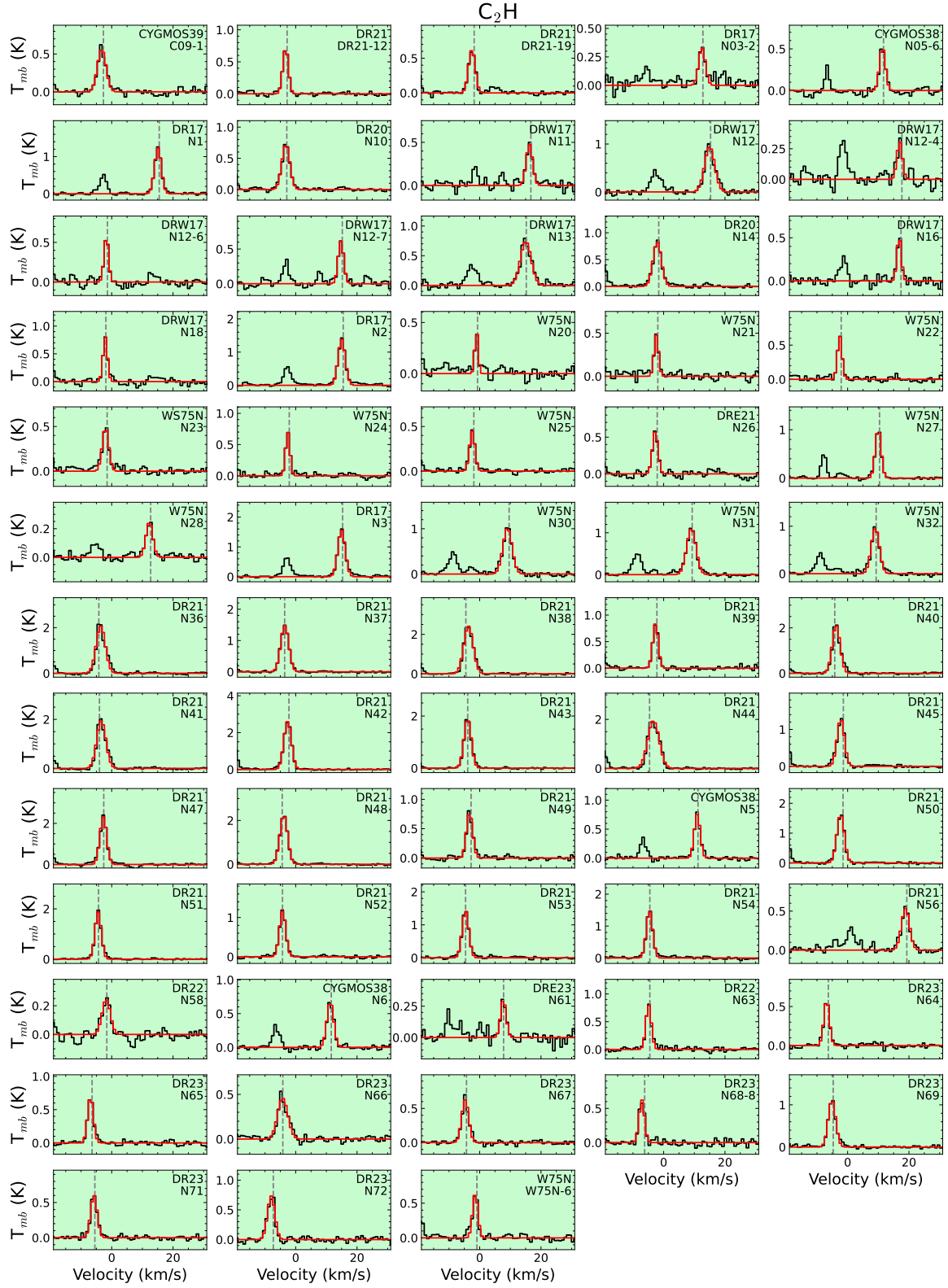


Figure B.6: Same as Fig. B.1 for C_2H $N=1-0$, $J=3/2-1/2$, $F=1-0^*$ towards the Cygnus-X sources.


 Figure B.7: Same as Fig. B.1 for C_2H $N=1-0$, $J=1/2-1/2$, $F=1-1^*$ towards the Cygnus-X sources.

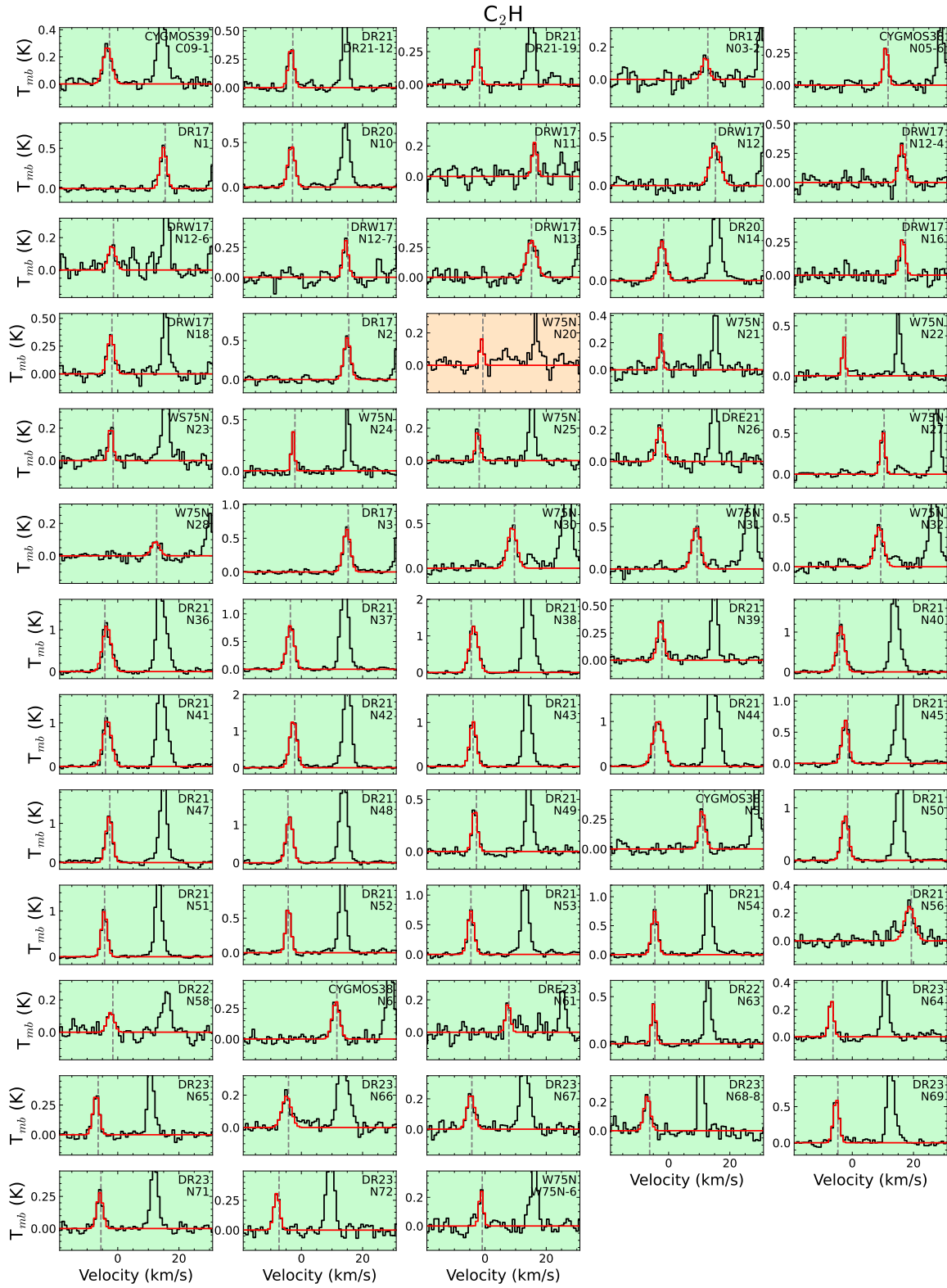


Figure B.8: Same as Fig. B.1 for C_2H $N=1-0$, $J=1/2-1/2$, $F=0-1^*$ towards the Cygnus-X sources.


 Figure B.9: Same as Fig. B.1 for C_2H $N=1-0$, $J=1/2-1/2$, $F=1-0^*$ towards the Cygnus-X sources.

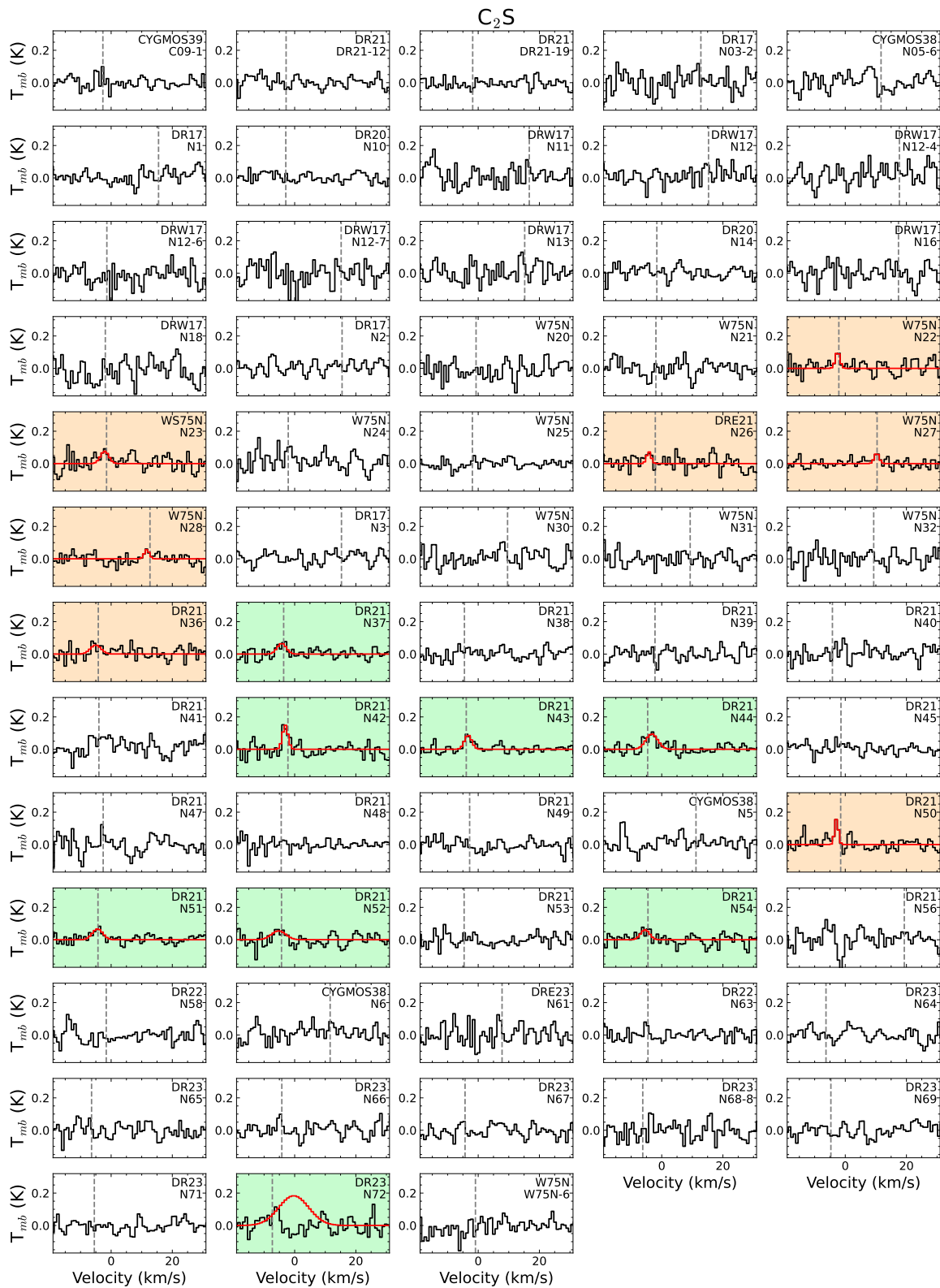


Figure B.10: Same as Fig. B.1 for $\text{C}_2\text{S } N = 6 - 5, J = 5 - 4$ towards the Cygnus-X sources.

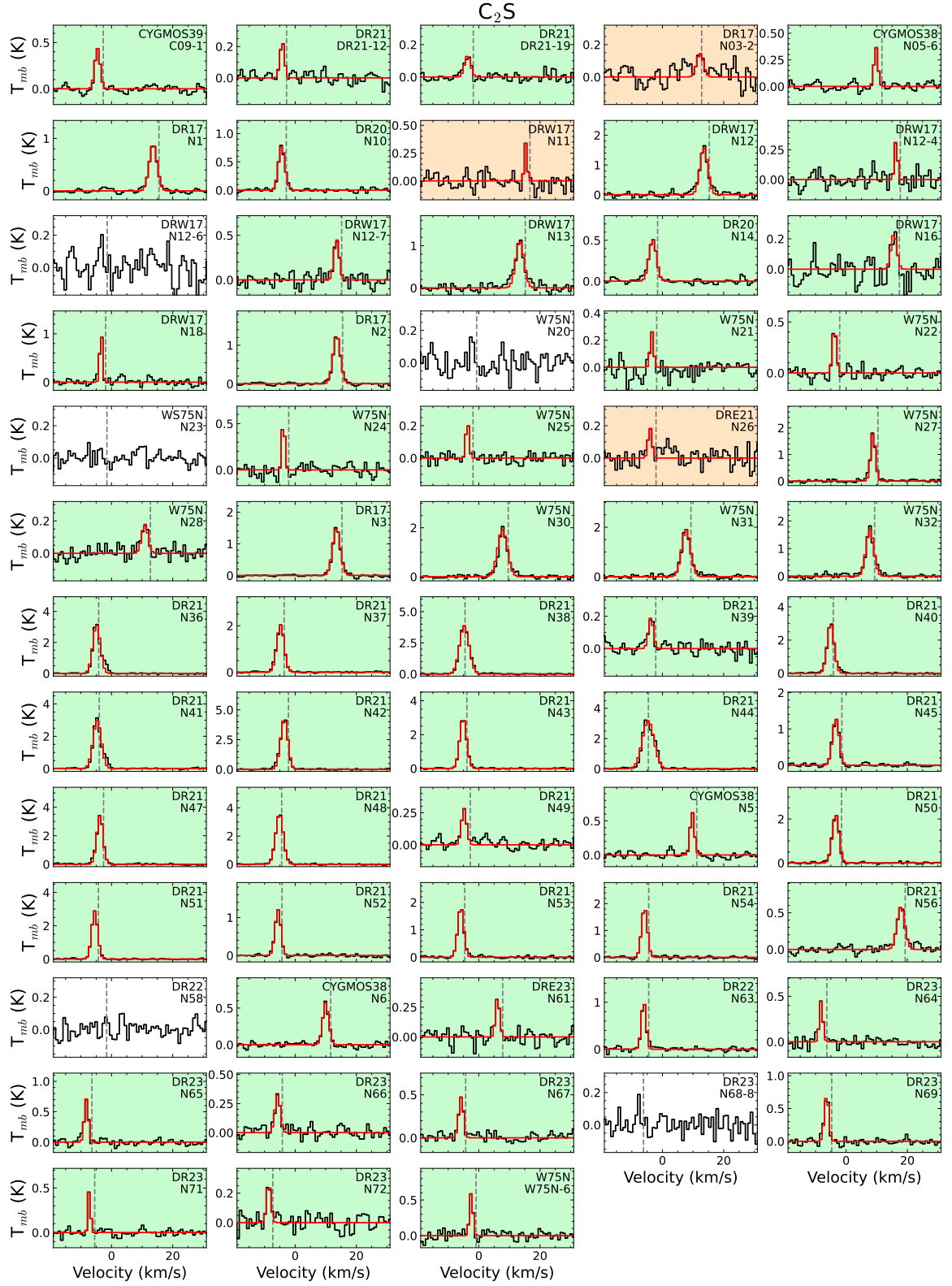

 Figure B.11: Same as Fig. B.1 for C_2S $N = 11 - 10$, $J = 10 - 10$ towards the Cygnus-X sources.



Figure B.12: Same as Fig. B.1 for $\text{CH}_3\text{CN } J = 4(1) - 3(1)$ towards the Cygnus-X sources.


 Figure B.13: Same as Fig. B.1 for CH₃CN $J = 4(0) - 3(0)$ towards the Cygnus-X sources.

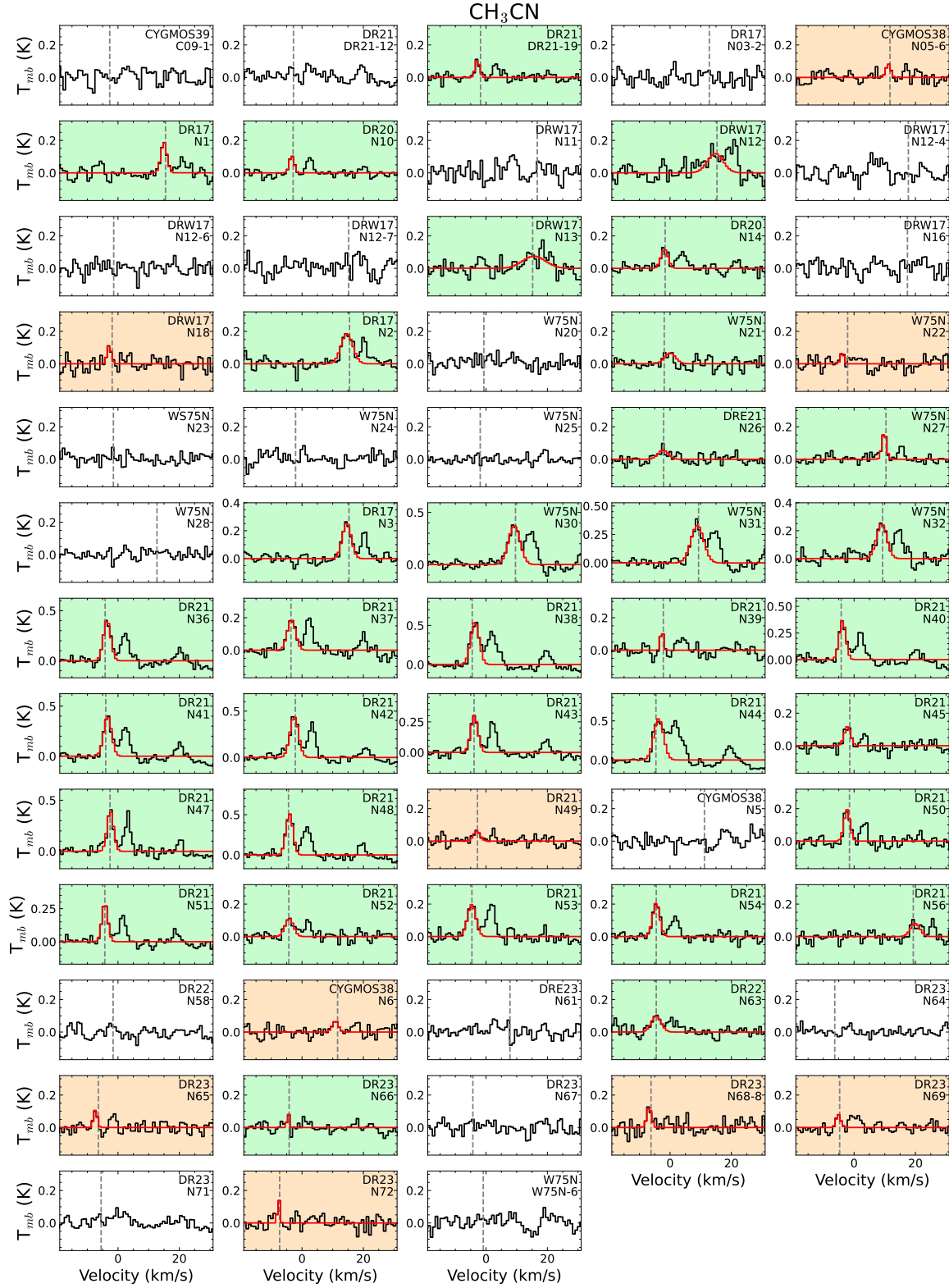
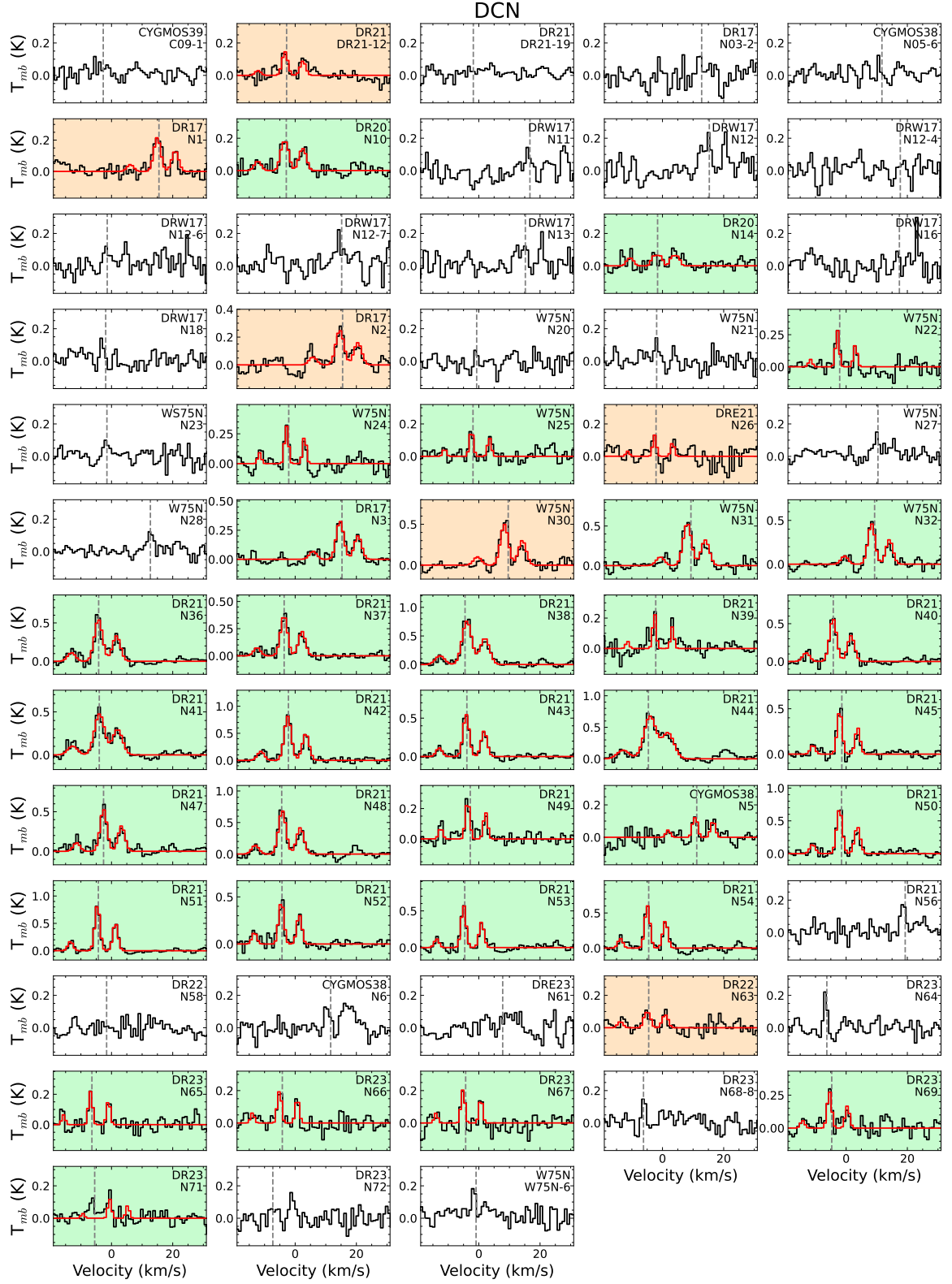


Figure B.14: Same as Fig. B.1 for CH_3CN $J = 5(0) - 4(0)$ towards the Cygnus-X sources.


 Figure B.15: Same as Fig. B.1 for DCN $J = 1 - 0$ towards the Cygnus-X sources.

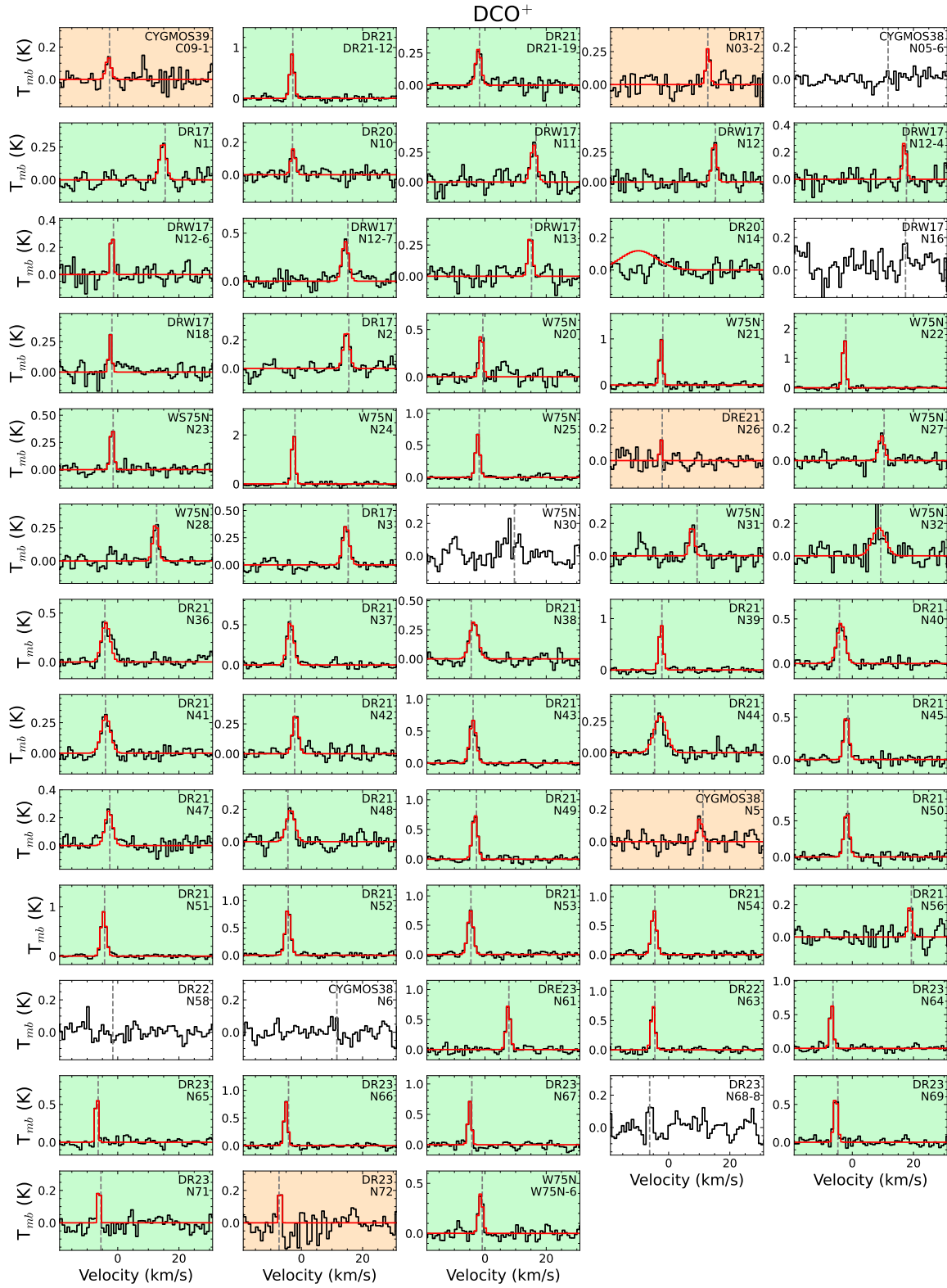
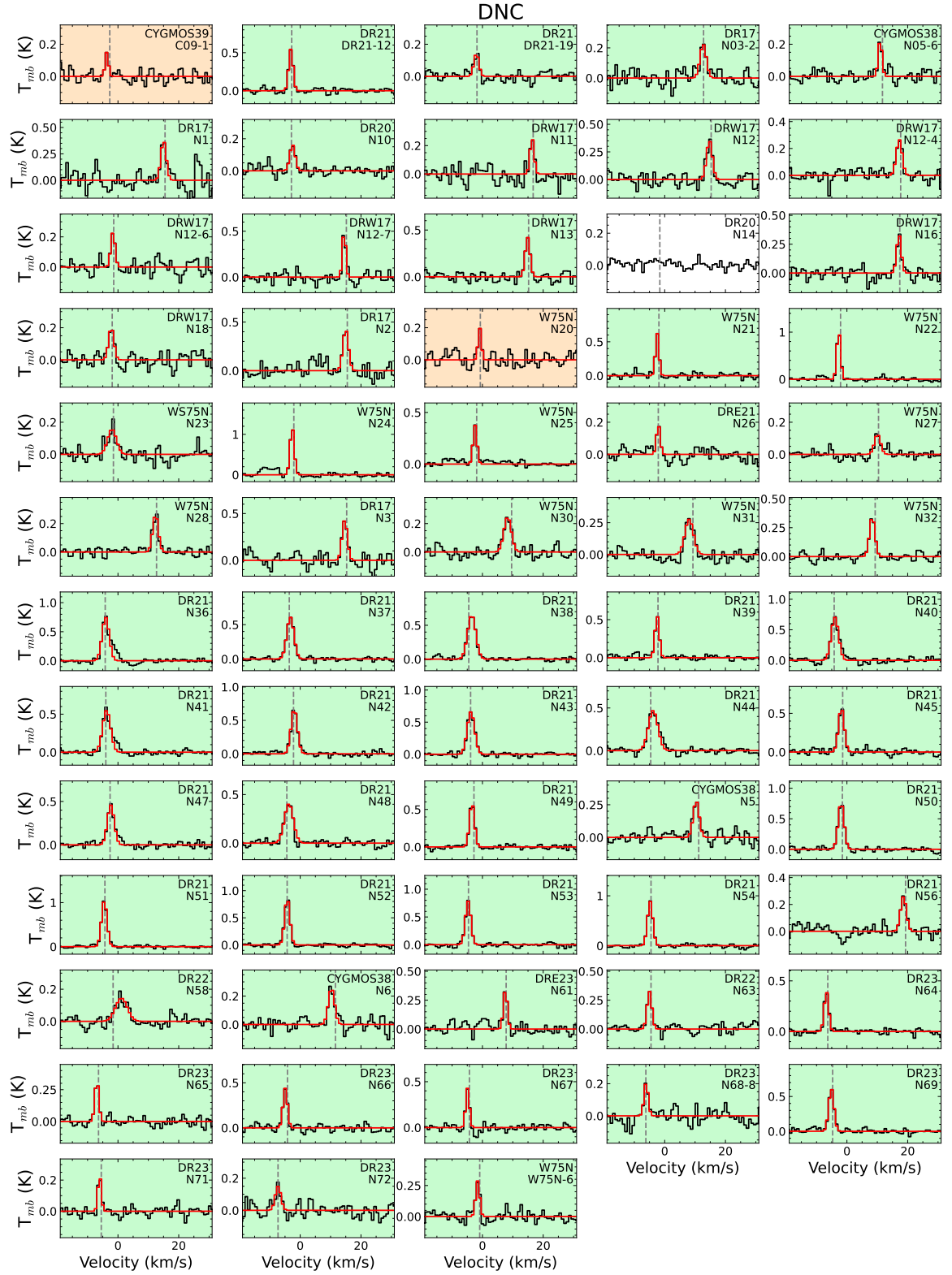


Figure B.16: Same as Fig. B.1 for DCO^+ $J=1-0$, $F=1-1$ towards the Cygnus-X sources.


 Figure B.17: Same as Fig. B.1 for DNC $J = 1 - 0$ towards the Cygnus-X sources.

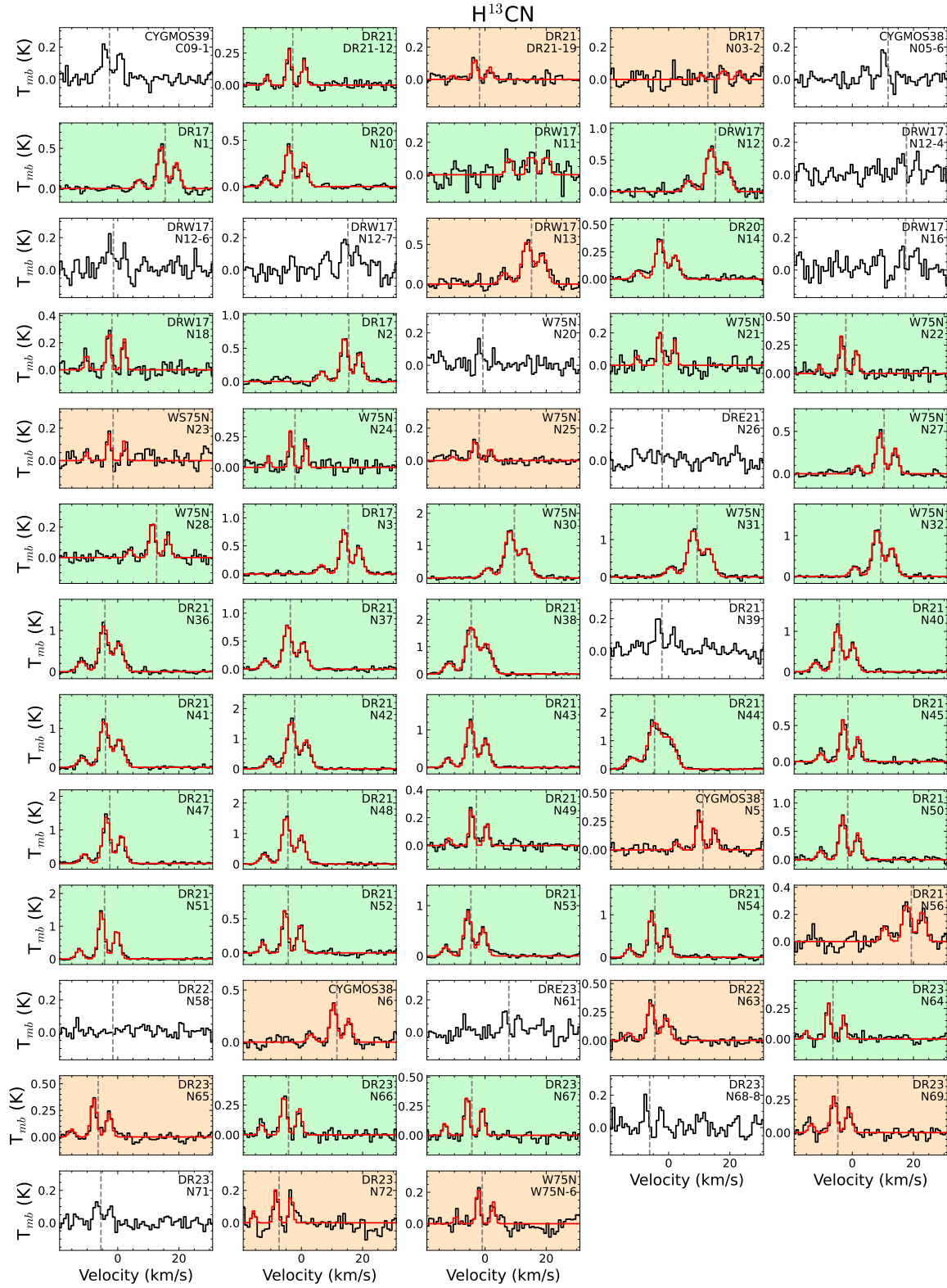
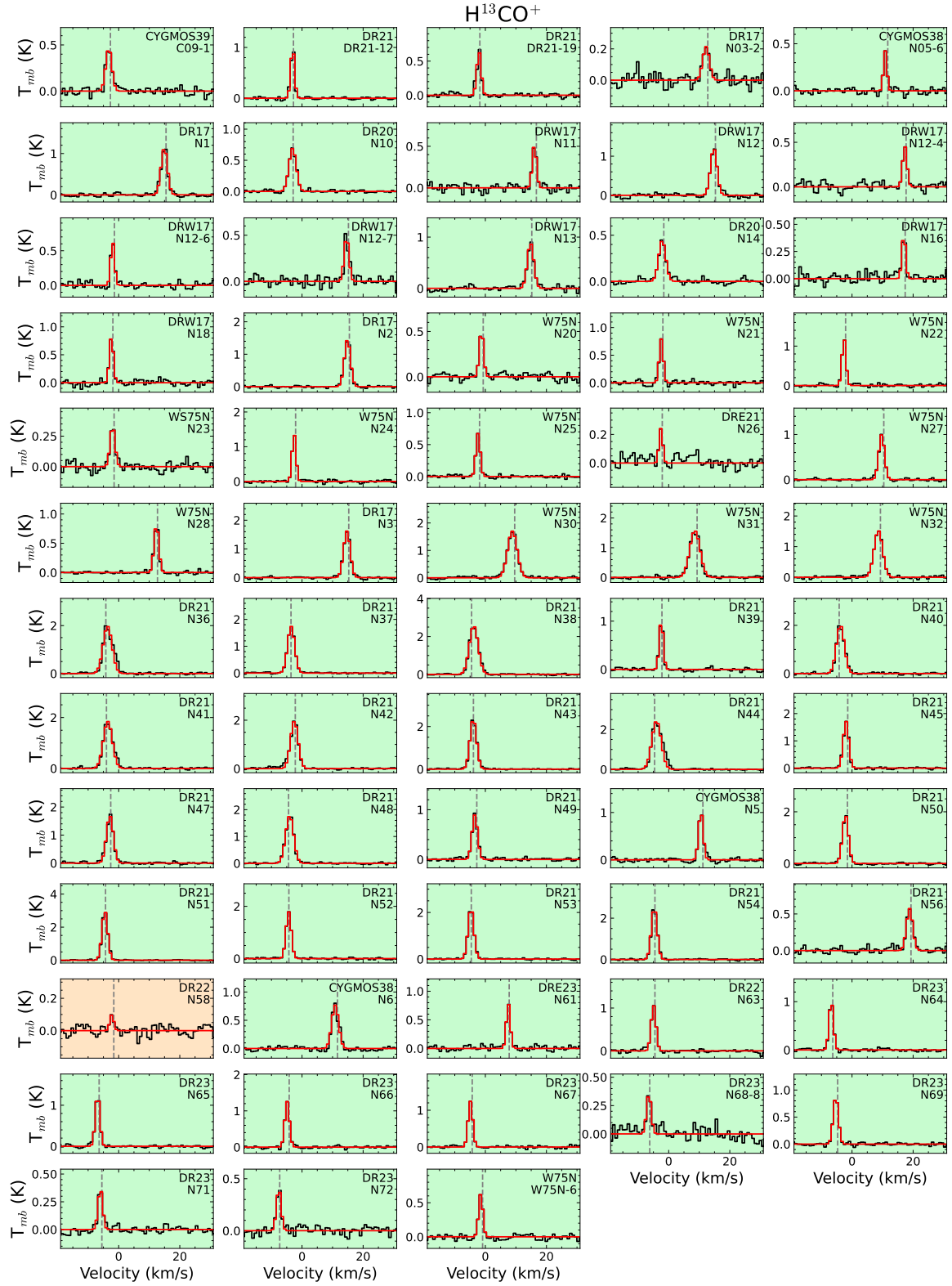


Figure B.18: Same as Fig. B.1 for H^{13}CN $J = 1 - 0$ towards the Cygnus-X sources.


 Figure B.19: Same as Fig. B.1 for $\text{H}^{13}\text{CO}^+ J = 1 - 0$ towards the Cygnus-X sources.

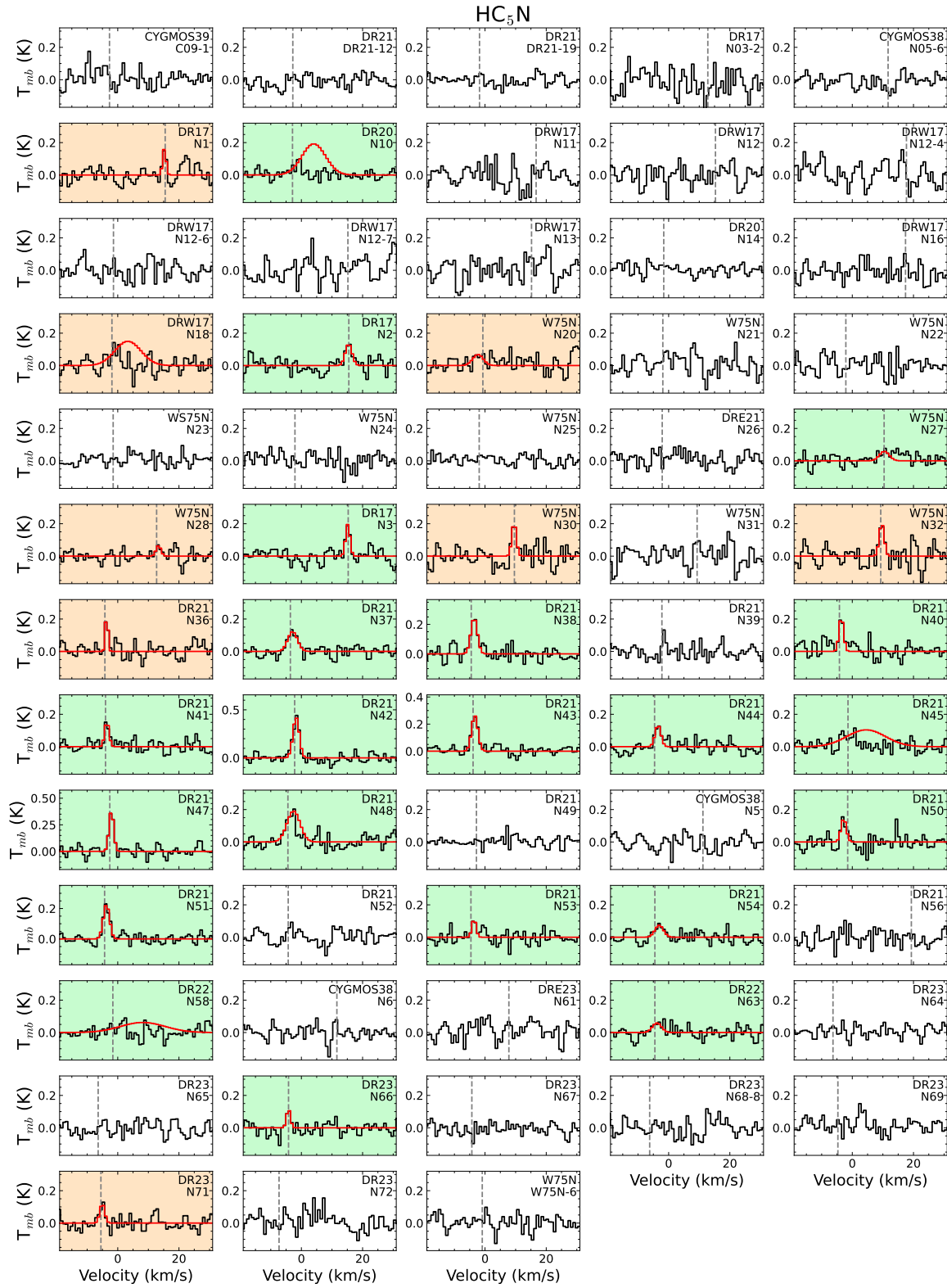


Figure B.20: Same as Fig. B.1 for HC_5N $J = 27 - 26$ towards the Cygnus-X sources.

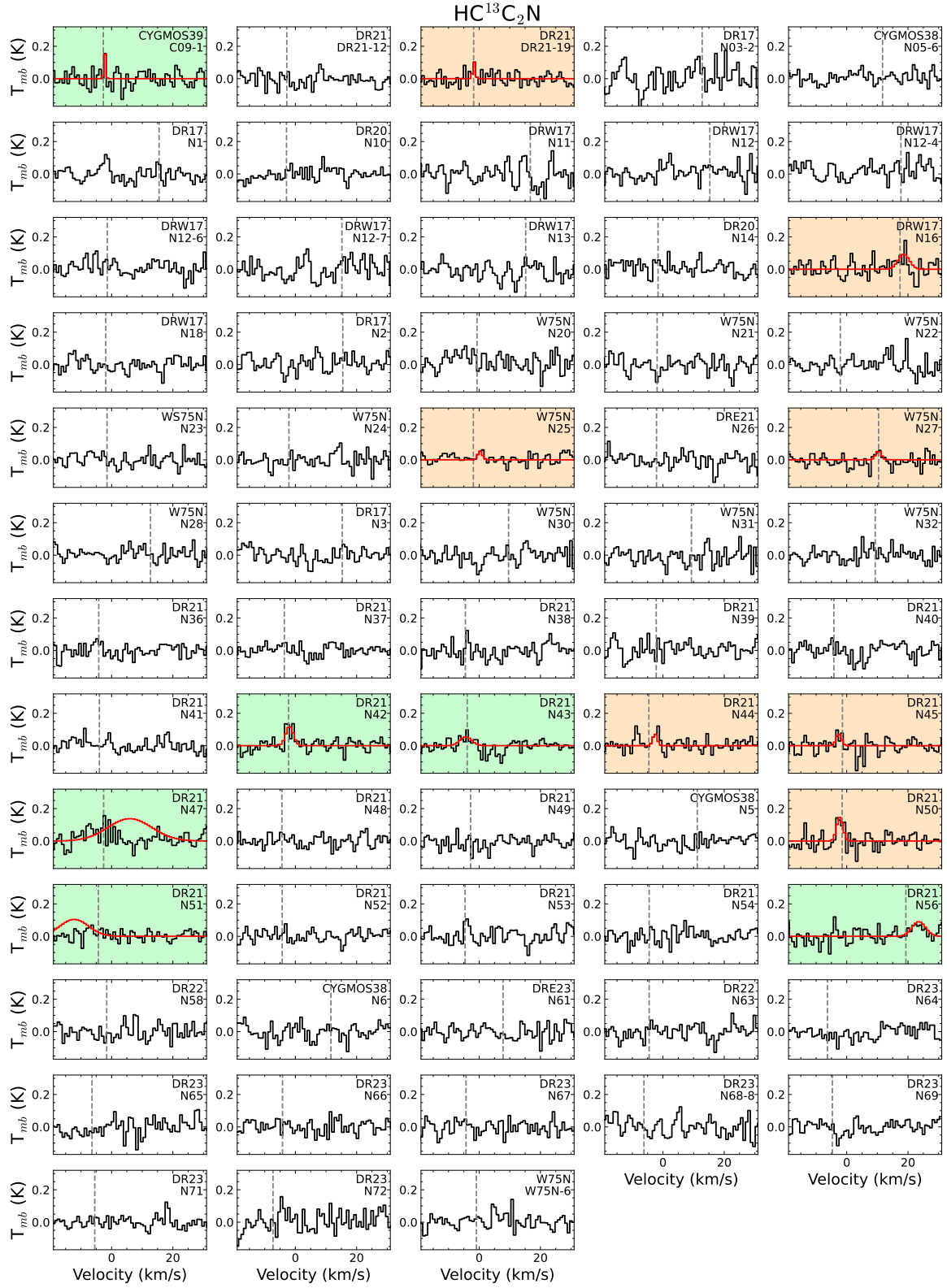

 Figure B.21: Same as Fig. B.1 for $\text{HC}^{13}\text{CCN } J = 8 - 7, F = 8 - 7$ towards the Cygnus-X sources.



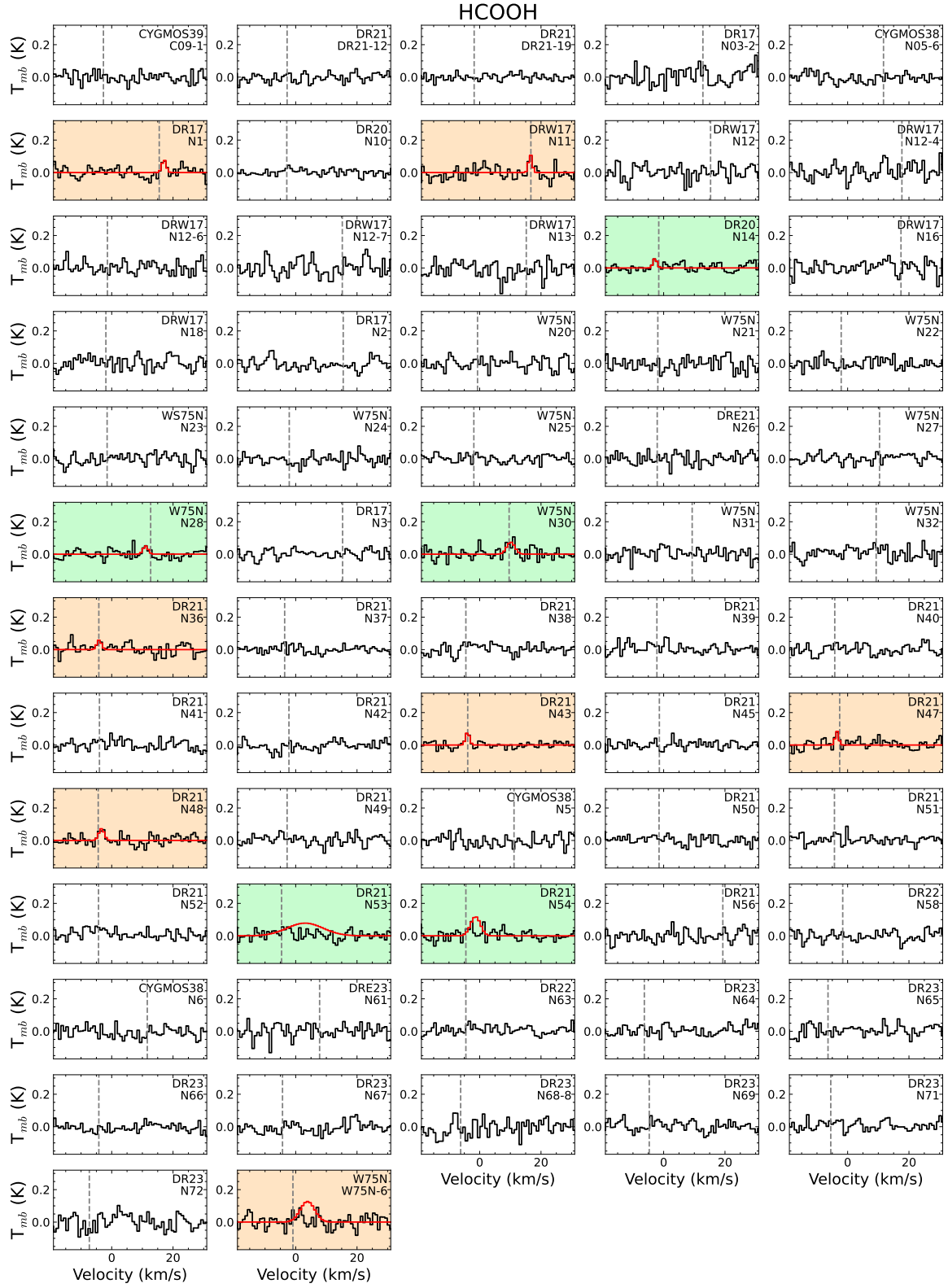
Figure B.22: Same as Fig. B.1 for HCO $1(0,1) - 0(0,0)$, $J = 3/2 - 1/2$, $F = 2 - 1^*$ towards the Cygnus-X sources.



Figure B.23: Same as Fig. B.1 for HCO $1(0,1) - 0(0,0)$, $J = 3/2 - 1/2$, $F = 1 - 0^*$ towards the Cygnus-X sources.



Figure B.24: Same as Fig. B.1 for HCO $1(0,1) - 0(0,0)$, $J = 1/2 - 1/2$, $F = 1 - 1^*$ towards the Cygnus-X sources.


 Figure B.25: Same as Fig. B.1 for HCOOH $J = 4(1, 4) - 3(1, 3)$ towards the Cygnus-X sources.

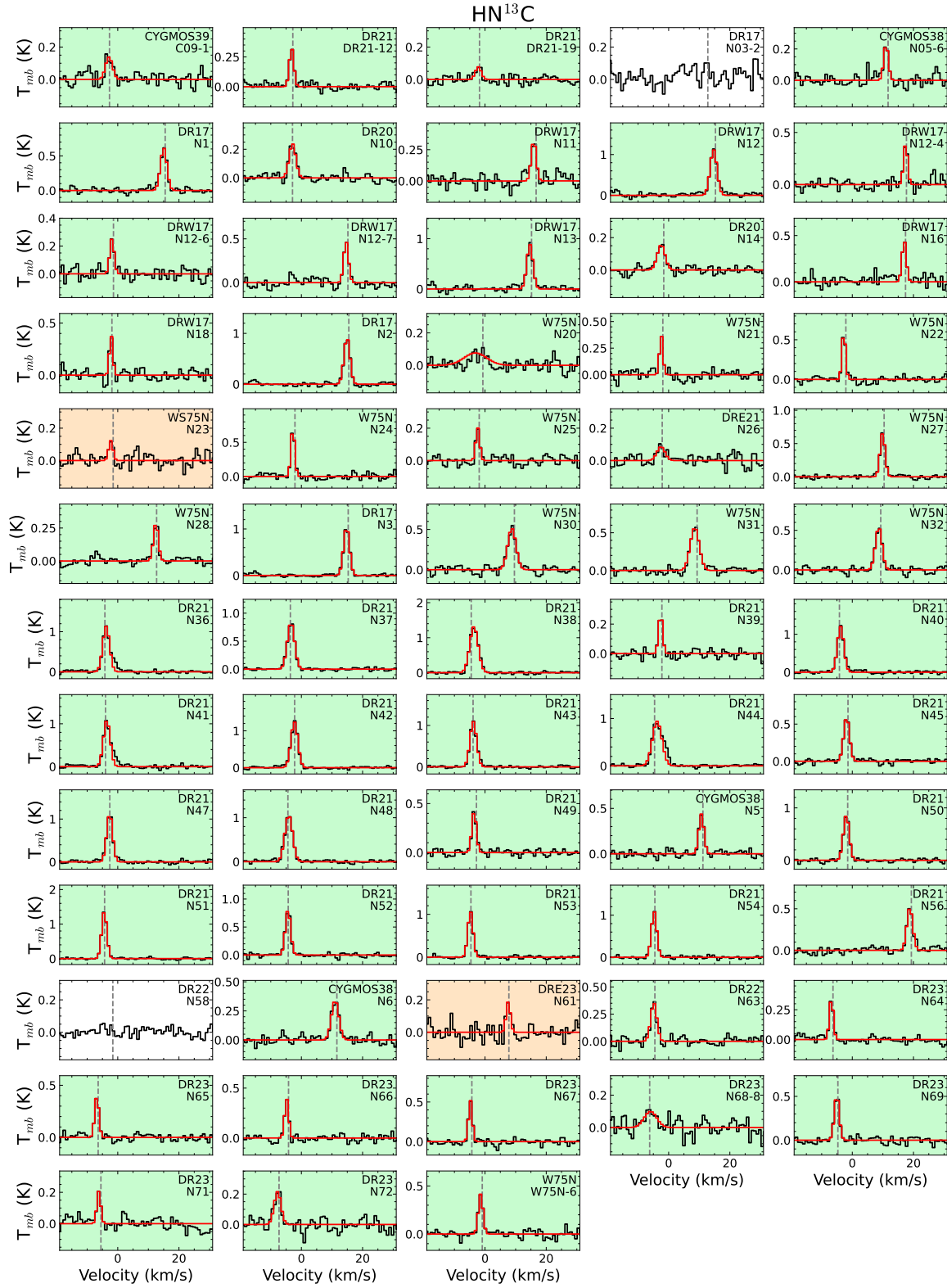
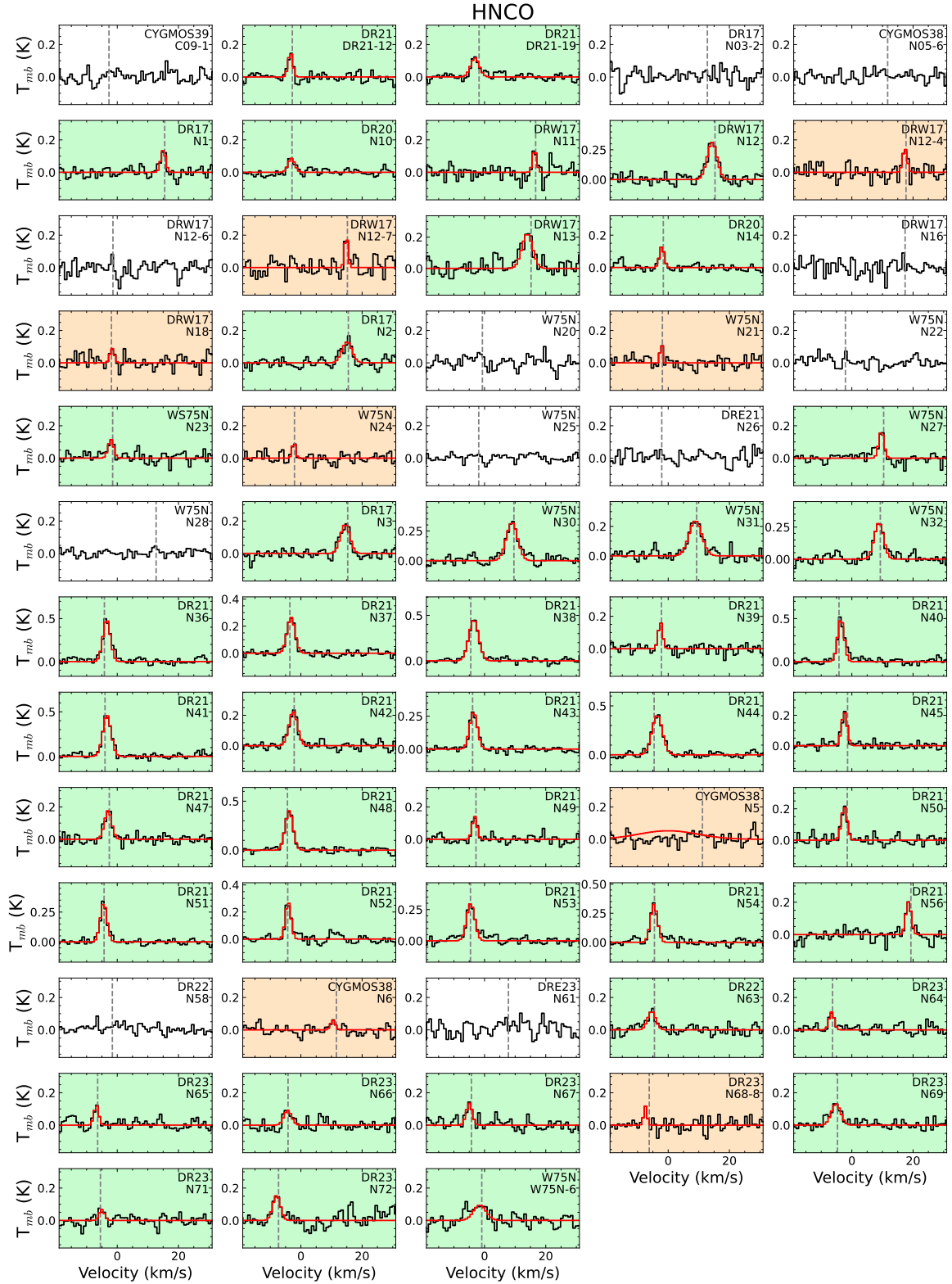


Figure B.26: Same as Fig. B.1 for HN^{13}C $J=1-0$ towards the Cygnus-X sources.


 Figure B.27: Same as Fig. B.1 for HNCO $J = 4(0, 4) - 3(0, 3)$ towards the Cygnus-X sources.

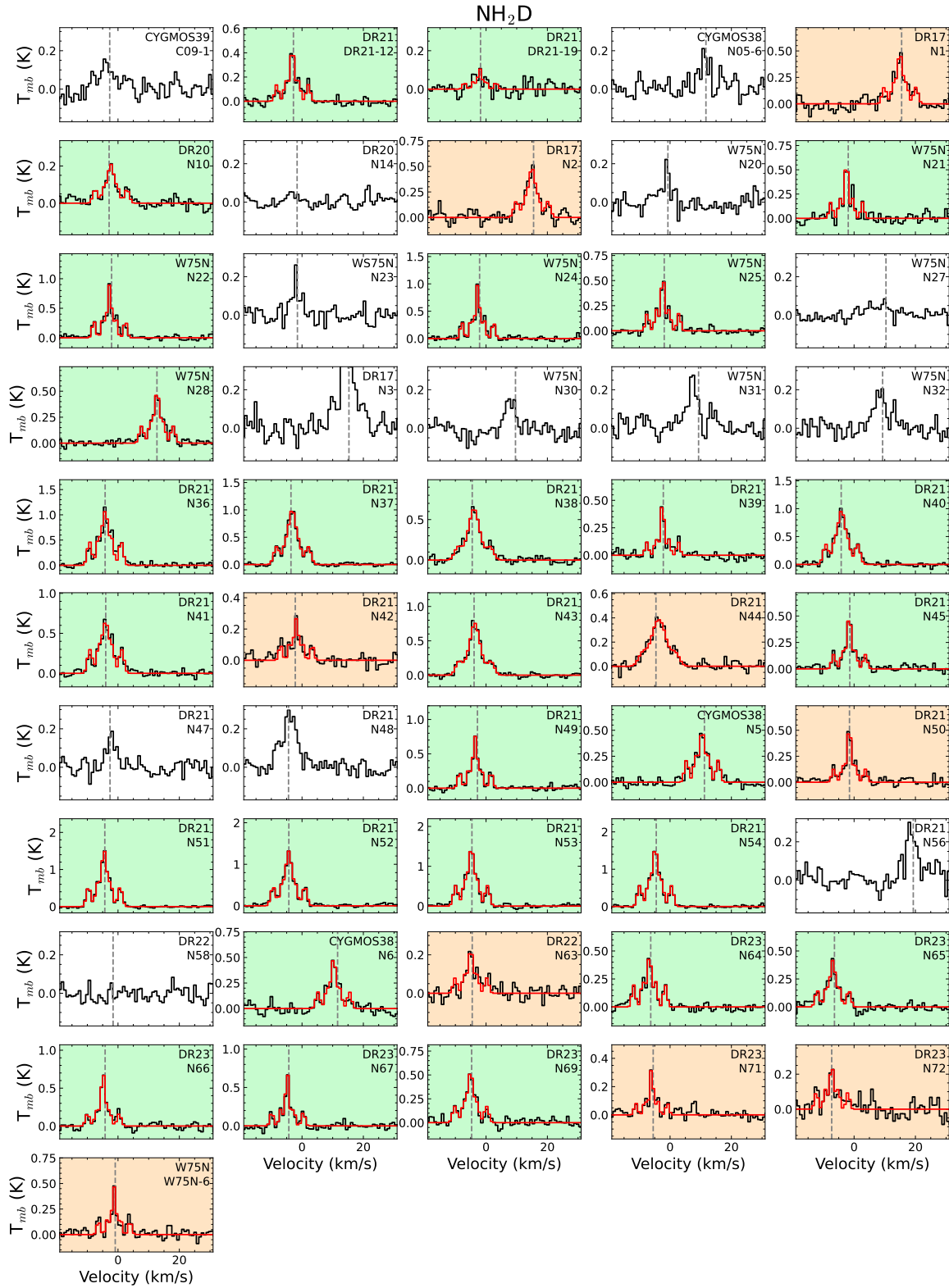
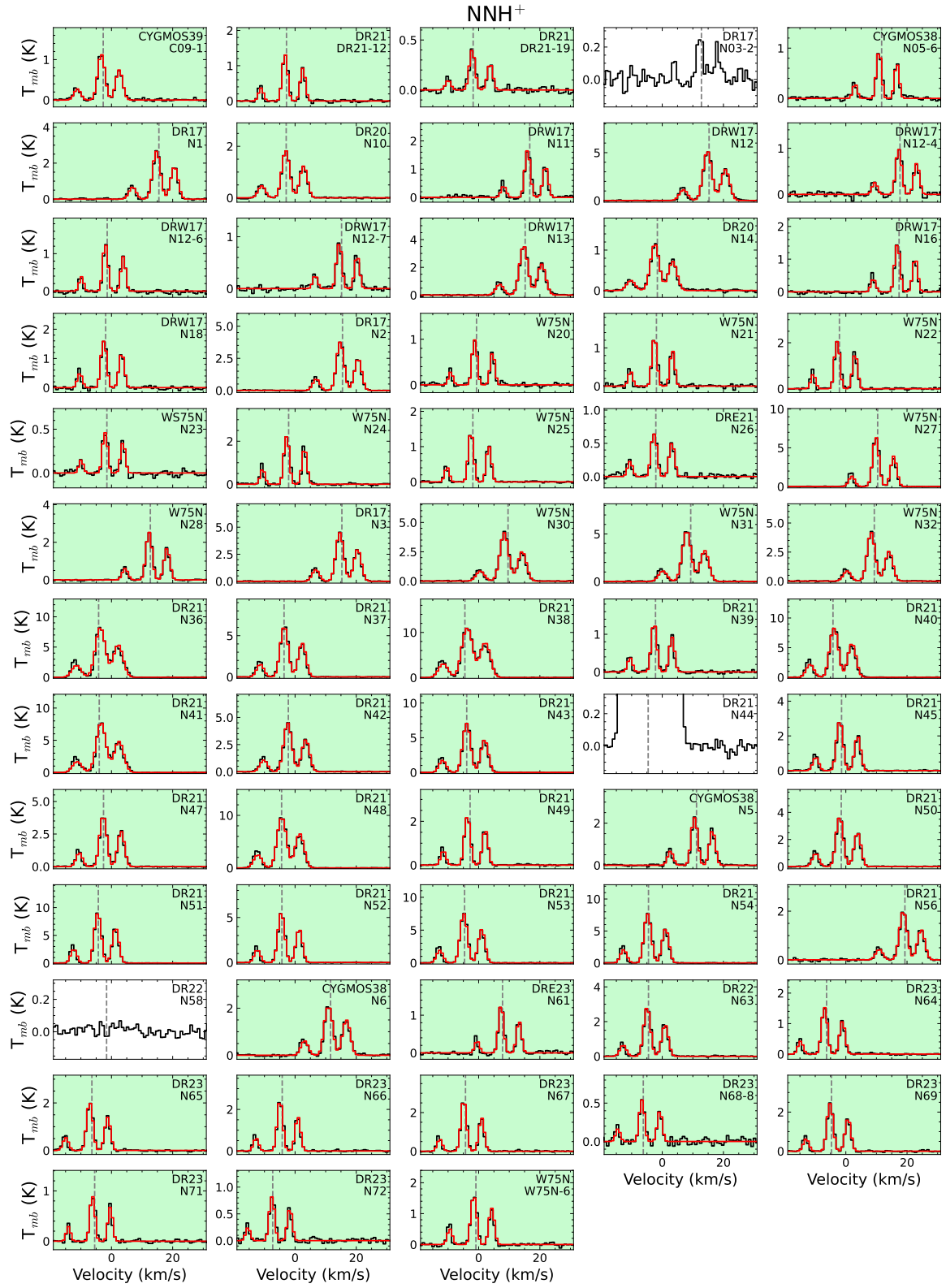


Figure B.28: Same as Fig. B.1 for NH_2D $1(1,1)0_s - 1(0,1)0_a$ towards the Cygnus-X sources.


 Figure B.29: Same as Fig. B.1 for $\text{N}_2\text{H}^+ J = 1 - 0$ towards the Cygnus-X sources.

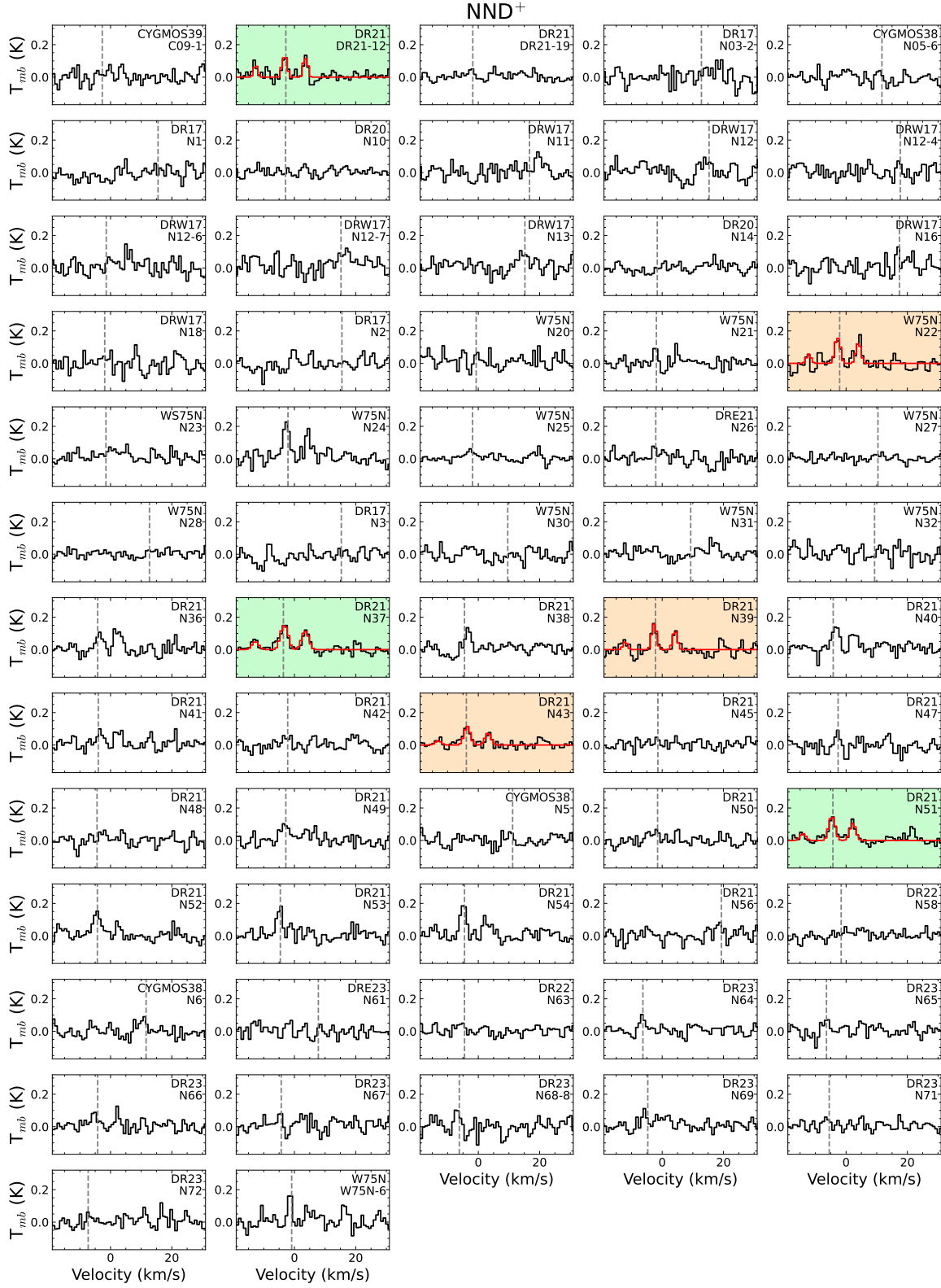
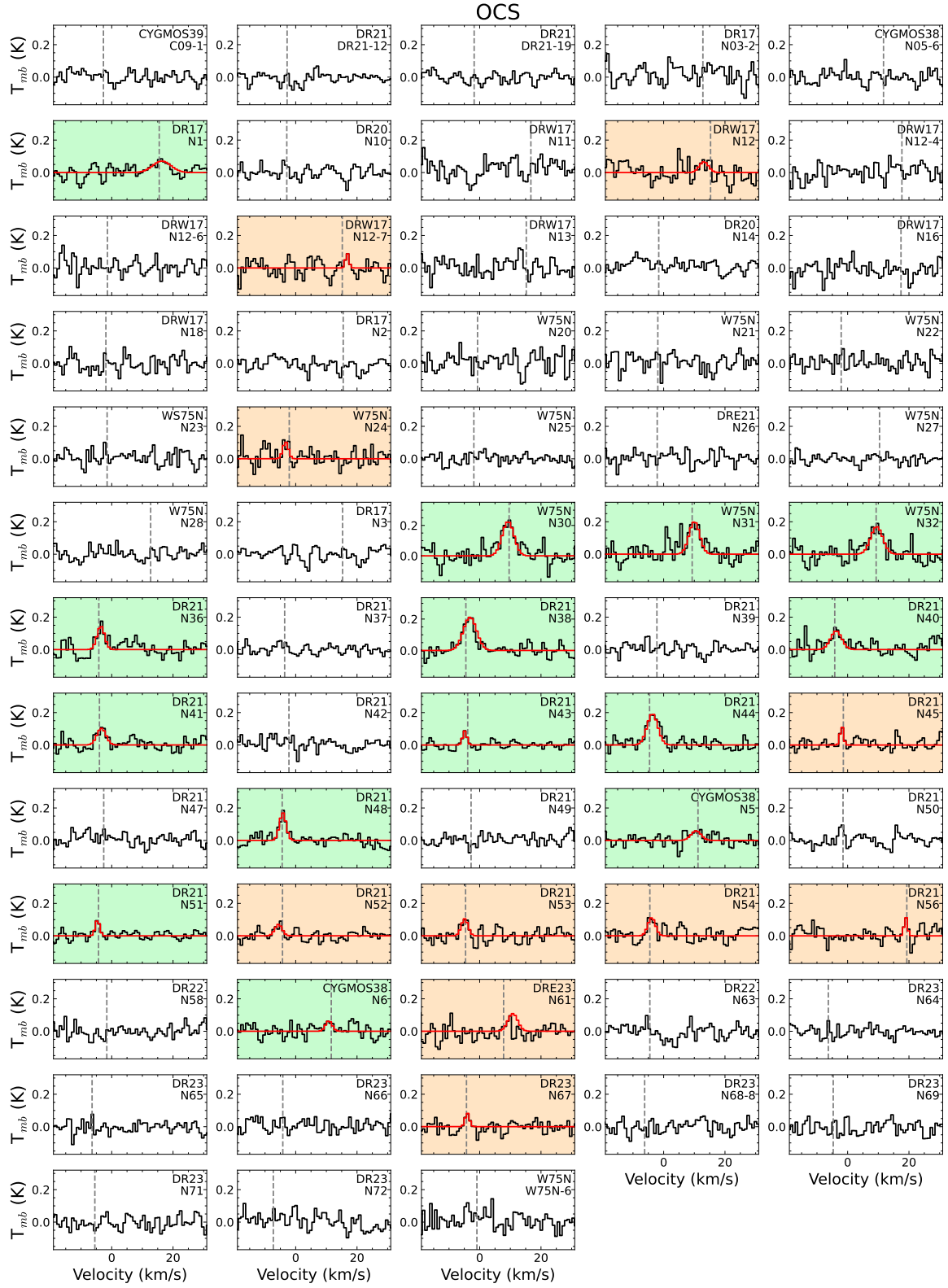


Figure B.30: Same as Fig. B.1 for $N_2D^+ J = 1 - 0$ towards the Cygnus-X sources.


 Figure B.31: Same as Fig. B.1 for OCS $J = 6 - 5$ towards the Cygnus-X sources.

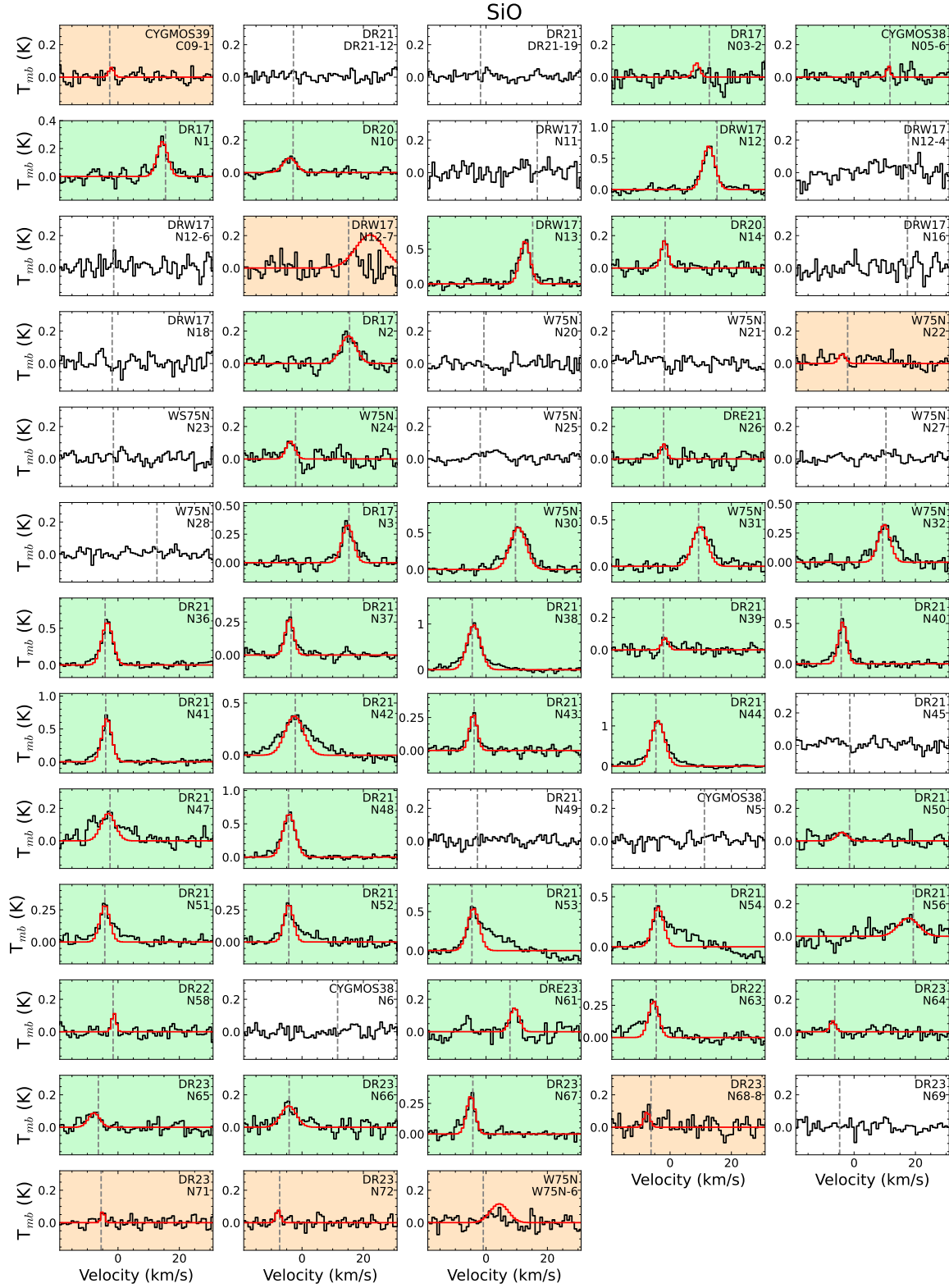
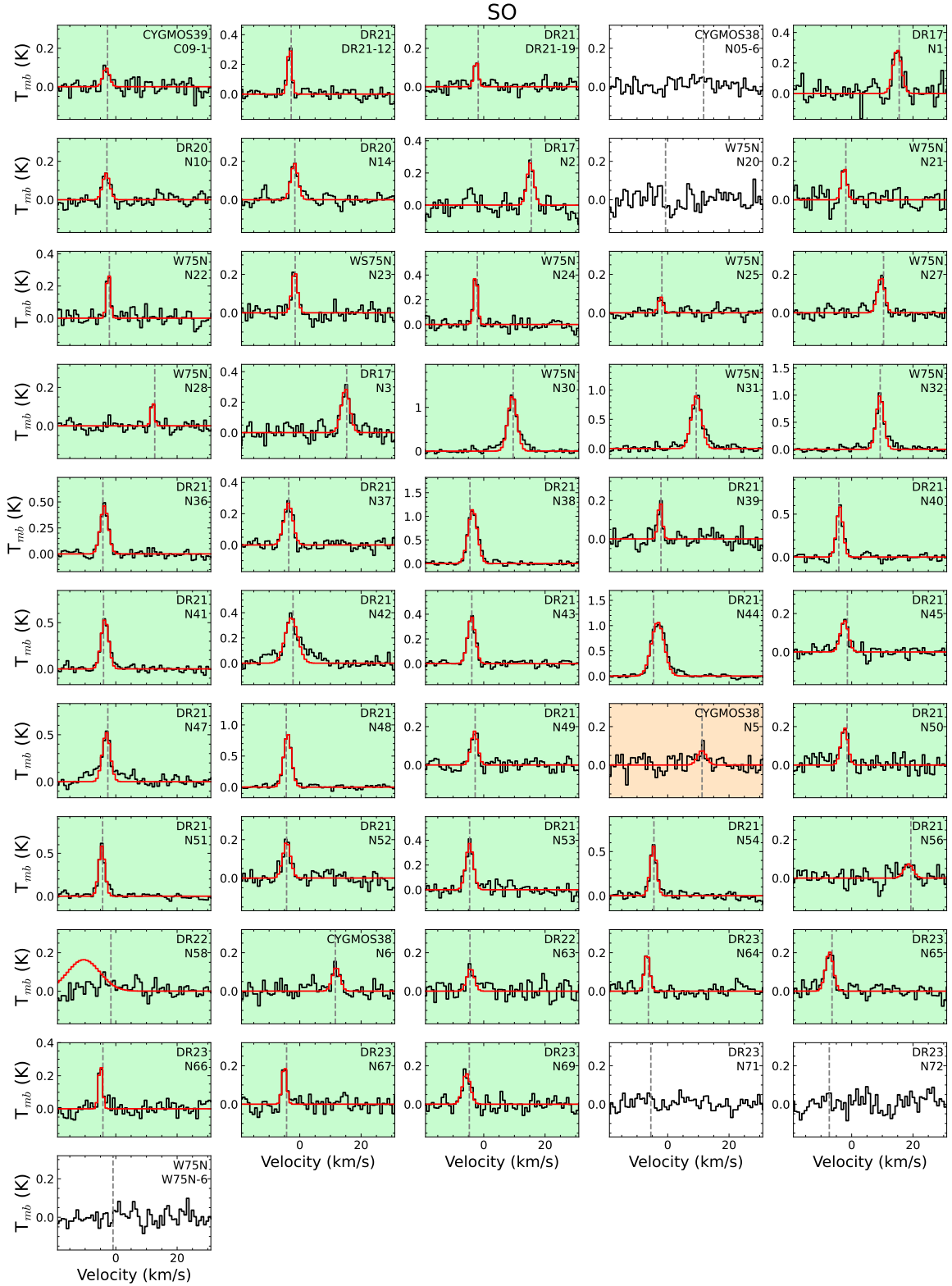


Figure B.32: Same as Fig. B.1 for SiO $J = 2 - 1$, $v = 0 - 0$ towards the Cygnus-X sources.


 Figure B.33: Same as Fig. B.1 for SO $J = 2(2) - 1(1)$ towards the Cygnus-X sources.

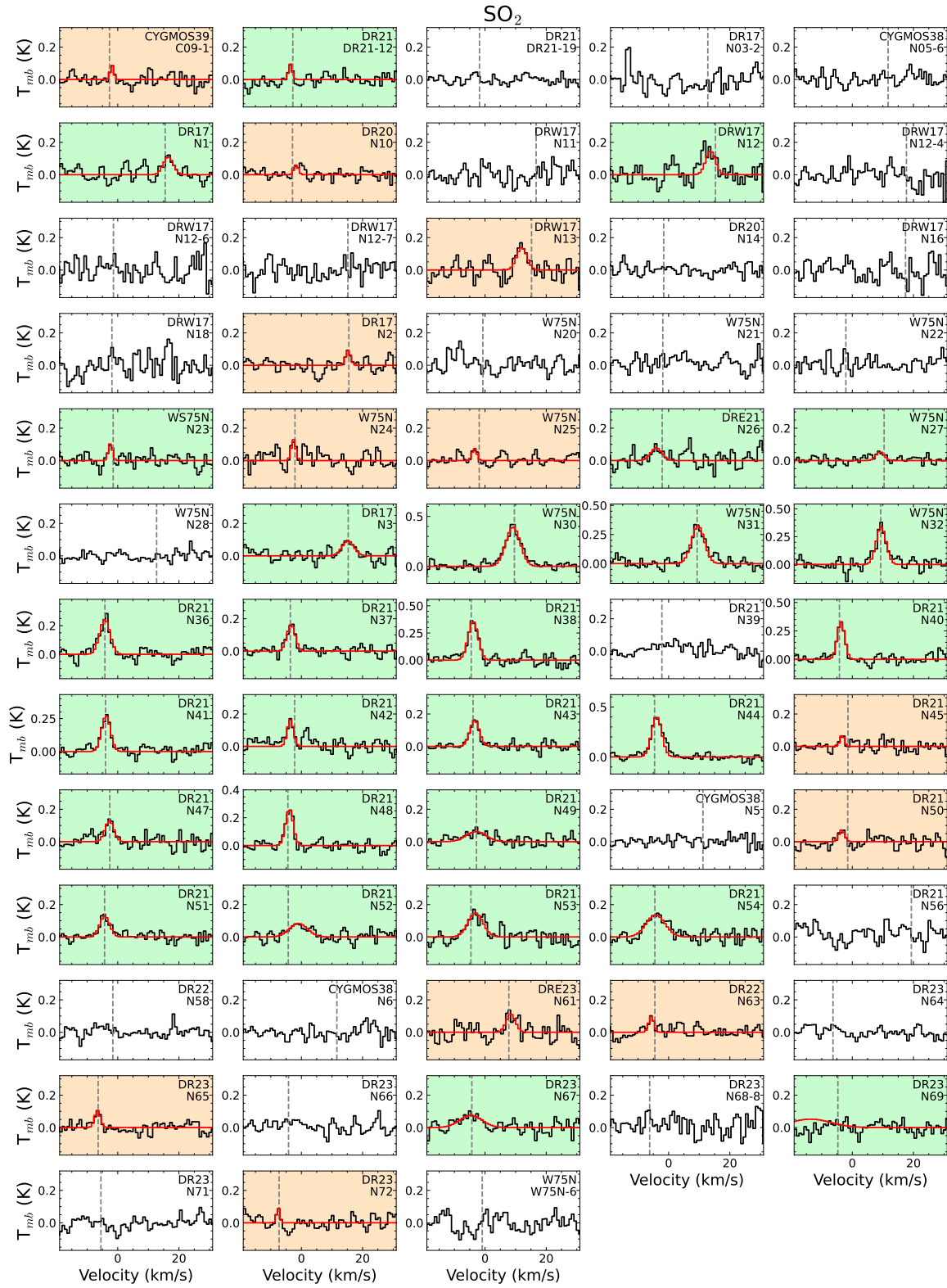


Figure B.34: Same as Fig. B.1 for SO_2 $J = 6(0,6) - 5(1,5)$ towards the Cygnus-X sources.

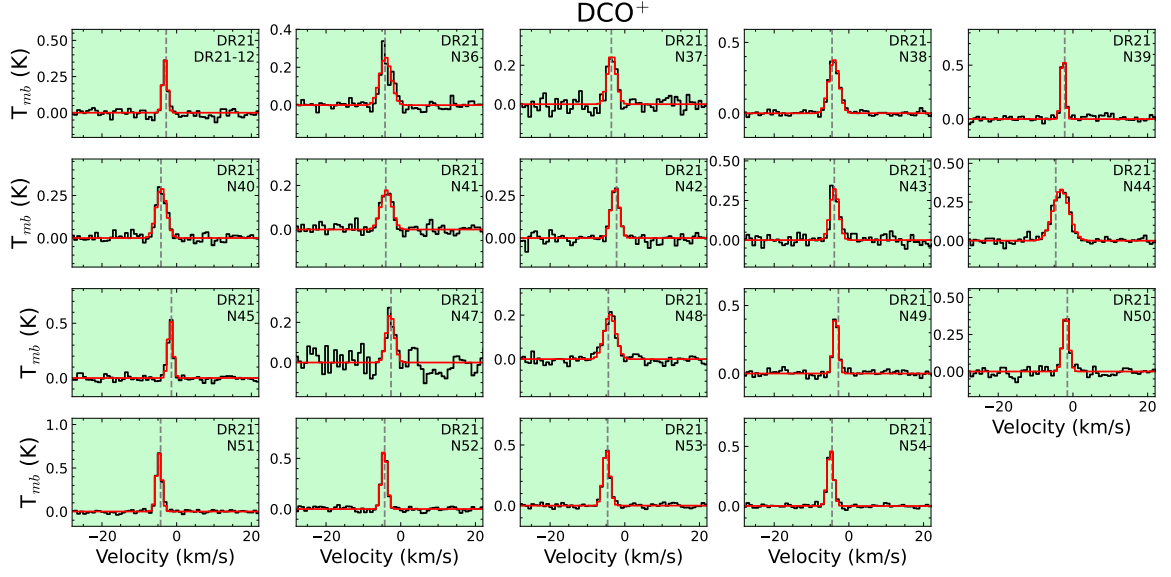


Figure B.35: Same as Fig. B.1 for $\text{DCO}^+ J = 3 - 2, F = 3 - 2$ towards the DR21 sources.

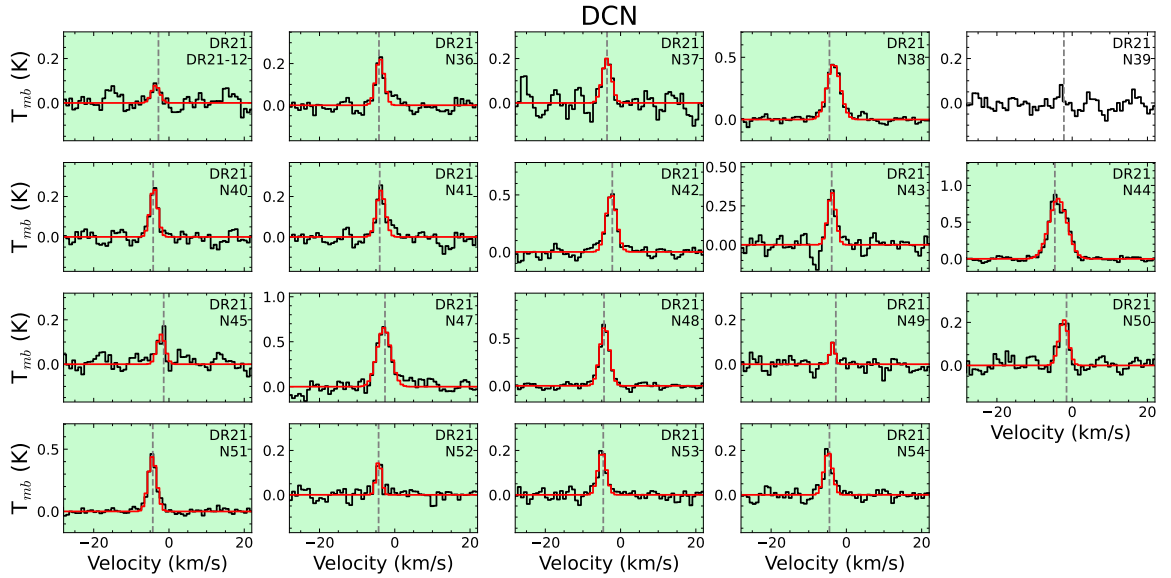


Figure B.36: Same as Fig. B.1 for $\text{DCN } J = 3 - 2$ towards the DR21 sources.

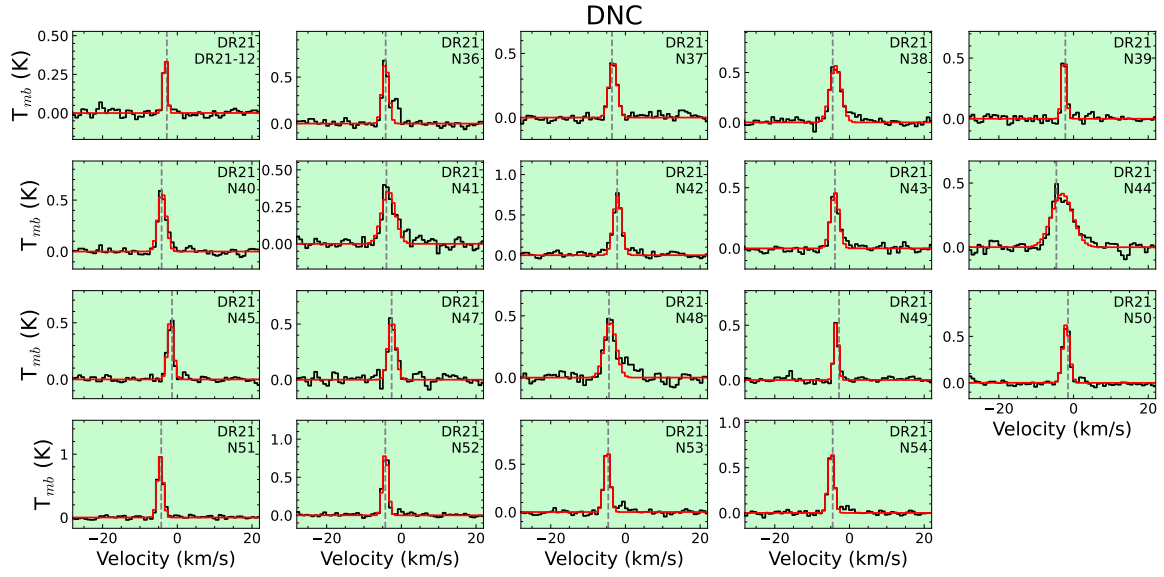


Figure B.37: Same as Fig. B.1 for DNC $J = 2 - 1$ towards the DR21 sources.

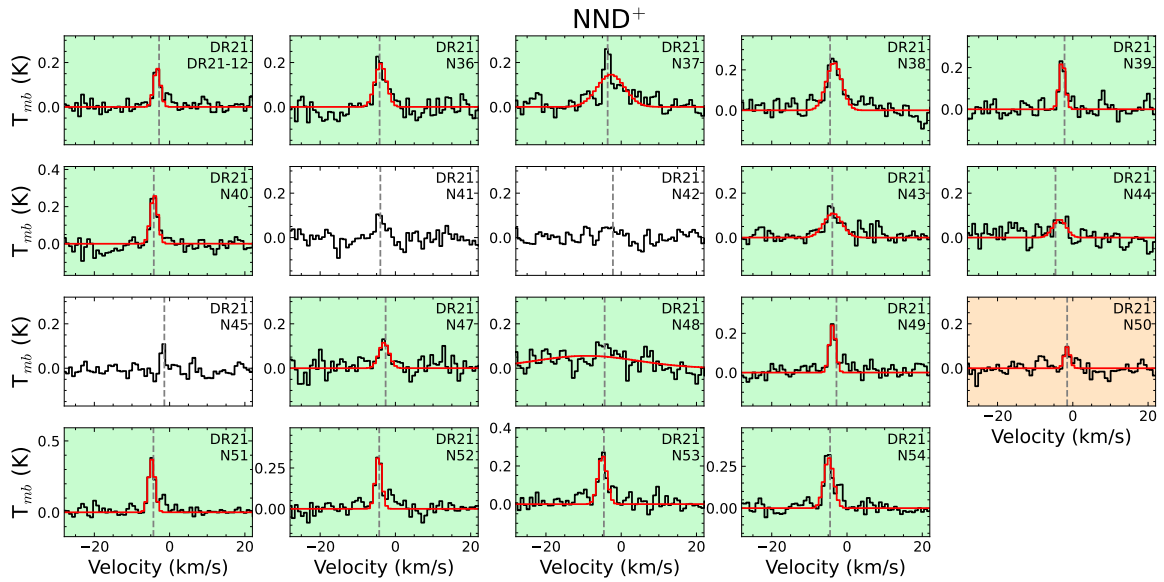


Figure B.38: Same as Fig. B.1 for $\text{N}_2\text{D}^+ J = 2 - 1$ towards the DR21 sources.

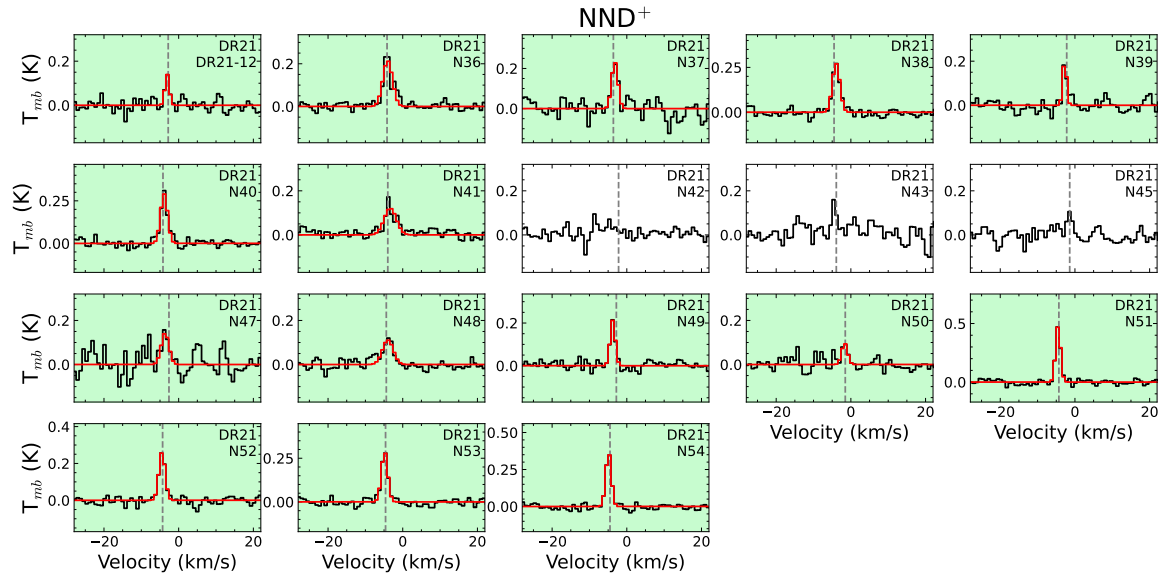


Figure B.39: Same as Fig. B.1 for N_2D^+ $J = 3 - 2$ towards the DR21 sources.

Table B.1: Central position of clumps in Cygnus-X adopted from Motte et al. (2007) and Cao et al. (2019). and the corresponding integrated line intensities and linewidths measured of this work.

Names	Region	R.A. (J2000)	Dec. (J2000)	¹³ CS $J = 2 - 1$		C ₂ D N=1-0, J=3/2-1/2, F=5/2-3/2*	
				$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	CYGMOS39	20 ^h 34 ^m 59 ^s .6	+41°34′48″.7	0.82±0.11	3.22±0.23	–	–
C09-2	CYGMOS39	20 ^h 34 ^m 50 ^s .2	+41°33′58″.8	–	–	–	–
DR21-12	DR21	20 ^h 34 ^m 51 ^s .7	+42°27′14″.5	0.32±0.06	1.84±0.06	0.23±0.05	1.74±0.16
DR21-19	DR21	20 ^h 34 ^m 02 ^s .1	+42°16′53″.0	0.12±0.02	1.87±0.27	–	–
N03-2	DR17	20 ^h 34 ^m 55 ^s .6	+42°11′19″.9	0.10±0.04	0.80±4.38	0.27±0.10	2.53±0.46
N05-5	DR20	20 ^h 34 ^m 25 ^s .4	+41°35′37″.6	0.07±0.03	1.14±0.04	0.24±0.07	3.65±0.48
N05-6	CYGMOS38	20 ^h 34 ^m 03 ^s .6	+41°39′45″.2	0.08±0.03	0.80±0.00	0.14±0.04	1.71±0.13
N1	DR17	20 ^h 34 ^m 32 ^s .7	+42°19′53″.0	0.72±0.10	2.77±0.09	0.32±0.10	4.33±1.19
N10	DR20	20 ^h 34 ^m 52 ^s .2	+41°36′23″.0	0.51±0.07	2.28±0.13	–	–
N11	DRW17	20 ^h 34 ^m 56 ^s .8	+42°13′19″.9	0.11±0.04	1.74±0.18	–	–
N12	DRW17	20 ^h 34 ^m 57 ^s .4	+42°11′26″.9	0.75±0.12	2.67±0.23	–	–
N12-4	DRW17	20 ^h 34 ^m 22 ^s .9	+42°16′37″.9	0.29±0.08	3.34±0.77	0.15±0.04	0.80±0.00
N12-6	DRW17	20 ^h 34 ^m 31 ^s .3	+42°13′16″.6	–	–	0.19±0.08	1.09±0.18
N12-7	DRW17	20 ^h 34 ^m 05 ^s .7	+42°11′50″.9	0.25±0.07	1.51±0.20	–	–
N13	DRW17	20 ^h 34 ^m 58 ^s .4	+42°11′17″.9	0.66±0.11	2.60±0.35	–	–
N14	DR20	20 ^h 34 ^m 00 ^s .9	+41°34′57″.0	0.62±0.07	2.94±0.09	–	–
N15	DR20	20 ^h 34 ^m 10 ^s .9	+41°33′38″.9	0.25±0.04	3.93±0.57	–	–
N16	DRW17	20 ^h 34 ^m 16 ^s .9	+42°16′31″.1	0.19±0.06	1.69±0.21	–	–
N17	DR20	20 ^h 34 ^m 26 ^s .5	+41°33′19″.1	–	–	0.10±0.05	1.55±0.13
N18	DRW17	20 ^h 34 ^m 30 ^s .2	+42°13′59″.2	0.16±0.07	0.80±0.84	–	–
N2	DR17	20 ^h 34 ^m 34 ^s .0	+42°20′22″.9	0.70±0.10	2.59±0.10	–	–
N20	W75N	20 ^h 34 ^m 47 ^s .4	+42°38′42″.0	0.30±0.07	3.88±1.14	–	–
N21	W75N	20 ^h 34 ^m 01 ^s .7	+42°39′33″.1	0.19±0.06	2.84±1.86	0.12±0.04	1.20±0.04
N22	W75N	20 ^h 34 ^m 03 ^s .4	+42°39′56″.2	0.28±0.06	1.49±0.31	0.29±0.07	1.40±0.08
N23	WS75N	20 ^h 34 ^m 04 ^s .9	+42°33′16″.9	0.14±0.04	1.47±0.31	–	–
N24	W75N	20 ^h 34 ^m 05 ^s .8	+42°39′51″.8	0.23±0.05	0.91±1.56	0.46±0.11	1.60±0.05
N25	W75N	20 ^h 34 ^m 10 ^s .4	+42°38′04″.9	–	–	0.09±0.03	1.30±0.03
N26	DRE21	20 ^h 34 ^m 21 ^s .2	+42°11′30″.8	0.32±0.06	1.82±0.09	0.10±0.04	0.80±0.00
N27	W75N	20 ^h 34 ^m 31 ^s .6	+42°38′03″.8	0.59±0.08	1.96±0.02	–	–
N28	W75N	20 ^h 34 ^m 33 ^s .7	+42°39′43″.9	0.35±0.05	2.37±0.32	–	–
N3	DR17	20 ^h 34 ^m 34 ^s .2	+42°20′04″.9	0.94±0.11	2.90±0.09	0.16±0.04	2.65±0.25
N30	W75N	20 ^h 34 ^m 36 ^s .6	+42°37′30″.0	2.28±0.25	3.23±0.12	0.12±0.03	0.80±0.00
N31	W75N	20 ^h 34 ^m 36 ^s .9	+42°37′50″.2	2.31±0.24	3.42±0.09	–	–
N32	W75N	20 ^h 34 ^m 38 ^s .3	+42°37′32″.9	1.81±0.19	3.17±0.07	0.16±0.06	0.80±3.59
N33	W75N	20 ^h 34 ^m 47 ^s .0	+42°37′59″.9	0.09±0.03	0.96±0.01	0.19±0.06	2.27±0.42
N36A	DR21	20 ^h 34 ^m 58 ^s .5	+42°23′30″.1	–	–	0.24±0.09	2.65±0.43
N36B	DR21	20 ^h 34 ^m 58 ^s .5	+42°23′30″.1	1.98±0.21	3.07±0.18	–	–
N37	DR21	20 ^h 34 ^m 58 ^s .6	+42°24′34″.9	1.09±0.12	2.70±0.16	0.23±0.06	2.68±0.23
N38A	DR21	20 ^h 34 ^m 59 ^s .4	+42°22′23″.2	–	–	0.24±0.07	2.24±0.41

Table B.2: Continued.

Names	Region	R.A. (J2000)	Dec. (J2000)	¹³ CS $J = 2 - 1$		C ₂ D N=1-0, J=3/2-1/2, F=5/2-3/2*	
				$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	DR21	20 ^h 34 ^m 59 ^s .4	+42°22′23″.2	4.18±0.43	3.58±0.11	—	—
N39	DR21	20 ^h 34 ^m 59 ^s .9	+42°27′32″.0	0.22±0.06	1.94±0.41	0.10±0.03	0.81±0.86
N40	DR21	20 ^h 34 ^m 59 ^s .8	+42°23′43″.1	1.87±0.20	3.06±0.09	0.23±0.07	2.35±0.49
N41A	DR21	20 ^h 34 ^m 00 ^s .2	+42°23′25″.1	—	—	—	—
N41B	DR21	20 ^h 34 ^m 00 ^s .2	+42°23′25″.1	2.09±0.23	3.12±0.07	0.20±0.06	2.91±0.62
N42A	DR21	20 ^h 34 ^m 00 ^s .3	+42°19′07″.0	—	—	—	—
N42B	DR21	20 ^h 34 ^m 00 ^s .3	+42°19′07″.0	1.71±0.18	2.46±0.09	0.46±0.10	3.95±0.59
N43	DR21	20 ^h 34 ^m 00 ^s .6	+42°24′34″.9	1.49±0.16	2.67±0.12	0.22±0.06	1.85±0.11
N44A	DR21	20 ^h 34 ^m 01 ^s .0	+42°22′45″.8	4.16±0.42	3.99±0.26	0.13±0.06	1.48±0.17
N45	DR21	20 ^h 34 ^m 01 ^s .1	+42°18′14″.0	0.54±0.07	2.64±0.17	0.27±0.06	2.42±0.13
N46	DR21	20 ^h 34 ^m 01 ^s .4	+42°19′34″.0	1.69±0.18	2.70±0.05	0.42±0.12	3.32±0.73
N47	DR21	20 ^h 34 ^m 01 ^s .4	+42°19′54″.1	2.03±0.21	2.30±0.07	0.21±0.07	1.73±0.18
N48	DR21	20 ^h 34 ^m 01 ^s .5	+42°22′03″.0	2.41±0.25	2.88±0.13	0.16±0.06	1.82±0.16
N49	DR21	20 ^h 34 ^m 02 ^s .0	+42°27′00″.0	0.31±0.04	1.96±0.13	0.20±0.07	1.65±0.16
N5	CYGMOS38	20 ^h 34 ^m 06 ^s .5	+41°39′58″.0	0.30±0.06	1.89±0.14	—	—
N50	DR21	20 ^h 34 ^m 01 ^s .9	+42°18′34″.9	0.72±0.09	2.08±0.07	0.25±0.07	1.97±0.46
N51	DR21	20 ^h 34 ^m 02 ^s .4	+42°24′59″.0	1.47±0.15	2.34±0.09	0.28±0.07	2.72±0.64
N52	DR21	20 ^h 34 ^m 03 ^s .0	+42°26′15″.0	0.58±0.07	2.27±0.03	0.15±0.06	1.22±0.01
N53	DR21	20 ^h 34 ^m 03 ^s .2	+42°25′49″.1	0.88±0.10	2.25±0.14	0.09±0.04	1.11±0.56
N54	DR21	20 ^h 34 ^m 03 ^s .6	+42°25′30″.0	1.06±0.13	2.40±0.08	0.12±0.07	0.85±0.18
N55A	DR21	20 ^h 34 ^m 06 ^s .1	+42°18′19″.1	—	—	—	—
N55B	DR21	20 ^h 34 ^m 06 ^s .1	+42°18′19″.1	0.19±0.04	1.39±0.02	0.17±0.06	1.32±0.15
N56	DR21	20 ^h 34 ^m 16 ^s .9	+42°16′07″.0	0.22±0.05	3.56±0.97	—	—
N57	DR21	20 ^h 34 ^m 19 ^s .3	+42°15′56″.2	0.32±0.07	2.92±0.98	0.13±0.07	0.80±3.54
N58	DR22	20 ^h 34 ^m 25 ^s .9	+41°20′01″.0	—	—	—	—
N6	CYGMOS38	20 ^h 34 ^m 08 ^s .1	+41°39′58″.0	0.66±0.09	1.98±0.12	—	—
N61	DRE23	20 ^h 34 ^m 57 ^s .6	+41°59′11″.0	—	—	—	—
N63	DR22	20 ^h 34 ^m 05 ^s .2	+41°32′12″.8	0.27±0.06	2.25±0.33	0.24±0.05	1.90±0.32
N64	DR23	20 ^h 34 ^m 27 ^s .2	+41°56′51″.0	0.33±0.05	2.66±0.32	0.30±0.07	4.19±0.72
N65	DR23	20 ^h 34 ^m 28 ^s .4	+41°57′11″.2	0.43±0.07	2.36±0.26	0.18±0.04	2.11±0.48
N66	DR23	20 ^h 34 ^m 29 ^s .8	+41°49′32″.9	0.38±0.06	1.86±0.17	0.12±0.04	0.80±0.00
N67	DR23	20 ^h 34 ^m 31 ^s .0	+41°49′57″.0	0.38±0.06	1.92±0.14	0.30±0.09	4.08±4.04
N68	DR23	20 ^h 34 ^m 33 ^s .5	+41°59′03″.1	0.31±0.07	3.93±0.33	0.14±0.04	1.81±0.45
N68-8	DR23	20 ^h 34 ^m 45 ^s .4	+42°01′41″.1	0.17±0.07	1.07±0.17	—	—
N69	DR23	20 ^h 34 ^m 33 ^s .7	+41°50′58″.9	0.42±0.06	3.91±0.50	0.15±0.04	0.94±0.66
N71	DR23	20 ^h 34 ^m 38 ^s .2	+41°52′59″.2	0.44±0.08	11.48±7.05	—	—
N72	DR23	20 ^h 34 ^m 45 ^s .7	+41°57′50″.0	0.18±0.04	2.71±0.76	0.34±0.09	3.09±0.91
W75N-6	W75N	20 ^h 34 ^m 55 ^s .1	+42°40′54″.8	0.09±0.03	0.80±0.00	—	—

Table B.3: Continued.

Names	C ₂ D N=1-0, J=1/2-1/2, F=3/2-3/2*		C ₂ H N=1-0, J=3/2-1/2, F=1-1*		C ₂ H N=1-0, J=3/2-1/2, F=2-1*	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	0.27±0.08	2.36±0.36	0.48±0.07	2.93±0.45	3.13±0.33	3.00±0.08
C09-2	—	—	0.21±0.06	2.02±0.30	0.88±0.11	2.02±0.24
DR21-12	—	—	0.36±0.05	1.64±0.15	3.02±0.31	2.46±0.07
DR21-19	—	—	0.54±0.07	3.29±0.10	3.20±0.33	2.75±0.10
N03-2	—	—	0.30±0.08	1.69±0.34	1.97±0.23	3.18±0.22
N05-5	—	—	—	—	0.74±0.09	2.45±0.52
N05-6	0.17±0.06	1.92±0.36	0.25±0.06	2.07±0.13	2.72±0.28	2.13±0.06
N1	0.06±0.05	0.84±0.00	0.93±0.12	3.09±0.26	6.60±0.66	2.80±0.04
N10	—	—	0.76±0.09	2.75±0.17	3.35±0.34	3.28±0.07
N11	—	—	0.18±0.07	0.80±0.00	1.81±0.20	2.11±0.16
N12	0.27±0.10	3.14±1.05	0.70±0.12	3.12±0.45	7.21±0.74	3.89±0.08
N12-4	0.30±0.09	2.36±0.50	0.22±0.07	3.20±0.65	1.14±0.18	1.68±0.30
N12-6	—	—	0.26±0.08	2.74±0.57	2.01±0.22	1.84±0.12
N12-7	0.14±0.06	2.19±0.84	0.22±0.06	1.19±0.93	2.08±0.23	2.06±0.15
N13	—	—	0.52±0.10	3.53±0.30	5.80±0.59	4.18±0.14
N14	—	—	0.58±0.07	3.16±0.29	4.87±0.49	3.14±0.07
N15	—	—	0.39±0.06	3.78±0.41	2.38±0.26	4.43±0.25
N16	0.66±0.39	19.75±17.80	0.16±0.07	1.04±0.03	1.54±0.20	1.77±0.21
N17	—	—	0.30±0.06	2.29±0.31	0.92±0.14	3.57±0.50
N18	—	—	0.26±0.07	1.31±0.02	2.86±0.30	1.79±0.08
N2	—	—	0.94±0.11	2.59±0.05	7.64±0.77	2.90±0.05
N20	0.39±0.12	3.55±0.57	0.20±0.04	1.58±0.17	1.09±0.13	1.47±0.10
N21	0.12±0.06	0.80±0.00	0.20±0.05	2.03±0.19	1.65±0.18	2.01±0.10
N22	0.36±0.11	4.17±2.16	0.32±0.05	1.51±0.04	2.32±0.24	1.92±0.08
N23	—	—	0.25±0.06	1.79±0.22	2.02±0.21	1.98±0.09
N24	0.17±0.06	1.58±0.06	0.27±0.05	0.80±10.63	2.26±0.24	1.90±0.08
N25	0.10±0.03	1.67±0.19	0.21±0.04	1.86±0.16	1.51±0.16	1.98±0.06
N26	—	—	0.31±0.06	2.33±0.43	2.77±0.30	2.35±0.11
N27	0.14±0.03	2.34±0.32	0.63±0.07	2.06±0.07	4.05±0.42	2.39±0.09
N28	—	—	0.22±0.04	3.02±0.64	1.12±0.13	2.66±0.24
N3	—	—	1.15±0.15	2.88±0.15	8.89±0.89	2.97±0.04
N30	—	—	0.85±0.13	2.67±0.11	6.67±0.68	3.59±0.13
N31	0.08±0.06	1.19±0.05	0.91±0.12	2.83±0.12	7.28±0.74	3.53±0.12
N32	0.11±0.05	0.80±0.01	0.76±0.10	2.53±0.18	6.04±0.63	3.38±0.15
N33	—	—	—	—	1.17±0.15	2.56±0.37
N36A	—	—	2.09±0.21	3.08±0.20	13.21±1.33	3.80±0.03
N36B	—	—	—	—	—	—
N37	—	—	1.34±0.14	2.78±0.12	8.60±0.86	3.32±0.03
N38A	—	—	2.28±0.24	3.17±0.10	15.91±1.60	3.84±0.03

Table B.4: Continued.

Names	C_2D N=1-0, J=1/2-1/2, F=3/2-3/2*		C_2H N=1-0, J=3/2-1/2, F=1-1*		C_2H N=1-0, J=3/2-1/2, F=2-1*	
	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$
	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]
N38B	0.51±0.12	12.72±20.70	—	—	—	—
N39	0.39±0.10	5.45±2.22	0.52±0.08	1.99±0.21	3.37±0.34	2.34±0.05
N40	—	—	1.94±0.20	2.82±0.15	11.50±1.16	3.20±0.04
N41A	0.39±0.10	5.84±1.90	2.01±0.20	2.95±0.13	12.49±1.26	3.87±0.03
N41B	—	—	—	—	—	—
N42A	—	—	—	—	—	—
N42B	1.00±0.21	18.18±8.78	2.08±0.22	2.71±0.07	14.40±1.44	2.99±0.02
N43	0.15±0.04	1.75±0.51	1.54±0.16	2.60±0.05	9.52±0.96	2.99±0.02
N44A	—	—	2.10±0.22	3.52±0.12	15.83±1.59	4.66±0.02
N45	—	—	1.08±0.12	2.44±0.11	7.02±0.71	2.94±0.05
N46	0.36±0.11	2.96±1.20	1.85±0.22	2.96±0.14	12.48±1.27	3.22±0.10
N47	0.22±0.06	3.45±3.31	1.64±0.18	2.51±0.13	11.45±1.15	2.72±0.07
N48	0.21±0.07	2.29±0.43	2.07±0.22	3.15±0.23	12.52±1.26	3.17±0.03
N49	0.08±0.03	0.80±0.23	0.59±0.07	1.95±0.13	3.53±0.35	2.63±0.05
N5	0.47±0.08	4.33±1.53	0.35±0.06	1.42±0.04	3.45±0.36	2.12±0.05
N50	—	—	1.33±0.15	2.44±0.07	8.87±0.89	3.00±0.03
N51	0.12±0.03	1.65±0.40	1.36±0.15	2.55±0.06	8.54±0.86	2.49±0.02
N52	—	—	0.96±0.10	2.51±0.30	5.32±0.54	2.68±0.06
N53	0.60±0.12	5.11±2.55	1.11±0.13	2.56±0.11	7.09±0.71	2.72±0.05
N54	0.84±0.21	15.20±3.83	1.15±0.13	2.54±0.10	7.10±0.71	2.61±0.04
N55A	—	—	—	—	—	—
N55B	—	—	0.56±0.07	1.97±0.13	4.43±0.45	3.52±0.21
N56	—	—	0.36±0.09	3.12±0.52	2.89±0.31	2.65±0.12
N57	—	—	0.38±0.08	1.77±0.03	2.82±0.30	2.28±0.08
N58	—	—	0.21±0.05	2.22±0.33	1.69±0.19	3.07±0.22
N6	—	—	0.45±0.09	1.92±0.20	3.55±0.36	2.49±0.05
N61	0.07±0.05	0.80±0.02	0.28±0.08	2.01±0.26	0.98±0.13	1.58±0.18
N63	—	—	0.46±0.08	1.80±0.12	3.21±0.33	2.16±0.05
N64	—	—	0.20±0.04	1.41±0.13	2.45±0.26	2.12±0.08
N65	—	—	0.35±0.05	2.16±0.28	3.62±0.37	2.52±0.06
N66	—	—	0.41±0.07	3.15±0.59	3.64±0.37	3.94±0.11
N67	—	—	0.52±0.07	3.10±0.53	3.55±0.36	2.96±0.06
N68	—	—	0.20±0.04	2.36±0.51	2.66±0.28	2.63±0.10
N68-8	—	—	0.36±0.07	3.96±0.48	2.95±0.32	2.18±0.09
N69	—	—	0.76±0.08	2.32±0.12	5.85±0.59	2.78±0.04
N71	0.11±0.03	1.94±0.70	0.52±0.07	2.73±0.44	3.31±0.34	2.73±0.07
N72	0.31±0.10	3.69±1.81	0.70±0.11	2.83±0.27	4.43±0.45	2.93±0.07
W75N-6	0.36±0.11	5.63±3.46	0.56±0.10	2.79±0.18	2.16±0.23	1.94±0.06

Table B.5: Continued.

Names	C ₂ H N=1-0,J=3/2-1/2, F=1-0*		C ₂ H N=1-0,J=1/2-1/2, F=1-1*		C ₂ H N=1-,J=1/2-1/2, F=0-1*	
	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$
	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]
C09-1	1.71±0.18	2.92±0.11	1.96±0.21	3.29±0.18	0.97±0.12	3.31±0.25
C09-2	0.51±0.07	1.71±0.20	0.33±0.05	1.15±0.50	0.33±0.07	1.17±0.42
DR21-12	1.64±0.18	2.19±0.10	1.62±0.17	2.16±0.09	0.84±0.09	2.24±0.16
DR21-19	1.65±0.17	2.59±0.05	1.70±0.18	2.58±0.09	0.69±0.09	2.19±0.23
N03-2	0.75±0.10	3.06±0.39	0.92±0.14	2.60±0.60	0.37±0.09	2.59±1.43
N05-5	0.44±0.08	2.11±0.25	0.54±0.08	2.24±0.34	0.46±0.11	4.54±0.96
N05-6	1.30±0.15	2.07±0.15	1.25±0.15	2.27±0.10	0.60±0.08	1.88±0.11
N1	3.30±0.34	2.70±0.07	3.39±0.35	2.58±0.09	1.38±0.14	2.54±0.25
N10	2.39±0.25	2.90±0.09	2.33±0.24	3.05±0.10	1.34±0.14	2.72±0.08
N11	0.84±0.10	1.80±0.19	1.24±0.15	2.46±0.27	0.46±0.10	1.92±0.37
N12	3.80±0.41	3.78±0.20	3.86±0.40	3.86±0.25	1.74±0.21	4.05±0.28
N12-4	0.54±0.09	1.71±0.07	0.68±0.11	2.09±0.49	0.84±0.14	2.47±0.18
N12-6	0.97±0.14	1.89±0.13	1.09±0.15	1.81±0.14	0.45±0.09	2.82±0.40
N12-7	1.25±0.18	1.95±0.14	1.41±0.18	2.15±0.17	0.70±0.13	2.12±0.22
N13	3.01±0.32	4.03±0.25	3.25±0.35	4.14±0.23	1.23±0.17	3.75±0.23
N14	2.70±0.28	3.15±0.10	2.82±0.29	3.22±0.12	1.25±0.13	2.98±0.15
N15	1.50±0.17	4.24±0.21	1.46±0.16	4.34±0.26	0.89±0.11	5.59±0.62
N16	0.63±0.14	1.29±0.27	0.94±0.13	1.73±0.16	0.63±0.10	2.12±0.20
N17	0.42±0.09	2.64±0.32	0.60±0.12	3.53±0.27	0.22±0.05	1.89±0.59
N18	1.61±0.19	1.55±0.09	1.48±0.20	1.76±0.13	0.97±0.13	2.65±0.12
N2	3.89±0.40	2.73±0.15	4.06±0.41	2.75±0.06	1.50±0.17	2.64±0.18
N20	0.62±0.09	1.26±0.14	0.57±0.09	1.34±0.29	0.26±0.07	1.48±0.26
N21	0.95±0.11	1.91±0.07	0.89±0.11	1.76±0.20	0.41±0.08	1.46±0.21
N22	1.19±0.14	1.84±0.11	1.20±0.13	1.79±0.12	0.52±0.07	1.21±0.15
N23	1.20±0.13	2.01±0.05	1.29±0.14	2.51±0.36	0.39±0.06	1.72±0.32
N24	1.20±0.13	1.60±0.11	1.27±0.14	1.71±0.11	0.52±0.07	1.26±0.14
N25	0.90±0.10	2.03±0.09	1.00±0.11	2.11±0.14	0.36±0.05	1.79±0.20
N26	1.44±0.18	2.51±0.10	1.32±0.16	2.15±0.06	0.64±0.10	2.72±0.38
N27	2.25±0.27	2.17±0.06	2.40±0.24	2.24±0.07	1.02±0.12	1.82±0.18
N28	0.63±0.10	2.32±0.14	0.70±0.08	2.68±0.18	0.29±0.04	3.11±0.52
N3	4.62±0.47	2.91±0.08	4.70±0.48	2.83±0.09	1.90±0.20	2.82±0.14
N30	3.46±0.39	3.24±0.10	3.79±0.39	3.53±0.15	1.71±0.20	3.51±0.22
N31	3.86±0.43	3.49±0.12	4.20±0.43	3.60±0.10	1.78±0.21	3.36±0.11
N32	2.89±0.35	2.90±0.13	3.18±0.33	3.14±0.14	1.47±0.18	3.42±0.27
N33	0.37±0.08	1.30±0.39	0.54±0.08	2.02±0.43	0.29±0.04	1.85±0.55
N36A	7.67±0.77	3.53±0.30	7.75±0.78	3.52±0.31	3.83±0.39	3.30±0.32

Table B.6: Continued.

Names	C ₂ H N=1-0, J=3/2-1/2, F=1-0*		C ₂ H N=1-0, J=1/2-1/2, F=1-1*		C ₂ H N=1-, J=1/2-1/2, F=0-1*	
	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$
	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]
N38B	—	—	—	—	—	—
N39	1.93±0.21	2.15±0.06	1.87±0.19	2.09±0.04	1.00±0.11	2.51±0.38
N40	6.81±0.68	3.00±0.15	6.78±0.68	3.04±0.20	3.56±0.36	2.94±0.16
N41A	7.26±0.73	3.46±0.17	7.26±0.73	3.52±0.22	3.67±0.37	3.23±0.25
N41B	—	—	—	—	—	—
N42A	—	—	—	—	—	—
N42B	7.85±0.79	2.95±0.05	8.03±0.81	2.89±0.06	3.90±0.40	2.84±0.11
N43	5.53±0.56	2.73±0.08	5.61±0.56	2.78±0.09	2.84±0.29	2.60±0.10
N44A	9.07±0.91	4.39±0.20	9.09±0.91	4.40±0.22	4.42±0.44	4.08±0.15
N45	3.89±0.40	2.79±0.14	3.83±0.39	2.82±0.17	1.85±0.19	2.50±0.19
N46	6.71±0.70	3.08±0.09	6.83±0.71	3.03±0.11	3.60±0.42	3.04±0.11
N47	6.45±0.66	2.69±0.14	6.40±0.65	2.60±0.10	3.27±0.38	2.62±0.08
N48	7.18±0.72	3.01±0.07	7.13±0.72	3.00±0.04	3.50±0.36	2.73±0.05
N49	1.91±0.20	2.31±0.10	1.96±0.20	2.42±0.15	0.94±0.11	2.19±0.15
N5	1.84±0.21	2.40±0.09	1.82±0.20	2.28±0.07	0.85±0.11	2.45±0.20
N50	5.08±0.52	2.91±0.11	4.94±0.50	2.85±0.07	2.50±0.25	2.75±0.11
N51	4.86±0.49	2.43±0.06	4.82±0.48	2.42±0.10	2.44±0.25	2.29±0.02
N52	3.03±0.31	2.43±0.04	3.03±0.32	2.45±0.06	1.43±0.16	2.05±0.11
N53	3.97±0.40	2.60±0.07	3.90±0.40	2.55±0.07	1.96±0.21	2.52±0.12
N54	3.98±0.41	2.59±0.05	3.82±0.39	2.41±0.06	1.91±0.21	2.40±0.09
N55A	—	—	—	—	—	—
N55B	2.34±0.24	3.01±0.58	2.18±0.23	2.90±0.20	0.97±0.14	3.00±0.20
N56	1.28±0.17	2.31±0.22	1.78±0.19	3.16±0.21	1.02±0.13	3.88±0.60
N57	1.46±0.19	2.06±0.09	1.65±0.18	2.39±0.07	0.85±0.10	2.28±0.39
N58	0.94±0.11	3.50±0.39	0.83±0.11	3.18±0.25	0.36±0.07	2.78±0.19
N6	1.96±0.21	2.89±0.15	1.89±0.20	2.67±0.13	0.95±0.12	2.91±0.12
N61	0.48±0.09	2.22±0.22	0.69±0.11	2.15±0.37	0.37±0.09	1.92±1.15
N63	1.52±0.17	1.87±0.10	1.81±0.19	2.14±0.16	0.74±0.08	1.64±0.11
N64	1.25±0.14	1.98±0.08	1.33±0.15	2.18±0.06	0.55±0.07	1.90±0.18
N65	1.83±0.19	2.31±0.13	1.63±0.18	2.24±0.10	0.87±0.11	2.43±0.11
N66	2.04±0.22	3.85±0.38	1.90±0.20	3.90±0.35	0.74±0.09	3.59±0.51
N67	1.94±0.21	2.71±0.12	1.78±0.19	2.67±0.08	0.72±0.10	2.95±0.22
N68	1.29±0.14	2.29±0.28	1.42±0.16	2.55±0.16	0.53±0.07	2.44±0.24
N68-8	1.30±0.16	2.07±0.19	1.41±0.18	2.12±0.14	0.64±0.13	2.49±0.40
N69	3.16±0.33	2.72±0.09	3.37±0.34	2.87±0.10	1.46±0.15	2.26±0.16
N71	1.60±0.17	2.52±0.11	1.61±0.17	2.49±0.12	0.70±0.10	2.35±0.17
N72	2.33±0.26	2.89±0.21	2.21±0.24	2.84±0.22	0.76±0.10	2.30±0.06
W75N-6	1.16±0.13	1.87±0.10	1.38±0.17	2.05±0.25	0.44±0.07	1.64±0.39

Table B.7: Continued.

Names	C ₂ H		C ₂ S		C ₂ S	
	N=1-0, J=1/2-1/2, F=1-0*		N=6-5, J=5-4		N=11-10, J=10-10	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	0.51±0.09	2.81±0.17	—	—	0.96±0.12	2.06±0.01
C09-2	0.28±0.06	3.93±1.64	0.31±0.09	3.03±0.37	0.37±0.07	1.16±0.04
DR21-12	0.44±0.05	2.32±0.43	—	—	0.43±0.07	1.73±0.06
DR21-19	0.49±0.06	2.76±0.22	—	—	0.33±0.05	2.35±0.37
N03-2	0.22±0.09	1.66±0.15	0.21±0.08	1.84±0.55	0.42±0.13	2.69±0.16
N05-5	0.25±0.06	3.02±0.79	—	—	0.09±0.04	0.80±0.07
N05-6	0.27±0.07	2.76±0.59	—	—	0.60±0.08	1.53±0.01
N1	0.73±0.10	2.09±0.12	—	—	2.84±0.31	3.03±0.05
N10	0.81±0.08	3.47±0.13	—	—	2.05±0.21	2.47±0.08
N11	0.30±0.08	2.00±0.08	0.14±0.07	0.80±2.22	0.39±0.11	1.07±0.00
N12	0.83±0.14	2.77±0.11	0.19±0.06	1.81±0.41	5.07±0.55	3.03±0.23
N12-4	0.22±0.07	1.11±0.06	0.11±0.06	0.80±3.90	0.41±0.08	1.16±0.11
N12-6	0.21±0.06	0.95±2.45	—	—	0.28±0.10	1.07±0.07
N12-7	0.57±0.12	2.16±0.24	—	—	0.98±0.16	2.03±0.07
N13	0.73±0.13	3.93±0.55	0.22±0.07	1.41±0.34	3.73±0.42	3.20±0.33
N14	0.54±0.07	2.43±0.14	—	—	1.56±0.17	2.87±0.04
N15	0.30±0.05	3.06±1.62	—	—	0.08±0.03	0.80±0.00
N16	0.25±0.07	1.94±0.48	0.09±0.05	0.80±79.73	0.56±0.13	2.27±0.43
N17	—	—	—	—	0.23±0.07	1.91±0.10
N18	0.38±0.06	1.35±0.09	—	—	1.29±0.16	1.10±0.06
N2	1.06±0.14	2.73±0.13	—	—	3.75±0.38	2.84±0.06
N20	—	—	—	—	0.23±0.08	0.80±0.74
N21	0.23±0.05	1.18±0.05	—	—	0.37±0.08	1.32±0.17
N22	0.22±0.06	1.68±0.08	0.20±0.06	1.79±0.13	0.73±0.11	1.52±0.06
N23	0.20±0.04	1.13±0.00	0.26±0.07	3.23±0.79	—	—
N24	0.32±0.06	1.37±0.05	0.28±0.10	2.36±0.58	0.68±0.10	1.13±0.05
N25	0.14±0.02	1.26±0.05	—	—	0.31±0.05	1.24±0.02
N26	0.53±0.10	2.50±0.34	0.14±0.04	1.75±0.28	0.30±0.08	1.52±0.11
N27	0.65±0.08	2.06±0.17	0.13±0.04	1.92±0.31	3.54±0.37	1.84±0.06
N28	0.42±0.08	24.31±8.44	0.12±0.03	1.96±0.16	0.47±0.08	2.46±0.21
N3	1.05±0.13	2.65±0.14	0.09±0.04	1.20±0.00	4.74±0.48	2.98±0.11
N30	0.70±0.10	2.65±0.16	0.26±0.09	2.11±0.18	7.57±0.77	3.71±0.26
N31	0.92±0.14	3.33±0.13	0.09±0.04	1.52±0.46	6.80±0.69	3.37±0.14
N32	0.57±0.12	3.23±0.25	0.12±0.06	1.84±0.25	5.38±0.56	2.98±0.23
N33	0.22±0.07	2.22±0.40	0.11±0.04	1.41±0.08	0.36±0.10	1.45±0.07
N36A	2.10±0.23	2.94±0.27	0.24±0.06	4.12±1.73	9.62±0.97	2.89±0.24
N36B	—	—	—	—	—	—
N37	1.34±0.14	2.90±0.10	0.25±0.05	3.50±0.95	6.12±0.62	2.82±0.06
N38A	2.40±0.25	3.03±0.09	—	—	15.04±1.51	3.65±0.08

Table B.8: Continued.

Names	C ₂ H		C ₂ S		C ₂ S	
	N=1-0, J=1/2-1/2, F=1-0*		N=6-5, J=5-4		N=11-10, J=10-10	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	—	—	—	—	—	—
N39	0.40±0.05	1.84±0.13	—	—	0.39±0.06	1.93±0.28
N40	1.84±0.20	2.72±0.08	0.09±0.04	0.80±0.28	8.50±0.85	2.67±0.08
N41A	2.03±0.21	2.97±0.14	—	—	10.06±1.01	3.19±0.27
N41B	—	—	—	—	—	—
N42A	—	—	—	—	—	—
N42B	2.16±0.22	2.73±0.10	0.34±0.08	2.11±0.46	12.64±1.27	2.80±0.09
N43	1.51±0.16	2.62±0.06	0.26±0.04	2.82±0.43	8.40±0.84	2.66±0.05
N44A	2.32±0.24	3.43±0.13	0.46±0.08	4.61±1.22	15.14±1.52	4.48±0.34
N45	1.08±0.13	2.61±0.13	—	—	3.49±0.36	2.54±0.12
N46	2.18±0.23	2.90±0.10	0.21±0.06	1.70±0.34	11.21±1.13	2.88±0.09
N47	1.85±0.20	2.72±0.16	0.15±0.07	0.80±0.00	8.79±0.88	2.42±0.07
N48	2.03±0.21	2.87±0.10	—	—	11.23±1.13	2.95±0.04
N49	0.43±0.05	1.93±0.05	—	—	0.60±0.08	2.02±0.13
N5	0.46±0.08	2.18±0.31	0.07±0.04	0.80±0.00	1.12±0.14	1.67±0.05
N50	1.47±0.16	2.69±0.13	0.25±0.07	1.46±0.09	6.10±0.61	2.58±0.08
N51	1.34±0.14	2.30±0.08	0.29±0.04	4.07±0.93	7.15±0.72	2.34±0.03
N52	0.73±0.08	2.08±0.11	0.32±0.08	5.50±1.62	2.87±0.29	2.23±0.04
N53	0.98±0.12	2.21±0.13	—	—	4.55±0.46	2.35±0.06
N54	1.06±0.13	2.12±0.05	0.23±0.06	3.46±0.95	4.42±0.45	2.25±0.02
N55A	—	—	—	—	—	—
N55B	0.62±0.07	2.78±0.22	1.36±0.19	5.26±0.99	0.55±0.09	2.80±0.24
N56	0.52±0.09	3.05±0.25	—	—	1.85±0.22	3.00±0.13
N57	0.57±0.08	2.49±0.22	0.09±0.04	1.18±0.02	2.27±0.26	3.46±0.31
N58	0.23±0.06	2.72±0.60	—	—	0.12±0.04	1.35±0.09
N6	0.40±0.07	2.81±0.41	0.19±0.07	1.95±0.24	1.42±0.16	2.33±0.10
N61	0.16±0.04	2.68±0.45	0.17±0.07	0.80±0.00	0.57±0.11	1.59±0.09
N63	0.61±0.09	2.53±0.30	0.11±0.06	0.80±2.44	1.97±0.22	1.84±0.12
N64	0.45±0.06	3.32±0.24	—	—	0.67±0.09	1.39±0.07
N65	0.53±0.08	2.50±0.25	—	—	1.17±0.13	1.55±0.08
N66	0.41±0.06	3.10±0.47	0.16±0.06	1.32±0.09	0.70±0.11	2.05±0.20
N67	0.64±0.10	3.19±0.33	0.11±0.04	1.74±0.40	0.95±0.13	1.88±0.10
N68	0.29±0.04	1.82±0.31	—	—	0.57±0.08	1.95±0.19
N68-8	0.32±0.10	2.78±0.42	—	—	0.21±0.07	0.91±0.78
N69	0.87±0.10	2.69±0.22	—	—	1.30±0.15	1.74±0.13
N71	0.44±0.08	2.12±0.10	—	—	0.51±0.08	0.95±0.00
N72	0.54±0.09	3.01±0.65	0.99±0.24	11.52±3.33	0.48±0.11	1.69±0.11
W75N-6	0.35±0.06	2.25±0.33	—	—	0.86±0.13	1.33±0.07

Table B.9: Continued.

Names	CH ₃ CN 4(1)–3(1)		CH ₃ CN 4(0)–3(0)		CH ₃ CN 5(0)–4(0)	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	0.39±0.10	5.26±1.45	0.16±0.06	1.59±0.07	–	–
C09-2	–	–	–	–	0.09±0.04	1.21±0.01
DR21-12	–	–	0.21±0.05	2.17±0.38	0.12±0.04	1.61±0.04
DR21-19	0.16±0.04	1.27±0.01	0.21±0.05	1.87±0.14	0.19±0.04	1.69±0.24
N03-2	0.77±0.17	6.06±0.97	0.36±0.12	3.07±0.40	–	–
N05-5	0.20±0.07	2.62±0.69	0.26±0.09	1.93±0.23	0.11±0.06	0.80±0.90
N05-6	–	–	–	–	0.16±0.04	1.82±0.10
N1	0.39±0.09	2.63±0.09	0.44±0.08	1.82±0.04	0.47±0.09	2.35±0.10
N10	0.25±0.06	2.69±0.17	0.27±0.06	2.50±0.29	0.21±0.04	1.83±0.08
N11	0.13±0.08	0.80±3.65	0.17±0.07	0.80±0.00	0.12±0.06	1.34±0.19
N12	0.67±0.18	3.82±0.69	0.90±0.19	3.82±0.66	0.77±0.13	6.06±1.95
N12-4	–	–	–	–	–	–
N12-6	0.14±0.05	1.64±0.40	–	–	–	–
N12-7	0.17±0.07	0.80±1.21	0.38±0.09	6.70±9.12	0.10±0.04	1.00±0.54
N13	0.53±0.13	2.30±0.31	0.99±0.19	6.31±3.52	0.70±0.13	8.79±9.69
N14	–	–	0.42±0.08	3.30±0.27	0.34±0.05	2.74±0.36
N15	–	–	0.36±0.07	3.09±0.44	0.70±0.10	16.04±9.11
N16	–	–	0.13±0.05	0.80±0.01	0.08±0.04	0.80±0.00
N17	0.25±0.07	2.93±0.33	0.18±0.06	2.60±0.59	–	–
N18	0.13±0.07	0.80±0.00	2.31±0.34	28.18±30.00	0.20±0.06	1.62±0.10
N2	0.46±0.09	2.78±0.16	0.73±0.13	3.57±0.69	0.90±0.12	4.54±0.40
N20	–	–	–	–	0.12±0.04	1.77±0.65
N21	0.11±0.05	1.53±0.01	–	–	0.29±0.06	4.21±1.58
N22	0.12±0.06	1.66±0.31	–	–	0.10±0.03	1.34±0.46
N23	–	–	0.28±0.08	2.46±0.29	0.07±0.03	0.80±0.04
N24	–	–	–	–	–	–
N25	–	–	0.20±0.04	3.10±0.62	–	–
N26	–	–	0.06±0.04	1.09±0.01	0.23±0.04	3.90±2.15
N27	0.20±0.04	1.37±0.07	0.35±0.05	2.35±0.20	0.30±0.04	1.72±0.23
N28	–	–	–	–	–	–
N3	0.41±0.08	2.03±0.31	0.73±0.13	3.41±0.67	0.93±0.12	3.40±0.19
N30	1.01±0.19	3.36±0.23	1.11±0.19	3.03±0.38	1.77±0.22	4.47±0.12
N31	1.29±0.24	3.96±0.42	0.93±0.18	3.22±0.55	1.72±0.22	4.93±0.45
N32	0.99±0.16	3.84±0.46	0.58±0.11	2.34±0.45	1.06±0.14	3.98±0.25
N33	–	–	–	–	0.09±0.04	1.57±0.50
N36A	1.05±0.15	3.47±0.28	1.23±0.18	3.03±0.21	1.20±0.15	2.82±0.13
N36B	–	–	–	–	–	–
N37	0.65±0.08	3.34±0.32	0.64±0.10	2.99±0.11	0.64±0.10	3.17±0.13
N38A	1.55±0.20	3.93±0.10	1.53±0.20	2.96±0.12	1.88±0.25	3.24±0.24

Table B.10: Continued.

Names	CH ₃ CN 4(1)–3(1)		CH ₃ CN 4(0)–3(0)		CH ₃ CN 5(0)–4(0)	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	–	–	–	–	–	–
N39	0.36±0.09	5.02±2.48	0.25±0.07	2.52±0.21	0.15±0.03	1.02±4.39
N40	0.81±0.12	2.50±0.32	1.06±0.13	2.72±0.15	0.99±0.13	2.54±0.15
N41A	1.35±0.17	3.95±0.50	1.39±0.19	3.22±0.10	1.28±0.16	3.02±0.17
N41B	–	–	–	–	–	–
N42A	–	–	–	–	–	–
N42B	0.82±0.12	2.44±0.16	1.03±0.15	2.97±0.05	1.53±0.17	3.28±0.20
N43	0.71±0.10	2.77±0.19	0.85±0.11	2.69±0.09	0.89±0.11	2.78±0.08
N44A	1.87±0.21	4.63±0.28	1.66±0.23	3.40±0.31	2.11±0.28	3.74±0.32
N45	0.23±0.06	2.80±0.53	0.39±0.09	2.46±0.12	0.31±0.04	2.47±0.27
N46	0.38±0.08	1.71±0.16	0.69±0.13	3.14±0.45	1.50±0.18	3.63±0.40
N47	0.48±0.11	2.13±0.07	0.67±0.13	2.15±0.22	1.05±0.14	2.51±0.23
N48	1.22±0.16	3.61±0.33	1.51±0.20	3.34±0.10	1.48±0.18	2.71±0.10
N49	0.07±0.04	1.01±0.65	0.18±0.06	1.68±0.12	0.17±0.04	2.61±0.39
N5	–	–	–	–	–	–
N50	0.28±0.08	2.60±0.46	0.56±0.11	2.79±0.23	0.48±0.09	2.31±0.22
N51	0.66±0.09	2.14±0.08	0.82±0.11	2.65±0.11	0.71±0.09	2.29±0.08
N52	0.21±0.05	1.62±0.05	0.46±0.08	2.65±0.37	0.38±0.07	3.24±0.42
N53	0.52±0.09	2.55±0.41	0.64±0.10	2.67±0.35	0.69±0.10	3.29±0.12
N54	0.54±0.11	2.98±0.41	0.55±0.09	2.82±0.25	0.60±0.09	2.72±0.14
N55A	–	–	–	–	–	–
N55B	0.49±0.11	6.09±1.75	0.36±0.08	1.98±0.20	0.11±0.03	1.56±0.08
N56	0.34±0.09	4.07±0.96	0.46±0.11	2.59±0.18	0.31±0.07	3.66±1.13
N57	–	–	0.25±0.07	2.74±0.73	0.17±0.06	1.24±0.02
N58	0.44±0.10	5.31±1.47	–	–	–	–
N6	–	–	–	–	0.17±0.04	2.42±0.19
N61	0.20±0.06	2.51±0.41	0.09±0.04	0.80±0.16	–	–
N63	0.26±0.07	1.71±0.32	0.33±0.08	2.36±0.33	0.40±0.08	3.79±0.42
N64	0.15±0.03	2.44±0.82	0.19±0.04	1.67±0.17	–	–
N65	1.28±0.18	5.78±1.18	0.31±0.09	4.05±0.67	0.17±0.04	1.47±0.13
N66	0.20±0.07	1.49±0.24	0.16±0.04	2.38±1.33	0.09±0.02	0.80±0.69
N67	0.32±0.07	0.81±18.04	1.77±0.25	16.40±11.67	–	–
N68	0.19±0.04	2.75±0.89	0.14±0.04	1.67±0.12	0.20±0.04	1.97±0.26
N68-8	–	–	0.08±0.05	0.93±2.62	0.24±0.06	1.78±0.35
N69	0.26±0.06	1.51±0.43	0.32±0.06	2.25±0.18	0.15±0.04	1.75±0.08
N71	–	–	0.19±0.06	2.47±0.28	–	–
N72	0.47±0.09	2.12±0.16	0.42±0.09	2.79±0.35	0.16±0.04	0.89±1.83
W75N-6	–	–	0.11±0.06	1.62±0.11	–	–

Table B.11: Continued.

Names	DCN $J=1-0$		DCN $J=3-2$		DCO ⁺ $J=1-0, F=1-1$	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	—	—	—	—	0.30±0.09	2.04±0.15
C09-2	—	—	—	—	0.71±0.12	1.50±0.12
DR21-12	0.27±0.08	2.17±0.37	0.23±0.06	2.67±1.14	1.60±0.19	1.72±0.05
DR21-19	0.10±0.04	3.66±1.71	—	—	0.64±0.10	2.16±0.18
N03-2	—	—	—	—	0.47±0.13	1.60±0.16
N05-5	—	—	—	—	0.91±0.14	1.77±0.07
N05-6	0.14±0.06	1.55±0.62	—	—	0.06±0.03	0.94±1.86
N1	0.40±0.13	2.64±0.28	—	—	0.76±0.12	2.53±0.10
N10	0.59±0.12	2.55±0.40	—	—	0.30±0.06	1.79±0.15
N11	—	—	—	—	0.81±0.18	2.47±0.27
N12	0.52±0.18	2.90±0.45	—	—	0.67±0.14	1.85±0.15
N12-4	—	—	—	—	0.45±0.11	1.50±0.17
N12-6	0.22±0.12	1.33±6.36	—	—	0.41±0.08	1.11±0.00
N12-7	0.30±0.16	2.53±0.85	—	—	1.14±0.17	2.59±0.19
N13	0.34±0.11	1.33±0.48	—	—	0.63±0.14	1.77±0.04
N14	0.81±0.11	2.21±0.92	—	—	0.93±0.19	13.82±4.16
N15	—	—	—	—	0.44±0.09	2.51±0.26
N16	—	—	—	—	0.38±0.15	1.97±0.21
N17	—	—	—	—	0.48±0.09	1.92±0.12
N18	0.18±0.07	1.52±0.70	—	—	0.39±0.08	1.19±0.15
N2	0.53±0.15	2.96±0.56	—	—	0.66±0.10	2.39±0.15
N20	—	—	—	—	0.75±0.12	1.43±0.30
N21	—	—	—	—	1.46±0.16	1.35±0.09
N22	0.52±0.11	1.41±0.15	—	—	2.55±0.26	1.35±0.03
N23	0.15±0.06	2.22±0.54	—	—	0.62±0.09	1.44±0.06
N24	0.91±0.16	1.33±0.73	—	—	3.17±0.34	1.40±0.03
N25	0.47±0.08	1.33±0.24	—	—	1.22±0.14	1.71±0.02
N26	0.30±0.09	1.33±2.08	—	—	0.13±0.03	0.80±0.44
N27	0.24±0.08	2.36±0.76	—	—	0.38±0.06	2.31±0.32
N28	0.17±0.06	2.81±1.17	—	—	0.65±0.10	2.15±0.23
N3	0.63±0.15	2.82±0.28	—	—	0.99±0.14	2.56±0.16
N30	0.92±0.23	3.00±0.17	—	—	—	—
N31	0.99±0.24	3.18±0.16	—	—	0.38±0.09	1.88±0.37
N32	0.85±0.21	2.72±0.17	—	—	0.94±0.15	5.09±3.11
N33	—	—	—	—	0.49±0.10	1.14±0.02
N36A	1.01±0.20	3.09±0.17	0.64±0.07	2.69±0.37	1.41±0.16	3.29±0.38
N36B	—	—	—	—	—	—
N37	0.69±0.13	2.66±0.12	0.63±0.11	2.94±0.18	1.49±0.17	2.61±0.16
N38A	1.40±0.24	3.61±0.07	2.00±0.21	4.23±0.16	1.12±0.16	3.30±0.17

Table B.12: Continued.

Names	DCN $J=1-0$		DCN $J=3-2$		DCO ⁺ $J=1-0, F=1-1$	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	—	—	—	—	—	—
N39	0.44±0.08	1.33±0.11	—	—	1.58±0.18	1.63±0.01
N40	1.04±0.19	2.73±0.13	0.63±0.07	2.45±0.28	1.52±0.19	3.15±0.26
N41A	0.94±0.20	3.75±0.20	0.69±0.08	2.83±0.50	1.17±0.16	3.60±0.21
N41B	—	—	—	—	—	—
N42A	—	—	—	—	—	—
N42B	1.50±0.22	2.66±0.11	1.78±0.21	3.32±0.23	0.78±0.11	2.21±0.06
N43	1.01±0.15	2.33±0.12	0.91±0.14	2.54±0.36	1.79±0.19	2.51±0.13
N44A	1.25±0.24	4.61±0.10	4.92±0.50	5.64±0.10	1.50±0.20	4.77±0.73
N45	0.89±0.13	1.90±0.10	0.37±0.06	2.59±0.55	1.13±0.14	2.01±0.06
N46	1.07±0.20	3.10±0.18	3.92±0.46	6.32±0.22	1.21±0.16	3.56±0.31
N47	0.98±0.18	2.63±0.23	3.05±0.43	4.38±0.26	0.78±0.13	2.96±0.18
N48	1.27±0.21	2.82±0.12	2.04±0.21	3.07±0.12	0.70±0.12	3.31±0.23
N49	0.71±0.12	1.52±0.26	0.16±0.03	1.51±0.41	1.67±0.19	2.08±0.07
N5	0.48±0.10	1.62±0.41	—	—	0.29±0.08	1.92±0.35
N50	1.25±0.20	2.21±0.12	0.68±0.10	2.99±0.30	1.41±0.16	2.12±0.07
N51	1.54±0.18	1.99±0.06	1.27±0.14	2.70±0.11	1.96±0.21	2.06±0.07
N52	1.19±0.15	1.83±0.24	0.29±0.04	1.76±0.32	1.90±0.20	2.09±0.04
N53	1.06±0.17	1.89±0.12	0.55±0.07	2.67±0.31	1.72±0.19	2.17±0.06
N54	1.26±0.19	1.93±0.18	0.55±0.06	2.67±0.35	1.67±0.19	2.06±0.03
N55A	—	—	—	—	—	—
N55B	0.63±0.12	1.44±0.29	—	—	1.75±0.20	1.77±0.02
N56	0.28±0.13	2.61±0.56	—	—	0.32±0.07	1.41±0.29
N57	0.43±0.15	2.28±0.55	—	—	0.84±0.13	1.97±0.26
N58	—	—	—	—	—	—
N6	0.20±0.12	4.04±0.90	—	—	0.12±0.04	1.10±0.95
N61	—	—	—	—	1.31±0.18	1.66±0.04
N63	0.42±0.12	1.96±0.67	—	—	1.28±0.14	1.60±0.06
N64	—	—	—	—	1.00±0.11	1.36±0.04
N65	0.65±0.12	1.33±0.25	—	—	0.82±0.09	1.00±0.15
N66	0.64±0.12	1.41±0.28	—	—	1.23±0.13	1.43±0.05
N67	0.61±0.12	1.33±0.14	—	—	1.06±0.13	1.39±0.07
N68	0.34±0.07	1.39±0.35	—	—	0.43±0.07	1.26±0.10
N68-8	0.30±0.10	1.33±1.43	—	—	0.25±0.09	1.54±0.25
N69	0.51±0.12	1.71±0.36	—	—	1.04±0.12	1.53±0.11
N71	0.28±0.06	1.33±0.35	—	—	0.28±0.05	0.80±0.00
N72	—	—	—	—	0.27±0.08	0.80±5.95
W75N-6	0.21±0.16	4.26±0.99	—	—	0.73±0.11	1.73±0.12

Table B.13: Continued.

Names	DCO ⁺		DNC		DNC	
	<i>J</i> =3–2, <i>F</i> =3–2		<i>J</i> = 1 – 0		<i>J</i> = 2 – 1	
	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]
C09-1	–	–	0.21±0.06	1.29±0.04	–	–
C09-2	–	–	0.30±0.06	1.47±0.06	–	–
DR21-12	0.60±0.07	1.55±0.13	0.99±0.11	1.70±0.04	0.53±0.05	1.28±0.13
DR21-19	–	–	0.30±0.04	1.98±0.37	–	–
N03-2	–	–	0.59±0.13	2.46±0.50	–	–
N05-5	–	–	0.54±0.09	3.73±0.40	–	–
N05-6	–	–	0.36±0.05	1.47±0.13	–	–
N1	–	–	0.83±0.18	2.10±0.24	–	–
N10	–	–	0.36±0.06	2.08±0.10	–	–
N11	–	–	0.43±0.10	1.61±0.20	–	–
N12	–	–	0.85±0.14	2.28±0.23	–	–
N12-4	–	–	0.64±0.11	2.25±0.17	–	–
N12-6	–	–	0.41±0.08	1.65±0.04	–	–
N12-7	–	–	0.71±0.12	1.32±0.22	–	–
N13	–	–	0.85±0.13	1.90±0.07	–	–
N14	–	–	–	–	–	–
N15	–	–	0.17±0.04	2.36±0.34	–	–
N16	–	–	0.63±0.10	1.78±0.15	–	–
N17	–	–	–	–	–	–
N18	–	–	0.44±0.09	2.09±0.19	–	–
N2	–	–	0.98±0.16	2.18±0.10	–	–
N20	–	–	0.27±0.08	1.30±0.11	–	–
N21	–	–	0.93±0.10	1.41±0.04	–	–
N22	–	–	1.65±0.18	1.49±0.04	–	–
N23	–	–	0.57±0.12	3.42±0.94	–	–
N24	–	–	2.06±0.22	1.64±0.02	–	–
N25	–	–	0.62±0.07	1.54±0.05	–	–
N26	–	–	0.29±0.05	1.47±0.05	–	–
N27	–	–	0.31±0.05	2.37±0.32	–	–
N28	–	–	0.61±0.07	2.21±0.24	–	–
N3	–	–	0.94±0.16	2.06±0.08	–	–
N30	–	–	0.76±0.10	2.92±0.20	–	–
N31	–	–	0.97±0.12	3.32±0.31	–	–
N32	–	–	0.78±0.10	2.14±0.04	–	–
N33	–	–	0.25±0.06	1.65±0.52	–	–
N36A	0.98±0.10	3.65±0.24	2.18±0.23	2.74±0.25	1.45±0.15	2.10±0.28
N36B	–	–	–	–	–	–
N37	0.77±0.09	2.84±0.27	1.80±0.19	2.78±0.05	1.22±0.13	2.57±0.13
N38A	1.33±0.14	3.31±0.09	2.21±0.23	3.20±0.08	2.17±0.23	3.59±0.19

Table B.14: Continued.

Names	DCO ⁺		DNC		DNC	
	<i>J</i> =3–2, <i>F</i> =3–2		<i>J</i> = 1 – 0		<i>J</i> = 2 – 1	
	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]
N38B	–	–	–	–	–	–
N39	0.94±0.10	1.43±0.08	0.98±0.11	1.68±0.05	0.85±0.10	1.46±0.09
N40	1.01±0.10	3.23±0.18	2.13±0.23	2.84±0.16	1.61±0.17	2.64±0.11
N41A	0.68±0.07	3.58±0.27	1.80±0.19	3.08±0.24	1.63±0.18	4.28±0.31
N41B	–	–	–	–	–	–
N42A	–	–	–	–	–	–
N42B	0.85±0.11	2.66±0.17	1.76±0.19	2.49±0.09	2.10±0.21	2.69±0.13
N43	0.95±0.12	2.78±0.21	2.01±0.20	2.86±0.09	1.33±0.14	2.72±0.15
N44A	1.81±0.19	5.14±0.18	1.85±0.19	3.70±0.17	2.96±0.31	6.65±0.32
N45	0.92±0.10	1.63±0.09	1.35±0.15	2.25±0.07	1.09±0.12	1.91±0.08
N46	0.94±0.11	2.89±0.30	1.78±0.19	3.23±0.33	2.15±0.22	2.89±0.14
N47	0.67±0.13	2.60±0.26	1.28±0.14	2.64±0.11	1.41±0.16	2.50±0.17
N48	0.80±0.09	3.73±0.25	1.51±0.17	3.50±0.15	1.81±0.19	3.80±0.44
N49	0.79±0.09	1.72±0.09	1.23±0.13	1.97±0.04	0.83±0.08	1.45±0.07
N5	–	–	0.69±0.11	2.33±0.22	–	–
N50	0.84±0.09	2.05±0.15	1.87±0.20	2.31±0.04	1.48±0.17	2.20±0.07
N51	1.27±0.13	1.79±0.05	2.39±0.25	2.16±0.06	1.87±0.19	1.84±0.05
N52	1.16±0.12	1.85±0.07	1.87±0.20	2.06±0.07	1.57±0.16	1.77±0.05
N53	1.08±0.12	2.19±0.07	1.77±0.19	2.13±0.06	1.42±0.14	2.02±0.09
N54	1.01±0.10	1.97±0.06	1.95±0.21	2.06±0.03	1.43±0.15	1.94±0.08
N55A	–	–	–	–	–	–
N55B	1.07±0.12	1.41±0.09	1.41±0.15	1.72±0.05	0.90±0.09	1.25±0.06
N56	–	–	0.62±0.09	2.26±0.09	–	–
N57	–	–	0.96±0.12	2.04±0.06	–	–
N58	–	–	0.70±0.10	4.58±0.54	–	–
N6	–	–	0.66±0.10	2.45±0.35	–	–
N61	–	–	0.56±0.09	1.55±0.20	–	–
N63	–	–	0.64±0.08	1.86±0.05	–	–
N64	–	–	0.74±0.08	1.75±0.07	–	–
N65	–	–	0.54±0.08	1.56±0.09	–	–
N66	–	–	0.81±0.09	1.74±0.07	–	–
N67	–	–	0.67±0.07	1.46±0.07	–	–
N68	–	–	0.50±0.06	2.09±0.16	–	–
N68-8	–	–	0.36±0.08	1.63±0.08	–	–
N69	–	–	1.34±0.15	2.05±0.06	–	–
N71	–	–	0.33±0.05	1.35±0.20	–	–
N72	–	–	0.35±0.08	2.20±0.52	–	–
W75N-6	–	–	0.48±0.09	1.57±0.21	–	–

Table B.15: Continued.

Names	H^{13}CN		H^{13}CO^+		HC_5N	
	$J = 1 - 0$		$J = 1 - 0$		$J = 27 - 26$	
	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]
C09-1	0.23±0.08	2.50±0.29	1.16±0.14	2.36±0.19	0.18±0.06	1.61±0.07
C09-2	—	—	0.67±0.09	1.88±0.12	—	—
DR21-12	0.40±0.07	1.62±0.14	1.61±0.16	1.50±0.12	—	—
DR21-19	0.13±0.04	1.93±0.22	1.16±0.12	1.70±0.22	—	—
N03-2	0.23±0.06	1.57±1.11	0.59±0.11	2.57±0.14	—	—
N05-5	0.11±0.07	2.42±0.79	0.82±0.11	2.25±0.15	—	—
N05-6	0.17±0.07	1.70±0.33	0.61±0.07	1.35±0.06	—	—
N1	0.56±0.13	2.71±0.11	2.98±0.30	2.48±0.15	0.23±0.06	1.32±0.22
N10	0.45±0.09	2.80±0.07	2.08±0.21	2.83±0.06	1.08±0.16	9.11±1.85
N11	1.37±0.21	1.71±0.27	0.90±0.12	1.66±0.06	—	—
N12	0.95±0.20	3.29±0.19	3.25±0.34	2.55±0.07	—	—
N12-4	0.29±0.11	1.75±0.10	0.82±0.12	1.70±0.05	0.26±0.10	1.49±0.15
N12-6	0.31±0.13	1.33±0.43	1.01±0.13	1.50±0.11	0.07±0.05	0.80±0.42
N12-7	0.30±0.16	2.50±0.63	0.96±0.12	1.88±0.42	—	—
N13	0.79±0.20	3.34±0.25	2.35±0.25	2.51±0.08	0.22±0.08	2.28±0.64
N14	0.38±0.09	3.18±0.10	1.29±0.14	2.75±0.08	—	—
N15	—	—	1.10±0.12	3.94±0.45	—	—
N16	0.09±0.10	2.81±1.79	0.64±0.10	1.47±0.12	0.13±0.05	1.13±0.25
N17	0.26±0.08	2.31±0.38	0.61±0.07	2.24±0.17	—	—
N18	0.75±0.14	1.33±0.54	1.36±0.16	1.55±0.04	0.77±0.21	10.09±13.78
N2	0.80±0.14	2.69±0.12	3.70±0.38	2.40±0.07	0.37±0.07	2.61±0.32
N20	0.17±0.09	1.33±0.15	0.89±0.12	1.64±0.05	0.29±0.09	4.08±1.19
N21	0.37±0.09	1.49±0.40	1.32±0.14	1.56±0.06	0.21±0.08	2.03±0.16
N22	0.37±0.09	1.70±0.21	1.97±0.21	1.54±0.02	—	—
N23	0.30±0.08	1.33±0.58	0.68±0.09	1.93±0.18	—	—
N24	0.50±0.09	1.33±0.13	2.24±0.23	1.54±0.01	—	—
N25	0.13±0.04	2.04±0.40	1.19±0.12	1.66±0.00	—	—
N26	—	—	0.37±0.06	1.44±0.08	0.45±0.16	8.91±5.22
N27	0.52±0.09	2.51±0.11	2.37±0.24	2.24±0.07	0.24±0.05	3.84±1.10
N28	0.27±0.06	2.11±0.27	1.62±0.17	1.86±0.08	0.13±0.03	1.90±0.30
N3	0.83±0.16	2.91±0.06	4.43±0.45	2.56±0.07	0.36±0.08	1.70±0.12
N30	1.53±0.22	3.82±0.06	6.69±0.68	3.69±0.07	0.39±0.11	1.76±0.33
N31	1.31±0.19	3.88±0.08	6.67±0.67	3.99±0.18	—	—
N32	1.21±0.19	3.30±0.06	5.35±0.55	3.30±0.04	0.41±0.13	1.90±0.24
N33	0.30±0.06	1.77±0.68	1.26±0.14	1.42±0.04	0.15±0.08	1.35±1.12
N36A	1.32±0.20	3.29±0.09	7.24±0.73	3.46±0.27	0.26±0.07	1.04±0.07
N36B	—	—	—	—	—	—
N37	0.83±0.16	3.18±0.05	5.09±0.51	2.75±0.03	0.48±0.09	3.75±0.39
N38A	2.10±0.26	3.75±0.06	9.28±0.93	3.40±0.08	0.65±0.09	2.50±0.13

Table B.16: Continued.

Names	H^{13}CN $J = 1 - 0$		H^{13}CO^+ $J = 1 - 0$		HC_5N $J = 27 - 26$	
	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]
N38B	—	—	—	—	—	—
N39	0.22±0.08	2.25±0.35	1.68±0.18	1.56±0.07	0.17±0.06	1.18±0.03
N40	1.18±0.18	3.06±0.06	6.55±0.66	3.08±0.13	0.40±0.09	1.76±0.06
N41A	1.25±0.19	3.36±0.05	6.79±0.68	3.46±0.13	0.28±0.05	1.71±0.27
N41B	—	—	—	—	—	—
N42A	1.64±0.22	3.31±0.04	—	—	—	—
N42B	—	—	6.16±0.62	2.96±0.12	1.09±0.14	2.45±0.23
N43	1.28±0.16	2.95±0.03	6.33±0.64	2.54±0.06	0.69±0.08	2.45±0.14
N44A	2.10±0.26	4.48±0.07	9.26±0.93	3.59±0.17	0.32±0.07	2.28±0.21
N45	0.61±0.09	2.31±0.08	3.88±0.40	2.13±0.07	0.87±0.16	14.89±14.00
N46	1.24±0.19	4.34±0.09	6.65±0.67	3.43±0.18	0.99±0.15	2.44±0.16
N47	1.45±0.20	2.89±0.05	4.76±0.49	2.66±0.10	0.73±0.11	1.81±0.01
N48	1.63±0.21	3.06±0.03	5.83±0.59	3.09±0.10	1.02±0.14	5.05±0.89
N49	0.29±0.06	1.64±0.15	2.05±0.21	2.15±0.08	—	—
N5	0.35±0.10	2.04±0.16	1.91±0.20	1.77±0.11	—	—
N50	0.81±0.15	2.47±0.07	4.67±0.48	2.34±0.04	0.32±0.08	2.08±0.50
N51	1.51±0.17	2.46±0.03	6.96±0.70	2.20±0.06	0.58±0.07	2.43±0.17
N52	0.84±0.13	2.07±0.11	3.87±0.39	2.03±0.01	0.13±0.06	1.06±0.13
N53	0.95±0.16	2.77±0.14	5.25±0.53	2.25±0.03	0.19±0.04	1.62±0.03
N54	1.12±0.17	2.54±0.01	6.03±0.61	2.26±0.06	0.26±0.06	3.28±0.52
N55A	—	—	—	—	—	—
N55B	0.29±0.09	2.12±0.20	2.30±0.24	1.54±0.04	—	—
N56	0.66±0.17	2.46±0.30	1.48±0.17	2.42±0.08	—	—
N57	0.40±0.13	2.10±0.25	1.48±0.17	2.00±0.09	—	—
N58	0.06±0.03	1.33±0.16	0.16±0.04	1.55±0.16	0.48±0.11	17.18±11.25
N6	0.39±0.12	2.49±0.18	2.17±0.23	2.66±0.22	—	—
N61	0.15±0.08	1.80±0.42	1.29±0.14	1.55±0.03	0.12±0.05	1.59±0.13
N63	0.35±0.11	2.80±0.19	2.12±0.22	1.88±0.05	0.22±0.05	3.50±0.46
N64	0.37±0.09	1.57±0.19	1.86±0.19	1.71±0.03	—	—
N65	0.38±0.11	2.21±0.20	2.38±0.24	1.78±0.05	—	—
N66	0.48±0.10	1.93±0.21	2.41±0.25	1.80±0.01	0.19±0.04	1.50±0.22
N67	0.61±0.11	1.59±0.12	2.39±0.25	1.81±0.00	—	—
N68	0.31±0.10	2.49±0.11	1.21±0.14	1.81±0.05	—	—
N68-8	0.22±0.11	1.36±0.98	0.68±0.12	1.81±0.10	—	—
N69	0.37±0.11	2.12±0.21	1.89±0.19	2.02±0.03	0.06±0.04	0.80±83.96
N71	0.20±0.07	1.77±0.50	0.70±0.09	1.79±0.17	0.24±0.06	1.90±0.34
N72	0.44±0.11	1.38±0.61	0.79±0.10	1.82±0.10	—	—
W75N-6	0.24±0.07	1.54±0.21	1.10±0.12	1.64±0.01	0.12±0.05	0.80±0.00

Table B.17: Continued.

Names	HC ¹³ CCN		HCO		HCO	
	$J = 8 - 7, F = 8 - 7$		1(0,1)–0(0,0), J=3/2–1/2, F=2–1*		1(0,1)–0(0,0), J=3/2–1/2, F=1–0*	
	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]
C09-1	0.14±0.03	0.80±0.02	1.13±0.17	14.94±1.36	0.53±0.11	4.54±1.41
C09-2	0.75±0.14	4.09±1.60	–	–	–	–
DR21-12	–	–	0.56±0.08	2.14±0.20	0.42±0.06	2.35±0.14
DR21-19	0.12±0.03	1.01±0.01	0.74±0.08	2.31±0.14	0.50±0.06	2.65±0.08
N03-2	0.29±0.10	1.96±0.52	0.39±0.08	2.26±0.37	0.27±0.08	2.56±0.30
N05-5	–	–	0.08±0.03	0.80±0.00	–	–
N05-6	–	–	0.39±0.06	1.69±0.19	0.21±0.05	1.61±0.29
N1	–	–	0.38±0.07	2.39±0.51	0.33±0.07	2.46±0.50
N10	–	–	0.48±0.06	2.67±0.06	0.37±0.06	3.09±0.44
N11	–	–	0.18±0.07	1.50±0.08	0.19±0.10	2.58±6.41
N12	0.16±0.08	2.64±0.34	0.08±0.05	0.80±4.24	0.24±0.07	3.60±1.13
N12-4	0.13±0.08	1.22±0.17	–	–	–	–
N12-6	0.26±0.13	8.63±4.59	0.14±0.06	1.47±0.06	0.19±0.06	1.63±0.35
N12-7	0.10±0.10	0.80±11.08	0.36±0.08	2.29±0.48	0.31±0.10	1.42±0.20
N13	–	–	1.21±0.23	15.16±9.05	0.27±0.08	3.42±1.28
N14	0.12±0.06	1.89±0.40	0.63±0.07	2.74±0.30	0.41±0.06	2.65±0.25
N15	–	–	0.70±0.09	4.29±0.17	0.31±0.05	3.26±0.30
N16	0.41±0.12	4.31±2.20	0.15±0.06	1.56±0.21	0.27±0.10	2.30±0.24
N17	0.20±0.04	2.12±0.58	0.11±0.03	1.54±0.21	0.20±0.04	2.52±0.34
N18	–	–	–	–	0.35±0.06	2.42±0.25
N2	0.08±0.04	0.82±2.44	0.54±0.09	3.31±0.32	0.33±0.09	2.69±0.40
N20	0.13±0.07	0.80±0.06	0.10±0.03	1.60±0.48	–	–
N21	–	–	0.24±0.06	2.44±0.71	0.21±0.06	3.69±0.84
N22	–	–	0.21±0.07	3.05±1.13	0.29±0.06	2.19±0.36
N23	0.06±0.04	0.80±0.06	0.37±0.06	1.65±0.12	0.27±0.06	1.92±0.26
N24	–	–	0.19±0.04	1.25±0.02	0.26±0.07	2.08±0.28
N25	0.10±0.03	1.72±0.06	0.34±0.05	2.94±0.36	0.26±0.04	2.84±0.22
N26	–	–	0.24±0.06	2.15±0.58	0.27±0.06	1.85±0.21
N27	0.13±0.04	2.16±0.28	–	–	–	–
N28	–	–	0.08±0.02	0.98±0.01	–	–
N3	0.12±0.04	1.52±0.25	0.55±0.09	3.81±0.46	0.28±0.08	2.93±0.30
N30	–	–	–	–	0.13±0.04	1.85±0.34
N31	–	–	0.38±0.07	4.90±1.57	0.13±0.06	1.76±0.36
N32	0.11±0.04	1.34±0.15	0.30±0.06	3.64±1.19	–	–
N33	–	–	0.06±0.03	0.80±0.00	–	–
N36A	0.19±0.07	2.59±0.46	–	–	–	–
N36B	–	–	1.02±0.12	2.69±0.25	0.63±0.09	2.99±0.22
N37	–	–	0.74±0.09	3.16±0.25	0.57±0.08	3.91±0.24
N38A	–	–	–	–	–	–

Table B.18: Continued.

Names	HC ¹³ CCN		HCO		HCO	
	$J = 8 - 7, F = 8 - 7$		$1(0,1)-0(0,0),$ $J=3/2-1/2, F=2-1^*$		$1(0,1)-0(0,0),$ $J=3/2-1/2, F=1-0^*$	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	—	—	0.97±0.11	3.46±0.27	0.70±0.10	4.32±0.46
N39	0.10±0.04	0.80±1.35	0.63±0.09	1.87±0.13	0.41±0.06	1.80±0.23
N40	0.09±0.05	0.80±0.00	1.01±0.12	2.39±0.23	0.80±0.11	3.05±0.19
N41A	—	—	—	—	—	—
N41B	—	—	1.21±0.14	2.72±0.19	0.89±0.11	3.52±0.25
N42A	—	—	—	—	—	—
N42B	0.38±0.09	2.96±0.97	0.74±0.09	2.88±0.32	0.60±0.07	2.74±0.28
N43	0.27±0.07	4.57±1.82	0.79±0.09	2.58±0.10	0.45±0.06	2.70±0.34
N44A	0.13±0.04	1.69±0.04	1.06±0.12	3.13±0.27	0.70±0.10	3.22±0.29
N45	0.16±0.04	2.10±0.80	0.63±0.09	2.92±0.35	0.50±0.09	2.91±0.20
N46	0.21±0.07	0.94±0.02	0.58±0.10	2.49±0.07	0.43±0.07	3.05±0.17
N47	1.24±0.28	16.96±14.96	0.83±0.11	3.40±0.29	0.49±0.08	2.89±0.14
N48	0.08±0.04	1.20±0.07	1.07±0.12	3.24±0.30	0.57±0.09	3.02±0.38
N49	—	—	0.40±0.06	2.41±0.22	0.32±0.05	2.58±0.31
N5	—	—	0.43±0.07	1.93±0.11	0.34±0.08	2.87±0.43
N50	0.38±0.11	2.45±0.48	0.48±0.07	2.68±0.33	0.54±0.09	3.21±0.18
N51	0.54±0.12	10.95±5.12	0.56±0.07	2.27±0.12	0.38±0.06	2.57±0.38
N52	0.08±0.03	0.80±0.47	0.51±0.07	1.89±0.05	0.37±0.05	1.69±0.12
N53	0.21±0.07	1.61±0.37	0.50±0.06	2.79±0.22	0.42±0.06	2.98±0.32
N54	0.08±0.04	0.80±0.00	0.46±0.08	2.95±0.43	0.46±0.06	3.82±0.64
N55A	—	—	—	—	—	—
N55B	—	—	0.63±0.09	2.48±0.21	0.33±0.06	1.97±0.18
N56	0.47±0.11	5.21±5.59	0.20±0.07	1.73±0.14	0.21±0.05	2.34±0.36
N57	—	—	0.24±0.06	2.90±0.65	0.32±0.08	2.86±0.37
N58	—	—	0.34±0.06	2.58±0.84	0.23±0.06	3.10±0.51
N6	—	—	0.38±0.07	2.96±0.24	0.22±0.07	2.18±0.33
N61	—	—	—	—	—	—
N63	—	—	0.12±0.03	1.13±0.01	0.17±0.04	1.57±0.27
N64	—	—	0.29±0.04	1.65±0.16	0.21±0.04	1.66±0.38
N65	—	—	0.23±0.06	2.52±0.80	0.09±0.02	0.80±7.13
N66	0.08±0.05	0.80±0.00	0.35±0.07	3.07±0.46	0.29±0.07	2.59±0.21
N67	—	—	0.20±0.04	1.54±0.12	0.31±0.07	2.80±0.38
N68	—	—	0.35±0.07	2.65±0.25	0.22±0.04	2.92±0.42
N68-8	—	—	0.50±0.09	2.02±0.06	0.64±0.11	3.48±0.61
N69	—	—	0.76±0.10	3.19±0.29	0.41±0.07	2.56±0.33
N71	—	—	0.38±0.08	2.78±0.35	0.38±0.07	2.56±0.16
N72	—	—	0.79±0.11	2.61±0.14	0.47±0.09	2.57±0.28
W75N-6	—	—	—	—	—	—

Table B.19: Continued.

Names	HCO		HCOOH		HN ¹³ C	
	1(0,1)–0(0,0), J=1/2–1/2, F=1–1*		4(1,4)–3(1,3)		J = 1 – 0	
	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]
C09-1	0.17±0.04	0.80±0.00	–	–	0.40±0.07	2.68±0.51
C09-2	–	–	–	–	0.37±0.06	1.29±0.03
DR21-12	0.30±0.06	2.31±0.18	–	–	0.60±0.08	1.74±0.05
DR21-19	0.51±0.07	2.44±0.21	–	–	0.19±0.04	2.26±0.50
N03-2	0.14±0.06	1.74±0.37	0.19±0.07	2.72±0.99	0.20±0.07	1.57±0.15
N05-5	–	–	–	–	0.19±0.06	1.33±0.07
N05-6	0.52±0.09	6.83±3.83	–	–	0.44±0.08	1.81±0.15
N1	0.45±0.09	2.89±0.40	0.14±0.04	1.67±0.08	1.63±0.18	2.49±0.13
N10	0.34±0.05	2.88±0.37	–	–	0.66±0.08	2.60±0.21
N11	0.12±0.05	1.14±0.04	0.16±0.04	1.39±0.22	0.66±0.10	1.95±0.17
N12	–	–	–	–	3.15±0.33	2.65±0.08
N12-4	0.14±0.06	1.13±0.33	–	–	0.66±0.10	1.58±0.10
N12-6	–	–	–	–	0.46±0.08	1.71±0.05
N12-7	0.39±0.09	3.14±0.77	–	–	0.93±0.14	1.87±0.07
N13	–	–	–	–	2.21±0.25	2.35±0.09
N14	0.36±0.05	2.17±0.05	0.10±0.02	1.52±0.04	0.50±0.06	3.01±0.18
N15	0.40±0.06	2.75±0.21	–	–	0.39±0.05	6.86±2.78
N16	0.19±0.06	1.67±0.24	–	–	0.80±0.11	1.68±0.02
N17	–	–	0.22±0.06	2.96±1.11	0.22±0.06	3.23±0.52
N18	–	–	–	–	0.55±0.09	1.34±0.20
N2	0.30±0.08	1.48±0.15	–	–	2.26±0.24	2.33±0.06
N20	–	–	–	–	0.51±0.11	8.73±6.88
N21	0.10±0.04	1.09±0.02	–	–	0.53±0.09	1.35±0.01
N22	0.17±0.04	2.29±0.37	–	–	0.90±0.12	1.40±0.06
N23	–	–	–	–	0.22±0.06	1.68±0.28
N24	0.14±0.04	1.97±0.28	–	–	1.12±0.14	1.49±0.05
N25	–	–	–	–	0.33±0.04	1.52±0.14
N26	0.16±0.04	1.33±0.22	–	–	0.28±0.07	3.11±0.80
N27	–	–	–	–	1.36±0.15	1.95±0.06
N28	–	–	0.11±0.02	1.98±0.44	0.58±0.08	1.90±0.17
N3	0.27±0.06	2.11±0.26	–	–	2.56±0.27	2.33±0.04
N30	0.18±0.06	1.59±0.38	0.25±0.06	3.15±0.88	1.74±0.20	3.19±0.12
N31	–	–	–	–	2.11±0.23	3.50±0.09
N32	0.48±0.09	8.25±5.48	–	–	1.47±0.16	2.58±0.07
N33	0.18±0.06	2.73±0.63	–	–	0.16±0.04	1.67±0.17
N36A	–	–	0.11±0.03	1.82±0.28	3.17±0.33	2.63±0.09
N36B	0.83±0.10	4.09±0.69	–	–	–	–
N37	0.45±0.06	2.93±0.28	–	–	2.47±0.25	2.79±0.06
N38A	–	–	–	–	4.55±0.46	3.25±0.11

Table B.20: Continued.

Names	HCO		HCOOH		HN ¹³ C	
	1(0,1)–0(0,0), J=1/2–1/2, F=1–1*		4(1,4)–3(1,3)		J = 1 – 0	
	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{–1}]	$\Delta\nu$ [km s ^{–1}]
N38B	0.80±0.09	4.52±1.17	–	–	–	–
N39	0.39±0.06	2.03±0.13	–	–	0.45±0.07	1.57±0.10
N40	0.72±0.10	2.71±0.18	–	–	3.15±0.33	2.46±0.04
N41A	0.81±0.11	3.77±0.52	–	–	3.00±0.31	2.62±0.10
N41B	–	–	–	–	–	–
N42A	–	–	–	–	–	–
N42B	0.42±0.06	2.00±0.17	–	–	3.53±0.36	2.67±0.08
N43	0.38±0.06	2.34±0.12	0.13±0.03	1.57±0.06	2.98±0.30	2.57±0.11
N44A	0.70±0.10	3.06±0.12	–	–	3.68±0.38	3.68±0.20
N45	0.47±0.08	2.86±0.37	–	–	1.43±0.16	2.29±0.03
N46	0.34±0.06	1.99±0.15	0.11±0.03	1.32±0.07	3.55±0.36	2.92±0.11
N47	0.35±0.06	2.10±0.18	0.12±0.03	1.35±0.23	2.74±0.29	2.30±0.08
N48	0.45±0.06	2.90±0.51	0.16±0.04	2.13±0.24	3.36±0.34	2.99±0.08
N49	0.44±0.08	2.55±0.16	0.12±0.04	1.62±0.07	0.79±0.10	1.78±0.11
N5	0.11±0.04	1.36±0.34	–	–	0.92±0.12	1.98±0.05
N50	0.39±0.08	3.46±0.46	–	–	2.10±0.22	2.30±0.05
N51	0.34±0.05	2.43±0.15	–	–	2.93±0.30	2.02±0.03
N52	0.32±0.04	2.39±0.40	–	–	1.76±0.19	2.06±0.08
N53	0.33±0.05	2.71±0.21	0.60±0.12	13.87±5.25	2.29±0.24	2.02±0.04
N54	0.38±0.07	2.58±0.25	0.48±0.09	3.79±0.74	2.38±0.25	2.07±0.03
N55A	–	–	–	–	–	–
N55B	0.45±0.07	2.24±0.20	–	–	0.64±0.09	1.80±0.14
N56	–	–	0.06±0.03	0.97±0.02	1.26±0.15	2.31±0.17
N57	–	–	–	–	1.48±0.17	2.12±0.07
N58	0.15±0.03	2.42±0.34	–	–	0.06±0.03	0.98±0.21
N6	0.15±0.03	1.69±0.07	–	–	1.03±0.15	2.87±0.13
N61	0.15±0.04	1.52±0.09	–	–	0.33±0.10	1.65±0.34
N63	–	–	0.09±0.03	1.17±0.16	0.89±0.11	2.37±0.25
N64	0.14±0.03	1.39±0.21	–	–	0.55±0.06	1.52±0.07
N65	0.11±0.04	1.09±0.34	–	–	0.69±0.09	1.65±0.02
N66	0.13±0.03	2.28±0.58	–	–	0.65±0.08	1.57±0.12
N67	0.50±0.15	25.74±22.54	–	–	0.83±0.10	1.49±0.05
N68	0.11±0.02	1.81±0.19	–	–	0.51±0.07	1.62±0.04
N68-8	0.25±0.07	2.11±0.25	–	–	0.51±0.11	4.85±0.79
N69	0.47±0.08	3.08±0.28	–	–	1.06±0.14	1.94±0.04
N71	0.31±0.06	3.02±0.28	–	–	0.33±0.06	1.52±0.06
N72	0.40±0.09	2.52±2.22	–	–	0.61±0.09	2.64±0.31
W75N-6	–	–	0.43±0.12	5.53±2.44	0.80±0.11	1.80±0.06
–	–	–	0.43±0.08	3.70±0.56	–	–

Table B.21: Continued.

Names	HNCO		NH ₂ D		N ₂ D ⁺	
	4(0,4)–3(0,3)		1(1,1)0s–1(0,1)0a		<i>J</i> = 1 – 0	
	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]	$\int T_{\text{MB}} d\nu$ [K km s ^{−1}]	$\Delta\nu$ [km s ^{−1}]
C09-1	–	–	0.41±0.15	1.81±0.53	–	–
C09-2	0.12±0.03	0.80±0.38	0.04±0.04	3.41±1.18	–	–
DR21-12	0.29±0.04	1.80±0.30	0.58±0.12	1.50±0.09	0.57±0.10	1.33±0.14
DR21-19	0.42±0.06	3.37±0.51	0.14±0.03	1.33±0.17	–	–
N03-2	–	–	–	–	–	–
N05-5	0.16±0.04	2.12±0.41	0.09±0.05	1.98±0.68	–	–
N05-6	–	–	0.38±0.13	1.33±0.04	–	–
N1	0.28±0.04	1.91±0.42	0.67±0.20	1.70±0.20	–	–
N10	0.24±0.03	2.59±0.43	0.32±0.08	1.81±0.18	–	–
N11	0.24±0.05	1.60±0.18	–	–	–	–
N12	1.26±0.17	3.80±0.31	–	–	–	–
N12-4	0.28±0.08	1.75±0.37	–	–	–	–
N12-6	–	–	–	–	0.13±0.07	1.33±0.25
N12-7	0.29±0.08	1.33±0.23	–	–	0.09±0.14	4.94±1.38
N13	0.96±0.14	4.12±0.62	–	–	0.06±0.07	4.59±1.31
N14	0.26±0.04	1.86±0.11	–	–	–	–
N15	0.65±0.09	7.72±2.36	0.04±0.03	4.88±1.11	–	–
N16	0.08±0.05	0.80±0.22	–	–	0.07±0.07	3.18±1.52
N17	0.90±0.14	9.56±4.24	0.08±0.03	1.33±0.83	–	–
N18	0.16±0.04	1.73±0.11	–	–	–	–
N2	0.53±0.09	3.84±0.91	0.67±0.21	1.96±0.28	–	–
N20	0.15±0.06	2.10±0.29	–	–	–	–
N21	0.13±0.04	0.80±1.43	0.67±0.16	1.33±0.02	0.14±0.05	1.33±0.18
N22	–	–	1.20±0.19	1.33±0.01	0.34±0.09	1.71±0.41
N23	0.27±0.06	2.17±0.34	0.23±0.08	1.33±0.05	–	–
N24	0.14±0.04	1.34±0.18	1.22±0.18	1.33±0.01	0.27±0.09	2.27±0.40
N25	–	–	0.74±0.10	1.33±0.01	–	–
N26	–	–	–	–	–	–
N27	0.36±0.05	2.05±0.38	–	–	–	–
N28	–	–	0.71±0.10	1.67±0.09	–	–
N3	0.69±0.10	3.59±0.40	0.56±0.21	2.41±0.25	–	–
N30	1.48±0.17	4.35±0.20	–	–	–	–
N31	1.25±0.15	4.94±0.28	0.35±0.14	1.68±0.26	–	–
N32	1.08±0.13	3.58±0.20	0.32±0.14	1.94±0.67	–	–
N33	–	–	–	–	–	–
N36A	–	–	2.22±0.25	1.62±0.06	0.08±0.05	2.87±0.77
N36B	1.51±0.17	2.89±0.22	–	–	–	–
N37	0.87±0.10	3.08±0.12	1.39±0.16	2.12±0.07	0.28±0.07	2.44±0.30
N38A	1.82±0.20	3.79±0.09	0.66±0.15	2.82±0.24	–	–

Table B.22: Continued.

Names	HNCO 4(0,4)–3(0,3)		NH ₂ D 1(1,1)0s–1(0,1)0a		N ₂ D ⁺ J = 1 – 0	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	–	–	–	–	0.11±0.06	1.92±0.46
N39	0.29±0.06	1.67±0.04	0.46±0.10	1.33±0.07	0.27±0.08	1.63±0.36
N40	1.33±0.14	2.51±0.17	1.61±0.20	1.98±0.10	0.18±0.09	2.77±0.49
N41A	1.57±0.16	3.19±0.11	1.45±0.19	1.76±0.11	0.06±0.03	2.52±1.11
N41B	–	–	–	–	–	–
N42A	–	–	–	–	–	–
N42B	0.79±0.09	3.30±0.25	0.43±0.11	1.33±0.06	–	–
N43	0.90±0.09	3.01±0.15	0.81±0.11	2.64±0.13	0.14±0.04	2.28±0.53
N44A	1.74±0.18	4.05±0.27	0.49±0.13	3.34±0.41	–	–
N45	0.50±0.06	2.16±0.17	0.54±0.12	1.54±0.08	–	–
N46	0.78±0.10	3.41±0.62	0.37±0.12	1.84±0.21	–	–
N47	0.53±0.07	2.80±0.26	–	–	–	–
N48	1.29±0.14	3.01±0.07	0.38±0.13	2.57±0.10	–	–
N49	0.29±0.04	1.90±0.10	0.94±0.15	1.46±0.06	0.09±0.08	3.79±0.57
N5	0.36±0.12	22.58±9.82	1.02±0.18	1.54±0.09	–	–
N50	0.51±0.07	2.25±0.12	0.48±0.12	1.54±0.09	–	–
N51	0.90±0.10	2.61±0.20	2.30±0.24	1.62±0.03	0.23±0.06	2.15±0.38
N52	0.63±0.07	2.17±0.14	1.98±0.23	1.76±0.06	0.15±0.08	2.60±0.51
N53	0.99±0.11	3.15±0.16	2.27±0.25	1.73±0.06	0.17±0.07	1.79±0.34
N54	0.94±0.10	2.70±0.15	2.47±0.28	1.69±0.04	0.23±0.08	2.02±0.32
N55A	–	–	–	–	–	–
N55B	0.44±0.07	1.76±0.13	0.92±0.14	1.33±0.04	–	–
N56	0.45±0.07	2.08±0.24	0.20±0.15	2.97±0.53	–	–
N57	0.52±0.08	1.68±0.18	0.38±0.15	1.91±0.22	0.06±0.04	4.61±1.53
N58	–	–	–	–	–	–
N6	0.12±0.03	1.86±0.19	0.69±0.17	1.59±0.15	–	–
N61	0.40±0.18	25.21±15.89	–	–	–	–
N63	0.38±0.06	3.12±0.53	0.35±0.10	1.54±0.20	–	–
N64	0.24±0.04	2.00±0.15	0.95±0.12	1.33±0.04	0.09±0.03	1.93±0.51
N65	0.24±0.06	1.84±0.18	0.64±0.13	1.57±0.19	–	–
N66	0.29±0.04	2.97±0.61	0.62±0.13	1.61±0.08	0.07±0.04	2.31±0.82
N67	0.33±0.06	2.32±0.29	0.70±0.12	1.33±0.08	–	–
N68	0.27±0.04	4.36±0.84	0.98±0.15	1.34±0.05	0.10±0.05	1.53±0.47
N68-8	0.17±0.04	1.33±0.08	–	–	–	–
N69	0.51±0.07	3.62±0.30	0.73±0.14	1.75±0.16	0.08±0.05	3.46±0.82
N71	0.15±0.03	2.08±0.77	0.32±0.10	1.33±0.04	0.06±0.02	1.67±0.59
N72	0.49±0.10	2.95±0.23	0.44±0.14	1.34±0.16	–	–
W75N-6	0.48±0.09	4.83±0.84	0.52±0.14	1.33±0.03	0.17±0.07	1.73±0.42

Table B.23: Continued.

Names	N_2D^+ $J = 2 - 1$		N_2D^+ $J = 3 - 2$		N_2H^+ $J = 1 - 0$	
	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]	$\int T_{\text{MB}} d\nu$ [K km s $^{-1}$]	$\Delta\nu$ [km s $^{-1}$]
C09-1	—	—	—	—	1.43±0.19	2.58±0.06
C09-2	—	—	—	—	0.95±0.14	1.73±0.09
DR21-12	0.40±0.06	2.14±0.39	0.21±0.04	1.41±0.27	1.99±0.23	1.84±0.04
DR21-19	—	—	—	—	0.51±0.09	2.05±0.12
N03-2	—	—	—	—	0.48±0.17	1.83±0.31
N05-5	—	—	—	—	0.86±0.14	2.17±0.10
N05-6	—	—	—	—	1.65±0.19	1.67±0.06
N1	—	—	—	—	3.56±0.38	2.71±0.03
N10	—	—	—	—	2.47±0.27	2.76±0.02
N11	—	—	—	—	2.13±0.29	1.97±0.06
N12	—	—	—	—	5.81±0.61	3.17±0.02
N12-4	—	—	—	—	1.39±0.21	2.03±0.09
N12-6	—	—	—	—	2.16±0.25	1.66±0.05
N12-7	—	—	—	—	1.41±0.23	1.81±0.07
N13	—	—	—	—	3.95±0.44	3.09±0.03
N14	—	—	—	—	1.26±0.15	3.24±0.05
N15	—	—	—	—	0.48±0.10	3.77±2.66
N16	—	—	—	—	2.18±0.27	1.84±0.06
N17	—	—	—	—	0.48±0.13	3.01±0.31
N18	—	—	—	—	2.75±0.31	1.89±0.05
N2	—	—	—	—	4.66±0.49	2.67±0.02
N20	—	—	—	—	1.55±0.21	1.71±0.07
N21	—	—	—	—	2.21±0.25	1.67±0.05
N22	—	—	—	—	3.54±0.37	1.77±0.02
N23	—	—	—	—	0.85±0.13	1.66±0.10
N24	—	—	—	—	3.98±0.42	1.77±0.02
N25	—	—	—	—	2.33±0.24	1.75±0.02
N26	—	—	—	—	1.35±0.17	1.84±0.07
N27	—	—	—	—	6.73±0.68	2.36±0.01
N28	—	—	—	—	3.20±0.33	2.18±0.02
N3	—	—	—	—	5.59±0.58	2.77±0.01
N30	—	—	—	—	4.33±0.45	3.24±0.01
N31	—	—	—	—	5.59±0.60	3.28±0.01
N32	—	—	—	—	4.40±0.47	2.95±0.01
N33	—	—	—	—	0.56±0.12	2.04±0.16
N36A	0.75±0.14	3.63±0.63	0.69±0.07	3.02±0.29	10.26±1.05	3.55±0.01
N36B	—	—	—	—	—	—
N37	1.34±0.15	8.60±1.87	0.49±0.09	1.98±0.15	8.12±0.82	2.76±0.01
N38A	1.23±0.17	4.90±0.70	0.68±0.08	2.35±0.16	16.67±1.68	3.63±0.01

Table B.24: Continued.

Names	N_2D^+ $J = 2 - 1$		N_2D^+ $J = 3 - 2$		N_2H^+ $J = 1 - 0$	
	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$	$\int T_{\text{MB}} d\nu$	$\Delta\nu$
	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]	[K km s ⁻¹]	[km s ⁻¹]
N38B	—	—	—	—	—	—
N39	0.48±0.07	1.94±0.31	0.27±0.04	1.24±0.42	2.05±0.24	1.85±0.04
N40	0.65±0.08	2.31±0.31	0.68±0.08	2.22±0.19	11.77±1.18	2.95±0.01
N41A	—	—	0.49±0.07	3.84±0.51	8.55±0.87	3.58±0.01
N41B	—	—	—	—	—	—
N42A	—	—	—	—	—	—
N42B	—	—	—	—	5.62±0.59	2.89±0.03
N43	0.66±0.09	5.71±1.39	—	—	9.18±0.92	2.74±0.01
N44A	0.36±0.09	4.15±1.61	0.32±0.04	5.66±1.24	—	—
N45	—	—	—	—	4.17±0.44	2.22±0.02
N46	—	—	0.56±0.09	3.56±0.65	6.36±0.66	2.90±0.02
N47	0.40±0.10	3.28±1.35	0.37±0.09	2.44±0.96	5.72±0.58	2.43±0.02
N48	1.90±0.22	32.00±8.26	0.40±0.06	3.43±0.87	13.21±1.33	3.16±0.01
N49	0.52±0.07	2.03±0.32	0.37±0.05	1.63±0.17	3.67±0.37	1.97±0.03
N5	—	—	—	—	3.73±0.39	2.13±0.03
N50	0.19±0.05	1.85±0.71	0.19±0.04	1.86±0.69	5.12±0.53	2.50±0.02
N51	0.83±0.09	2.10±0.26	0.81±0.09	1.59±0.08	13.75±1.38	2.34±0.01
N52	0.72±0.09	2.08±0.33	0.55±0.06	2.00±0.18	7.46±0.75	2.34±0.01
N53	0.76±0.08	2.80±0.57	0.62±0.07	2.02±0.13	10.28±1.03	2.48±0.01
N54	0.98±0.11	3.08±0.59	0.69±0.07	1.76±0.09	11.20±1.13	2.44±0.01
N55A	—	—	—	—	—	—
N55B	0.59±0.07	1.66±0.17	0.42±0.07	1.33±0.15	2.78±0.30	1.93±0.04
N56	—	—	—	—	2.19±0.26	2.80±0.03
N57	—	—	—	—	2.20±0.26	2.61±0.03
N58	—	—	—	—	—	—
N6	—	—	—	—	3.43±0.37	2.71±0.03
N61	—	—	—	—	1.69±0.21	1.83±0.06
N63	—	—	—	—	3.36±0.36	2.46±0.00
N64	—	—	—	—	2.30±0.24	1.97±0.03
N65	—	—	—	—	2.91±0.30	2.13±0.03
N66	—	—	—	—	3.30±0.36	1.98±0.03
N67	—	—	—	—	3.24±0.35	2.01±0.03
N68	—	—	—	—	3.41±0.35	2.04±0.03
N68-8	—	—	—	—	0.92±0.17	1.72±0.14
N69	—	—	—	—	3.40±0.37	2.12±0.02
N71	—	—	—	—	1.67±0.18	1.62±0.05
N72	—	—	—	—	1.36±0.17	1.75±0.09
W75N-6	—	—	—	—	2.88±0.31	1.90±0.04

Table B.25: Continued.

Names	OCS		SO		SO ₂	
	$J = 6 - 5$		$2(2) - 1(1)$		$6(0,6) - 5(1,5)$	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	—	—	0.27±0.06	2.55±0.61	0.13±0.03	1.36±0.13
C09-2	0.19±0.04	1.49±0.03	—	—	—	—
DR21-12	—	—	0.57±0.08	1.66±0.17	0.15±0.03	1.46±0.08
DR21-19	—	—	0.24±0.04	1.70±0.09	—	—
N03-2	0.26±0.10	2.99±0.86	—	—	—	—
N05-5	0.16±0.04	1.09±0.01	0.36±0.09	2.79±0.32	0.22±0.06	2.11±0.27
N05-6	—	—	—	—	0.08±0.03	1.27±0.03
N1	0.52±0.11	7.01±2.09	1.01±0.16	3.31±0.59	0.45±0.10	3.88±0.90
N10	0.10±0.04	0.94±0.06	0.41±0.08	2.76±0.43	0.11±0.03	1.74±0.42
N11	—	—	—	—	—	—
N12	0.25±0.07	3.55±1.43	—	—	0.58±0.13	3.76±0.86
N12-4	0.14±0.05	2.50±0.38	—	—	—	—
N12-6	0.05±0.05	0.80±1.05	—	—	0.12±0.05	1.09±0.00
N12-7	0.13±0.04	1.36±0.05	—	—	0.09±0.06	0.80±1.98
N13	—	—	—	—	0.58±0.16	3.97±1.32
N14	—	—	0.57±0.07	2.82±0.21	—	—
N15	0.09±0.02	1.37±0.09	0.41±0.05	3.17±0.26	0.13±0.03	0.80±14.21
N16	—	—	—	—	—	—
N17	—	—	0.57±0.09	2.72±0.25	—	—
N18	—	—	—	—	0.17±0.06	1.44±0.18
N2	—	—	0.75±0.14	2.69±0.12	0.19±0.05	1.95±0.11
N20	—	—	—	—	—	—
N21	0.10±0.07	0.80±0.00	0.37±0.09	2.08±0.15	0.11±0.06	0.80±1.71
N22	0.11±0.06	0.80±0.00	0.47±0.08	1.49±0.11	0.14±0.06	0.80±0.00
N23	0.10±0.04	0.80±11.42	0.51±0.08	2.21±0.16	0.18±0.04	1.63±0.24
N24	0.24±0.07	2.14±0.54	0.70±0.10	1.60±0.06	0.25±0.07	1.80±0.15
N25	—	—	0.16±0.03	1.86±0.30	0.15±0.04	1.87±0.23
N26	—	—	—	—	0.36±0.09	4.36±1.06
N27	—	—	0.56±0.07	2.87±0.22	0.18±0.04	3.17±0.37
N28	—	—	0.19±0.04	1.35±0.13	—	—
N3	—	—	1.01±0.15	3.31±0.41	0.45±0.08	4.59±0.36
N30	1.09±0.18	4.52±0.37	4.68±0.48	3.49±0.08	2.32±0.27	5.53±0.38
N31	0.87±0.14	4.09±0.56	3.77±0.39	3.91±0.15	1.72±0.22	4.98±0.41
N32	0.84±0.17	4.63±0.72	3.13±0.33	2.97±0.15	1.38±0.18	3.82±0.44
N33	0.19±0.07	1.38±0.14	—	—	0.10±0.03	1.43±0.28
N36A	0.45±0.09	2.94±0.53	1.52±0.17	3.09±0.13	1.05±0.13	4.04±0.54
N36B	—	—	—	—	—	—
N37	—	—	1.00±0.11	3.52±0.24	0.55±0.07	3.18±0.33
N38A	—	—	4.39±0.45	3.60±0.10	1.48±0.18	3.91±0.20

Table B.26: Continued.

Names	OCS $J = 6 - 5$		SO $2(2)-1(1)$		SO ₂ $6(0,6)-5(1,5)$	
	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]	$\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
N38B	1.15±0.15	5.11±0.46	—	—	—	—
N39	—	—	0.35±0.06	1.71±0.25	—	—
N40	0.53±0.11	4.30±0.68	1.57±0.17	2.53±0.14	1.02±0.12	2.91±0.10
N41A	0.38±0.08	3.49±0.65	1.70±0.19	2.98±0.08	0.99±0.13	3.45±0.17
N41B	—	—	—	—	—	—
N42A	—	—	—	—	0.42±0.07	2.44±0.12
N42B	—	—	1.86±0.19	4.86±0.54	—	—
N43	0.15±0.02	1.65±0.08	1.21±0.13	2.98±0.11	0.62±0.08	3.65±0.19
N44A	0.85±0.14	4.14±0.29	5.54±0.56	4.91±0.29	1.68±0.19	3.93±0.16
N45	0.16±0.04	1.33±0.10	0.54±0.07	3.08±0.38	0.13±0.04	1.68±0.24
N46	0.32±0.09	4.11±1.64	1.86±0.21	4.36±0.33	0.47±0.11	4.00±0.83
N47	0.08±0.03	0.89±3.94	1.73±0.19	3.09±0.19	0.47±0.08	3.43±0.64
N48	0.46±0.09	2.53±0.21	2.76±0.29	3.03±0.08	0.83±0.11	2.97±0.21
N49	—	—	0.50±0.06	2.65±0.23	0.49±0.08	7.68±4.01
N5	0.24±0.04	3.87±0.69	0.28±0.09	3.48±1.78	—	—
N50	0.18±0.06	1.58±0.08	0.56±0.11	2.70±0.27	0.17±0.04	2.26±0.52
N51	0.18±0.04	1.73±0.25	1.49±0.16	2.40±0.24	0.53±0.07	3.81±0.48
N52	0.21±0.05	2.81±0.65	0.61±0.08	3.04±0.73	0.57±0.10	6.91±3.50
N53	0.29±0.08	2.60±0.39	1.16±0.14	2.91±0.21	0.90±0.15	5.77±1.05
N54	0.35±0.09	2.92±0.44	1.52±0.17	2.54±0.15	1.04±0.15	7.26±0.87
N55A	—	—	—	—	0.50±0.11	6.11±1.81
N55B	—	—	0.43±0.07	3.14±0.75	—	—
N56	0.16±0.04	1.32±0.07	0.28±0.06	3.59±0.52	0.26±0.10	3.27±0.77
N57	—	—	0.08±0.03	0.80±79.70	0.11±0.04	1.51±0.23
N58	—	—	1.10±0.17	12.42±2.73	—	—
N6	0.18±0.04	2.57±0.33	0.40±0.07	3.02±0.65	—	—
N61	0.39±0.12	3.77±0.82	—	—	0.42±0.11	3.56±1.00
N63	0.10±0.04	0.94±0.00	0.36±0.07	2.85±0.60	0.21±0.05	2.01±0.24
N64	—	—	0.44±0.06	2.10±0.07	—	—
N65	—	—	0.66±0.08	3.04±0.21	0.25±0.07	2.23±0.32
N66	0.09±0.06	0.80±0.00	0.45±0.07	1.54±0.15	—	—
N67	0.15±0.04	1.67±0.06	0.39±0.07	1.77±0.19	0.64±0.13	8.56±3.76
N68	—	—	0.53±0.09	2.90±0.73	0.20±0.04	2.76±0.51
N68-8	—	—	—	—	0.21±0.07	1.62±0.17
N69	—	—	0.52±0.09	3.06±0.35	0.37±0.08	15.53±11.19
N71	—	—	—	—	—	—
N72	—	—	0.09±0.06	0.80±0.00	0.13±0.03	1.26±0.07
W75N-6	0.57±0.25	17.89±12.59	—	—	—	—

Table B.27: Continued.

Names	SiO		Names	SiO	
	$J = 2 - 1, v = 0 - 0$ $\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]		$J = 2 - 1, v = 0 - 0$ $\int T_{\text{MB}} d\nu$ [K km s ⁻¹]	$\Delta\nu$ [km s ⁻¹]
C09-1	0.13±0.04	1.98±0.47	N38B	—	—
C09-2	0.10±0.03	1.51±0.28	N39	0.20±0.04	2.48±0.55
DR21-12	—	—	N40	1.77±0.20	3.22±0.39
DR21-19	—	—	N41A	2.66±0.28	3.81±0.25
N03-2	0.23±0.06	2.50±1.84	N41B	—	—
N05-5	—	—	N42A	—	—
N05-6	0.10±0.02	1.36±0.30	N42B	2.82±0.32	7.06±0.59
N1	1.08±0.13	4.08±0.61	N43	0.89±0.10	3.05±0.26
N10	0.50±0.07	5.14±0.85	N44A	6.18±0.63	5.15±0.10
N11	—	—	N45	—	—
N12	3.48±0.37	4.69±0.26	N46	4.41±0.49	13.04±3.23
N12-4	—	—	N47	0.98±0.11	5.42±0.68
N12-6	0.11±0.04	0.83±0.00	N48	3.30±0.34	4.79±0.18
N12-7	0.93±0.24	11.07±1.81	N49	—	—
N13	2.63±0.29	4.02±0.97	N5	—	—
N14	0.48±0.06	2.67±0.14	N50	0.22±0.04	3.96±0.84
N15	—	—	N51	1.17±0.13	3.85±0.37
N16	—	—	N52	1.12±0.14	3.60±0.24
N17	0.19±0.04	2.05±0.38	N53	2.63±0.32	4.59±0.29
N18	—	—	N54	1.81±0.23	4.31±0.32
N2	1.07±0.14	5.92±1.55	N55A	—	—
N20	—	—	N55B	—	—
N21	—	—	N56	0.91±0.20	7.74±1.68
N22	0.17±0.04	2.67±0.46	N57	0.39±0.09	3.89±1.30
N23	—	—	N58	0.21±0.04	1.70±0.19
N24	0.40±0.08	3.43±0.40	N6	—	—
N25	—	—	N61	0.55±0.11	3.58±0.47
N26	0.23±0.06	2.38±0.35	N63	1.19±0.16	3.98±0.28
N27	—	—	N64	0.16±0.02	2.22±0.42
N28	—	—	N65	0.41±0.06	4.35±0.80
N3	1.52±0.18	4.28±0.50	N66	0.81±0.12	5.83±2.12
N30	3.82±0.40	6.24±0.41	N67	1.10±0.12	3.32±0.24
N31	2.60±0.29	5.68±0.22	N68	1.02±0.15	8.29±2.07
N32	1.59±0.19	4.65±0.24	N68-8	0.23±0.07	2.30±1.10
N33	0.09±0.03	0.80±0.92	N69	—	—
N36A	2.65±0.28	4.29±0.39	N71	0.11±0.03	1.38±0.43
N36B	—	—	N72	0.15±0.04	1.80±0.22
N37	0.95±0.11	3.26±0.21	W75N-6	0.39±0.13	6.90±2.37
N38A	5.42±0.57	5.22±0.20	—	—	—

Paper II: Formaldehyde as a thermometer and densitometer

The pdf of the Barlach Christensen et al. (subm.) which is summarized in Chapter [5](#), is reproduced in its original form below.

Formaldehyde as densitometer and thermometer in Cygnus-X, GLOSTAR pilot region, and M8

Utilizing the H₂CO ground-state transition

I. Barlach Christensen^{*1}, C. Gieser^{2,3}, F. Wyrowski¹, H. Nguyen¹, T. D. Hoang¹, V. S. Veena¹, H. Beuther³, K. A. Kahle³, Y. Gong⁴, and K. M. Menten^{1**}

¹ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
* e-mail: ibarlach@mpi-fr-bonn.mpg.de

² Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany

³ Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

⁴ Purple Mountain Observatory, and Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, 10 Yuanhua Road, Nanjing 210023, PR China

Received: November 24, 2025;

ABSTRACT

Context. Measurements of the physical conditions in molecular clumps are key to our understanding of star formation. Formaldehyde (H₂CO) is a molecule prevalent in these regions that can be used as diagnostic for the physical conditions in them.

Aims. Here we explore a technique for determining the volume density and gas kinetic temperature in molecular clumps across various evolutionary phases and environments. The ground-state transition of H₂CO has a critical density of $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$, allowing us to use this molecule as a densitometer at $n \leq 10^5 \text{ cm}^{-3}$ and lessen the discrepancy between the measurements between gas densities derived from molecular tracers and those derived of dust observations.

Methods. The clumps have been observed with the IRAM 30-m telescope, marking the first extensive survey of the H₂CO (1_{0,1} – 0_{0,0}) line across a large sample of sources. These observations were complemented by the H₂CO $J = 3 - 2$ lines, obtained using the APEX telescope. These clumps have been surveyed in three regions, the Cygnus-X giant molecular cloud complex, the GLOSTAR pilot region covering the Galactic plane at longitudes $28^\circ \leq l \leq 36^\circ$, and the molecular cloud associated with the HII regions in the Lagoon nebula (M8).

Results. We analyzed a total of 127 clumps, including 78 from Cygnus-X, 12 from the GLOSTAR pilot region, and 37 from M8. We derived the gas kinetic temperature, volume densities and H₂CO column densities using radiative transfer modeling with pyradex+emcee in 102 clumps. We reproduce the observed line intensities in the sources with volume densities $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$, gas kinetic temperatures $T_{\text{gas}} = 16 - 219 \text{ K}$, and H₂CO column densities $N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} - 1.6 \times 10^{15} \text{ cm}^{-2}$.

Conclusions. The gas kinetic temperatures obtained from the non-LTE modeling with pyradex+emcee agree well with the LTE gas kinetic temperature obtained from the ratio of H₂CO (3_{0,3} – 2_{0,2}) and H₂CO (3_{2,1} – 2_{2,0}) lines at densities $n(\text{H}_2) \leq 10^{5.5} \text{ cm}^{-3}$. However, we find that, at higher densities, LTE temperatures derived from this ratio are overestimated by up to 0.5 dex. The measured volume densities are consistent with the volume densities obtained from dust continuum measurements, thereby probing the bulk of the gas. Furthermore, we find that the volume densities and dust temperatures increase, with increasing evolutionary phase. The newly available ground-state transition of H₂CO allows to constrain the physical conditions in various phases of star formation.

Key words. Stars: formation — Astrochemistry — ISM: abundances — ISM: molecules — ISM: evolution — Submillimeter: ISM

1. Introduction

The physical and chemical conditions during high-mass star formation are poorly understood (see e.g. McKee & Tan 2002; McKee & Ostriker 2007; Krumholz & Bonnell 2009; Tielens 2021). The formation of massive star clusters in particular is believed to take place in dense ($n(\text{H}_2) > 10^5 \text{ cm}^{-3}$) and cold clumps ($T_{\text{kin}} < 20 \text{ K}$) within molecular clouds (e.g. Pillai et al. 2011). Knowing the initial conditions of star formation prevailing in these regions can shed light on the formation mechanisms of

their stellar content (Girichidis et al. 2020). Molecular clouds are the largest structures ($\geq 10 \text{ pc}$), from which the gas fragments into clumps (size $\sim 1 \text{ pc}$), cores (size $\sim 0.05 - 0.1 \text{ pc}$), envelopes (size $\sim 300 - 3000 \text{ AU}$) and disks (size $\sim 10 - 200 \text{ AU}$) (Pokhrel et al. 2018), accreting onto protostars.

Previous studies attempted to probe the physical conditions using various molecular tracers, but these methods have limitations. Ammonia (NH₃) inversion lines are used to determine gas kinetic temperature (e.g. Walmsley & Ungerechts 1983; Tafalla et al. 2004; Wienen et al. 2012), but the NH₃ abundance is strongly affected by dust evaporation (Yamato et al. 2022; Redaelli et al. 2023). CH₃CCH, CH₃CN, and CH₃OH probe temperature, with the latter also sensitive to density (Giannetti et al. 2017; Lin et al. 2022). The K -level population of CH₃OH is sensitive to the gas temperature (e.g. Cummins et al. 1983; Remi-

* Member of the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne

** Karl M. Menten was unable to witness the completion of this article, having passed away. Nonetheless, his vital contributions to our project remain deeply valued and will always be remembered.

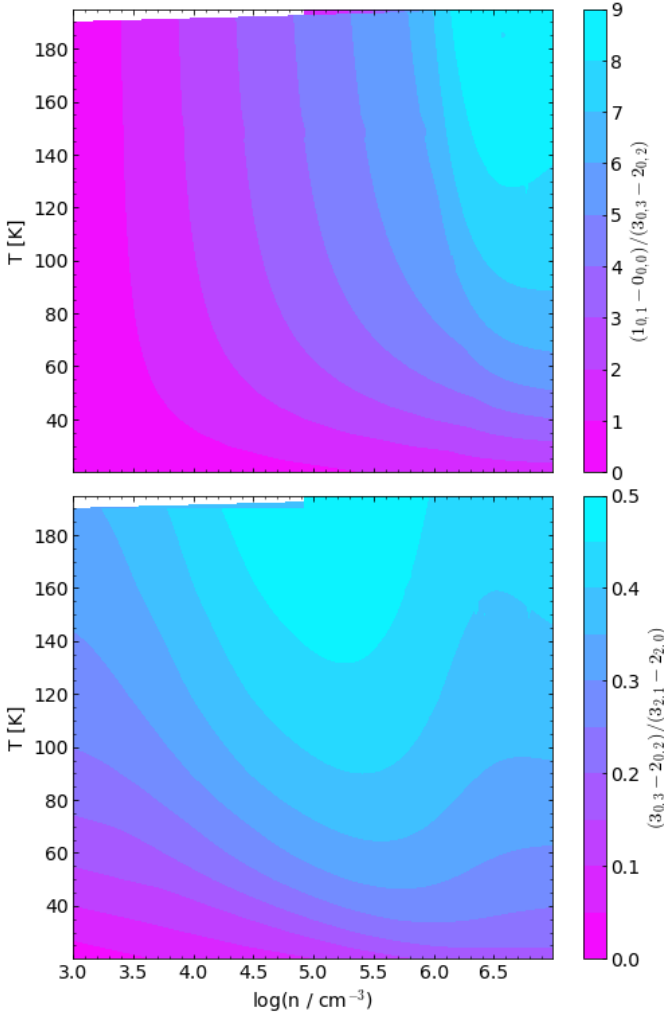


Fig. 1: Line-ratios of H₂CO ($3_{0,3} - 2_{0,2}$)/($1_{0,1} - 0_{0,0}$) (top) and H₂CO ($3_{2,1} - 2_{2,0}$)/($3_{0,3} - 2_{0,2}$) as a function of volume densities and gas kinetic temperature computed from pyradex. Bottom plot shows the “bump” at $n(\text{H}_2) \geq 10^{5.5} \text{ cm}^{-3}$, discussed in Sect 6.1.

jan et al. 2004). Higher J -lines of CH₃OH trace kinetic temperatures, and lower J -lines trace density in low-, intermediate-, and high-mass star-forming regions (Leurini et al. 2004, 2007). CH₃CN traces hot core temperatures, limiting its ability to measure temperatures in cold regions.

Formaldehyde (H₂CO) is a ubiquitous molecule believed to form through successive hydrogenation of CO on icy grain mantles (e.g. Mangum et al. 1990; Watanabe & Kouchi 2002; Woon 2002; Yan et al. 2019) or through the gas-phase reaction of CH₃ with atomic oxygen (e.g. Potapov & Garrod 2024; Punanova et al. 2025). It is a well-known tracer of high density, as well as a wide range of temperature environments in molecular clouds (Mangum & Wootten 1993; Ao et al. 2013; Okoh et al. 2014). An example of line intensity ratio increase of H₂CO ($3_{0,3} - 2_{0,2}$)/($1_{0,1} - 0_{0,0}$) and H₂CO ($3_{2,1} - 2_{2,0}$)/($3_{0,3} - 2_{0,2}$) is shown in Fig. 1. Downes et al. (1980) revealed the presence of this molecule via absorption measurements toward numerous HII regions.

Due to the line’s frequency (72.838 GHz) at the lower end of the receiver coverage of the 3/4 mm atmospheric window, only a limited amount of observations have been made of the $1_{0,1} - 0_{0,0}$

ground-state transition of para-H₂CO (hereafter H₂CO). This line, first detected in the ISM by Akabane et al. (1974, see also Kaifu et al. (1975)), has a relatively low critical density of $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$. This property allows us to use this molecule as a densitometer at $n \leq 10^5 \text{ cm}^{-3}$. H₂CO is a slightly asymmetric rotor molecule which has shown its usefulness in determining the volume density and gas kinetic temperature in a variety of sources due to the collisionally governed K -levels (e.g. Mangum & Wootten 1993; Mangum et al. 2013; Tang et al. 2018, 2021a; Gieser et al. 2021). Studies have shown that the ground-state transitions of ortho-H₂CO ($1_{1,0} - 1_{1,1}$) and ($2_{1,1} - 2_{1,2}$) at 6 and 2 cm, respectively, are density tracers (e.g. Mangum et al. 2008; Ginsburg et al. 2011, 2015; Gong et al. 2023). Tang et al. (2017) observed that the fractional abundance of H₂CO remains relatively stable across different phases of star formation. The fractional abundance with respect to H₂ of H₂CO varies by only one order of magnitude during these different phases, with $X(\text{H}_2\text{CO}) \simeq 10^{-10}$ (Tang et al. 2018).

Previous studies have revealed a significant discrepancy between gas densities derived from molecular tracers and those derived from dust observations. For example, studies using CS (Beuther et al. 2002) or higher J transitions of H₂CO (Tang et al. 2018) found higher gas densities compared to dust-based estimates. This discrepancy can be attributed to the high critical densities of the lines used in these studies. The H₂CO ground state transition, H₂CO ($1_{0,1} - 0_{0,0}$), now offers a lower critical density line to probe the bulk material of the clumps. This ground-state transition increases the diagnostic utility of H₂CO emission lines as tracers of both temperature and density, enabling the probing of lower-density regions (see Fig. 1).

In this paper, we measure the volume density and gas kinetic temperature using H₂CO toward a sample of sources in the Cygnus-X star-forming region, the GLOSTAR pilot region, and the Messier 8 (M8) region. The combination of rotational transitions with different critical densities will allow us to probe a large range of gas physical conditions. The paper is organized as follows: in Sect. 2, we present the details of the target sources. In Sect. 3, we present the observations and data reduction; in Sect. 4, we analyze averaged spectra to determine whether different H₂CO transitions are probing the same regions within the clumps. In Sect. 5, we describe the pyradex+emcee methodology and analysis. In Sect. 6, we discuss the obtained gas kinetic temperatures, volume densities, and H₂CO column densities, and explore the physical conditions across the evolutionary phases. Finally, in Sect. 7, we present our conclusions.

2. Source selection

This study focuses on three specific regions: Cygnus-X (as part of the CASCADE project), the GLOSTAR pilot region, and M8.

2.1. Cygnus Allscale Survey of Chemistry And Dynamical Environments

Cygnus-X is a nearby ($d \sim 1.5 \text{ kpc}$, Rygl et al. 2012) high-mass star-forming region with OB associations illuminating the cloud complex from the south-west (Knödseder 2000; Beerer et al. 2010; Wright et al. 2015). Star formation is triggered by strong stellar winds, and several clouds are interacting with their ambient H I envelope specifically in the DR21 filament, with clumps at different evolutionary phases along the structure (Motte et al. 2007; Schneider et al. 2010; Hennemann et al. 2012; Schneider et al. 2023). Recently, a survey using the NOthern Millimeter

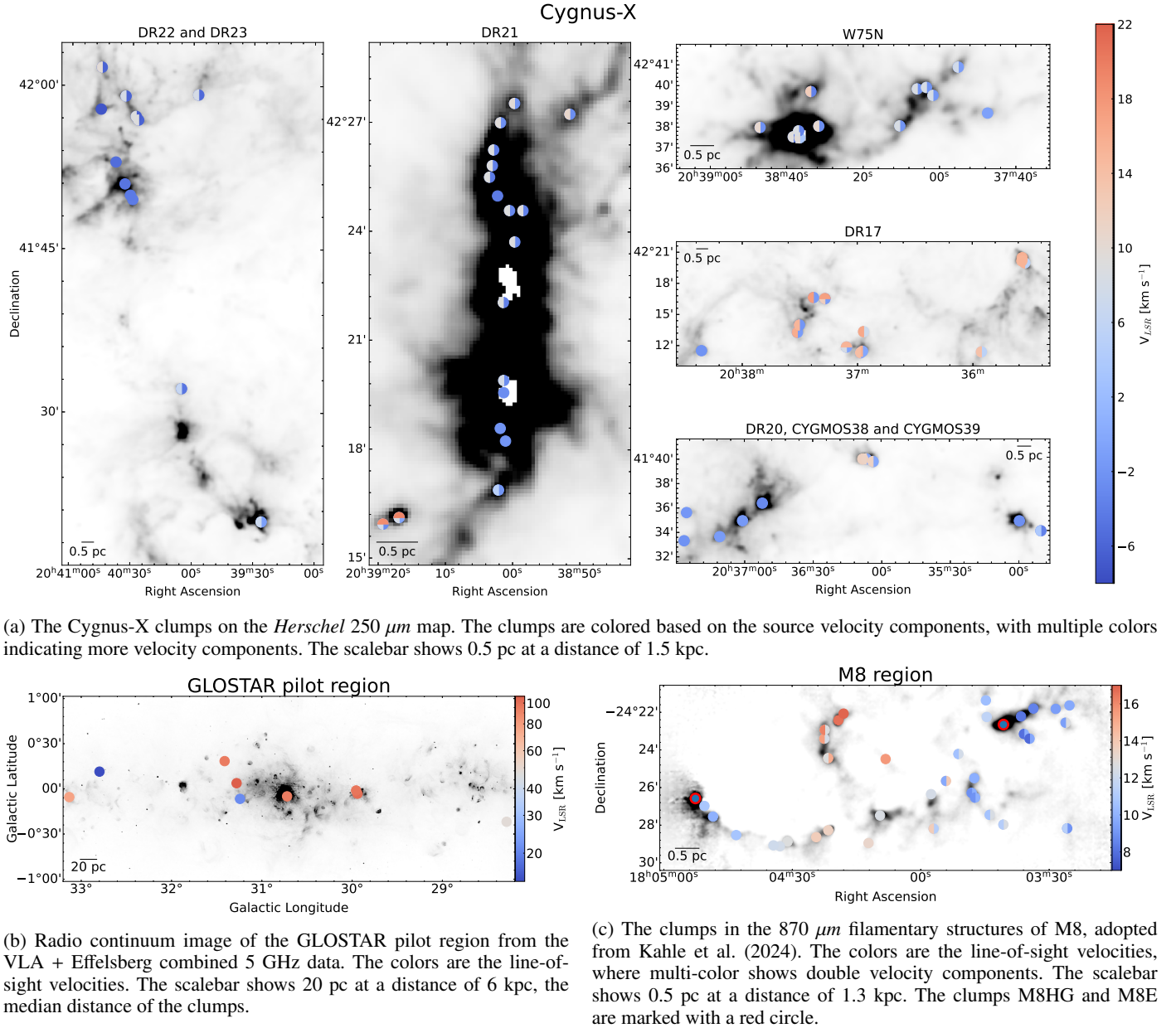


Fig. 2: Locations of clumps in Cygnus-X (top), the GLOSTAR pilot region (bottom left), and M8 (bottom right).

Array (NOEMA) and the IRAM 30-m telescope has been conducted with the goal to unveil and connect the chemical and dynamical structures of star formation across a wide range of spatial scales, namely Cygnus Allscale Survey of Chemistry and Dynamical Environments (CASCADE) (Beuther et al. 2022). Motte et al. (2007) and Cao et al. (2019) studied several regions in Cygnus-X, and, in this work, 72 clumps have been targeted. These clumps have masses in the range of $\sim 1 \times 10^4 - 2 \times 10^6 M_{\odot}$, and represent sources in a variety of evolutionary phases from starless clumps to HII regions (Motte et al. 2007; Cao et al. 2019). The observed positions are shown in Fig. 2a and listed in Table A.1.

2.2. GLOSTAR view on Star Formation in the Milky Way - pilot region

The GLOSTAR view on Star Formation in the Milky Way (GLOSTAR) project aims to characterize the unbiased statistical properties of star formation in the Galactic plane (for an overview, see Brunthaler et al. 2021). The GLOSTAR survey utilizes the Jansky Very Large Array (VLA; Perley et al. 2011) and the Effelsberg 100-m telescope¹ to conduct continuum observations covering the frequency range of 4–8 GHz. In addition, the survey includes simultaneous observations of the 6.7 GHz CH₃OH maser line, various radio recombination lines (RRL), and notably the 4.8 GHz H₂CO absorption line. The “GLOSTAR pilot region” of this survey, discussed by Brunthaler et al. (2021), covers $28^{\circ} < l < 36^{\circ}$, $|b| < 1^{\circ}$ and its radio continuum emission

¹ The 100-m telescope at Effelsberg is operated by the Max-Planck Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck Gesellschaft (MPG).

is shown in Fig. 2b. This 16 square-degree pilot region shows a diversity of extended and compact sources, including HII regions, supernova remnants, and several CH₃OH masers (Medina et al. 2019; Dokara et al. 2021; Nguyen et al. 2022; Dokara et al. 2023). We observed positions in the GLOSTAR pilot region toward which H₂CO absorption was observed in the survey. These are shown in Fig. 2b and listed in Table A.2.

We determined the distance using the radial velocity of the GLOSTAR sources, although this is challenging due to the kinematic velocity distance ambiguity discussed thoroughly in Roman-Duval et al. (2009). We utilize the Parallax-Based Distance Calculator² for the GLOSTAR sources, as described in Reid et al. (2019). In the case of G29.95−0.01 and G31.27+0.06, we adopt the trigonometric parallax distances measured by Zhang et al. (2014). The distances are listed in Table A.2.

2.3. Messier 8

The Lagoon Nebula, also known as Messier 8 (M8 hereafter), is a bright HII region illuminated by O- and B-stars. Located at a distance of 1.3 kpc, it is one of the nearest HII regions, characterized by a high UV flux (Damiani et al. 2017; Tiwari et al. 2019). Tothill et al. (2002) identified clumps associated with the molecular cloud. A plethora of molecules are identified in the M8 photodissociation region (PDR) and 38 dense dusty clumps that surround it, some of which also show PDR signatures, while 38% are likely hosting protostellar objects (Kahle et al. 2024). The clumps in the M8 region were found to have dust temperatures, T_{dust} , ranging from 15.7 - 43.2 K, and H₂ column densities, $N(\text{H}_2)$, ranging from 6.7×10^{21} to $6.1 \times 10^{22} \text{ cm}^{-2}$. Kahle et al. (2024) suggest that the remnant gas in the M8 region may be fragmenting due to the radiation pressure of the surrounding O- and B-stars. The data for four H₂CO transitions from 37 clumps within the M8 region in this study were reduced and analyzed by Kahle et al. (2024). The locations of the clumps can be seen in Fig. 2c with positions listed in Table A.3.

In order to determine volume densities, gas kinetic temperatures and H₂CO column densities using a consistent method, we combined data from all three regions. The considered clumps span a wide range of distances, molecular cloud conditions, kinematics, and evolutionary phases. This diversity allows us to apply our method across a variety of environments, thereby enhancing the robustness of our analysis.

2.4. Comparison sample

The APEX Telescope Large Area Survey of the GALaxy (ATLASGAL) provided a large inventory of ~ 10000 dense clumps within the inner Galactic region (Schuller et al. 2009). We compare our results, presented in Appendix C with measurements from the ATLASGAL clumps; sources representative of high-mass clumps in our inner Galaxy at different evolutionary phases (Urquhart et al. 2018).

A sub-sample of 110 clumps, namely the “ATLASGAL Top 100”, is designed to comprise sources that represent different evolutionary phases of high-mass star formation: starless/pre-stellar, mid-infrared weak, mid-infrared bright cores and HII regions (König et al. 2017). The ATLASGAL selected TOP 100 sources probe the clumps on the scales of 0.12 – 1.95 pc (Csengeri et al. 2014; König et al. 2017; Tang et al. 2018), similar to that probed in this study (0.18 – 1 pc for all three regions). Tang et al. (2018) determined the volume density and gas kinetic

temperatures using H₂CO ($3_{0,3} - 2_{0,2}$), ($3_{2,2} - 2_{2,1}$), ($3_{2,1} - 2_{2,0}$), ($4_{0,4} - 3_{0,3}$), ($4_{2,3} - 3_{2,2}$), and ($4_{2,2} - 3_{2,1}$). This study and Tang et al. (2018) both utilize the three $J = 3 - 2$ H₂CO transition, listed above. However, this study additionally used the $J = 1 - 0$ transition, allowing us to study the lower density material, while Tang et al. (2018) used $J = 4 - 3$.

3. Observations

We observed several H₂CO transitions toward molecular clumps in the Cygnus-X, GLOSTAR, and M8 regions described in Sect. 2. An overview of the targeted H₂CO transitions and their detection rates is presented in Table 1.

3.1. IRAM 30-m telescope observations with EMIR 090

We conducted observations with the Institut de Radioastronomie Millimétrique (IRAM; Baars et al. 1987) 30-m telescope, located on the Pico Veleta in the Spanish Sierra Nevada. We used this telescope to observe the ground-state H₂CO ($J = 1 - 0$) transition. For these observations, we employed the Eight MIXer Receiver (EMIR³; Carter et al. 2012) and the Fourier Transform Spectrometer FTS200 as backend, which provides a channel width of 195 kHz (corresponding to a velocity interval, Δv , of 0.80 km s^{−1}). At the line’s rest frequency, 72.8 GHz, the telescope’s FWHM beam width is $\approx 33''$.

Cygnus-X was mapped as part of the CASCADE program (Project ID: 145-19 and 031-20; PIs: F. Wyrowski and H. Beuther, Beuther et al. 2022). Observations of the GLOSTAR sources were carried out with the IRAM 30-m telescope on 2016 May 28th and 29th (Project ID: 110-15; PI: H. Nguyen). A bandwidth of 8 GHz per sideband was employed, providing a total frequency coverage of 16 GHz across the Cygnus-X and GLOSTAR sources, specifically 70.2–78.2 GHz in the lower sideband and 85.9–93.9 GHz in the upper sideband. The IRAM 30-m telescope observations of the 72.8 GHz H₂CO ground state line toward the Cygnus-X sources used on-the-fly mapping. The spectrum of each clump is extracted from a region matching the angular resolution of $\sim 33''$. The telescope pointing and focus were checked with Mars and 1741–038 for the Cygnus-X and GLOSTAR sources, respectively. The clumps in M8 were observed during several runs between 2022 March and June (Project ID: 141-21; PI: F. Wyrowski). The M8 sources were covered as part of a spectral line survey by Kahle et al. (2024), covering a frequency range of 40.3 GHz between 70 and 117 GHz, for which the FWHM beam size varies between $34''$ and $21''$. The FWHM beam width of the IRAM 30-m telescope⁴ θ_B , in arcseconds, is given by $2460/\nu$, where ν is the observed frequency in GHz.

We converted the observed corrected antenna temperatures, T_A^* , which assumed a forward efficiency, η_{eff} , of 0.95, to main beam temperatures, T_{MB} , using a main-beam efficiency, η_{MB} , that depends on the observing frequency⁵. At 72.8 GHz, the frequency of ground-state H₂CO line, $\eta_{\text{eff}} = 0.79$.

3.2. APEX observations with nFLASH230

H₂CO ($J = 3 - 2$) observations were performed using the 12-m Atacama Pathfinder EXperiment (APEX) telescope (Güsten

² <http://bessel.vlbi-%astrometry.org/node/378>

³ <http://www.iram.es/IRAMES/mainWiki/>

EmirforAstronomers

⁴ <https://publicwiki.iram.es/Iram30mEfficiencies>

⁵ <https://web-archives.iram.fr/ARN/feb01/node5.html>

Table 1: The H₂CO transitions observed with the IRAM 30-m and the APEX 12-m telescopes.

Telescope	H ₂ CO $J_{Ka,Kc}$	Frequency [GHz]	E_{up}/k [K]	A_{ij} [s ⁻¹]	g_{up}	n_{crit} [cm ⁻³]	Detection Rate [%] and Noise [mK]					
							Cygnus-X 78 sources	GLOSTAR 12 sources	M8 37 sources			
IRAM 30-m	1 _{0,1} → 0 _{0,0}	72.838	3.5	8.2(-6)	3	$2.8 \cdot 10^4$ ^a	100%	30	100%	23	94%	30
APEX	3 _{0,3} → 2 _{0,2}	218.222	21.0	2.8(-4)	7	$7.8 \cdot 10^5$ ^a	100%	23	100%	24	94%	25
APEX	3 _{2,2} → 2 _{2,1}	218.475	68.1	1.6(-4)	7	$3.2 \cdot 10^5$ ^b	83%	96	92%	72	48%	53
APEX	3 _{2,1} → 2 _{2,0}	218.760	68.1	1.6(-4)	7	$3.1 \cdot 10^5$ ^b	83%	90	92%	61	64%	46

Notes. The rest frequencies, upper energies, and critical densities of the four observed transitions of H₂CO. The detection rates for each line in each region are also presented. The Einstein coefficients are written in the form of $A(-x) = A \times 10^{-x}$.

References. ^a Shirley (2015); critical density at $T = 20$ K. ^b Order of critical density estimated based on collisional rates of Wiesenfeld & Faure (2013), assuming optically thin conditions and considering p-H₂ as the main collider. Molecular properties were taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2001).

et al. 2006a), located on the Chajnantor plateau in the Atacama desert (Güsten et al. 2006b).

We carried out single-pointing observations toward the selected 72 clumps in Cygnus-X during 2022 July and August (project ID: M-0109.F-9508C-2022; PI: Ivalu Barlach Christensen) and 10 clumps in the GLOSTAR pilot region during 2024 April and May (project ID: M-099.F-9519A-2017; PI: H. Nguyen and I. B. Christensen). We made use of the nFLASH 230 receiver, tuning the lower sideband (LSB) to 217.538 GHz to cover three H₂CO lines (3_{0,3}–2_{0,2}, 3_{2,2}–2_{2,1}, and 3_{2,1}–2_{2,0}, see Table 1 for the summary of spectral line properties) for clumps in Cygnus-X and the GLOSTAR pilot region. The observations were performed in position switching mode, with selected clean reference positions for each sub-regions within Cygnus-X and a fixed offset of (+600'', 0) for each source in the GLOSTAR pilot region. The telescope focus and pointing were checked, depending on the day, with Mars, Jupiter, or Saturn, achieving an estimated pointing accuracy of $\sim 5''$. The frequency range coverage was 200.4 – 208.4 GHz in the lower sideband and 216.4 – 224.4 GHz in the upper sideband, with a typical integration time of 5 minutes. However, the 5 clumps in Cygnus-X DR20 have additional observations of 30 minutes each. Additional integrations were performed for clumps in which the strongest H₂CO (3_{0,3} – 2_{0,2}) line was observed but the fainter H₂CO (3_{2,2} – 2_{2,1}) and H₂CO (3_{2,1} – 2_{2,0}) lines were not detected above 4σ . An overview of the reference positions is presented in Appendix A. An in-depth description of observations and data processing in the spectral survey of M8 is presented in Kahle et al. (2024) (project-ID: M-0107.F-9530C-2021; P.I. Karl M. Menten). The frequency coverage of the spectral line survey in M8 clumps spans 58.3 GHz between 210 – 280 GHz.

We converted the APEX T_A^* scale to a T_{MB} scale using $\eta_{eff} = 0.95$ and a main-beam efficiency depending on the date of observations. In the case of Cygnus-X sources, observations of Mars, Jupiter, and Saturn allow us to estimate the beam efficiencies from observations, and found $0.68 < \eta_{MB} < 0.86$. Based on Mars observations, we found $\eta_{MB} = 0.77$ for the GLOSTAR sources. For the M8 sources, $\eta_{MB} = 0.80$ is adopted, based on Jupiter⁶. An overview of the receiver tuning parameters of the observations of the three sub-samples is presented in Table 2.

⁶ The beam efficiency for the M8 sources is adopted from the publicly available line monitoring of APEX telescope receivers <https://www.apex-telescope.org/telescope/efficiency/>

We applied a beam correction factor of $\eta_{bf} = \left(\frac{\theta_{APEX}}{\theta_{IRAM}}\right)^2 = 0.73$ to account for the difference in beam sizes. The observations were conducted with the IRAM and APEX telescopes, which were chosen because their beam sizes are comparable, thereby minimizing systematic uncertainties introduced by beam mismatch.

3.3. Data processing of spectroscopic data

All data of observed transitions of H₂CO were reduced using the Grenoble Image and Line Data Analysis Software (GILDAS) software developed by IRAM⁷ (Pety 2018).

The spectrum of each H₂CO transition for each clump in CASCADE was produced using the Continuum and Line Analysis Single-dish Software (CLASS). All spectra were smoothed to a spectral resolution of the H₂CO (1_{0,1}–0_{0,0}) line, that is, 0.8 km s⁻¹. For each H₂CO line, the spectrum of every source is centered on the source's systemic LSR velocity, v_{LSR} , and covers a span of 160 km s⁻¹, $v_{LSR} \pm 80$ km s⁻¹. This method of data processing was performed on Cygnus-X and GLOSTAR sources. The data processing of M8 is described in Kahle et al. (2024).

4. Results

Using data from the IRAM 30-m and APEX 12-m telescopes, we investigate in detail H₂CO emission lines observed toward the clumps in Cygnus-X (78 sources), GLOSTAR (12 sources), and M8 (37 sources). We first fit Gaussian line profiles to the spectra of these clumps as input for the subsequent analysis of the physical conditions in the gas.

4.1. Spectral analysis

We analyze the spectra of each clump focusing on the H₂CO (1_{0,1} – 0_{0,0}), (3_{0,3} – 2_{0,2}), (3_{2,2} – 2_{2,1}), and (3_{2,1} – 2_{2,0}) lines. We utilize the Gaussian fitting procedure of CLASS to obtain the integrated intensity, $\int T_{MB}$, peak main-beam brightness temperature T_{MB} , velocity of peak emission, v_{peak} , and linewidth at the full width at half maximum (FWHM), Δv . In the case of clumps with several velocity components, as indicated in Fig. 2, a single Gaussian was fitted to each velocity component. These clumps are indicated with “A” and “B” in Appendix B. The maximum number of velocity components is 2 for a single clump; 6

⁷ <http://www.iram.fr/IRAMFR/GILDAS>

Table 2: Parameters of the IRAM and APEX observations.

Sources	Telescope (Receiver)	θ_B [""]	Tuning [GHz]	SB	η_{MB}	# pointings
Cygnus-X	IRAM (EMIR 090)	33	72.8	LSB inner	0.83	72
	APEX (nFLASH230)	29	218.5	USB	0.68 – 0.86	
GLOSTAR	IRAM (EMIR 090)	33	72.6	LSB inner	0.83	10
	APEX (nFLASH230)	29	218.5	USB	0.77	
M8	IRAM (EMIR 090)	33	Spectral line survey		0.8	37
	APEX (nFLASH230)	29	Spectral line survey		0.797	

sources in Cygnus-X and 2 sources in the GLOSTAR pilot region are found to have two velocity components.

Figure 3 shows example spectra of all the H_2CO lines and the Gaussian fit results for two sources each in Cygnus-X, GLOSTAR pilot region, and M8 region. The line parameters for the Cygnus-X, the GLOSTAR pilot region, and the M8 region sources are presented in Appendix B. A detailed description of the analysis can be found in Sect. 5.1. The parameters obtained for our Cygnus-X, GLOSTAR pilot region, and M8 sources are presented in Appendix B.

4.2. Detection rates

To estimate the H_2 volume density, gas kinetic temperature, and H_2CO column density, we require at least three emission lines detected for each clump. With a detection criterion of $\geq 4\sigma$, the highest detection rates of the formaldehyde lines are the ground-state transition $H_2CO(1_{0,1}-0_{0,0})$ and $H_2CO(3_{0,3}-2_{0,2})$ ($E_{up}/k = 3.50$ K and $E_{up}/k = 20.96$ K, respectively). These two emission lines are observed in all 72 clumps in Cygnus-X and 10 clumps in the GLOSTAR pilot region. Of these 72 clumps in Cygnus-X, 6 clumps exhibit two velocity components, resulting in 78 H_2CO measurements. In the GLOSTAR pilot region, 8 of the 10 clumps have a single velocity component, while 2 have an additional velocity component. Despite possibly originating from the same source, each velocity component is treated as if originating in a separate clump.

The detection rates for Cygnus-X, the GLOSTAR pilot region, and M8 are summarized in Table 1. High detection rates ($>80\%$) of the weaker H_2CO transitions (i.e., $3_{2,2}-2_{2,1}$ and $3_{2,1}-2_{2,0}$) are observed in both Cygnus-X and GLOSTAR clumps. In Cygnus-X, all four H_2CO lines are detected above 4σ in 60 sources. Of the remaining 10 clumps, these two strong lines are detected along with either $3_{2,2}-2_{2,1}$ in 5 sources or $3_{2,1}-2_{2,0}$ in the other 5.

In the GLOSTAR pilot region, all 10 clumps show all four lines above 4σ .

In contrast, M8 shows lower detection rates across all four transitions: the stronger lines are detected in 95% of sources, while the weaker $H_2CO(3_{2,2}-2_{2,1})$ and $(3_{2,1}-2_{2,0})$ transitions are detected in only 49% and 65% of clumps, respectively. Of the 37 M8 clumps observed, 13 were excluded from further analysis due to having fewer than three detected H_2CO transitions.

The high detection rate of $H_2CO(1_{0,1}-0_{0,0})$ and $(3_{0,3}-2_{0,2})$ across all regions suggest the abundant nature of H_2CO in the clumps. The different, and lower, detection rates of the higher excitation lines reveal the underlying excitation conditions (e.g. density and temperature) of these regions, which will be investigated further.

4.3. Line parameter comparisons

We examine the line profile of each transition for every clump in Cygnus-X, the GLOSTAR pilot region, and M8 to ensure consistency. Comparing the peak velocity, v_{LSR} , and line width, Δv , of each measurement, we confirm that all lines are probing similar gas components within each clump.

Figure 4 shows the difference in peak velocity between the four transitions (top), and the linewidth comparison of the four transitions (bottom). The green shaded areas in Fig. 4 indicate the regions of the accepted range. Both of the accepted ranges the v_{LSR} and Δv are based on the spectral resolution of 0.8 km s^{-1} . The accepted range for the difference between v_{peak} is $\pm 0.8 \text{ km s}^{-1}$, and for the difference between Δv , the range is $\pm 3 \times 0.8 \text{ km s}^{-1}$. The peak velocities are obtained by fitting a Gaussian for each H_2CO transition (see Sect. 4.1). Each $J = 3-2$ transition's peak velocity is compared with the peak velocity of $H_2CO(1_{0,1}-0_{0,0})$. None of the sources in Cygnus-X, GLOSTAR, and M8 are discarded, as all lines are aligned. Similar linewidths further ensure that the transitions originate from the same cloud component. Similar to the peak velocity comparison, we also compare the linewidths of $J = 3-2$ with the strongest transition $H_2CO(1_{0,1}-0_{0,0})$. Sources with a linewidth different than $\Delta v(H_2CO(1_{0,1}-0_{0,0}))$ are discarded. Two sources in Cygnus-X and none in the GLOSTAR pilot region and M8 region are discarded due to the difference of linewidths.

$H_2CO(3_{2,2}-2_{2,1})$ and $H_2CO(3_{2,1}-2_{2,0})$ are expected to exhibit similar emission line profiles, as their values for E_{up} and A_{ij} are identical (see Table 1 for reference, Müller et al. 2001). If, as one expects, these transitions originate under the same physical conditions, their line integrated intensities should be comparable. This comparison is shown in Fig. 5, which plots the intensities of the two transitions from the three different regions in this study: within the uncertainties, the integrated intensities of both lines are identical.

To summarize, we discarded sources based on the following criteria: less than three lines detected, misaligned velocities within a source, differing linewidths among transitions, insufficient agreement between line intensities of the $H_2CO(3_{2,2}-2_{2,1})$ and $H_2CO(3_{2,1}-2_{2,0})$ transitions. As a result, a total of 10 sources are discarded in Cygnus-X, none are discarded in the GLOSTAR pilot region, and 13 are discarded in M8. An overview of the sources discarded is presented in Table B.4.

5. Analysis

In the following section, we analyze the volume density, gas kinetic temperature and H_2CO column density for clumps in

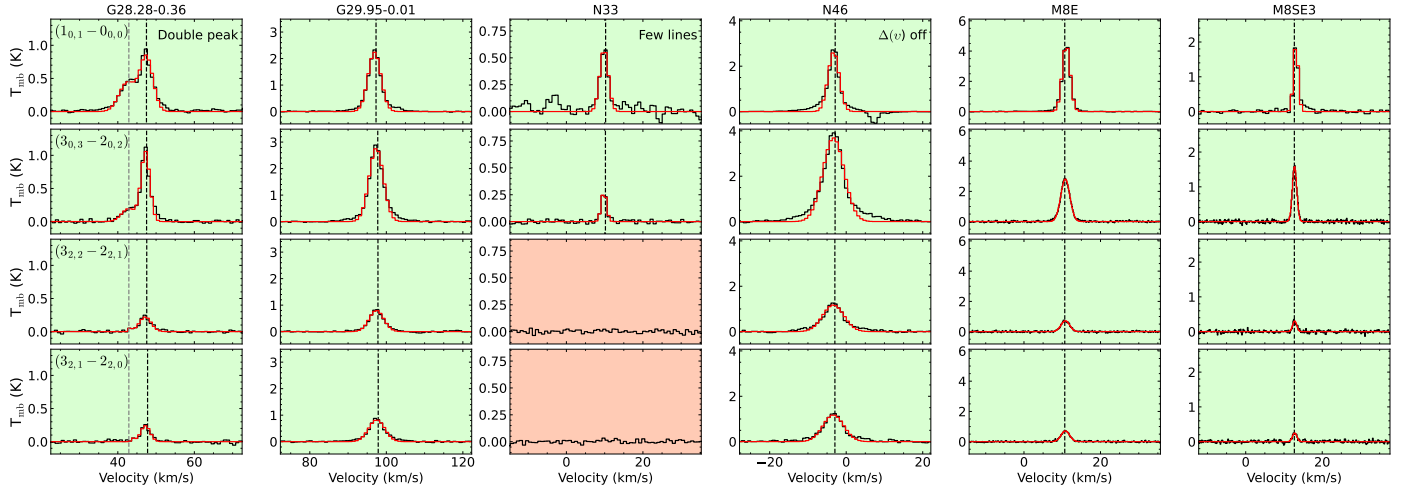


Fig. 3: Spectra of the four H_2CO transitions towards 6 clumps, two from each region. The background color indicates whether a line is at $\geq 4\sigma$ (green) or $< 4\sigma$ (red). The black dashed line indicates the peak velocity of the fitted Gaussian for each transition. Examples of clumps with either too few lines (N33), differences in Δv (N46), or double peak (G28.28–0.36) are shown.

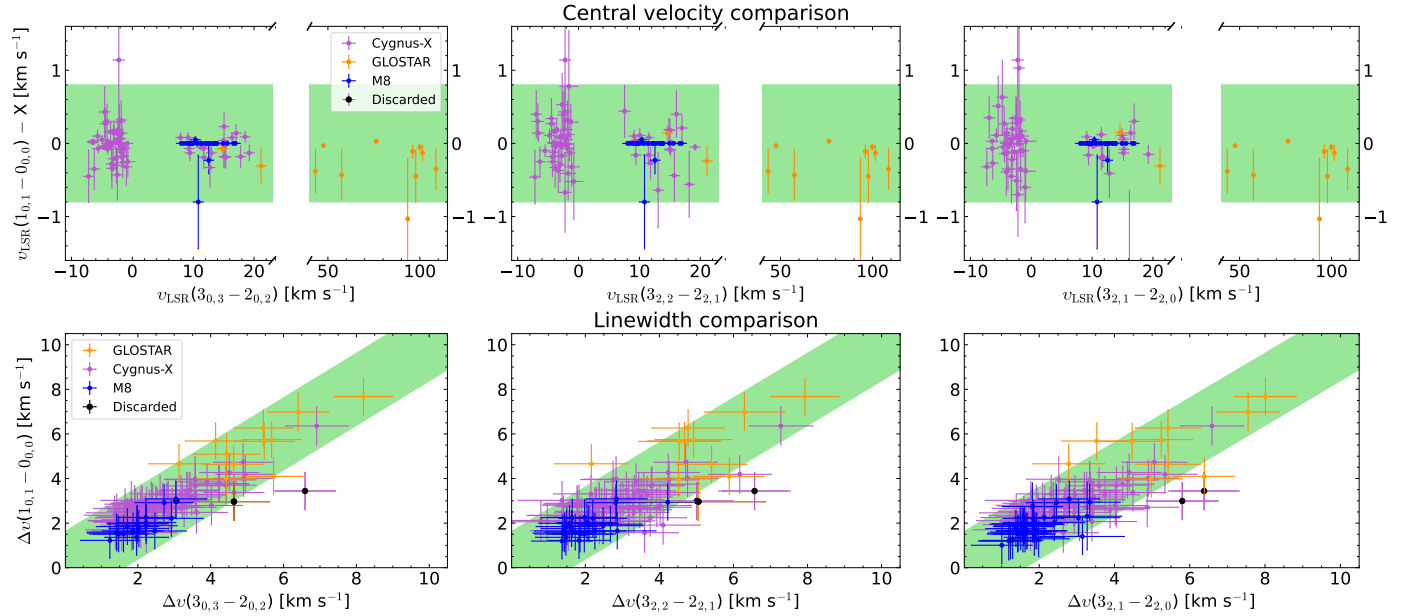


Fig. 4: *Top row*: Difference in v_{peak} between the H_2CO $(1_{0,1} - 0_{0,0})$ line and the three higher J -transitions of H_2CO . X (in the y -axis) denotes the v_{peak} noted in the x -axis. *Bottom row*: Line widths of the different H_2CO transitions. In top and bottom rows, sources in Cygnus-X are shown in purple, GLOSTAR sources in orange and M8 sources in blue. The black symbols indicate clumps that do not satisfy the velocity criterion (green shaded region) and are discarded for further analysis.

Cygnus-X (68 sources), the GLOSTAR pilot region (10 sources), and the M8 region (24 sources).

5.1. Modeling the physical conditions using H_2CO

The goal is to determine the volume density, gas kinetic temperature, and column density of H_2CO by comparing the line intensities with a model. We utilize `pyradex`⁸ under non-local thermodynamic equilibrium (LTE) conditions, the publicly available Python wrapper for RADEX (van der Tak et al. 2007), in conjunction with the Python package `emcee`⁹. The following descrip-

tion outlines the `pyradex+emcee` analysis approach for a single clump.

The modeled line parameters for a given set of physical conditions are obtained using `pyradex`. The background temperature, T_{bg} , taken to be 2.725 K (the temperature of the cosmic microwave background; Fixsen 2009), and the linewidth are assumed to be fixed, and it is assumed that the clump behaves as an expanding sphere so that the radiative transfer can be treated under the local velocity gradient (LVG) assumption. This assumption implies that there are no non-local radiative effects, and the line-of-sight line intensity, molecular column density, and H_2 volume density are independent. The `pyradex+emcee` modeling assumes an LVG geometry and yields uniformly distributed physical conditions. We adopt a spherical geometry and set the

⁸ <https://github.com/keflavich/pyradex>

⁹ <https://emcee.readthedocs.io/en/stable/>

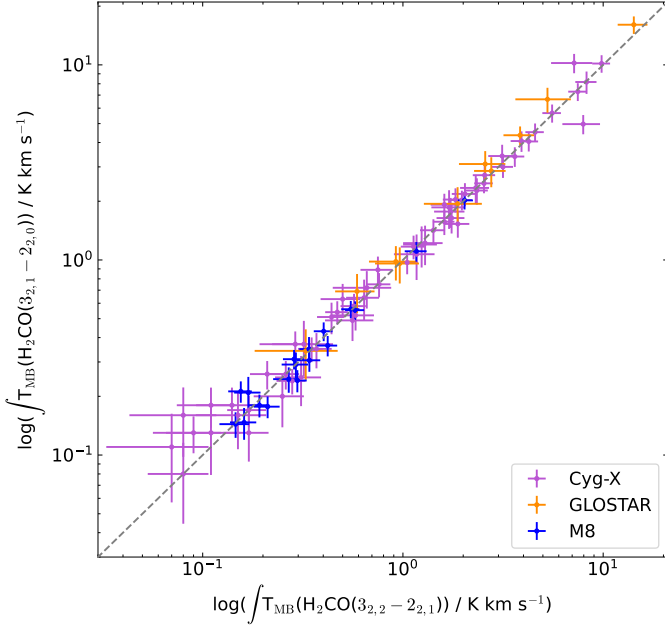


Fig. 5: Comparison of H_2CO ($3_{2,2} - 2_{2,1}$) and H_2CO ($3_{2,1} - 2_{2,0}$) integrated intensities. The sources in Cygnus-X, the GLOSTAR pilot region, and M8 are shown in purple, orange, and blue, respectively.

beam filling factor to $f = 1$ for the modeling, as the beam dilution has been accounted for in the input line intensities. The linewidth is determined as the weighted average of the transitions measured towards the clump, with the condition that the transitions have similar linewidths, indicating that they probe the same gas. The collision rate coefficients for H_2CO are adopted from Wiesenfeld & Faure (2013), who calculated them for 21 temperatures in the range from 10 to 300 K. The collisional partners of H_2CO are assumed to be p- and o- H_2 , with an assumed H_2 ortho-to-para ratio of 0.01 (Pagani et al. 2009; Dislaire et al. 2012).

The model parameters are $p = (n(\text{H}_2), T_{\text{kin}}, N(\text{H}_2\text{CO}))$. We define a Bayesian approach, with the posterior probability distribution ($\text{Pr}(p|I^{\text{data}})$) of the model parameters p (notation following Yang et al. 2017):

$$\text{Pr}(p|I^{\text{data}}) = \frac{\text{Pr}(p)\text{Pr}(I^{\text{data}}|p)}{\text{Pr}(I^{\text{data}})}, \quad (1)$$

defined in terms of the prior probability $\text{Pr}(p)$, the likelihood of the observed intensity of H_2CO given the parameter values, $\text{Pr}(I^{\text{data}}|p)$, and the probability of the data (commonly referred to as “evidence”), $\text{Pr}(I^{\text{data}})$, serving as a normalizing factor. The likelihood, assuming the noise is independent, is the product of Gaussian probability density functions:

$$\text{Pr}(I^{\text{data}}|p) = \prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(I_i^{\text{data}} - I_i^{\text{model}}(p))^2}{2\sigma_i^2}\right). \quad (2)$$

σ_i is the respective error of the observed intensity of H_2CO in I_i^{data} , and I_i^{model} is the respective modeled intensities of H_2CO with *pyradex*. We use the logarithmic form of Eq. (2). To ensure that the parameters remain within reasonable astrophysical

conditions while still allowing freedom to explore the parameter space, boundaries are set for the ranges of $\log(n(\text{H}_2)/\text{cm}^3)$, $\log(T_{\text{kin}}/\text{K})$, and $\log(N(\text{H}_2\text{CO})/\text{cm}^2)$. These boundaries are defined as $\log(n(\text{H}_2)) = 0 - 7$, $\log(T_{\text{kin}}) = 1 - 2.47$ (constrained by the availability of collisional rate coefficients; see above) and $\log(N(\text{H}_2\text{CO})/\text{cm}^2) = 10 - 17$.

We utilize 400 “walkers” to explore the parameter space. We designate a “burn-in” stage consisting of 100 iterations. We initialize the parameter space by fitting the input line parameters using *scipy.curve_fit* and *pyradex* to generate a starting position for the parameter space. After the first 100 iterations, the initial position of the parameter space is “forgotten”, and the model parameters have converged to the posterior distribution. The following stage (“walking” stage) consists of 1000 iterations, samples the posterior distribution.

The H_2 volume density, gas kinetic temperature and H_2CO column densities are obtained by the median of the posterior probability of each parameters and the respective $\pm 1\sigma_{\text{model}}$ range. These modeled parameters are presented in Table C.1.

5.2. H_2 volume density, gas kinetic temperature, and H_2CO abundance

Figure 6 shows the distribution of H_2 volume density, gas kinetic temperature, H_2CO column density, and H_2CO abundance of sources in Cygnus-X, the GLOSTAR pilot region, and M8. We compared the results of this study with the ATLASGAL Top 100 sources obtained by Tang et al. (2018). We accept the modeled physical parameters with a relative error tolerance of $\sigma_{\text{model,rel}} \leq 50\%$, where σ_{model} is obtained from the posterior distribution. The H_2 volume densities comprising sources in Cygnus-X, the GLOSTAR pilot region, and the M8 region, span a range of $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$. Figure 1 shows *pyradex* computed a range of line ratios with H_2CO ($3_{0,3} - 2_{0,2}$)/($1_{0,1} - 0_{0,0}$) and H_2CO ($3_{2,1} - 2_{2,0}$)/($3_{0,3} - 2_{0,2}$), illustrating the wide range of line ratios for the large span of volume densities we obtain.

The gas kinetic temperatures vary within the range of $T_{\text{gas}} = 16 - 219 \text{ K}$, while the H_2CO column densities span the range of $N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} - 1.6 \times 10^{15} \text{ cm}^{-2}$.

We estimate the H_2 column density, with the line-of-sight length, L , assuming a spherical structure of the clumps. The ratio of the column density and volume density yields the line-of-sight scale length

$$L = \frac{N(\text{H}_2)}{n(\text{H}_2)}. \quad (3)$$

The size of the clumps is taken as the angular resolution, $\theta_{\text{APEX}} = 29''$. To determine the sources’ scale length, L , it is essential to have well-determined distances. The clumps in Cygnus-X have sizes of 0.21 pc and the clumps in the M8 region of 0.18 pc, as the distances to the entire cloud of Cygnus-X and M8 are constant (Rygl et al. 2012; Damiani et al. 2017). The clumps of the GLOSTAR pilot region have varying distances (as described in Sect. 2.2; Reid et al. 2019), resulting in clump sizes spanning 0.26 – 1.72 pc. Utilizing this H_2 column density, we obtain the fractional abundance of H_2CO . The mean of $X(\text{H}_2\text{CO})$ in all three catalogs is $\geq 10^{-10}$ (see the rightmost part of Fig. 6 for the distribution). We obtain H_2CO abundances comparable to those in dense cores, photodissociation regions, and cloud scales, ranging from $\sim 10^{-11}$ to $\sim 10^{-9}$ (Guzmán et al. 2013; Gerin et al. 2024). We also find H_2CO abundances higher than 10^{-9} , in the Cygnus-X region.

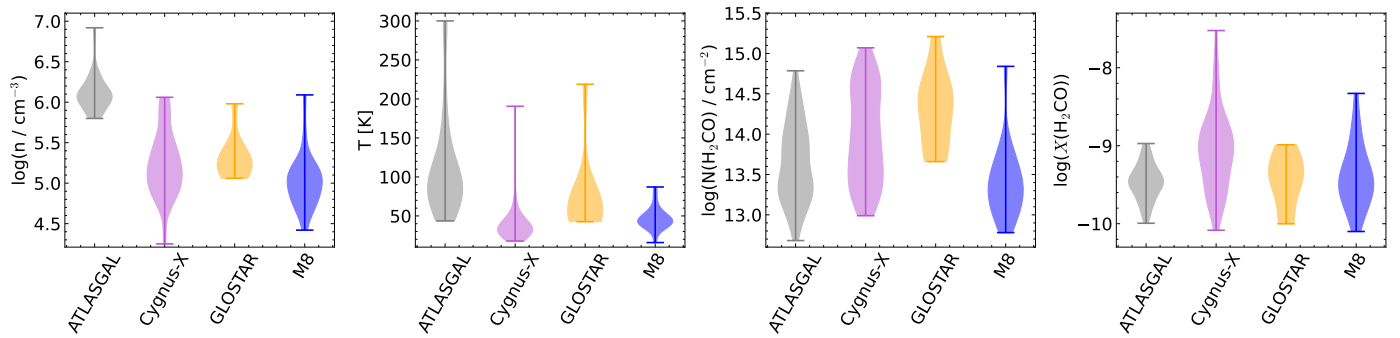


Fig. 6: Distribution of (left to right) H_2 volume density, gas kinetic temperature, H_2CO column density, and fractional abundance. The sources in Cygnus-X, the GLOSTAR pilot region, and M8 are shown in purple, orange, and blue across all distributions, respectively. Similar high-mass sources from the ATLASGAL Top 100, measured using higher J -transitions of H_2CO by Tang et al. (2018), are depicted in grey.

6. Discussion

Here, we discuss the results of all the clumps (102 in total) in the three regions and their obtained physical conditions.

The higher J -transitions analyzed by Tang et al. (2018) probe higher critical densities, with the critical density of the additional transition ($n_{\text{crit}}(\text{H}_2\text{CO } (4_{0,4} - 3_{0,3})) \sim 10^6 \text{ cm}^{-3}$) being an order of magnitude higher than that of the highest J -transition used in this study ($n_{\text{crit}}(\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})) \sim 10^5 \text{ cm}^{-3}$). We find the volume densities of sources in Cygnus-X, the GLOSTAR pilot region, and the M8 region to be an order of magnitude lower than the ATLASGAL sources. Furthermore, the upper levels of the higher J -transitions are higher than that of the J -transitions used in this study. The gas kinetic temperatures are found to be slightly higher, albeit overlapping with some higher temperature clumps in Cygnus-X and GLOSTAR pilot region. We discuss the obtained gas kinetic temperatures and volume densities further in Sects. 6.1 and 6.2.

6.1. LTE and non-LTE gas kinetic temperatures

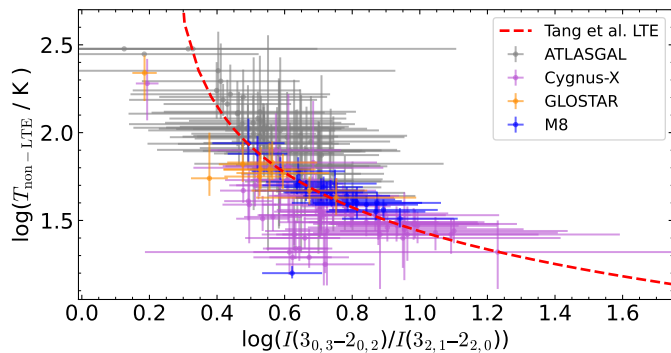


Fig. 7: The gas kinetic temperature of sources in Cygnus-X (purple), the GLOSTAR pilot region (orange) and M8 (blue) using pyradex+emcee. Grey points show the temperatures obtained for the ATLASGAL sources by Tang et al. (2018). The red dashed line shows the LTE gas kinetic temperature function presented in Eq. (4).

In this section, we present a comparison of the gas kinetic temperature obtained using a non-LTE analysis using pyradex+emcee (described in Sect. 5.1) and T_{kin} values derived

from the $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ to $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ ratio under the LTE assumption.

Mangum & Wootten (1993) and Tang et al. (2018) found a dependence of the LTE gas kinetic temperature and the $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ integrated intensity ratio:

$$T_{\text{LTE}} = \frac{47.1}{\ln\left(0.556 \times \frac{I(3_{0,3}-2_{0,2})}{I(3_{2,1}-2_{2,0})}\right)} \text{ K} \quad (4)$$

Figure 7 plots the non-LTE gas kinetic temperature versus the $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ integrated intensity ratio for the sources in our target samples and the ATLASGAL sources discussed by Tang et al. (2018).

The ATLASGAL sources exhibit higher kinetic temperatures compared to the Cygnus-X and M8 sources, but their kinetic temperatures overlap with those sources in the GLOSTAR pilot region (see Fig. 6). The clumps in the GLOSTAR pilot region trace the envelopes of HII regions, and therefore likely trace heated gas. Furthermore, we expand the relation towards lower temperatures. Tang et al. (2018) discussed that at higher densities, the gas kinetic temperatures exceeding 60 K obtained with this ratio might be overestimated at volume densities of 10^{5-7} cm^{-3} .

The LTE gas kinetic temperatures calculated using Eq. (4) are higher than non-LTE measurements as the volume density increases (see Fig. 8). Tang et al. (2018) discussed a large “bump” in the $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ line intensity ratios in their temperature-volume density plot (see their Fig. 4). The bump begins at $n(\text{H}_2) \approx 10^{5.5} \text{ cm}^{-3}$. This bump suggests that for a constant gas kinetic temperature and constant $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ and $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ line intensity ratio, no unique volume densities can be determined. The bump occurs because the $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ line intensity increases more rapidly than the line intensity of $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ for increasing densities $n(\text{H}_2) > 10^5 \text{ cm}^{-3}$. Tang et al. (2018) noted that the bump becomes more pronounced as the line ratios increase. Thus, the increasing difference between LTE and non-LTE gas kinetic temperature found in Fig. 8 is due to the LTE gas kinetic temperature calculation does not account for the rapid increase of $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ line compared with $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$.

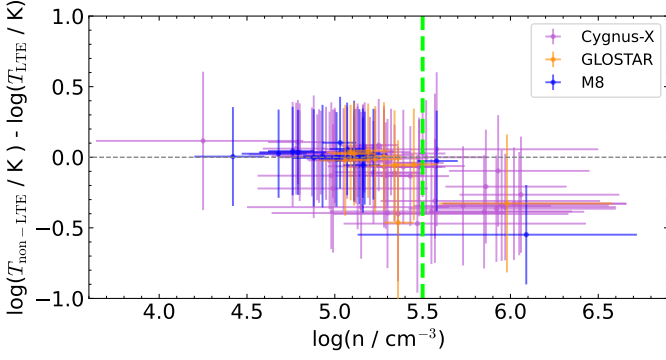


Fig. 8: Difference between the gas kinetic temperature of sources in Cygnus-X (purple), the GLOSTAR pilot region (orange), and M8 (blue) using pyradex+emcee compared with the LTE gas kinetic temperature function presented in Tang et al. (2018). The green dashed line marks $n(\text{H}_2) = 10^{5.5} \text{ cm}^{-3}$.

6.2. Volume densities

We investigate the obtained volume densities from our set of H_2CO lines, and compare them with the gas densities obtained from dust continuum measurements.

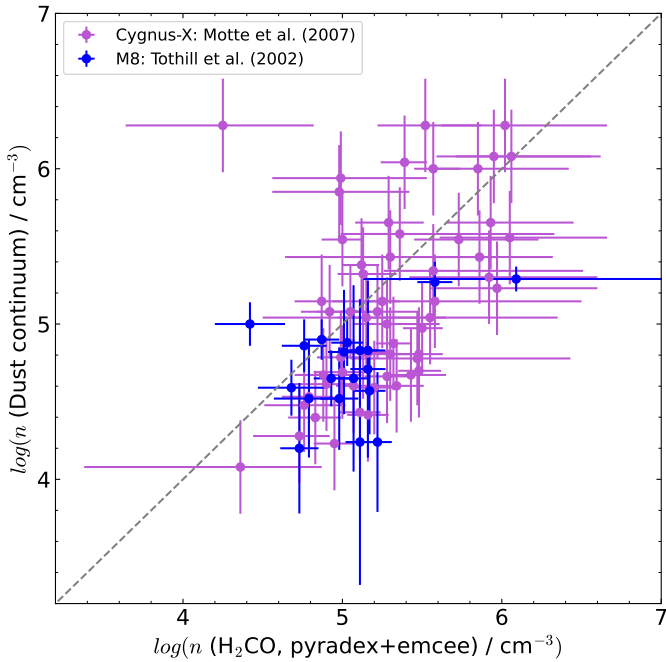


Fig. 9: Comparison of volume densities in Cygnus-X (purple) and M8 (blue) obtained with pyradex+emcee and the 1.2-mm continuum emission by Motte et al. (2007) for Cygnus-X and Tothill et al. (2002) for M8. The grey dashed line shows $x = y$.

Figure 9 shows the comparison between the volume densities obtained from the H_2CO emission lines and the 1.2-mm continuum emission, as reported by Motte et al. (2007) for Cygnus-X and by Tothill et al. (2002) for M8. Figure 9 reveals that the regions where the gas and dust are probed overlap with the detection of H_2CO . Line emission measurements typically yield higher volume densities compared to dust continuum measurements. This bias occurs because emission lines require specific densities for efficient excitation, while contin-

uum measurements probe all line emissions combined. Beuther et al. (2002) compared volume densities derived from dust continuum data with values determined through the LVG modeling of CS emission. They found that molecular line emission measurements yielded volume densities an order of magnitude larger than those obtained from dust continuum measurements. Given that $n_{\text{crit}}(\text{H}_2\text{CO}(1_{0,1} - 0_{0,0}))$ is $2.8 \times 10^4 \text{ cm}^{-3}$, this line appears well suited for probing the bulk of the gas in massive clumps that have an average H_2 density of $\sim 10^4 \text{ cm}^{-3}$ (Csengeri et al. 2014; Urquhart et al. 2018).

Weaker lines (i.e. $3_{2,2} - 2_{2,1}$ and $3_{2,1} - 2_{2,0}$) result in the higher number of clumps discarded in the M8 regions. Kahle et al. (2024) determined the H_2 column density from the spectral energy distributions (SEDs) of the clumps. Clumps with the two weaker lines not detected in the M8 region have an order of magnitude lower H_2 column densities than clumps analyzed with pyradex+emcee in the M8 region. The clumps M8SC5, M8C2, and M8C3 show particular cases of non-detection in either of the two stronger lines (i.e. $1_{0,1} - 0_{0,0}$ and $3_{0,3} - 2_{0,2}$). $\text{H}_2\text{CO}(1_{0,1} - 0_{0,0})$ was not detected at $> 3\sigma$ in M8C2, although a faint line was observed. For the clump M8C3, we did not observe the $\text{H}_2\text{CO}(1_{0,1} - 0_{0,0})$. Only $\text{H}_2\text{CO}(1_{0,1} - 0_{0,0})$ was detected in M8SC5. The remaining $J = 3 - 2$ transitions could likely not be detected as the IRAM 30-m observations are offset from the APEX observations in the case of M8SC5 (and M8WC3 and M8SE8).

The physical processes contributing to fragmentation during star formation remain a question. The clump density structure has been proposed to determine the fragmentation (e.g. Pandian et al. 2024). Observations of clumps indicate that clumps form stars at a higher rate than expected from their average spatial densities. This higher rate is proposed to be a result from the dynamic free-fall (e.g. Tan et al. 2006; Parmentier 2020), as seen from the more evolved star-forming regions exhibiting steeper density slopes (Lin et al. 2022).

Conversely, Girichidis et al. (2011) suggests that the density structure of the large-scale clump (inside-out formation process) gives insight to the initial conditions and the fragmentation of the region. Beuther et al. (2024) found that the density structure of clumps is flatter compared to that observed on core scales by Gieser et al. (2021), possibly because the star-forming regions are still embedded within larger-scale structures.

Nevertheless, in an attempt to understand the density structures of star-forming regions, constraining the volume density at different scales provides important insights into understanding star formation.

6.3. Physical conditions in different evolutionary stages of clumps

We utilize the method described by Urquhart et al. (2022) to determine the evolutionary phase of each clump in Cygnus-X and the M8 region. The SEDs of the quiescent phase and star-forming clumps can be described as greybody radiation, a modified version of blackbody radiation.

Quiescent clumps are dark at wavelengths of $70 \mu\text{m}$ or less. As **protostellar** objects form within clumps, their accretion luminosity warms the envelope, shifting the SED peak to shorter wavelengths. This warming process makes the protostar detectable first at $70 \mu\text{m}$, then at mid-infrared ($\leq 24 \mu\text{m}$), and finally at near-infrared wavelengths as it evolves into a young stellar object (YSO). High-mass stars produce significant UV flux, ionizing their surroundings and creating H II regions detectable by compact radio and mid-infrared emission. This gradual evo-

lution in the SED allows to use carefully selected far- and mid-infrared wavelength images ($3.6\ \mu\text{m}$, $24\ \mu\text{m}$, and $70\ \mu\text{m}$) to distinguish between quiescent and star-forming clumps and classify embedded objects.

The *Spitzer* Legacy Survey of the Cygnus-X Region (Kraemer et al. 2010; Beerer et al. 2010) provides observations of $3.6\ \mu\text{m}$ and $24\ \mu\text{m}$ emission in Cygnus-X. The Herschel imaging survey of OB Young Stellar objects (HOBYS) program (Motte et al. 2010) supplies the $70\ \mu\text{m}$ emission data. The continuum maps of the clumps in Cygnus-X are obtained with MUSTANG-2 camera on the Green Bank Telescope (GBT) under project GBT22A-280 (Kim et al. 2025).

For the M8 region, we obtain the $3.6\ \mu\text{m}$ and $24\ \mu\text{m}$ emission from archival data of the *Spitzer* telescope (Carey et al. 2009; Churchwell et al. 2009). We use the AKARI data covering $65\ \mu\text{m}$, calibrated by Kahle et al. (2024), to estimate the $70\ \mu\text{m}$ emission. The AKARI satellite has a lower spatial resolution than this work ($\theta_{\text{beam}} = 63.4''$; Kahle et al. (2024)). We extract the $65\ \mu\text{m}$ emission centered at each clump over the entire beam size. The continuum emission of the M8 region are obtained with the Submillimetre Common-User Bolometer Array (SCUBA; Holland et al. 1999) of the James Clerk Maxwell Telescope¹⁰ by Tothill et al. (2002) (see Fig. 2c). Following the approach by Urquhart et al. (2022), we visually examine the evolutionary phases to determine if emission is present at each of these wavelengths. For the $65\ \mu\text{m}$ emission in the M8 region, we rely on the work of Kahle et al. (2024) to decide whether a clump shows detectable emission at $65\ \mu\text{m}$.

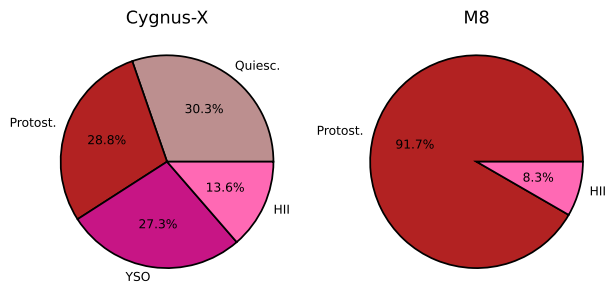


Fig. 10: Distribution of the evolutionary phases of the clumps in the Cygnus-X (left) and M8 region (right). “Protost.” denotes protostellar and “Quiesc.” denotes quiescent stage.

We determine the evolutionary phases of clumps for which the physical conditions have been measured. These are in Cygnus-X (66) and clumps in M8 (24). We discard the clumps where the evolutionary phase was ambiguous (2 in Cygnus-X). Fig. 10 shows the distribution of the evolutionary phases of Cygnus-X and M8 clumps. The quiescent phase is the most numerous in the Cygnus-X region. In M8 region, only protostellar and HII phases are observed, with the protostellar phase being the most prevalent. The sample in the GLOSTAR pilot regions are all in the HII phase (Brunthaler et al. 2021; Dokara et al. 2021, H. Nguyen priv. comm.).

The determined evolutionary phase in the M8 region identifies two of the 24 clumps as HII regions, while the remaining clumps are classified as protostellar. The clumps, M8HG and M8E (marked in red circle in Fig. 2c), have previously been determined as HII regions (see e.g. Molinari et al. 1998; Tothill et al. 2008). The “S*” clumps in the southern part of M8 are associated with a larger structure known as “the central ridge”,

which has been identified as a prominent site of star formation activity (Tothill et al. 2002, 2008). All sources in the central ridge are classified as protostellar. The clumps, designated EC 1–5, lie near the open cluster NGC 6530 (Tothill et al. 2008; Chen et al. 2007), and are also classified as protostellar clumps. The open cluster has triggered star formation in M8E (Tiwari et al. 2020), and M8HG represents one of the most recent starbursts in the M8 region (Arias et al. 2006).

Figure 11 shows the distribution of the H_2 volume density, temperature and H_2CO fractional abundance with the evolutionary phases in comparison with the ATLASGAL sample (Urquhart et al. 2022) and densities derived with CH_3OH of the ATLASGAL Top 100 sample (Giannetti et al. 2025). The three physical parameters are discussed in the following sections.

6.3.1. H_2 volume density

The left-most plot in Fig. 11 demonstrates an increase in H_2 volume density across evolutionary phases, with medians increasing ~ 0.5 dex. This increase is particularly significant as it highlights the dynamic processes at play in star formation regions, and reinforces that the density increases with evolutionary phase. Comparatively, the mean H_2 volume densities of the ATLASGAL sources do not exhibit the increasing trend observed in our sample. Specifically, the H_2 volume densities of our sample, spanning from the quiescent to the YSO evolutionary phase, overlap with those of the ATLASGAL sources. While some overlap occurs at the HII phase, our sample generally shows higher volume densities. Similarly, the H_2 volume densities of the ATLASGAL Top 100, derived from CH_3OH observations, increase as the clumps evolve (Giannetti et al. 2025). These densities generally exceed those derived for our source sample.

Theoretical models predict such an increase in H_2 volume density as gas continuously accretes onto clumps throughout the four phases (e.g. Shu et al. 1987; Offner et al. 2022). Observationally, Lin et al. (2022) observed that clumps become denser with increasing evolutionary phase. For instance, during the initial phases of star formation, the gravitational collapse of molecular clouds leads to the formation of denser regions where material can accumulate. The observed increasing trend across these phases indicates that gas accretion likely outpaces negative feedback mechanisms, resulting in denser clumps. This is critical because it suggests that the conditions necessary for star formation are being met more effectively than previously understood. Moreover, Coletta et al. (2025) observed this increasing density trend, interpreted as accretion over time, in massive dense cores across various Galactic locations. We contribute to the understanding of multi-scale processes and find this trend on larger-scale structures. The similar behavior at different scales points to self-similar physical processes.

The *pyradex+emcee* modeling assumes that the clumps are uniform within the size. On the scales observed in this study, the core-scales are averaged, assuming a power-law density profile of 1 in all clumps within the size of the clump. Gieser et al. (2023) and Beuther et al. (2024) observed a steepening of the power-law density profile from clumps to cores. In a simple idealized scenario with the various cloud scales interconnected, clumps harboring star-forming regions grow in density, mass and size due to accretion (Vázquez-Semadeni et al. 2019, 2024). The power-law density profile in the clumps of Cygnus-X will be analyzed in a forth-coming paper (Christensen et al., in prep.).

¹⁰ <https://www.eaobservatory.org/jcmt/>

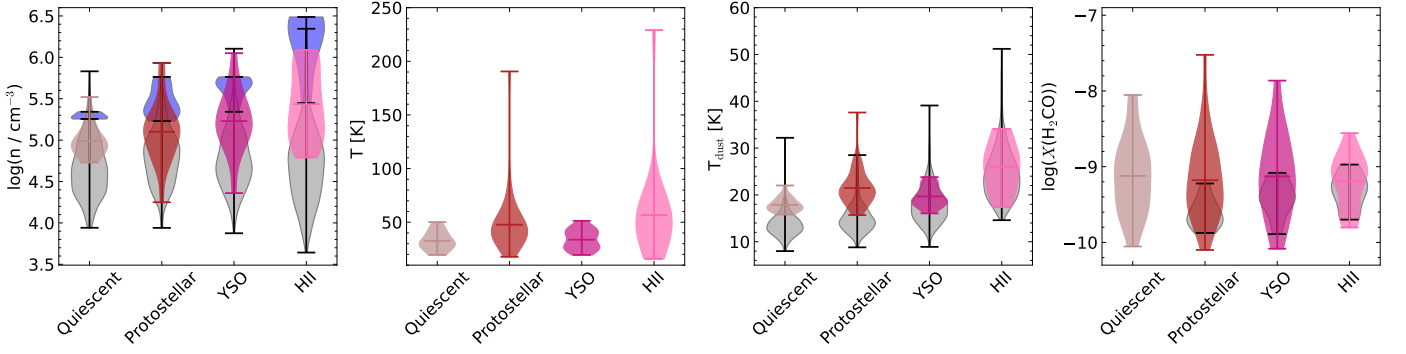


Fig. 11: Distribution of (left to right) the H_2 volume density, gas kinetic temperature, dust temperature, and H_2CO fractional abundance with evolutionary phases of our sample. The horizontal lines within the distribution marks the mean of our sub-sample, grey distributions in the H_2 volume density and dust temperature shows the mean of the ATLASGAL sample by Urquhart et al. (2022), and blue distribution in the H_2 volume density is the ATLASGAL Top 100 sample by Giannetti et al. (2025).

6.3.2. Temperatures

We observe that the gas kinetic temperature remains rather constant throughout the evolutionary phases from quiescent to clumps containing YSO (see middle plot in Fig. 11). We find that a wider range gas kinetic temperatures are seen in the HII phase, many tracing the higher temperature regime. In contrast, the dust temperature, as presented by Bonne et al. (2023) based on data from the Herschel imaging survey of OB Young Stellar objects (HOBYs) program (Motte et al. 2010) for Cygnus-X, and Kahle et al. (2024) for M8, increases with evolutionary phases. We find that our sample generally shows dust temperatures higher than the ATLASGAL sources in all but the HII stage. In contrast, the HII phase shows overlapping dust temperatures.

The differences between the gas kinetic and dust temperatures across the evolutionary stages are consistently significant within the errors. One clump in particular is an outlier with the largest difference; N44B (commonly known as DR21(OH)) with $T_{\text{gas-dust}} = 190.5^{+72}_{-73}$ K. We do not infer the unique velocity component nor spatially resolve unique cores from the continuum emissions; we use them to estimate the evolutionary phase. This study found that N44 has two velocity components; we determined both components' evolutionary phase as protostellar. Mookerjee et al. (2012) found that the cores in DR21(OH) (N44A coincides as MM1, and N44B as MM2, based on their velocities) are more evolved, using carbon-chain molecules as an evolutionary diagnostics.

The finding that gas kinetic temperatures remain constant is surprising. Mean values consistently range between 30 and 40 K, which appears high, in comparison with the dust temperature. For instance, in the CMZ, dust temperatures reach around 20 K, while gas kinetic temperatures can reach up to 100 K (Marsh et al. 2016; Tang et al. 2021b; Henshaw et al. 2023; Battersby et al. 2024). The temperature difference between the dust temperature and gas kinetic temperature occurs in areas where gas and dust are not coupled well ($\leq 10^{4.5} \text{ cm}^{-3}$ Goldsmith 2001). The gas and dust exchange energy efficiently through collisions at higher densities, and they equalize the gas and dust temperatures. However, dust cooling is more effective via infrared cooling in diffuse regions, and it leads to lower dust temperatures. This could explain the discrepancy between the H_2CO and dust temperatures, as we find that the gas kinetic temperature is consistently higher than the dust temperature.

6.3.3. Fractional abundance of H_2CO

The right-most plot in Fig. 11 shows a constant H_2CO fractional abundance of $\sim 10^{-10}$ across evolutionary phases, with mean values differing by less than a factor of two. This apparent uniformity, also noted by Tang et al. (2017), suggests that the formation and destruction of H_2CO is not strongly influenced by the dynamical evolution of the star-forming environment. Given that H_2CO can form through both gas-phase reactions (e.g., $\text{CH}_3 + \text{O} \rightarrow \text{H} + \text{H}_2\text{CO}$) and grain-surface processes (e.g., $\text{H} + \text{HCO} \rightarrow \text{H}_2\text{CO}$ Punanova et al. 2025; Potapov & Garrod 2024), the observed stability may reflect a balance between these formation pathways across different phases. Consequently, we affirm that H_2CO is a reliable trace of dense gas in various stages of star formation, largely due to its chemically resilient abundance profile.

7. Summary and Conclusion

In this paper, we determined the gas kinetic temperature, volume density, and column density of clumps in Cygnus-X, the GLOSTAR pilot region, and M8 using the pyradex+emcee approach. Our analysis encompasses four transitions of H_2CO , observed with the IRAM 30-m and APEX 12-m telescopes. The main results are summarized as follows:

1. We observe a high detection rate of the four transitions. $\text{H}_2\text{CO} (1_{0,1} - 0_{0,0})$ and $\text{H}_2\text{CO} (3_{0,3} - 2_{0,2})$ were detected in 100% of sources in Cygnus-X and the GLOSTAR pilot region. The weaker emission lines $\text{H}_2\text{CO} (3_{2,2} - 2_{2,1})$ and $\text{H}_2\text{CO} (3_{2,1} - 2_{2,0})$ have detection rates of $> 80\%$ in these two regions. In M8, $\text{H}_2\text{CO} (1_{0,1} - 0_{0,0})$ and $\text{H}_2\text{CO} (3_{0,3} - 2_{0,2})$ were detected in 94% of sources, while the detection rate for $\text{H}_2\text{CO} (3_{2,2} - 2_{2,1})$ was 48%, the lowest among the transitions. The consistently high detection rates of these low-energy H_2CO lines highlight their effectiveness as widespread tracers of molecular gas in diverse environments.
2. The pyradex+emcee method, assuming non-LTE conditions succeeds in reproducing the intensities of H_2CO transitions that probe the same gas. We examined 102 sources across the three source catalogs and successfully obtained the physical conditions.
3. We obtain volume densities of $n(\text{H}_2) = 5.4 \times 10^4 - 3.8 \times 10^5 \text{ cm}^{-3}$, gas kinetic temperatures $T_{\text{gas}} = 16 - 219 \text{ K}$, and H_2CO column densities of $N(\text{H}_2\text{CO}) = 6.0 \times 10^{12} -$

$1.6 \times 10^{15} \text{ cm}^{-2}$ in the Cygnus-X region, GLOSTAR pilot region, and M8 region. The non-LTE and LTE gas kinetic temperatures agree well below the critical density of H_2CO ($3_{0,3} - 2_{0,2}$) ($\sim 10^{5.5} \text{ cm}^{-3}$). Above this value, the LTE gas kinetic temperatures, obtained from the intensity ratios of $I(3_{0,3} - 2_{0,2})/I(3_{2,1} - 2_{2,0})$, overestimate the modeled non-LTE gas kinetic temperatures. The volume densities that we measured in Cygnus-X and M8 using H_2CO align well with those determined from the 1.2-mm continuum emission.

4. We determine the evolutionary phases of 90 clumps in the Cygnus-X and the M8 region. We find a significant order-of-magnitude increase in H_2 volume density across evolutionary phases, indicating dynamic processes in star forming regions. This observed trend, predicted by theoretical models, suggests gas accretion outpaces negative feedback, leading to denser clumps and more effective conditions for star formation. The dust temperature increases with evolutionary phases. We observe that the dust temperatures during the evolutionary phases consistently remain lower than the gas kinetic temperatures. Surprisingly, we find that the gas kinetic temperatures, obtained with `pyradex+emcee`, remain constant throughout the evolutionary phases. The H_2CO may trace more diffuse gas despite its critical densities suggesting it should exist in denser regions (e.g., the case for HCN; Kauffmann et al. 2017). The temperature discrepancy found between the dust and gas indicates that the gas and dust are decoupled.
5. The H_2CO fractional abundance remains relatively constant at $\sim 10^{-10}$ across different evolutionary phases. This stable abundance throughout star formation affirms that H_2CO can be effectively used to study gas in different phases, consistent with findings from Tang et al. (2017).

The H_2CO ($1_{0,1} - 0_{0,0}$) line, newly accessible with the IRAM 30-m telescope, along with beam-matched data for the H_2CO ($3_{0,3} - 2_{0,2}$), H_2CO ($3_{2,2} - 2_{2,1}$), and H_2CO ($3_{2,1} - 2_{2,0}$) lines from APEX 12-m, allows us to constrain a wide range of physical conditions in molecular clouds. The ground-state transition allows to probe the bulk of the gas volume densities. An increasing trend is found of H_2 volume densities with evolving clumps. The CASCADE survey has done equivalent observations of Cygnus-X with the NOEMA telescope, making it possible to expand this analysis to smaller core scales.

Acknowledgements. The authors would like to thank the anonymous referee for their suggestions and constructive comments that improved the overall quality of the manuscript. The authors are grateful to the staff at the Pico Veleta observatories and APEX for their support of these observations. I.B.C. is a fellow of the International Max-Planck-Research School (IMPRS) for A&A at the Universities of Bonn and Cologne. This work is based on observations carried out under project number 145-19, 031-20, 110-15, and 141-21 with the IRAM 30-m telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain). This publication is based on data acquired with the Atacama Pathfinder Experiment (APEX) under program ID M-0109.F9508C-2022, M-099.F9519A-2017, and M-0107.F9530C-2021. APEX has been a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory. I.B.C. thanks A. Cheema for help with the determination of evolutionary phases in the M8 clumps.

References

Akabane, K., Morimoto, M., Nagane, K., et al. 1974, PASJ, 26, 1
 Ao, Y., Henkel, C., Menten, K. M., et al. 2013, A&A, 550, A135
 Arias, J. I., Barbá, R. H., Maíz Apellániz, J., Morrell, N. I., & Rubio, M. 2006, MNRAS, 366, 739
 Baars, J. W. M., Hooghoudt, B. G., Mezger, P. G., & de Jonge, M. J. 1987, A&A, 175, 319

Battersby, C., Walker, D. L., Barnes, A., et al. 2024, arXiv e-prints, arXiv:2410.17334
 Beerer, I. M., Koenig, X. P., Hora, J. L., et al. 2010, ApJ, 720, 679
 Beuther, H., Gieser, C., Soler, J. D., et al. 2024, A&A, 682, A81
 Beuther, H., Schilke, P., Menten, K. M., et al. 2002, ApJ, 566, 945
 Beuther, H., Wyrowski, F., Menten, K. M., et al. 2022, A&A, 665, A63
 Bonne, L., Bontemps, S., Schneider, N., et al. 2023, ApJ, 951, 39
 Brunthaler, A., Menten, K. M., Dzib, S. A., et al. 2021, A&A, 651, A85
 Cao, Y., Qiu, K., Zhang, Q., et al. 2019, ApJS, 241, 1
 Carey, S. J., Noriega-Crespo, A., Mizuno, D. R., et al. 2009, PASP, 121, 76
 Carter, M., Lazareff, B., Maier, D., et al. 2012, A&A, 538, A89
 Chen, L., de Grijis, R., & Zhao, J. L. 2007, AJ, 134, 1368
 Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, PASP, 121, 213
 Coletta, A., Molinari, S., Schisano, E., et al. 2025, arXiv e-prints, arXiv:2503.05663
 Csengeri, T., Urquhart, J. S., Schuller, F., et al. 2014, A&A, 565, A75
 Cummins, S. E., Green, S., Thaddeus, P., & Linke, R. A. 1983, ApJ, 266, 331
 Damiani, F., Bonito, R., Prisinzano, L., et al. 2017, A&A, 604, A135
 Dislaire, V., Hily-Blant, P., Faure, A., et al. 2012, A&A, 537, A20
 Dokara, R., Brunthaler, A., Menten, K. M., et al. 2021, A&A, 651, A86
 Dokara, R., Gong, Y., Reich, W., et al. 2023, A&A, 671, A145
 Downes, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, A&AS, 40, 379
 Fixsen, D. J. 2009, ApJ, 707, 916
 Gerin, M., Liszt, H., Pety, J., & Faure, A. 2024, A&A, 686, A49
 Giannetti, A., Leurini, S., Schisano, E., et al. 2025, A&A, 698, A90
 Giannetti, A., Leurini, S., Wyrowski, F., et al. 2017, A&A, 603, A33
 Gieser, C., Beuther, H., Semenov, D., et al. 2023, A&A, 674, A160
 Gieser, C., Beuther, H., Semenov, D., et al. 2021, A&A, 648, A66
 Ginsburg, A., Bally, J., Battersby, C., et al. 2015, A&A, 573, A106
 Ginsburg, A., Darling, J., Battersby, C., Zeiger, B., & Bally, J. 2011, ApJ, 736, 149
 Girichidis, P., Federrath, C., Banerjee, R., & Klessen, R. S. 2011, MNRAS, 413, 2741
 Girichidis, P., Offner, S. S. R., Kritsuk, A. G., et al. 2020, Space Sci. Rev., 216, 68
 Goldsmith, P. F. 2001, ApJ, 557, 736
 Gong, Y., Ortiz-León, G. N., Rugel, M. R., et al. 2023, A&A, 678, A130
 Güsten, R., Nyman, L. Å., Schilke, P., et al. 2006a, A&A, 454, L13
 Güsten, R., Nyman, L. Å., Schilke, P., et al. 2006b, A&A, 454, L13
 Guzmán, V. V., Goicoechea, J. R., Pety, J., et al. 2013, A&A, 560, A73
 Hennemann, M., Motte, F., Schneider, N., et al. 2012, A&A, 543, L3
 Henshaw, J. D., Barnes, A. T., Battersby, C., et al. 2023, in Astronomical Society of the Pacific Conference Series, Vol. 534, Protostars and Planets VII, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 83
 Holland, W. S., Robson, E. I., Gear, W. K., et al. 1999, MNRAS, 303, 659
 Kahle, K. A., Wyrowski, F., König, C., et al. 2024, arXiv e-prints, arXiv:2404.07920
 Kaifu, N., Iguchi, T., & Morimoto, M. 1975, ApJ, 196, 719
 Kauffmann, J., Goldsmith, P. F., Melnick, G., et al. 2017, A&A, 605, L5
 Kim, W. J., Beuther, H., Wyrowski, F., et al. 2025, A&A, 694, A30
 Knödseder, J. 2000, A&A, 360, 539
 König, C., Urquhart, J. S., Csengeri, T., et al. 2017, A&A, 599, A139
 Kraemer, K. E., Hora, J. L., Egan, M. P., et al. 2010, AJ, 139, 2319
 Krumholz, M. R. & Bonnell, I. A. 2009, in Structure Formation in Astrophysics, ed. G. Chabrier, 288–320
 Leurini, S., Schilke, P., Menten, K. M., et al. 2004, A&A, 422, 573
 Leurini, S., Schilke, P., Wyrowski, F., & Menten, K. M. 2007, A&A, 466, 215
 Lin, Y., Wyrowski, F., Liu, H. B., et al. 2022, A&A, 658, A128
 Mangum, J. G., Darling, J., Henkel, C., & Menten, K. M. 2013, ApJ, 766, 108
 Mangum, J. G., Darling, J., Menten, K. M., & Henkel, C. 2008, ApJ, 673, 832
 Mangum, J. G. & Wootten, A. 1993, ApJS, 89, 123
 Mangum, J. G., Wootten, A., Loren, R. B., & Wadiak, E. J. 1990, ApJ, 348, 542
 Marsh, K. A., Ragan, S. E., Whitworth, A. P., & Clark, P. C. 2016, MNRAS, 461, L16
 McKee, C. F. & Ostriker, E. C. 2007, ARA&A, 45, 565
 McKee, C. F. & Tan, J. C. 2002, Nature, 416, 59
 Medina, S. N. X., Urquhart, J. S., Dzib, S. A., et al. 2019, A&A, 627, A175
 Molinari, S., Brand, J., Cesaroni, R., Palla, F., & Palumbo, G. G. C. 1998, A&A, 336, 339
 Mookerjee, B., Hassel, G. E., Gerin, M., et al. 2012, A&A, 546, A75
 Motte, F., Bontemps, S., Schilke, P., et al. 2007, A&A, 476, 1243
 Motte, F., Zavagno, A., Bontemps, S., et al. 2010, A&A, 518, L77
 Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, A&A, 370, L49
 Nguyen, H., Rugel, M. R., Murugesan, C., et al. 2022, A&A, 666, A59
 Offner, S. S. R., Taylor, J., Markey, C., et al. 2022, MNRAS, 517, 885
 Okoh, D., Esimbek, J., Zhou, J. J., et al. 2014, Ap&SS, 350, 657
 Pagani, L., Vastel, C., Hugo, E., et al. 2009, A&A, 494, 623
 Pandian, J. D., Chatterjee, R., Csengeri, T., et al. 2024, ApJ, 966, 54
 Parmentier, G. 2020, ApJ, 893, 32

- Perley, R. A., Chandler, C. J., Butler, B. J., & Wrobel, J. M. 2011, *ApJ*, 739, L1
- Pety, J. 2018, in *Submillimetre Single-dish Data Reduction and Array Combination Techniques*, 11
- Pillai, T., Kauffmann, J., Wyrowski, F., et al. 2011, *A&A*, 530, A118
- Pokhrel, R., Myers, P. C., Dunham, M. M., et al. 2018, *ApJ*, 853, 5
- Potapov, A. & Garrod, R. T. 2024, *A&A*, 692, A252
- Punanova, A. F., Borshcheva, K., Fedoseev, G. S., et al. 2025, *MNRAS*, 537, 3686
- Redaelli, E., Bizzocchi, L., Caselli, P., & Pineda, J. E. 2023, *A&A*, 674, L8
- Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2019, *ApJ*, 885, 131
- Remijan, A., Sutton, E. C., Snyder, L. E., et al. 2004, *ApJ*, 606, 917
- Roman-Duval, J., Jackson, J. M., Heyer, M., et al. 2009, *ApJ*, 699, 1153
- Rygl, K. L. J., Brunthaler, A., Sanna, A., et al. 2012, *A&A*, 539, A79
- Schneider, N., Bonne, L., Bontemps, S., et al. 2023, *Nature Astronomy*, 7, 546
- Schneider, N., Csengeri, T., Bontemps, S., et al. 2010, *A&A*, 520, A49
- Schuller, F., Menten, K. M., Contreras, Y., et al. 2009, *A&A*, 504, 415
- Shirley, Y. L. 2015, *PASP*, 127, 299
- Shu, F. H., Adams, F. C., & Lizano, S. 1987, *ARA&A*, 25, 23
- Tafalla, M., Myers, P. C., Caselli, P., & Walmsley, C. M. 2004, *A&A*, 416, 191
- Tan, J. C., Krumholz, M. R., & McKee, C. F. 2006, *ApJ*, 641, L121
- Tang, X. D., Henkel, C., Chen, C. H. R., et al. 2017, *A&A*, 600, A16
- Tang, X. D., Henkel, C., Menten, K. M., et al. 2021a, *A&A*, 655, A12
- Tang, X. D., Henkel, C., Wyrowski, F., et al. 2018, *A&A*, 611, A6
- Tang, Y., Wang, Q. D., & Wilson, G. W. 2021b, *MNRAS*, 505, 2377
- Tielens, A. 2021, *Molecular Astrophysics*
- Tiwari, M., Menten, K. M., Wyrowski, F., et al. 2020, *A&A*, 644, A25
- Tiwari, M., Menten, K. M., Wyrowski, F., et al. 2019, *A&A*, 626, A28
- Tothill, N. F. H., Gagné, M., Stecklum, B., & Kenworthy, M. A. 2008, in *Handbook of Star Forming Regions, Volume II*, ed. B. Reipurth, Vol. 5, 533
- Tothill, N. F. H., White, G. J., Matthews, H. E., et al. 2002, *ApJ*, 580, 285
- Urquhart, J. S., König, C., Giannetti, A., et al. 2018, *MNRAS*, 473, 1059
- Urquhart, J. S., Wells, M. R. A., Pillai, T., et al. 2022, *MNRAS*, 510, 3389
- van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, *A&A*, 468, 627
- Vázquez-Semadeni, E., Gómez, G. C., & González-Samaniego, A. 2024, *MNRAS*, 530, 3445
- Vázquez-Semadeni, E., Palau, A., Ballesteros-Paredes, J., Gómez, G. C., & Zamora-Avilés, M. 2019, *MNRAS*, 490, 3061
- Walmsley, C. M. & Ungerechts, H. 1983, *A&A*, 122, 164
- Watanabe, N. & Kouchi, A. 2002, *ApJ*, 571, L173
- Wienen, M., Wyrowski, F., Schuller, F., et al. 2012, *A&A*, 544, A146
- Wiesenfeld, L. & Faure, A. 2013, *MNRAS*, 432, 2573
- Woon, D. E. 2002, *ApJ*, 569, 541
- Wright, N. J., Drew, J. E., & Mohr-Smith, M. 2015, *MNRAS*, 449, 741
- Yamato, Y., Furuya, K., Aikawa, Y., et al. 2022, *ApJ*, 941, 75
- Yan, Y. T., Zhang, J. S., Henkel, C., et al. 2019, *ApJ*, 877, 154
- Yang, C., Omont, A., Beelen, A., et al. 2017, *A&A*, 608, A144
- Zhang, B., Moscadelli, L., Sato, M., et al. 2014, *ApJ*, 781, 89

Appendix A: Clumps locations in Cygnus-X, the GLOSTAR pilot region, and M8

The pointing coordinates of clumps in Cygnus-X, the GLOSTAR pilot region, and M8 are given in Tables A.1, A.2, and A.3, respectively.

Table A.1: Clump positions in Cygnus-X.

Source	RA (J2000)	Dec (J2000)
N1	20 ^h 35 ^m 32.7 ^s	+42°19'53"
N2	20 ^h 35 ^m 34.0 ^s	+42°20'23"
N3	20 ^h 35 ^m 34.2 ^s	+42°20'05"
N5	20 ^h 36 ^m 06.5 ^s	+41°39'58"
N6	20 ^h 36 ^m 08.1 ^s	+41°39'58"
N10	20 ^h 36 ^m 52.2 ^s	+41°36'23"
N11	20 ^h 36 ^m 56.8 ^s	+42°13'20"
N12	20 ^h 36 ^m 57.4 ^s	+42°11'27"
N13	20 ^h 36 ^m 58.4 ^s	+42°11'18"
N14	20 ^h 37 ^m 00.9 ^s	+41°34'57"
N15	20 ^h 37 ^m 10.9 ^s	+41°33'39"
N16	20 ^h 37 ^m 16.9 ^s	+42°16'31"
N17	20 ^h 37 ^m 26.5 ^s	+41°33'19"
N18	20 ^h 37 ^m 30.2 ^s	+42°13'59"
N20	20 ^h 37 ^m 47.4 ^s	+42°38'42"
N21	20 ^h 38 ^m 01.7 ^s	+42°39'33"
N22	20 ^h 38 ^m 03.4 ^s	+42°39'56"
N23	20 ^h 38 ^m 04.9 ^s	+42°33'17"
N24	20 ^h 38 ^m 05.8 ^s	+42°39'52"
N25	20 ^h 38 ^m 10.4 ^s	+42°38'05"
N26	20 ^h 38 ^m 21.2 ^s	+42°11'31"
N27	20 ^h 38 ^m 31.6 ^s	+42°38'04"
N28	20 ^h 38 ^m 33.7 ^s	+42°39'44"
N29	20 ^h 38 ^m 34.6 ^s	+42°06'19"
N30	20 ^h 38 ^m 36.6 ^s	+42°37'30"
N31	20 ^h 38 ^m 36.9 ^s	+42°37'50"
N32	20 ^h 38 ^m 38.3 ^s	+42°37'33"
N33	20 ^h 38 ^m 47.0 ^s	+42°38'00"
N34	20 ^h 38 ^m 54.3 ^s	+42°19'17"
N35	20 ^h 38 ^m 54.4 ^s	+42°18'55"
N36A	20 ^h 38 ^m 58.5 ^s	+42°23'30"
N36B	20 ^h 38 ^m 58.5 ^s	+42°23'30"
N37	20 ^h 38 ^m 58.6 ^s	+42°24'35"
N38A	20 ^h 38 ^m 59.4 ^s	+42°22'23"
N38B	20 ^h 38 ^m 59.4 ^s	+42°22'23"
N39	20 ^h 38 ^m 59.9 ^s	+42°27'32"
N40	20 ^h 38 ^m 59.8 ^s	+42°23'43"
N41A	20 ^h 39 ^m 00.2 ^s	+42°23'25"
N41B	20 ^h 39 ^m 00.2 ^s	+42°23'25"
N42A	20 ^h 39 ^m 00.3 ^s	+42°19'07"
N42B	20 ^h 39 ^m 00.3 ^s	+42°19'07"
N43	20 ^h 39 ^m 00.6 ^s	+42°24'35"
N44A	20 ^h 39 ^m 01.0 ^s	+42°22'46"
N44B	20 ^h 39 ^m 01.0 ^s	+42°22'46"
N45	20 ^h 39 ^m 01.1 ^s	+42°18'14"
N46	20 ^h 39 ^m 01.4 ^s	+42°19'34"
N47	20 ^h 39 ^m 01.4 ^s	+42°19'54"
N48	20 ^h 39 ^m 01.5 ^s	+42°22'03"
N49	20 ^h 39 ^m 02.0 ^s	+42°27'00"

N50	20 ^h 39 ^m 01.9 ^s	+42°18'35"
N51	20 ^h 39 ^m 02.4 ^s	+42°24'59"
N52	20 ^h 39 ^m 03.0 ^s	+42°26'15"
N53	20 ^h 39 ^m 03.2 ^s	+42°25'49"
N54	20 ^h 39 ^m 03.6 ^s	+42°25'30"
N55A	20 ^h 39 ^m 06.1 ^s	+42°18'19"
N55B	20 ^h 39 ^m 06.1 ^s	+42°18'19"
N56	20 ^h 39 ^m 16.9 ^s	+42°16'07"
N57	20 ^h 39 ^m 19.3 ^s	+42°15'56"
N58	20 ^h 39 ^m 25.9 ^s	+41°20'01"
N59	20 ^h 39 ^m 31.2 ^s	+41°20'03"
N60	20 ^h 39 ^m 36.2 ^s	+41°19'37"
N61	20 ^h 39 ^m 57.6 ^s	+41°59'11"
N62	20 ^h 40 ^m 03.6 ^s	+41°27'56"
N63	20 ^h 40 ^m 05.2 ^s	+41°32'13"
N64	20 ^h 40 ^m 27.2 ^s	+41°56'51"
N65	20 ^h 40 ^m 28.4 ^s	+41°57'11"
N66	20 ^h 40 ^m 29.8 ^s	+41°49'33"
N67	20 ^h 40 ^m 31.0 ^s	+41°49'57"
N68	20 ^h 40 ^m 33.5 ^s	+41°59'03"
N69	20 ^h 40 ^m 33.7 ^s	+41°50'59"
N71	20 ^h 40 ^m 38.2 ^s	+41°52'59"
N72	20 ^h 40 ^m 45.7 ^s	+41°57'50"
N05-5	20 ^h 37 ^m 25.4 ^s	+41°35'38"
N58-1	20 ^h 39 ^m 54.2 ^s	+41°23'27"
N68-8	20 ^h 40 ^m 45.4 ^s	+42°01'41"
DR21-19	20 ^h 39 ^m 02.1 ^s	+42°16'53"
DR21-22	20 ^h 39 ^m 07.3 ^s	+42°15'34"
DR21-12	20 ^h 38 ^m 51.7 ^s	+42°27'15"
W75N-6	20 ^h 37 ^m 55.0 ^s	+42°40'55"
N12-4	20 ^h 37 ^m 22.9 ^s	+42°16'38"
N12-6	20 ^h 37 ^m 31.3 ^s	+42°13'17"
N12-7	20 ^h 37 ^m 05.7 ^s	+42°11'51"
N03-2	20 ^h 35 ^m 55.6 ^s	+42°11'20"
N05-6	20 ^h 36 ^m 03.6 ^s	+41°39'45"
C09-1	20 ^h 34 ^m 59.6 ^s	+41°34'49"
C09-2	20 ^h 34 ^m 50.2 ^s	+41°33'59"
C08-2	20 ^h 35 ^m 07.6 ^s	+41°13'55"
C08-3	20 ^h 35 ^m 10.3 ^s	+41°13'10"

Table A.2: Clump positions in the GLOSTAR pilot region.

Source	RA (J2000)	Dec (J2000)	Distance (kpc)
G28.28-0.36A	18 ^h 44 ^m 15.2 ^s	-04°17'57"	7.13 ± 3.24
G28.28-0.36B	18 ^h 44 ^m 15.2 ^s	-04°17'54"	7.13 ± 3.24
G29.94-0.05	18 ^h 46 ^m 10.1 ^s	-02°41'10"	7.61 ± 0.69
G29.95-0.01	18 ^h 46 ^m 04.2 ^s	-02°39'22"	5.26 ± 0.62
G30.72-0.08	18 ^h 47 ^m 41.9 ^s	-02°00'20"	7.11 ± 0.81
G31.24-0.11	18 ^h 48 ^m 45.0 ^s	-01°33'17"	1.88 ± 0.30
G31.27+0.06	18 ^h 48 ^m 11.9 ^s	-01°26'30"	4.27 ± 0.85
G31.41+0.30	18 ^h 47 ^m 34.3 ^s	-01°12'44"	5.09 ± 0.52
G32.79+0.19A	18 ^h 50 ^m 30.8 ^s	-00°01'57"	12.22 ± 0.34
G32.79+0.19B	18 ^h 50 ^m 30.8 ^s	-00°01'57"	12.22 ± 0.34
G33.13-0.09	18 ^h 52 ^m 07.6 ^s	+00°08'12"	6.72 ± 0.27
G34.25+0.15	18 ^h 53 ^m 18.5 ^s	+01°14'56"	–

Table A.3: Clump positions observed with the APEX 12-m and the IRAM 30-m telescopes. Sources marked with a * have been observed at deviating positions with the IRAM 30 meter telescope (M8WC3: $18^{\text{h}}03^{\text{m}}44.8^{\text{s}}$, $-24^{\circ}21'03''$, M8SE8: $18^{\text{h}}04^{\text{m}}50.5^{\text{s}}$, $-24^{\circ}27'33''$, M8SC5: $18^{\text{h}}03^{\text{m}}40.7^{\text{s}}$, $-24^{\circ}26'59''$) to properly match the dust continuum peaks.

Source	RA (J2000)	Dec (J2000)
M8HG	$18^{\text{h}}03^{\text{m}}40.7^{\text{s}}$	$-24^{\circ}22'40''$
M8WC1	$18^{\text{h}}03^{\text{m}}36.6^{\text{s}}$	$-24^{\circ}22'14''$
M8WC2	$18^{\text{h}}03^{\text{m}}33.7^{\text{s}}$	$-24^{\circ}21'49''$
M8WC3*	$18^{\text{h}}03^{\text{m}}44.8^{\text{s}}$	$-24^{\circ}21'23''$
M8WC4	$18^{\text{h}}03^{\text{m}}44.6^{\text{s}}$	$-24^{\circ}22'16''$
M8WC5	$18^{\text{h}}03^{\text{m}}35.9^{\text{s}}$	$-24^{\circ}23'10''$
M8WC6	$18^{\text{h}}03^{\text{m}}34.6^{\text{s}}$	$-24^{\circ}23'25''$
M8WC7	$18^{\text{h}}03^{\text{m}}26.2^{\text{s}}$	$-24^{\circ}22'34''$
M8WC8	$18^{\text{h}}03^{\text{m}}28.5^{\text{s}}$	$-24^{\circ}21'50''$
M8WC9	$18^{\text{h}}03^{\text{m}}25.3^{\text{s}}$	$-24^{\circ}21'39''$
M8SW1	$18^{\text{h}}03^{\text{m}}25.8^{\text{s}}$	$-24^{\circ}28'11''$
M8EC1	$18^{\text{h}}04^{\text{m}}21.6^{\text{s}}$	$-24^{\circ}24'27''$
M8EC2	$18^{\text{h}}04^{\text{m}}22.5^{\text{s}}$	$-24^{\circ}23'25''$
M8EC3	$18^{\text{h}}04^{\text{m}}22.4^{\text{s}}$	$-24^{\circ}22'57''$
M8EC4	$18^{\text{h}}04^{\text{m}}19.2^{\text{s}}$	$-24^{\circ}22'26''$
M8EC5	$18^{\text{h}}04^{\text{m}}18.0^{\text{s}}$	$-24^{\circ}22'05''$
M8E	$18^{\text{h}}04^{\text{m}}52.6^{\text{s}}$	$-24^{\circ}26'35''$
M8SE1	$18^{\text{h}}04^{\text{m}}21.6^{\text{s}}$	$-24^{\circ}28'17''$
M8SE2	$18^{\text{h}}04^{\text{m}}24.4^{\text{s}}$	$-24^{\circ}28'39''$
M8SE3	$18^{\text{h}}04^{\text{m}}31.1^{\text{s}}$	$-24^{\circ}28'53''$
M8SE4	$18^{\text{h}}04^{\text{m}}32.9^{\text{s}}$	$-24^{\circ}29'08''$
M8SE5	$18^{\text{h}}04^{\text{m}}34.4^{\text{s}}$	$-24^{\circ}29'05''$
M8SE6	$18^{\text{h}}04^{\text{m}}43.1^{\text{s}}$	$-24^{\circ}28'32''$
M8SE7	$18^{\text{h}}04^{\text{m}}48.5^{\text{s}}$	$-24^{\circ}27'33''$
M8SE8*	$18^{\text{h}}04^{\text{m}}50.5^{\text{s}}$	$-24^{\circ}26'59''$
M8SC1	$18^{\text{h}}03^{\text{m}}47.5^{\text{s}}$	$-24^{\circ}25'31''$
M8SC2	$18^{\text{h}}03^{\text{m}}48.1^{\text{s}}$	$-24^{\circ}26'18''$
M8SC3	$18^{\text{h}}03^{\text{m}}47.3^{\text{s}}$	$-24^{\circ}26'33''$
M8SC4	$18^{\text{h}}03^{\text{m}}43.9^{\text{s}}$	$-24^{\circ}27'28''$
M8SC5*	$18^{\text{h}}03^{\text{m}}40.7^{\text{s}}$	$-24^{\circ}27'59''$
M8SC6	$18^{\text{h}}03^{\text{m}}57.6^{\text{s}}$	$-24^{\circ}26'22''$
M8SC7	$18^{\text{h}}03^{\text{m}}57.0^{\text{s}}$	$-24^{\circ}28'12''$
M8SC8	$18^{\text{h}}04^{\text{m}}09.5^{\text{s}}$	$-24^{\circ}27'30''$
M8SC9	$18^{\text{h}}04^{\text{m}}12.2^{\text{s}}$	$-24^{\circ}28'58''$
M8C1	$18^{\text{h}}03^{\text{m}}54.1^{\text{s}}$	$-24^{\circ}25'40''$
M8C2	$18^{\text{h}}03^{\text{m}}51.2^{\text{s}}$	$-24^{\circ}24'14''$
M8C3	$18^{\text{h}}04^{\text{m}}08.2^{\text{s}}$	$-24^{\circ}24'30''$

Table A.4: Overview of the reference positions and the number of clumps in the regions of Cygnus-X, including the number of clumps.

Region	No. of Clumps	Vel [km s ⁻¹]	Ref. R.A.	Ref. Dec
CYGMOS38	3	11.5	$20^{\text{h}}35^{\text{m}}33.0^{\text{s}}$	$+41^{\circ}47'53''$
CYGMOS39	2	11.5	$20^{\text{h}}35^{\text{m}}33.0^{\text{s}}$	$+41^{\circ}47'53''$
DR17	4	11.4	$20^{\text{h}}34^{\text{m}}29.3^{\text{s}}$	$+42^{\circ}03'26''$
DR20	5	-2.0	$20^{\text{h}}35^{\text{m}}33.0^{\text{s}}$	$+41^{\circ}47'53''$
DR21	24	-3.0	$20^{\text{h}}39^{\text{m}}30.1^{\text{s}}$	$+42^{\circ}40'55''$
DR22	2	-4.5	$20^{\text{h}}41^{\text{m}}38.3^{\text{s}}$	$+41^{\circ}35'06''$
DR23	9	-4.5	$20^{\text{h}}41^{\text{m}}38.3^{\text{s}}$	$+41^{\circ}35'06''$
DRE21	1	-1.5	$20^{\text{h}}39^{\text{m}}30.1^{\text{s}}$	$+42^{\circ}40'55''$
DRE23	1	-4.5	$20^{\text{h}}41^{\text{m}}38.3^{\text{s}}$	$+41^{\circ}35'06''$
DRW17	8	-1.5	$20^{\text{h}}37^{\text{m}}34.7^{\text{s}}$	$+42^{\circ}30'35''$
W75N	12	5.0	$20^{\text{h}}37^{\text{m}}34.7^{\text{s}}$	$+42^{\circ}30'35''$
WS75N	1	5.0	$20^{\text{h}}37^{\text{m}}34.7^{\text{s}}$	$+42^{\circ}30'35''$

Appendix B: Line profile measurements of H₂CO

The obtained integrated intensities and linewidths of H₂CO (1_{0,1}–0_{0,0}), H₂CO (3_{0,3}–2_{0,2}), H₂CO (3_{2,2}–2_{2,1}), and H₂CO (3_{2,1}–2_{2,0}) in Cygnus-X are presented in Table B.1. Similarly, Table B.2 presents the sources in the GLOSTAR pilot region, and Table B.3 presents the sources in the M8 region.

Table B.1: The integrated intensities and mean linewidth of the four H₂CO transitions.

Source	$\int T_{\text{mb}}(1_{0,1} - 0_{0,0}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{0,3} - 2_{0,2}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,2} - 2_{2,1}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,1} - 2_{2,0}) d\nu$ [K km s ⁻¹]	Linewidth $\Delta\nu$ [km s ⁻¹]
C09-1	3.66 ± 0.43	2.78 ± 0.32	0.56 ± 0.15	0.49 ± 0.11	2.71 ± 0.88
C09-2	0.88 ± 0.15	0.35 ± 0.05	-	-	1.93 ± 0.88
DR21-12	4.08 ± 0.43	1.64 ± 0.17	0.23 ± 0.06	-	2.42 ± 0.86
DR21-19	2.87 ± 0.31	0.98 ± 0.11	0.11 ± 0.04	0.13 ± 0.05	2.60 ± 0.98
N03-2	1.71 ± 0.27	0.51 ± 0.07	-	0.03 ± 0.02	2.47 ± 0.97
N05-5	2.52 ± 0.32	0.52 ± 0.08	-	-	2.66 ± 0.84
N05-6	1.88 ± 0.22	1.38 ± 0.14	0.21 ± 0.04	0.26 ± 0.04	1.90 ± 0.87
N1	8.11 ± 0.87	8.35 ± 0.85	1.75 ± 0.28	1.64 ± 0.27	3.24 ± 0.84
N10	4.12 ± 0.45	3.00 ± 0.31	0.57 ± 0.08	0.58 ± 0.08	3.16 ± 0.82
N11	1.93 ± 0.28	1.78 ± 0.20	0.29 ± 0.06	0.37 ± 0.06	2.51 ± 0.89
N12	11.47 ± 1.35	8.97 ± 0.98	2.04 ± 0.29	2.18 ± 0.30	4.35 ± 0.83
N12-4	1.57 ± 0.23	0.86 ± 0.12	0.07 ± 0.03	-	1.68 ± 0.92
N12-6	2.70 ± 0.29	1.28 ± 0.13	-	0.15 ± 0.04	1.43 ± 0.88
N12-7	2.24 ± 0.28	0.68 ± 0.07	0.04 ± 0.02	-	1.53 ± 1.03
N13	10.02 ± 1.30	6.24 ± 0.78	1.24 ± 0.25	1.20 ± 0.29	4.85 ± 0.84
N14	5.27 ± 0.55	3.42 ± 0.35	0.76 ± 0.11	0.75 ± 0.11	3.40 ± 0.82
N15	3.16 ± 0.42	0.82 ± 0.12	-	-	4.00 ± 0.82
N16	1.57 ± 0.21	1.34 ± 0.14	0.17 ± 0.04	0.17 ± 0.03	1.70 ± 0.88
N17	3.07 ± 0.35	0.87 ± 0.10	-	-	2.66 ± 0.83
N18	3.10 ± 0.36	1.64 ± 0.17	0.17 ± 0.04	0.13 ± 0.05	1.94 ± 0.90
N2	8.51 ± 0.88	7.88 ± 0.79	1.61 ± 0.20	1.57 ± 0.23	2.87 ± 0.84
N20	2.06 ± 0.25	0.98 ± 0.10	0.07 ± 0.03	0.11 ± 0.05	2.31 ± 0.99
N21	3.50 ± 0.38	1.28 ± 0.13	-	0.13 ± 0.03	1.65 ± 0.88
N22	4.51 ± 0.47	1.63 ± 0.17	-	0.17 ± 0.04	2.01 ± 0.91
N23	2.50 ± 0.27	1.54 ± 0.16	0.26 ± 0.04	0.26 ± 0.04	1.91 ± 0.87
N24	4.49 ± 0.47	1.47 ± 0.16	0.08 ± 0.04	0.16 ± 0.06	1.69 ± 0.92
N25	2.21 ± 0.23	1.36 ± 0.14	0.14 ± 0.04	0.18 ± 0.04	2.19 ± 0.91
N26	2.09 ± 0.28	1.25 ± 0.13	0.11 ± 0.05	0.18 ± 0.04	2.00 ± 0.90
N27	6.47 ± 0.65	3.16 ± 0.32	0.37 ± 0.07	0.35 ± 0.07	2.12 ± 0.87
N28	3.60 ± 0.37	2.42 ± 0.25	0.31 ± 0.08	0.25 ± 0.07	2.15 ± 0.90
N3	11.38 ± 1.18	13.70 ± 1.39	3.16 ± 0.39	3.00 ± 0.37	3.42 ± 0.83
N30	15.50 ± 1.60	30.51 ± 3.06	9.82 ± 1.01	10.16 ± 1.04	4.64 ± 0.81
N31	14.25 ± 1.48	19.40 ± 1.95	5.56 ± 0.59	5.66 ± 0.60	4.24 ± 0.81
N32	12.50 ± 1.30	14.41 ± 1.45	3.62 ± 0.42	3.39 ± 0.39	4.12 ± 0.82
N33	1.68 ± 0.25	0.52 ± 0.06	-	-	2.16 ± 0.87
N36A	6.43 ± 1.33	4.74 ± 0.52	1.13 ± 0.15	1.17 ± 0.16	2.33 ± 0.93
N36B	9.20 ± 1.50	7.21 ± 0.80	1.42 ± 0.21	1.42 ± 0.21	3.22 ± 0.89
N37	10.68 ± 1.08	6.48 ± 0.69	1.29 ± 0.29	1.22 ± 0.28	3.66 ± 0.84
N38A	14.32 ± 2.47	10.87 ± 1.13	2.54 ± 0.27	2.47 ± 0.28	2.52 ± 0.85
N38B	7.19 ± 0.79	14.71 ± 1.52	4.57 ± 0.48	4.52 ± 0.49	2.88 ± 0.83
N39	3.77 ± 0.40	1.29 ± 0.13	0.14 ± 0.05	-	2.55 ± 0.88
N40	13.96 ± 1.43	9.60 ± 0.98	1.83 ± 0.26	2.04 ± 0.29	3.40 ± 0.84
N41A	10.04 ± 1.37	4.69 ± 1.14	1.05 ± 0.15	0.97 ± 0.13	2.51 ± 0.87
N41B	4.86 ± 0.74	7.41 ± 1.28	1.61 ± 0.23	1.92 ± 0.25	3.71 ± 0.85
N42A	4.47 ± 0.59	11.36 ± 1.42	3.13 ± 0.45	3.41 ± 0.48	6.78 ± 0.85
N42B	7.76 ± 0.87	7.53 ± 1.01	1.88 ± 0.27	1.53 ± 0.23	2.78 ± 0.85
N43	12.14 ± 1.22	9.29 ± 0.95	1.73 ± 0.33	1.77 ± 0.31	3.30 ± 0.83
N44A	14.81 ± 1.61	25.31 ± 2.87	7.95 ± 1.69	4.97 ± 0.56	3.19 ± 0.85
N44B	7.33 ± 1.07	15.95 ± 2.09	7.16 ± 1.67	10.22 ± 1.13	3.70 ± 0.88

Continued from previous page.

Source	$\int T_{\text{mb}}(1_{0,1} - 0_{0,0}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{0,3} - 2_{0,2}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,2} - 2_{2,1}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,1} - 2_{2,0}) d\nu$ [K km s ⁻¹]	Linewidth $\Delta\nu$ [km s ⁻¹]
N45	6.50 ± 0.68	5.13 ± 0.53	0.64 ± 0.12	0.64 ± 0.15	2.18 ± 0.86
N46	9.82 ± 0.99	25.79 ± 2.67	8.26 ± 0.98	8.17 ± 1.07	5.74 ± 0.85
N47	9.82 ± 0.99	14.89 ± 1.50	4.25 ± 0.48	4.05 ± 0.45	3.41 ± 0.84
N48	17.14 ± 1.73	22.67 ± 2.28	7.47 ± 0.78	7.29 ± 0.76	3.62 ± 0.81
N49	4.26 ± 0.45	1.78 ± 0.18	0.15 ± 0.06	0.16 ± 0.05	2.54 ± 0.93
N5	3.21 ± 0.34	3.94 ± 0.41	0.50 ± 0.11	0.63 ± 0.12	2.26 ± 0.86
N50	7.47 ± 0.77	5.49 ± 0.59	0.66 ± 0.21	0.72 ± 0.18	2.70 ± 0.87
N51	12.42 ± 1.25	11.67 ± 1.18	2.56 ± 0.33	2.72 ± 0.31	2.81 ± 0.82
N52	7.36 ± 0.76	4.60 ± 0.50	0.75 ± 0.15	0.89 ± 0.17	2.60 ± 0.89
N53	11.60 ± 1.19	12.73 ± 1.32	3.91 ± 0.46	4.07 ± 0.48	3.99 ± 0.85
N54	11.90 ± 1.23	9.54 ± 0.98	2.34 ± 0.31	2.27 ± 0.35	3.56 ± 0.86
N55A	1.19 ± 0.32	1.02 ± 0.36	-	-	3.30 ± 1.00
N55B	4.44 ± 0.52	1.82 ± 0.31	-	-	2.34 ± 0.87
N56	5.95 ± 2.56	8.29 ± 3.69	1.97 ± 0.24	2.03 ± 0.23	5.16 ± 0.84
N57	4.65 ± 1.31	2.85 ± 0.34	-	-	2.67 ± 0.83
N58	0.89 ± 0.21	0.75 ± 0.10	0.25 ± 0.06	0.20 ± 0.06	3.08 ± 0.93
N6	4.23 ± 0.45	4.46 ± 0.46	0.58 ± 0.14	0.52 ± 0.09	2.37 ± 0.91
N61	2.44 ± 0.32	1.01 ± 0.11	0.18 ± 0.06	-	2.61 ± 0.90
N63	5.75 ± 0.62	7.75 ± 0.84	2.31 ± 0.38	2.34 ± 0.39	4.19 ± 0.84
N64	3.62 ± 0.37	2.79 ± 0.30	0.32 ± 0.13	0.37 ± 0.12	1.89 ± 1.00
N65	4.70 ± 0.50	5.92 ± 0.61	1.17 ± 0.24	1.07 ± 0.25	3.09 ± 0.85
N66	5.75 ± 0.59	3.23 ± 0.33	0.44 ± 0.07	0.51 ± 0.08	3.09 ± 0.84
N67	6.38 ± 0.66	3.26 ± 0.33	0.47 ± 0.07	0.54 ± 0.07	2.51 ± 0.85
N68	4.64 ± 0.49	7.92 ± 0.82	1.70 ± 0.29	1.86 ± 0.37	4.22 ± 0.91
N68-8	2.49 ± 0.30	1.31 ± 0.14	0.28 ± 0.06	0.24 ± 0.04	1.68 ± 0.88
N69	6.30 ± 0.66	2.43 ± 0.27	-	0.27 ± 0.10	2.26 ± 0.90
N71	2.73 ± 0.30	0.96 ± 0.11	0.09 ± 0.03	0.13 ± 0.03	1.85 ± 0.90
N72	3.74 ± 0.41	1.99 ± 0.20	0.35 ± 0.05	0.35 ± 0.05	2.17 ± 0.87
W75N-6	3.07 ± 0.37	0.99 ± 0.11	0.08 ± 0.03	0.08 ± 0.04	2.00 ± 1.02

Notes. The integrated intensities are obtained with the Gaussian fit.

Table B.2: GLOSTAR integrated intensities and mean linewidth of the four H₂CO transitions.

Source	$\int T_{\text{mb}}(1_{0,1} - 0_{0,0}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{0,3} - 2_{0,2}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,2} - 2_{2,1}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,1} - 2_{2,0}) d\nu$ [K km s ⁻¹]	Linewidth $\Delta\nu$ [km s ⁻¹]
G28.28-0.36A	2.37 ± 0.61	0.92 ± 0.19	-	-	4.76 ± 0.92
G28.28-0.36B	4.22 ± 0.57	3.25 ± 0.36	0.59 ± 0.14	0.69 ± 0.16	3.18 ± 0.91
G29.94-0.05	3.22 ± 0.38	1.93 ± 0.24	0.33 ± 0.15	0.34 ± 0.11	4.51 ± 0.89
G29.95-0.01	9.48 ± 0.96	13.04 ± 1.32	3.85 ± 0.67	4.36 ± 0.47	4.48 ± 0.85
G30.72-0.08	9.46 ± 0.97	6.97 ± 0.81	1.88 ± 0.62	1.94 ± 0.45	5.04 ± 0.89
G31.24-0.11	3.19 ± 0.34	3.51 ± 0.39	0.96 ± 0.24	0.96 ± 0.20	5.03 ± 0.86
G31.27+0.06	11.49 ± 1.17	10.41 ± 1.13	2.58 ± 0.67	3.10 ± 0.51	5.40 ± 0.87
G31.41+0.30	6.18 ± 0.68	10.21 ± 1.31	5.27 ± 1.66	6.66 ± 0.94	6.81 ± 0.90
G31.41+0.30B	1.88 ± 0.22	2.66 ± 0.60	1.38 ± 0.65	2.10 ± 0.32	6.87 ± 1.13
G32.79+0.19B	8.46 ± 0.90	9.67 ± 1.05	2.76 ± 0.50	2.86 ± 0.48	7.95 ± 0.84
G33.13-0.09	5.11 ± 0.56	3.86 ± 0.45	0.92 ± 0.26	0.98 ± 0.20	5.48 ± 0.87
G34.25+0.15	22.37 ± 2.29	38.31 ± 3.87	14.23 ± 2.38	16.06 ± 1.65	5.52 ± 0.84

Notes. The integrated intensities are obtained with the Gaussian fit.

Table B.3: M8 integrated intensities and linewidth of the four mean H₂CO transitions.

Source	$\int T_{\text{mb}}(1_{0,1} - 0_{0,0}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{0,3} - 2_{0,2}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,2} - 2_{2,1}) d\nu$ [K km s ⁻¹]	$\int T_{\text{mb}}(3_{2,1} - 2_{2,0}) d\nu$ [K km s ⁻¹]	Linewidth $\Delta\nu$ [km s ⁻¹]
M8C1	0.40 ± 0.08	0.24 ± 0.03	-	-	1.44 ± 1.12
M8C2	-	0.29 ± 0.04	-	-	2.74 ± 0.85
M8C3	-	0.56 ± 0.06	-	-	2.16 ± 0.81
M8E	11.54 ± 1.16	8.46 ± 0.85	2.03 ± 0.21	2.02 ± 0.21	2.58 ± 0.80
M8EC1	2.88 ± 0.30	1.40 ± 0.15	-	0.19 ± 0.02	1.63 ± 0.86
M8EC2	1.28 ± 0.15	0.64 ± 0.07	0.16 ± 0.02	0.15 ± 0.03	1.56 ± 0.92
M8EC3	1.96 ± 0.21	0.84 ± 0.09	-	0.16 ± 0.02	1.21 ± 0.82
M8EC4	5.90 ± 0.59	2.54 ± 0.26	0.29 ± 0.04	0.29 ± 0.04	1.89 ± 0.87
M8EC5	5.10 ± 0.51	1.91 ± 0.19	0.27 ± 0.04	0.24 ± 0.04	1.66 ± 0.88
M8HG	2.68 ± 0.29	4.88 ± 0.49	1.17 ± 0.15	1.11 ± 0.13	3.03 ± 0.87
M8SC1	1.55 ± 0.17	0.92 ± 0.09	0.16 ± 0.02	0.21 ± 0.03	1.24 ± 0.83
M8SC2	2.86 ± 0.29	1.00 ± 0.10	0.15 ± 0.02	0.14 ± 0.02	1.53 ± 0.90
M8SC3	2.52 ± 0.27	0.83 ± 0.09	-	0.13 ± 0.03	1.74 ± 1.05
M8SC4	2.05 ± 0.22	0.81 ± 0.08	-	0.24 ± 0.03	3.10 ± 0.92
M8SC5	1.14 ± 0.12	-	-	-	1.68 ± 0.81
M8SC6	1.57 ± 0.17	1.20 ± 0.12	0.29 ± 0.03	0.31 ± 0.04	2.06 ± 0.84
M8SC7	1.37 ± 0.16	0.41 ± 0.04	-	-	1.30 ± 0.81
M8SC8	4.32 ± 0.44	3.07 ± 0.31	0.55 ± 0.06	0.56 ± 0.06	1.51 ± 0.80
M8SC9	2.15 ± 0.22	0.79 ± 0.08	-	0.14 ± 0.02	1.47 ± 0.84
M8SE1	3.91 ± 0.39	2.93 ± 0.30	0.58 ± 0.06	0.55 ± 0.06	1.50 ± 0.81
M8SE2	3.33 ± 0.34	1.59 ± 0.16	0.34 ± 0.05	0.31 ± 0.04	1.65 ± 0.84
M8SE3	3.08 ± 0.32	2.31 ± 0.23	0.42 ± 0.05	0.36 ± 0.04	1.58 ± 0.82
M8SE4	2.01 ± 0.21	1.08 ± 0.11	0.21 ± 0.03	0.18 ± 0.02	1.69 ± 0.89
M8SE5	1.55 ± 0.17	0.96 ± 0.10	0.17 ± 0.03	0.21 ± 0.04	1.83 ± 1.12
M8SE6	1.50 ± 0.16	1.16 ± 0.12	0.19 ± 0.02	0.18 ± 0.02	1.68 ± 0.83
M8SE7	3.65 ± 0.37	2.64 ± 0.26	0.40 ± 0.04	0.43 ± 0.05	1.80 ± 0.81
M8SE8	4.76 ± 0.48	1.35 ± 0.14	0.30 ± 0.03	0.24 ± 0.03	2.19 ± 0.84
M8SW1	1.19 ± 0.13	0.30 ± 0.04	-	-	1.01 ± 0.84
M8WC1	3.55 ± 0.36	2.54 ± 0.27	0.50 ± 0.07	0.34 ± 0.06	1.90 ± 0.98
M8WC2	3.70 ± 0.38	2.16 ± 0.23	-	-	1.89 ± 0.80
M8WC3	2.31 ± 0.24	0.51 ± 0.10	-	-	1.82 ± 1.06
M8WC4	0.57 ± 0.12	0.48 ± 0.06	-	0.15 ± 0.03	2.04 ± 1.15
M8WC5	1.35 ± 0.22	-	-	-	2.76 ± 0.90
M8WC6	1.43 ± 0.30	0.32 ± 0.14	-	-	3.17 ± 1.58
M8WC7	0.58 ± 0.08	0.23 ± 0.06	-	-	1.19 ± 0.86
M8WC8	2.74 ± 0.29	0.63 ± 0.07	-	-	1.87 ± 0.81
M8WC9	2.66 ± 0.27	0.50 ± 0.06	-	-	1.85 ± 0.81

Notes. The integrated intensities are obtained with the Gaussian fit.

Table B.4: Number of discarded source with each criteria.

	Meas.	Too few	ν_{LSR}	$\Delta\nu$	Weak	Dis.
Cygnus-X	78	8	0	2	0	10
GLOSTAR	12	1	0	1	0	2
M8	37	13	0	0	0	13

Notes. Meas. are the total number of sources measured. Too few indicates when only H₂CO (1_{0,1} – 0_{0,0}) and H₂CO (3_{0,3} – 2_{0,2}) are detected. ν_{LSR} and $\Delta\nu$ indicates how many clumps do not satisfy the criterion of similar peak velocity and line width, respectively. Weak denotes the total number of clumps with dissimilar H₂CO (3_{2,2} – 2_{2,1}) and H₂CO (3_{2,1} – 2_{2,0}) integrated intensities.

Appendix C: pyradex+emcee results

The obtained values of volume density, gas kinetic temperature, and H₂CO column densities for clumps in all regions are presented in Table C.1.

Table C.1: Volume density, gas kinetic temperature, H₂CO column density, and number of lines used during modeling for all sources.

Source	$\log(n(\text{H}_2) / \text{cm}^3)$	$\log(T_{\text{kin}} / \text{K})$	$\log(N(\text{H}_2\text{CO}) / \text{cm}^2)$	No. of lines
C09-1	5.15 ^{0.13} _{0.14}	1.64 ^{0.10} _{0.10}	13.69 ^{0.05} _{0.05}	4(0)
DR21-12	4.80 ^{0.18} _{0.18}	1.57 ^{0.14} _{0.16}	13.69 ^{0.10} _{0.08}	3(2)
DR21-19	4.78 ^{0.18} _{0.19}	1.53 ^{0.12} _{0.14}	13.52 ^{0.10} _{0.08}	4(0)
N03-2	4.95 ^{0.28} _{0.26}	1.32 ^{0.18} _{0.21}	13.20 ^{0.10} _{0.09}	3(3)
N05-6	5.17 ^{0.10} _{0.10}	1.63 ^{0.07} _{0.06}	13.19 ^{0.04} _{0.05}	4(0)
N1	5.43 ^{0.22} _{0.17}	1.55 ^{0.10} _{0.11}	14.26 ^{0.06} _{0.05}	4(0)
N10	5.12 ^{0.11} _{0.12}	1.65 ^{0.07} _{0.06}	13.81 ^{0.05} _{0.05}	4(0)
N11	5.25 ^{0.11} _{0.11}	1.67 ^{0.08} _{0.07}	13.37 ^{0.04} _{0.04}	4(0)
N12	5.36 ^{0.97} _{0.37}	1.32 ^{0.33} _{0.13}	14.76 ^{0.43} _{0.20}	4(0)
N12-4	5.23 ^{0.27} _{0.21}	1.38 ^{0.16} _{0.21}	12.99 ^{0.07} _{0.07}	3(2)
N12-6	5.02 ^{0.14} _{0.13}	1.49 ^{0.09} _{0.11}	13.19 ^{0.06} _{0.06}	3(3)
N12-7	4.91 ^{0.28} _{0.27}	1.33 ^{0.17} _{0.20}	13.14 ^{0.12} _{0.10}	3(2)
N13	4.98 ^{0.44} _{0.42}	1.53 ^{0.19} _{0.40}	14.66 ^{0.79} _{0.18}	4(0)
N14	5.00 ^{0.12} _{0.13}	1.71 ^{0.08} _{0.07}	13.99 ^{0.06} _{0.06}	4(0)
N16	5.32 ^{0.11} _{0.11}	1.54 ^{0.06} _{0.06}	13.05 ^{0.05} _{0.05}	4(0)
N18	5.11 ^{0.13} _{0.13}	1.44 ^{0.07} _{0.07}	13.39 ^{0.06} _{0.06}	4(0)
N2	5.34 ^{0.17} _{0.15}	1.56 ^{0.08} _{0.08}	14.22 ^{0.06} _{0.05}	4(0)
N20	5.13 ^{0.21} _{0.16}	1.40 ^{0.12} _{0.17}	13.25 ^{0.06} _{0.06}	4(0)
N21	4.83 ^{0.16} _{0.17}	1.47 ^{0.08} _{0.10}	13.42 ^{0.10} _{0.08}	3(3)
N22	4.73 ^{0.19} _{0.29}	1.48 ^{0.09} _{0.09}	13.69 ^{0.19} _{0.11}	3(3)
N23	5.07 ^{0.10} _{0.11}	1.63 ^{0.07} _{0.06}	13.32 ^{0.05} _{0.05}	4(0)
N24	4.57 ^{0.34} _{1.16}	1.42 ^{0.16} _{0.15}	13.73 ^{0.96} _{0.19}	4(0)
N25	5.16 ^{0.11} _{0.11}	1.51 ^{0.08} _{0.09}	13.29 ^{0.05} _{0.05}	4(0)
N26	5.16 ^{0.13} _{0.13}	1.49 ^{0.08} _{0.08}	13.21 ^{0.06} _{0.06}	4(0)
N27	4.90 ^{0.16} _{0.21}	1.48 ^{0.07} _{0.06}	13.89 ^{0.12} _{0.09}	4(0)
N28	5.20 ^{0.13} _{0.12}	1.48 ^{0.08} _{0.08}	13.53 ^{0.05} _{0.05}	4(0)
N3	6.05 ^{0.61} _{0.44}	1.40 ^{0.12} _{0.06}	14.61 ^{0.08} _{0.08}	4(0)
N30	6.06 ^{0.56} _{0.35}	1.67 ^{0.14} _{0.07}	15.07 ^{0.06} _{0.05}	4(0)
N31	5.95 ^{0.61} _{0.36}	1.51 ^{0.13} _{0.07}	14.86 ^{0.07} _{0.07}	4(0)
N32	5.97 ^{0.63} _{0.42}	1.42 ^{0.13} _{0.06}	14.74 ^{0.08} _{0.08}	4(0)
N36A	5.05 ^{0.19} _{0.21}	1.73 ^{0.10} _{0.08}	13.96 ^{0.12} _{0.11}	4(0)
N36B	5.22 ^{0.26} _{0.23}	1.55 ^{0.10} _{0.15}	14.33 ^{0.21} _{0.11}	4(0)
N37	4.99 ^{0.54} _{0.43}	1.44 ^{0.20} _{0.31}	14.64 ^{0.92} _{0.21}	4(0)
N38A	5.30 ^{0.67} _{0.66}	1.34 ^{0.18} _{0.07}	14.70 ^{0.73} _{0.20}	4(0)
N38B	5.86 ^{0.46} _{0.23}	1.70 ^{0.13} _{0.12}	14.38 ^{0.06} _{0.04}	4(0)
N39	4.76 ^{0.26} _{0.25}	1.48 ^{0.18} _{0.23}	13.68 ^{0.13} _{0.10}	3(2)
N40	5.15 ^{0.50} _{0.65}	1.29 ^{0.16} _{0.06}	14.91 ^{0.77} _{0.24}	4(0)
N41A	4.25 ^{0.57} _{0.61}	1.83 ^{0.35} _{0.25}	14.54 ^{0.47} _{0.28}	4(0)
N41B	5.52 ^{0.35} _{0.30}	1.70 ^{0.22} _{0.15}	14.13 ^{0.06} _{0.06}	4(0)
N42A	5.93 ^{0.52} _{0.28}	1.73 ^{0.15} _{0.11}	14.56 ^{0.06} _{0.05}	4(0)
N42B	5.29 ^{0.22} _{0.21}	1.64 ^{0.13} _{0.11}	14.16 ^{0.06} _{0.06}	4(0)
N43	5.55 ^{0.80} _{0.58}	1.25 ^{0.18} _{0.05}	14.72 ^{0.57} _{0.19}	4(0)
N44A	5.85 ^{0.57} _{0.31}	1.53 ^{0.12} _{0.08}	14.74 ^{0.07} _{0.06}	4(0)
N44B	5.57 ^{0.17} _{0.12}	2.28 ^{0.14} _{0.21}	14.68 ^{0.05} _{0.05}	4(0)
N45	5.30 ^{0.16} _{0.15}	1.46 ^{0.07} _{0.08}	13.89 ^{0.06} _{0.06}	4(0)
N47	6.02 ^{0.64} _{0.40}	1.52 ^{0.15} _{0.08}	14.57 ^{0.08} _{0.07}	4(0)
N48	5.73 ^{0.50} _{0.28}	1.61 ^{0.16} _{0.11}	14.90 ^{0.07} _{0.06}	4(0)
N49	4.92 ^{0.17} _{0.18}	1.43 ^{0.09} _{0.10}	13.70 ^{0.10} _{0.08}	4(0)
N5	5.50 ^{0.13} _{0.12}	1.53 ^{0.07} _{0.07}	13.59 ^{0.04} _{0.04}	4(0)

Continued from previous page.

Source	$\log(n(\text{H}_2) / \text{cm}^3)$	$\log(T_{\text{kin}} / \text{K})$	$\log(N(\text{H}_2\text{CO}) / \text{cm}^2)$	No. of lines
N50	$5.28^{+0.33}_{-0.21}$	$1.42^{+0.11}_{-0.31}$	$14.09^{+0.31}_{-0.08}$	4(0)
N51	$5.92^{+0.68}_{-0.50}$	$1.34^{+0.16}_{-0.06}$	$14.59^{+0.12}_{-0.12}$	4(0)
N52	$5.00^{+0.16}_{-0.18}$	$1.59^{+0.09}_{-0.08}$	$14.06^{+0.08}_{-0.07}$	4(0)
N53	$5.57^{+0.94}_{-0.31}$	$1.59^{+0.21}_{-0.22}$	$14.66^{+0.15}_{-0.07}$	4(0)
N54	$5.47^{+0.96}_{-0.42}$	$1.29^{+0.34}_{-0.08}$	$14.72^{+0.38}_{-0.21}$	4(0)
N56	$5.58^{+0.92}_{-0.64}$	$1.80^{+0.42}_{-0.31}$	$14.36^{+0.17}_{-0.15}$	4(0)
N58	$5.13^{+0.18}_{-0.17}$	$1.90^{+0.21}_{-0.17}$	$13.14^{+0.09}_{-0.10}$	4(0)
N6	$5.48^{+0.14}_{-0.13}$	$1.47^{+0.06}_{-0.06}$	$13.72^{+0.04}_{-0.04}$	4(0)
N61	$4.88^{+0.24}_{-0.18}$	$1.62^{+0.22}_{-0.29}$	$13.44^{+0.09}_{-0.08}$	3(2)
N63	$5.39^{+0.14}_{-0.15}$	$1.81^{+0.15}_{-0.12}$	$14.27^{+0.04}_{-0.04}$	4(0)
N64	$5.28^{+0.17}_{-0.14}$	$1.49^{+0.11}_{-0.13}$	$13.50^{+0.05}_{-0.05}$	4(0)
N65	$5.48^{+0.15}_{-0.14}$	$1.59^{+0.10}_{-0.11}$	$13.96^{+0.04}_{-0.04}$	4(0)
N66	$4.99^{+0.13}_{-0.15}$	$1.55^{+0.07}_{-0.06}$	$13.97^{+0.08}_{-0.07}$	4(0)
N67	$4.87^{+0.15}_{-0.17}$	$1.58^{+0.06}_{-0.06}$	$13.96^{+0.10}_{-0.08}$	4(0)
N68-8	$4.97^{+0.11}_{-0.12}$	$1.67^{+0.07}_{-0.06}$	$13.26^{+0.06}_{-0.06}$	4(0)
N69	$4.36^{+0.51}_{-0.98}$	$1.45^{+0.21}_{-0.29}$	$14.31^{+0.77}_{-0.39}$	3(3)
N71	$4.79^{+0.15}_{-0.17}$	$1.53^{+0.09}_{-0.09}$	$13.34^{+0.09}_{-0.08}$	4(0)
N72	$4.95^{+0.12}_{-0.13}$	$1.64^{+0.07}_{-0.06}$	$13.58^{+0.07}_{-0.06}$	4(0)
W75N-6	$4.80^{+0.19}_{-0.23}$	$1.42^{+0.09}_{-0.11}$	$13.44^{+0.14}_{-0.10}$	4(0)
G28.28-0.36B	$5.19^{+0.12}_{-0.12}$	$1.67^{+0.08}_{-0.08}$	$13.68^{+0.05}_{-0.05}$	4(0)
G29.94-0.05	$5.09^{+0.13}_{-0.13}$	$1.63^{+0.11}_{-0.10}$	$13.66^{+0.05}_{-0.05}$	4(0)
G29.95-0.01	$5.45^{+0.14}_{-0.14}$	$1.82^{+0.13}_{-0.10}$	$14.43^{+0.03}_{-0.03}$	4(0)
G30.72-0.08	$5.06^{+0.14}_{-0.15}$	$1.79^{+0.15}_{-0.12}$	$14.35^{+0.06}_{-0.06}$	4(0)
G31.24-0.11	$5.28^{+0.10}_{-0.11}$	$1.83^{+0.12}_{-0.10}$	$13.85^{+0.04}_{-0.04}$	4(0)
G31.27+0.06	$5.23^{+0.15}_{-0.16}$	$1.75^{+0.13}_{-0.11}$	$14.51^{+0.05}_{-0.05}$	4(0)
G31.41+0.30	$5.36^{+0.09}_{-0.08}$	$2.34^{+0.10}_{-0.16}$	$14.59^{+0.04}_{-0.04}$	4(0)
G32.79+0.19B	$5.34^{+0.13}_{-0.14}$	$1.79^{+0.13}_{-0.11}$	$14.55^{+0.04}_{-0.04}$	4(0)
G33.13-0.09	$5.11^{+0.12}_{-0.12}$	$1.77^{+0.11}_{-0.09}$	$14.04^{+0.05}_{-0.05}$	4(0)
G34.25+0.15	$5.98^{+0.60}_{-0.39}$	$1.74^{+0.26}_{-0.10}$	$15.21^{+0.06}_{-0.06}$	4(0)
M8E	$6.09^{+0.63}_{-0.96}$	$1.20^{+0.04}_{-0.03}$	$14.84^{+0.48}_{-0.18}$	4(0)
M8EC1	$4.98^{+0.11}_{-0.12}$	$1.55^{+0.05}_{-0.05}$	$13.29^{+0.06}_{-0.05}$	3(3)
M8EC2	$4.93^{+0.10}_{-0.11}$	$1.78^{+0.08}_{-0.07}$	$12.94^{+0.05}_{-0.05}$	4(0)
M8EC3	$4.87^{+0.10}_{-0.11}$	$1.67^{+0.07}_{-0.06}$	$13.00^{+0.06}_{-0.06}$	3(3)
M8EC4	$4.79^{+0.16}_{-0.22}$	$1.51^{+0.06}_{-0.05}$	$13.81^{+0.14}_{-0.10}$	4(0)
M8EC5	$4.68^{+0.16}_{-0.21}$	$1.56^{+0.06}_{-0.05}$	$13.69^{+0.14}_{-0.10}$	4(0)
M8HG	$5.58^{+0.12}_{-0.11}$	$1.72^{+0.07}_{-0.06}$	$13.78^{+0.03}_{-0.03}$	4(0)
M8SC1	$5.03^{+0.09}_{-0.10}$	$1.70^{+0.06}_{-0.05}$	$12.92^{+0.04}_{-0.05}$	4(0)
M8SC2	$4.76^{+0.12}_{-0.14}$	$1.59^{+0.05}_{-0.05}$	$13.29^{+0.08}_{-0.07}$	4(0)
M8SC3	$4.73^{+0.13}_{-0.15}$	$1.60^{+0.09}_{-0.09}$	$13.29^{+0.09}_{-0.08}$	3(3)
M8SC4	$4.73^{+0.11}_{-0.12}$	$1.88^{+0.10}_{-0.09}$	$13.49^{+0.06}_{-0.06}$	3(3)
M8SC6	$5.11^{+0.09}_{-0.09}$	$1.79^{+0.07}_{-0.06}$	$13.20^{+0.04}_{-0.04}$	4(0)
M8SC8	$5.11^{+0.10}_{-0.11}$	$1.63^{+0.05}_{-0.05}$	$13.51^{+0.05}_{-0.05}$	4(0)
M8SC9	$4.78^{+0.11}_{-0.12}$	$1.66^{+0.07}_{-0.07}$	$13.13^{+0.07}_{-0.06}$	3(3)
M8SE1	$5.14^{+0.10}_{-0.11}$	$1.66^{+0.06}_{-0.05}$	$13.47^{+0.04}_{-0.04}$	4(0)
M8SE2	$4.88^{+0.11}_{-0.12}$	$1.69^{+0.06}_{-0.05}$	$13.41^{+0.06}_{-0.06}$	4(0)
M8SE3	$5.17^{+0.09}_{-0.10}$	$1.62^{+0.05}_{-0.04}$	$13.35^{+0.04}_{-0.04}$	4(0)
M8SE4	$5.01^{+0.09}_{-0.10}$	$1.64^{+0.05}_{-0.05}$	$13.15^{+0.05}_{-0.05}$	4(0)
M8SE5	$5.07^{+0.10}_{-0.10}$	$1.67^{+0.06}_{-0.06}$	$13.08^{+0.04}_{-0.04}$	4(0)
M8SE6	$5.22^{+0.08}_{-0.09}$	$1.61^{+0.05}_{-0.04}$	$13.04^{+0.04}_{-0.04}$	4(0)
M8SE7	$5.16^{+0.10}_{-0.11}$	$1.59^{+0.05}_{-0.04}$	$13.49^{+0.04}_{-0.04}$	4(0)
M8SE8	$4.42^{+0.18}_{-0.22}$	$1.71^{+0.08}_{-0.06}$	$13.85^{+0.16}_{-0.13}$	4(0)
M8WC1	$5.16^{+0.10}_{-0.11}$	$1.60^{+0.06}_{-0.05}$	$13.50^{+0.04}_{-0.04}$	4(0)
M8WC4	$5.12^{+0.14}_{-0.13}$	$1.94^{+0.14}_{-0.11}$	$12.78^{+0.07}_{-0.07}$	3(3)

Notes. The number of lines indicate how many of the four H_2CO transitions are utilized. 3(2) indicates the third line is H_2CO ($3_{2,2} - 2_{2,1}$) and 3(3) indicates third line is H_2CO ($3_{2,1} - 2_{2,0}$).

Appendix D: The evolutionary phases of clumps

Table D.1: The detection of emission in continuum, 70 μm , 24 μm , and 3.6 μm , and their determined evolutionary phase of clumps in Cygnus-X and M8.

Source	Cont.	Emission detected			Evolutionary phase	Source	Cont.	Emission detected			Evolutionary phase
		70 μm	24 μm	3.6 μm				70 μm	24 μm	3.6 μm	
C09-1	No	Yes	Yes	Yes	YSO	N53	No	Yes	Yes	Yes	YSO
DR21-12	No	No	No	No	Quiescent	N54	No	Yes	Yes	Yes	YSO
DR21-19	No	Weak	No	No	Ambiguous	N56	Yes	Yes	Yes	Yes	HII
N03-2	Yes	No	No	No	Quiescent	N58	Yes	Yes	Yes	Yes	HII
N05-6	No	Yes	Yes	Yes	YSO	N6	Yes	Yes	Yes	Yes	HII
N1	Yes	Yes	Yes	No	Ambiguous	N61	No	Yes	Yes	Yes	YSO
N10	No	Yes	Yes	Yes	YSO	N63	Yes	Yes	Yes	No	Protostellar
N11	Yes	Yes	No	No	Protostellar	N64	No	No	No	No	Quiescent
N12	No	Yes	Yes	Yes	YSO	N65	No	Yes	Yes	Yes	YSO
N12-4	Yes	No	No	No	Quiescent	N66	Yes	Yes	No	No	Protostellar
N12-6	No	Yes	No	No	Quiescent	N67	Yes	No	No	No	Quiescent
N12-7	No	No	No	No	Quiescent	N68-8	No	No	No	No	Quiescent
N13	Yes	No	No	No	Quiescent	N69	No	Yes	Yes	Yes	YSO
N14	No	Yes	Yes	Yes	YSO	N71	No	Yes	Yes	No	Protostellar
N16	No	Yes	Yes	Yes	YSO	N72	Yes	No	No	No	Quiescent
N18	No	Yes	Yes	Yes	YSO	W75N-6	No	Yes	Yes	Yes	YSO
N2	Yes	Yes	No	Yes	Protostellar	M8E	Yes	Yes	Yes	Yes	HII
N20	No	Yes	Yes	Yes	YSO	M8EC1	Yes	Yes	No	No	Protostellar
N21	No	No	No	No	Quiescent	M8EC2	No	Yes	No	No	Protostellar
N22	Yes	No	No	No	Quiescent	M8EC3	Yes	Yes	No	No	Protostellar
N23	Yes	No	No	No	Quiescent	M8EC4	Yes	Yes	No	No	Protostellar
N24	Yes	No	No	No	Quiescent	M8EC5	No	Yes	No	No	Protostellar
N25	Yes	Yes	Yes	No	Protostellar	M8HG	Yes	Yes	Yes	Yes	HII
N26	No	Yes	Yes	Yes	YSO	M8SC1	Yes	Yes	Yes	No	Protostellar
N27	Yes	No	No	No	Quiescent	M8SC2	Yes	Yes	No	No	Protostellar
N28	Yes	Yes	Yes	No	Protostellar	M8SC3	Yes	Yes	No	No	Protostellar
N3	No	Yes	Yes	Yes	YSO	M8SC4	Yes	Yes	No	No	Protostellar
N30	Yes	Yes	Yes	Yes	HII	M8SC6	No	Yes	No	No	Protostellar
N31	Yes	Yes	Yes	Yes	HII	M8SC8	Yes	Yes	No	No	Protostellar
N32	Yes	Yes	Yes	Yes	HII	M8SC9	Yes	Yes	No	No	Protostellar
N36A	Yes	Yes	No	No	Protostellar	M8SE1	Yes	Yes	No	No	Protostellar
N36B	Yes	Yes	No	No	Protostellar	M8SE2	Yes	Yes	No	No	Protostellar
N37	Yes	Yes	Yes	No	Protostellar	M8SE3	Yes	Yes	No	No	Protostellar
N38A	Yes	Yes	Yes	No	Protostellar	M8SE4	No	Yes	No	No	Protostellar
N38B	Yes	Yes	No	No	Protostellar	M8SE5	Yes	Yes	No	No	Protostellar
N39	Yes	No	No	No	Quiescent	M8SE6	Yes	Yes	No	No	Protostellar
N40	Yes	No	No	No	Quiescent	M8SE7	Yes	Yes	No	No	Protostellar
N41A	Yes	Yes	No	No	Protostellar	M8SE8	No	Yes	No	No	Protostellar
N41B	Yes	No	No	No	Quiescent	M8WC1	Yes	Yes	No	No	Protostellar
N42A	No	Yes	Yes	No	Protostellar	M8WC4	Yes	Yes	Yes	No	Protostellar
N42B	No	Yes	Yes	No	Protostellar						
N43	Yes	Yes	Yes	No	Protostellar						
N44A	Yes	Yes	Yes	No	Protostellar						
N44B	Yes	Yes	Yes	No	Protostellar						
N45	No	Yes	No	No	Protostellar						
N47	Yes	Yes	Yes	Yes	HII						
N48	No	Yes	Yes	Yes	YSO						
N49	No	No	No	No	Quiescent						
N5	Yes	Yes	Yes	Yes	HII						
N50	No	Yes	Yes	Yes	YSO						
N51	Yes	Yes	Yes	Yes	HII						
N52	Yes	No	No	No	Quiescent						

Formaldehyde spectra and pyradex+emcee results

D.1 Line profile measurements of H_2CO

The spectra of H_2CO ($1_{0,1} - 0_{0,0}$), H_2CO ($3_{0,3} - 2_{0,2}$), H_2CO ($3_{2,2} - 2_{2,1}$), and H_2CO ($3_{2,1} - 2_{2,0}$) in Cygnus-X are shown in Figs. [D.1](#), [D.2](#), [D.3](#), and [D.4](#), respectively. Similarly, the GLOSTAR spectra are presented in Figs. [D.5](#), [D.6](#), [D.7](#), and [D.8](#), and the spectra of M8 sources are presented in Figs. [D.9](#), [D.10](#), [D.11](#) and [D.12](#).

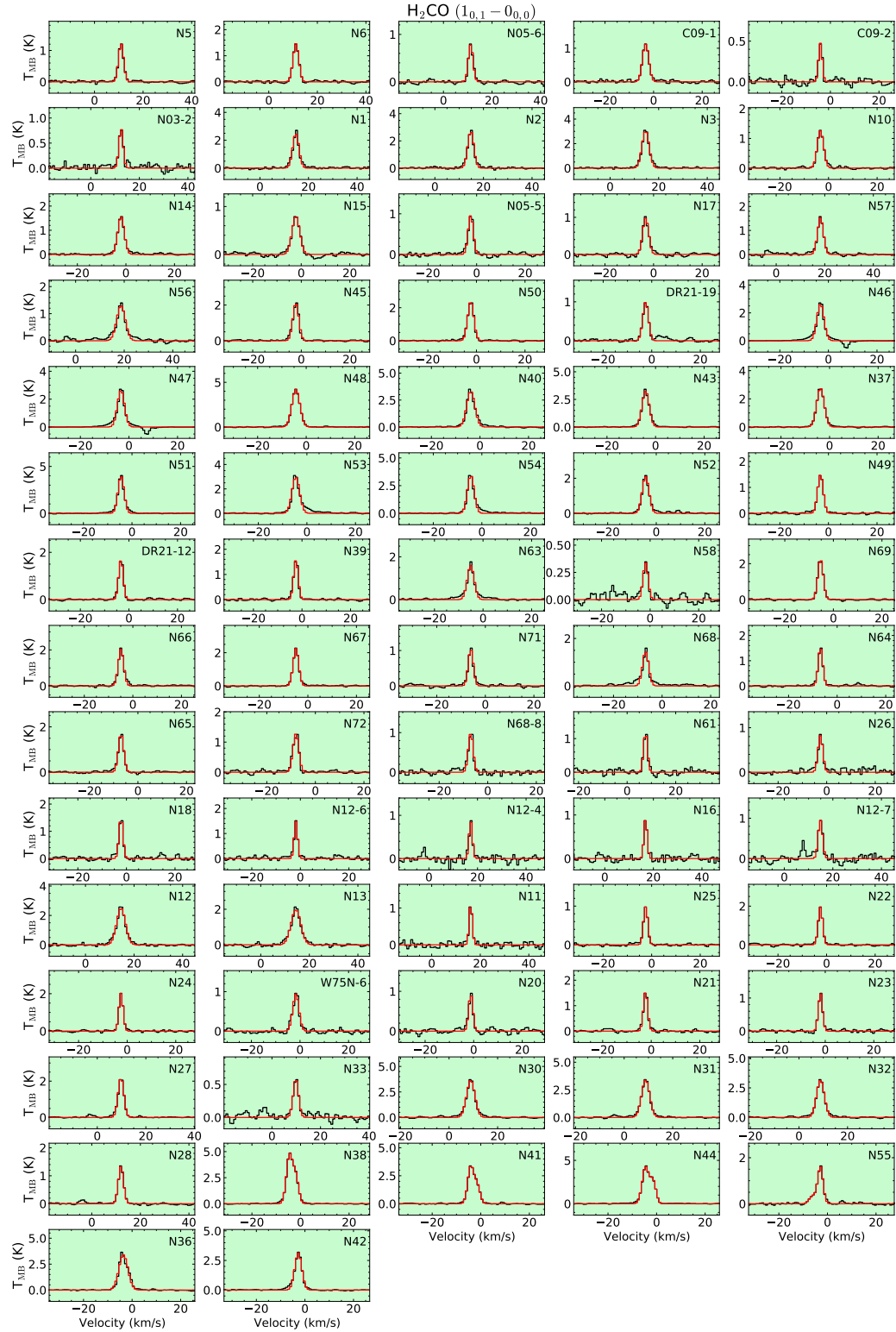


Figure D.1: Spectra of H_2CO ($1_{0,1} - 0_{0,0}$) towards the Cygnus-X sources. The green background indicated detection ($> 4\sigma$) and white background indicates no detection.

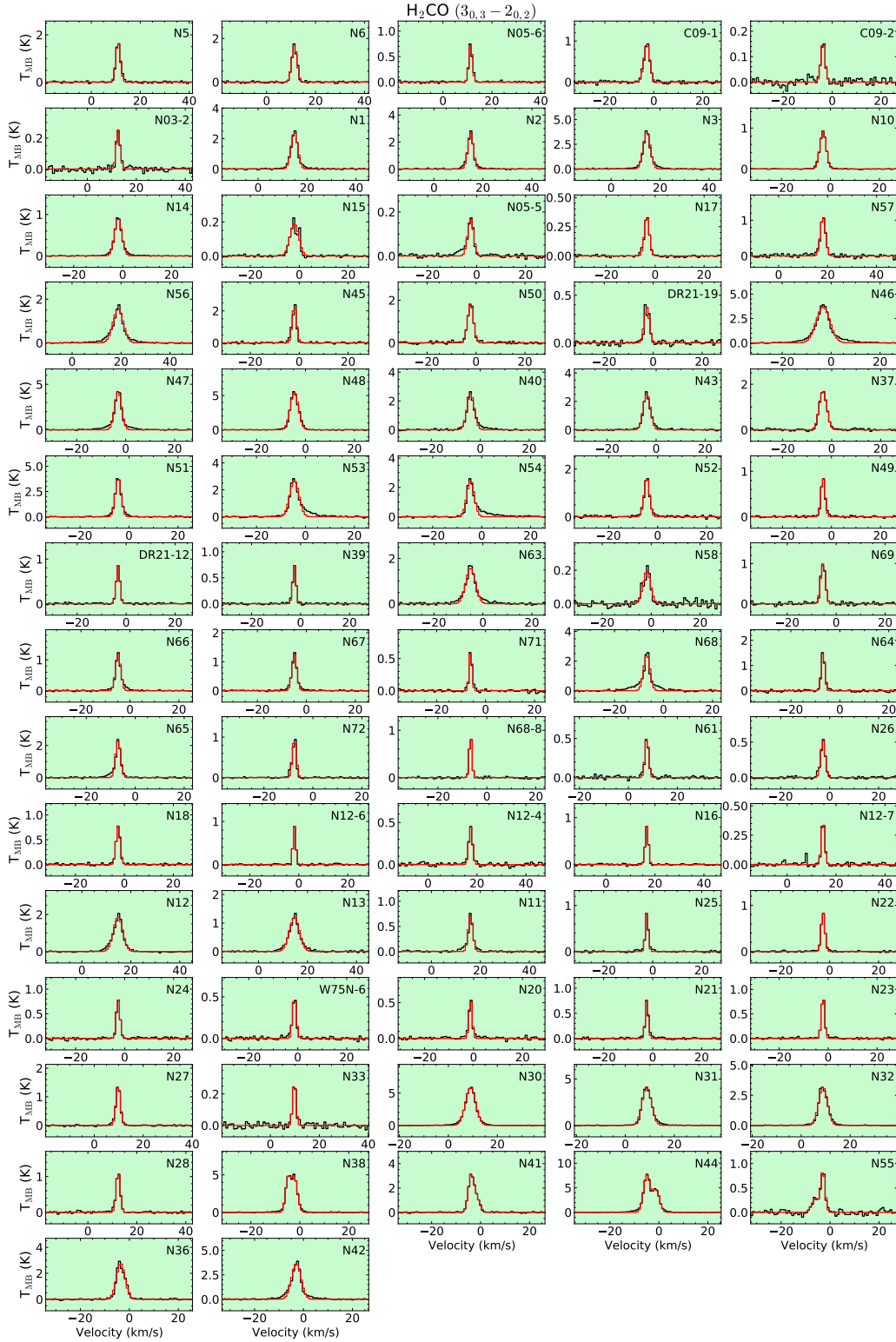


Figure D.2: Same as Fig. D.1 for H_2CO ($3_{0,3} - 2_{0,2}$) towards the Cygnus-X sources.

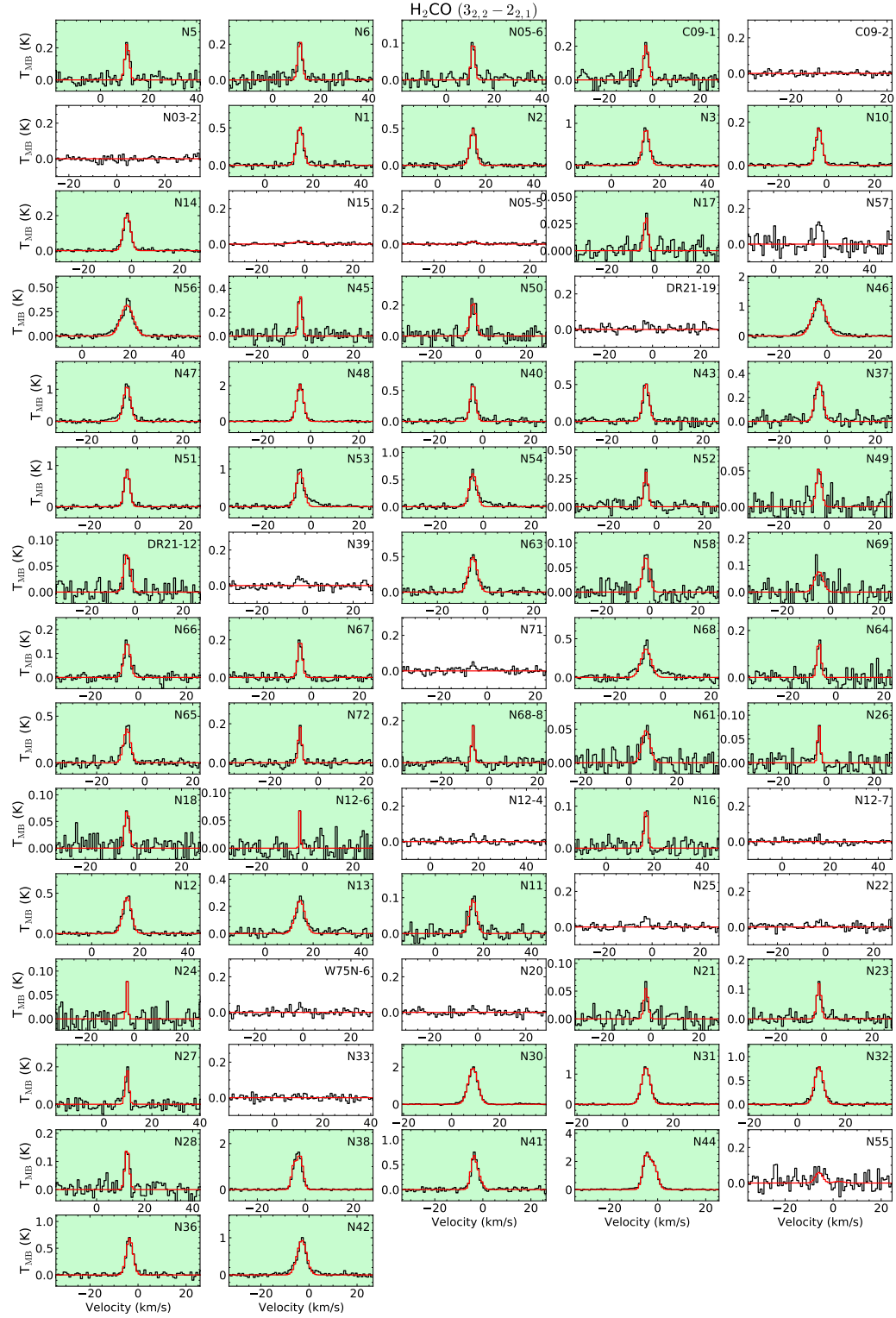


Figure D.3: Same as Fig. D.1 for $\text{H}_2\text{CO} (3_{2,2} - 2_{2,1})$ towards the Cygnus-X sources.

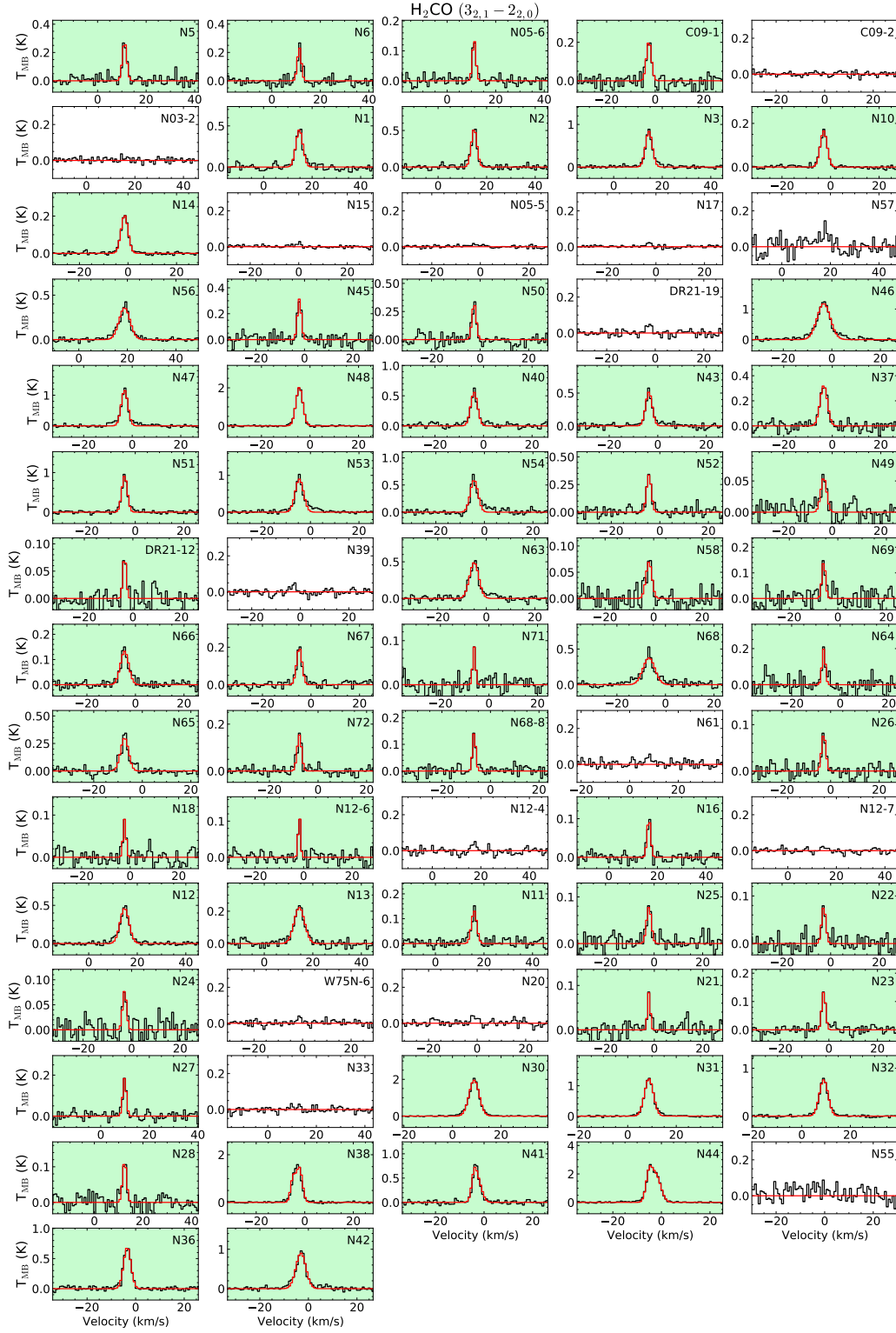


Figure D.4: Same as Fig. D.1 for H₂CO ($3_{2,1} - 2_{2,0}$) towards the Cygnus-X sources.

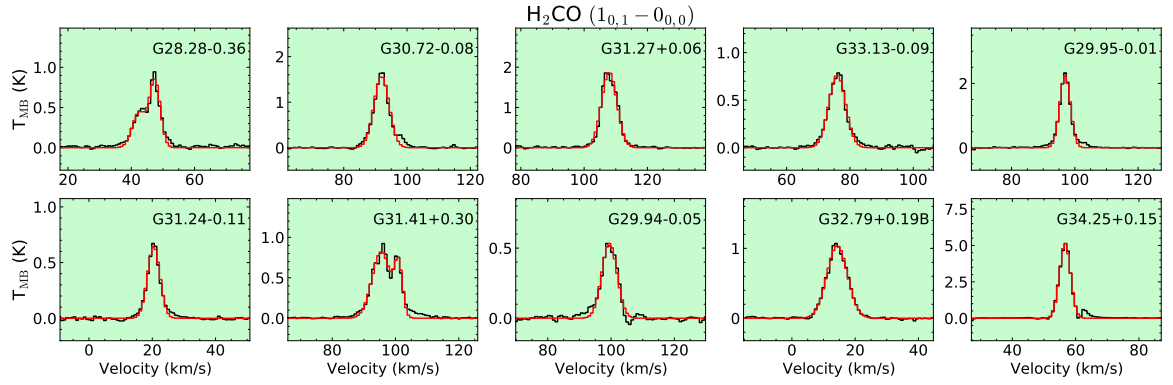


Figure D.5: Same as Fig. D.1 for $\text{H}_2\text{CO} (1_{0,1} - 0_{0,0})$ towards the GLOSTAR sources.

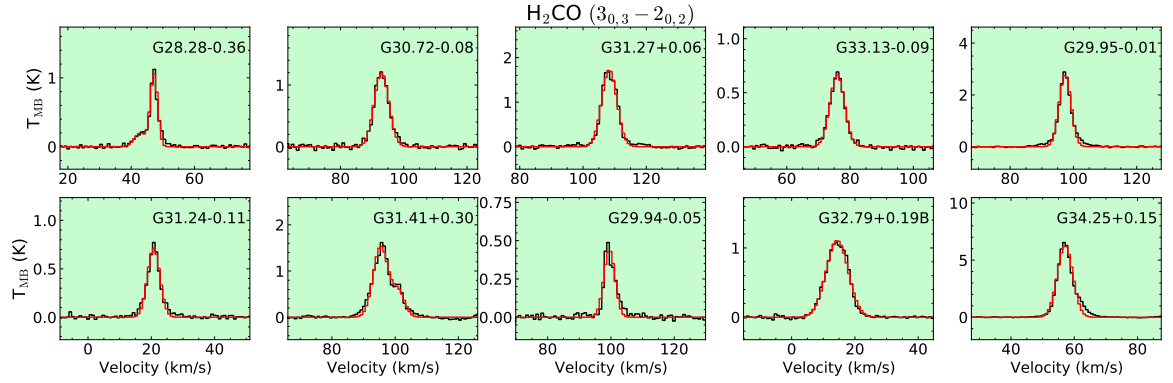


Figure D.6: Same as Fig. D.1 for $\text{H}_2\text{CO} (3_{0,3} - 2_{0,2})$ towards the GLOSTAR sources.

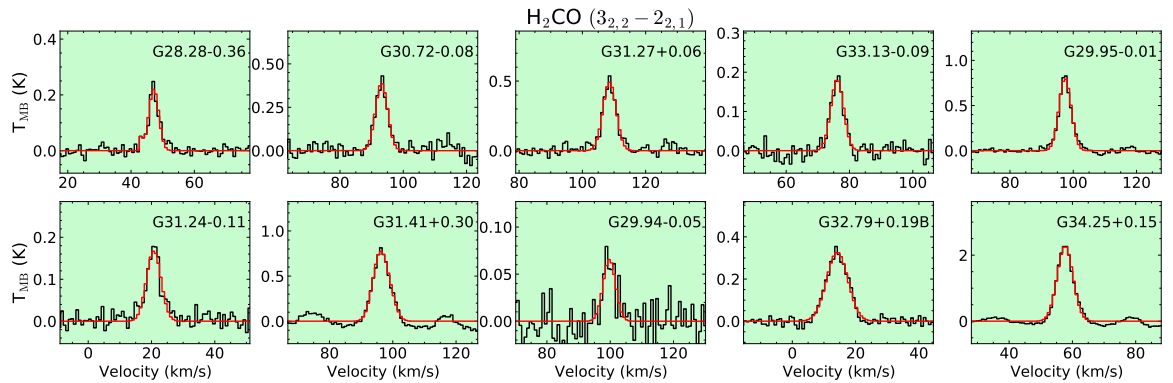


Figure D.7: Same as Fig. D.1 for $\text{H}_2\text{CO} (3_{2,2} - 2_{2,1})$ towards the GLOSTAR sources.

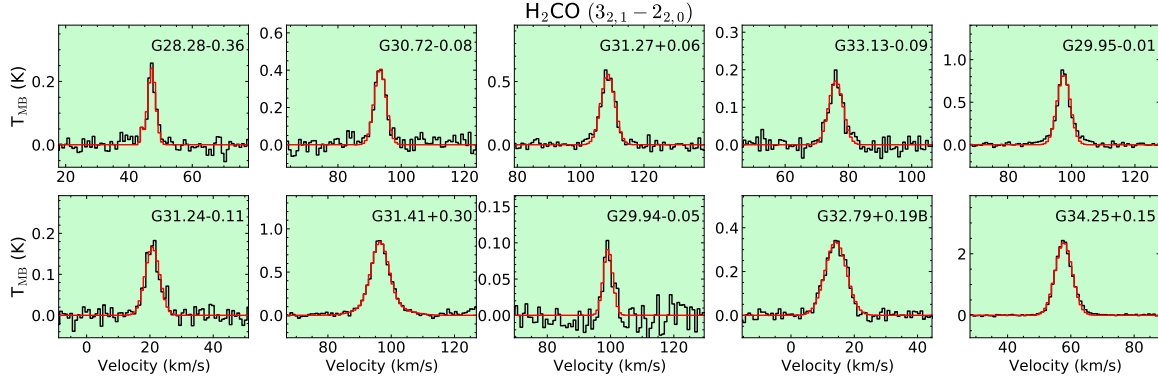


Figure D.8: Same as Fig. D.1 for H_2CO ($3_{2,1} - 2_{2,0}$) towards the GLOSTAR sources.

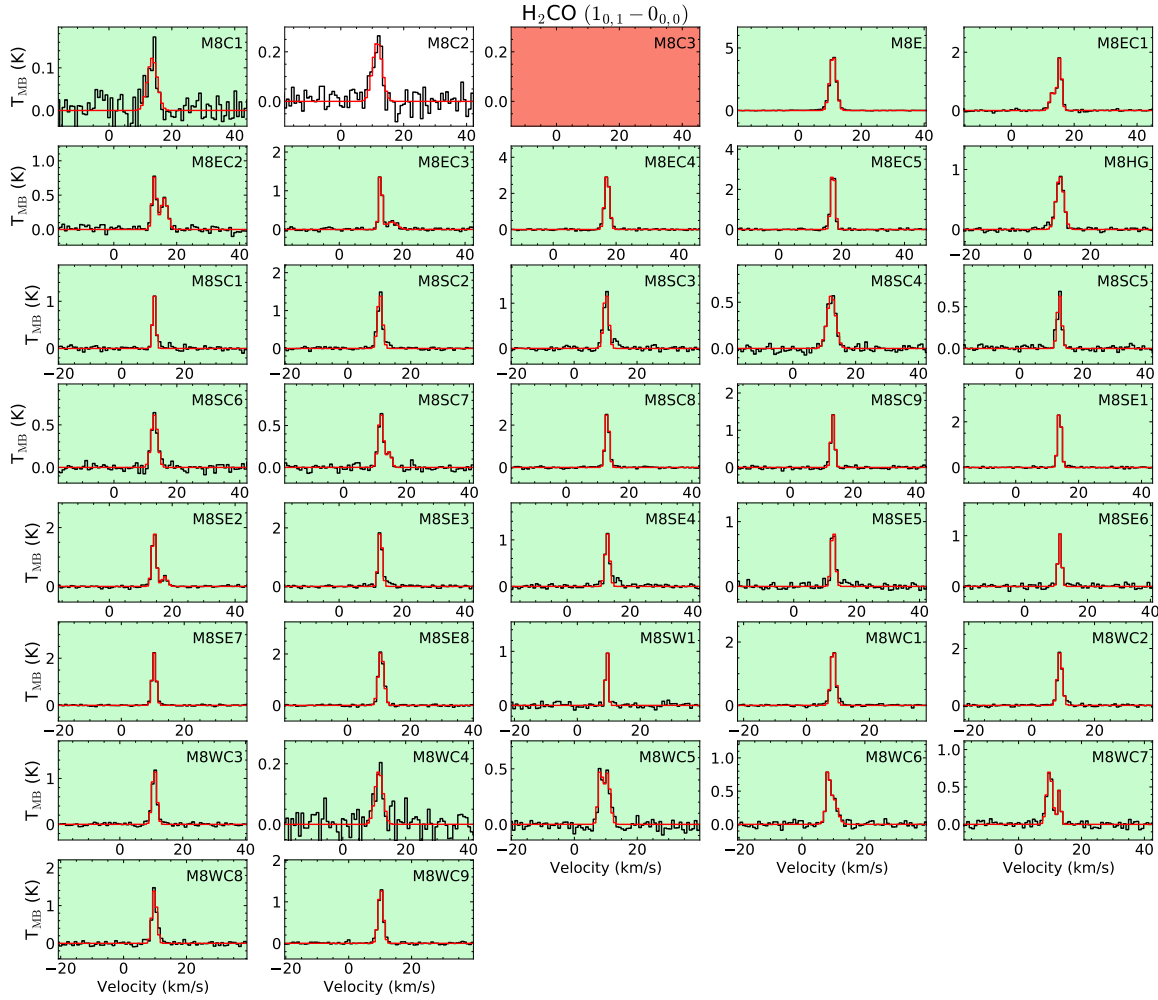


Figure D.9: Same as Fig. D.1 for H_2CO ($1_{0,1} - 0_{0,0}$) towards the M8 sources. Red indicates no observed spectrum.

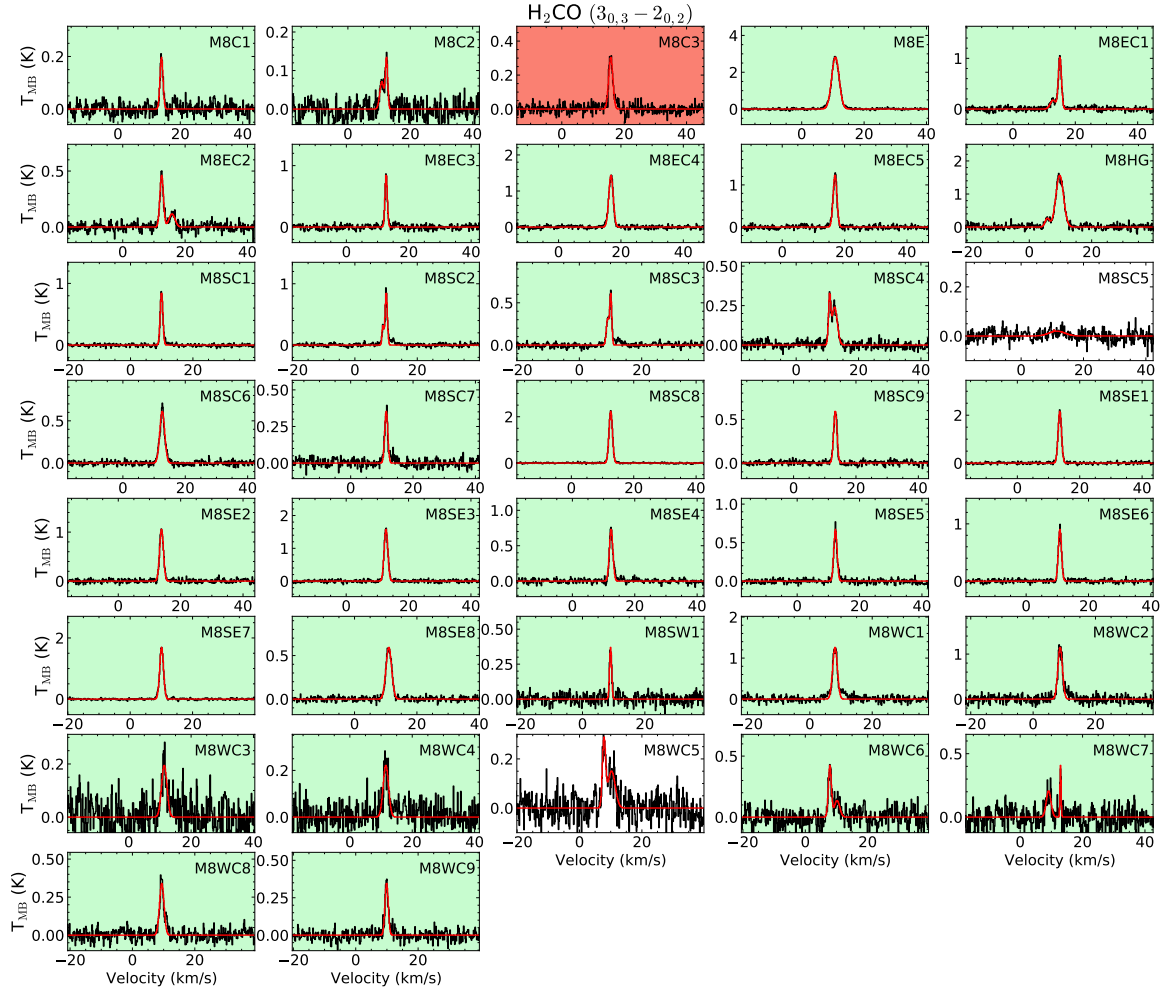
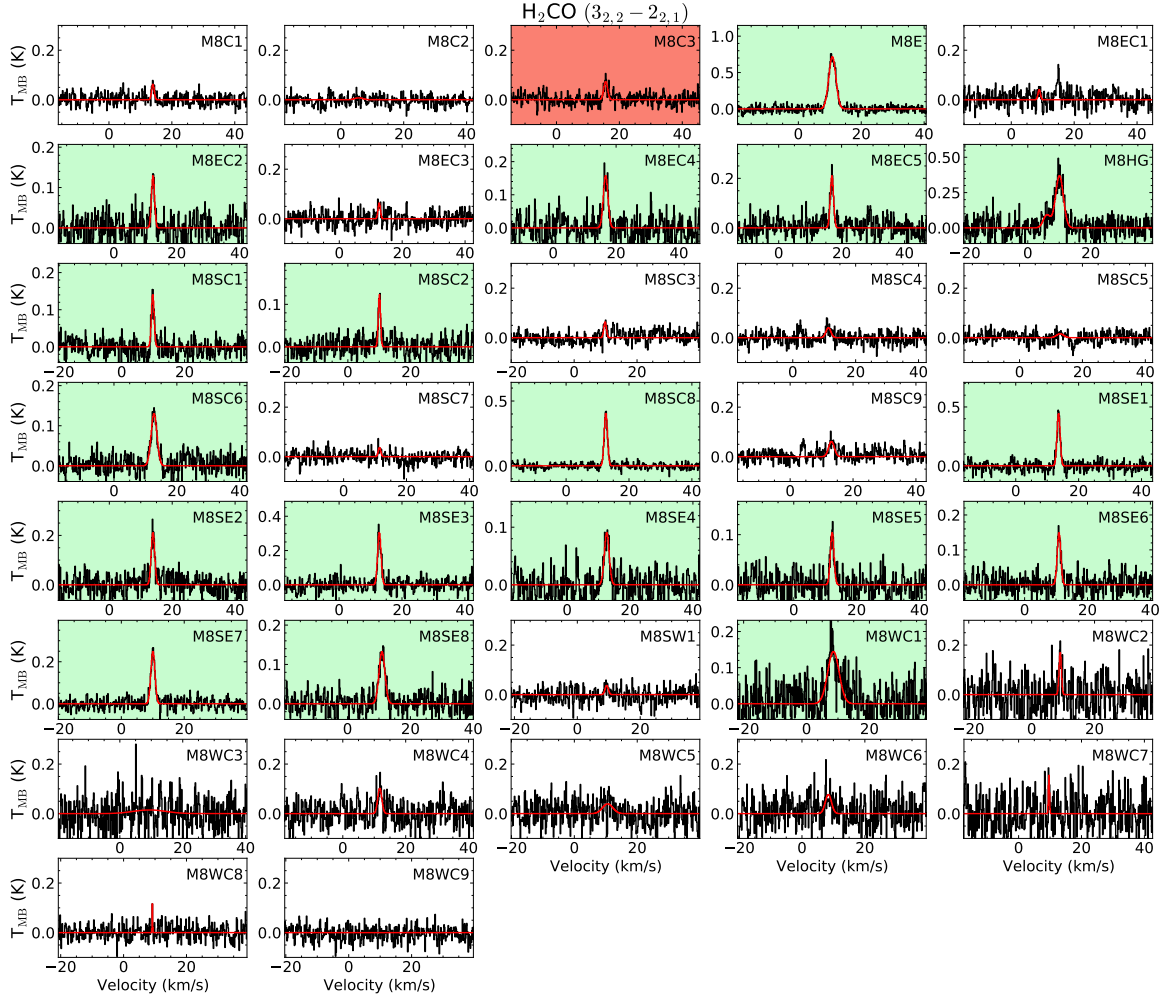


Figure D.10: Same as Fig. D.1 for H_2CO ($3_{0,3} - 2_{0,2}$) towards the M8 sources.

Figure D.11: Same as Fig. D.1 for H₂CO ($3_{2,2} - 2_{2,1}$) towards the M8 sources.

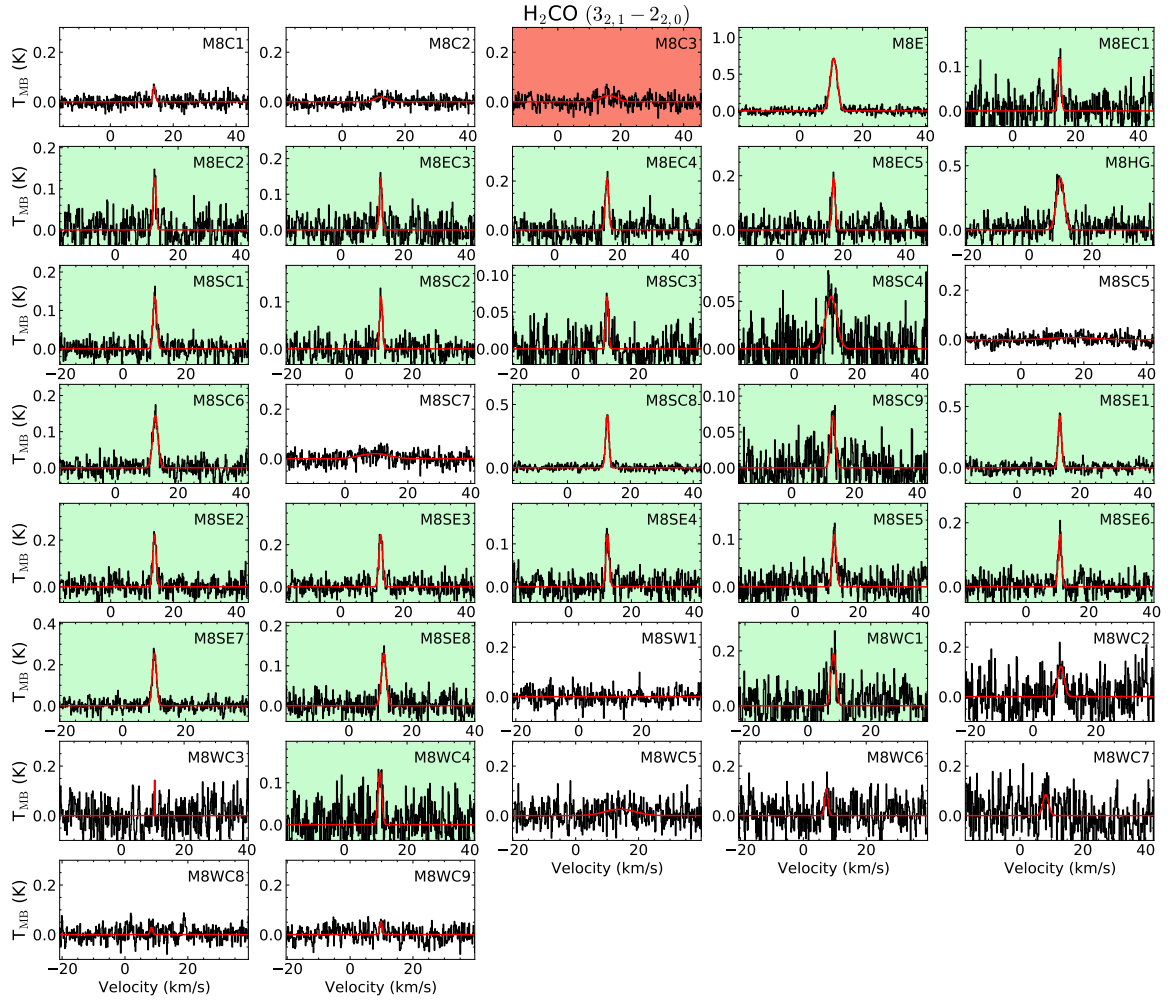


Figure D.12: Same as Fig. D.1 for $\text{H}_2\text{CO} (3_{2,1} - 2_{2,0})$ towards the M8 sources.

Molecules in the clumps of Cygnus X

E.1 Column Densities in Clumps

Table E.1: Beam-averaged column densities of C₂D, C₂H, C₂S, CH₃CN, CS and DCN towards clumps in Cygnus-X.

Clump	C ₂ D 10 ¹⁴ cm ⁻²	C ₂ H 10 ¹⁵ cm ⁻²	C ₂ S 10 ¹⁵ cm ⁻²	CH ₃ CN 10 ¹³ cm ⁻²	CS 10 ¹⁵ cm ⁻²	DCN 10 ¹³ cm ⁻²
C09-1	–	2.49±0.13	7.22±1.00	–	2.07±0.33	–
DR21-12	1.29±0.52	1.08±0.05	1.88±0.42	0.90±0.12	0.42±0.10	0.05±0.02
DR21-19	–	1.17±0.06	1.68±0.33	0.61±0.17	0.16±0.06	–
N03-2	–	0.04±0.05	–	0.34±0.89	–	–
N05-6	–	1.75±0.09	4.62±0.74	–	–	–
N1	–	2.21±0.10	13.20±1.34	1.99±0.14	0.94±0.13	–
N10	–	3.50±0.15	15.00±1.56	3.42±0.28	1.28±0.20	3.80±1.52
N11	–	1.28±0.09	–	–	–	–
N12	–	0.16±0.14	3.95±6.57	0.25±0.52	0.07±0.21	–
N12-4	–	0.56±0.04	3.56±0.88	–	–	–
N12-6	–	0.67±0.04	–	–	–	–
N12-7	–	0.05±0.06	0.56±1.82	0.10±2.70	–	–
N13	–	1.94±0.10	17.80±2.00	2.51±0.50	0.87±0.18	–
N14	–	3.53±0.16	10.20±1.11	4.34±0.45	1.54±0.20	24.80±26.70
N16	–	0.62±0.04	2.68±0.65	–	–	–
N18	–	1.12±0.06	8.72±1.08	10.80±7.76	–	–
N2	–	2.56±0.12	16.40±1.62	2.73±0.20	0.91±0.14	–

Continued from previous page.

Clump	C ₂ D 10 ¹⁴ cm ⁻²	C ₂ H 10 ¹⁵ cm ⁻²	C ₂ S 10 ¹⁵ cm ⁻²	CH ₃ CN 10 ¹³ cm ⁻²	CS 10 ¹⁵ cm ⁻²	DCN 10 ¹³ cm ⁻²
N20	–	0.39±0.03	–	–	0.42±0.11	–
N21	–	0.59±0.03	2.23±0.56	0.98±0.25	–	–
N22	1.67±0.54	0.79±0.04	4.25±0.60	–	0.38±0.10	0.69±0.12
N23	–	1.46±0.09	–	–	–	–
N24	2.69±0.80	0.81±0.05	4.97±0.89	–	0.32±0.12	2.60±0.70
N25	–	0.56±0.03	1.63±0.34	0.89±0.20	–	1.41±0.55
N26	–	0.95±0.05	–	0.77±0.18	–	–
N27	1.95±0.99	1.61±0.07	20.60±2.04	1.30±0.10	0.80±0.11	–
N28	–	0.49±0.03	2.74±0.47	–	0.47±0.08	–
N3	–	3.18±0.14	37.70±3.60	3.22±0.28	1.33±0.17	0.90±0.24
N30	–	4.77±0.23	51.80±5.15	14.80±1.06	5.69±0.62	–
N31	–	2.61±0.12	34.60±3.41	5.77±0.46	3.07±0.34	1.29±0.14
N32	–	2.10±0.11	41.00±4.08	4.28±0.35	2.55±0.28	1.14±0.13
N36A	–	10.90±0.50	59.30±5.78	13.30±0.92	–	0.89±0.08
N36B	–	–	–	–	2.60±0.28	–
N37	1.33±0.54	3.55±0.15	17.60±1.63	3.17±0.23	1.50±0.17	0.39±0.03
N38A	–	0.38±0.29	9.23±15.50	0.51±0.56	–	0.06±0.08
N38B	13.50±3.69	–	–	–	10.40±1.05	–
N39	–	1.26±0.06	2.35±0.56	0.77±0.26	–	0.58±0.11
N40	–	0.33±0.23	7.18±10.70	0.34±0.39	0.18±0.31	0.04±0.06
N41A	–	10.20±0.45	52.70±5.18	14.50±1.03	–	0.61±0.07
N41B	–	–	–	–	5.18±0.55	–
N42A	–	–	–	–	–	–
N42B	16.80±2.37	11.40±0.48	40.00±3.76	13.00±0.83	4.32±0.46	1.70±0.13
N43	–	0.15±0.09	0.78±0.97	0.12±0.12	0.08±0.12	0.03±0.04
N44A	–	6.16±0.26	7.67±0.67	8.27±0.56	5.51±0.55	1.38±0.10
N45	1.56±0.54	2.77±0.13	21.90±2.14	1.57±0.14	0.74±0.11	0.54±0.05
N47	–	4.56±0.20	44.70±4.33	2.96±0.21	2.70±0.29	0.94±0.08
N48	–	10.50±0.44	91.10±8.81	17.40±1.15	6.16±0.65	1.62±0.12
N49	–	1.36±0.07	4.39±0.69	–	0.43±0.09	0.17±0.04
N5	–	1.19±0.06	5.52±0.68	–	0.40±0.10	2.06±1.30
N50	–	3.66±0.16	44.60±4.26	2.33±0.24	1.01±0.17	0.62±0.05
N51	0.09±0.51	0.20±0.15	0.61±0.98	0.22±0.27	0.12±0.23	0.05±0.06
N52	–	4.33±0.19	12.00±1.14	3.93±0.33	1.49±0.21	0.43±0.06
N53	16.30±3.62	5.63±0.25	40.00±3.92	7.64±0.71	2.28±0.27	0.87±0.08
N54	–	0.18±0.13	1.88±2.85	0.19±0.26	0.10±0.19	0.02±0.04
N56	–	2.15±0.12	9.86±1.15	4.71±0.51	0.53±0.18	–
N58	–	1.88±0.11	–	12.30±3.04	–	–
N6	–	1.29±0.06	8.57±0.96	–	0.90±0.13	–
N61	–	0.70±0.06	4.51±0.94	–	–	–
N63	2.58±0.90	2.29±0.12	10.50±1.15	3.61±0.46	0.65±0.20	–
N64	1.72±0.43	0.87±0.04	3.77±0.56	0.87±0.10	0.45±0.09	–

Continued from previous page.

Clump	C_2D 10^{14} cm^{-2}	C_2H 10^{15} cm^{-2}	C_2S 10^{15} cm^{-2}	CH_3CN 10^{13} cm^{-2}	CS 10^{15} cm^{-2}	DCN 10^{13} cm^{-2}
N65	2.01±0.91	2.50±0.12	10.00±1.12	20.90±20.50	1.11±0.19	3.74±1.04
N66	–	1.21±0.07	3.24±0.54	0.28±0.19	0.50±0.10	2.14±1.15
N67	–	2.62±0.12	8.36±1.10	16.40±7.98	0.98±0.20	3.51±1.04
N68-8	–	1.87±0.11	–	–	–	–
N69	–	2.22±0.10	8.14±0.97	1.50±0.16	0.58±0.09	0.68±0.12
N71	–	1.12±0.05	2.51±0.49	–	–	0.55±0.13
N72	–	2.94±0.15	0.22±0.03	6.48±0.60	0.46±0.21	–
W75N-6	–	0.85±0.05	6.29±1.07	–	–	–

Table E.2: Same as Table E.1 for DCO^+ , DNC , H_2CO , HC_3N , HC_5N and HCN

Clump	DCO^+ 10^{12} cm^{-2}	DNC 10^{12} cm^{-2}	H_2CO 10^{13} cm^{-2}	HC_3N 10^{14} cm^{-2}	HC_5N 10^{13} cm^{-2}	HCN 10^{14} cm^{-2}
C09-1	–	–	4.90±0.53	1.95±1.38	–	–
DR21-12	2.68±0.22	4.23±0.36	4.90±0.91	–	–	3.47±0.77
DR21-19	4.55±0.84	3.25±0.82	3.31±0.62	–	–	–
N03-2	–	0.39±1.53	1.58±0.31	–	–	–
N05-6	–	7.58±1.65	1.55±0.15	–	–	–
N1	5.37±1.00	8.92±2.62	18.20±2.16	–	–	3.57±0.38
N10	4.14±1.31	7.55±1.64	6.46±0.70	–	3.42±0.39	5.58±0.57
N11	11.10±2.34	8.98±2.46	2.34±0.21	–	–	211.00±186.00
N12	0.31±1.53	0.60±2.10	58.90±29.90	–	–	0.53±1.61
N12-4	3.33±1.08	7.23±1.33	0.98±0.14	–	–	–
N12-6	2.94±0.84	4.48±1.07	1.55±0.20	–	–	–
N12-7	0.47±1.41	0.44±1.59	1.38±0.31	–	–	–
N13	4.46±1.35	9.16±1.76	44.70±25.60	–	–	–
N14	12.70±2.07	–	9.77±1.26	–	–	4.67±0.48
N16	–	6.79±1.27	1.12±0.11	–	–	–
N18	2.83±0.71	4.87±1.10	2.45±0.32	–	–	12.80±2.41
N2	4.64±0.90	10.50±2.09	16.60±1.97	–	0.73±0.16	5.80±0.92
N20	5.52±0.91	–	1.78±0.23	–	–	–
N21	10.50±1.27	10.20±1.27	2.63±0.49	–	–	4.01±2.40
N22	18.30±1.91	18.10±1.95	4.90±1.36	–	–	2.59±0.81
N23	8.59±1.51	12.00±2.79	2.09±0.23	–	–	–
N24	23.20±2.55	23.00±2.49	5.37±3.32	–	–	5.31±1.18
N25	8.70±0.97	6.73±0.80	1.95±0.21	–	–	–
N26	–	3.17±0.72	1.62±0.21	–	–	–
N27	2.73±0.57	3.39±0.64	7.76±1.65	–	0.64±0.18	3.38±0.36

Continued from previous page.

Clump	DCO ⁺ 10 ¹² cm ⁻²	DNC 10 ¹² cm ⁻²	H ₂ CO 10 ¹³ cm ⁻²	HC ₃ N 10 ¹⁴ cm ⁻²	HC ₅ N 10 ¹³ cm ⁻²	HCN 10 ¹⁴ cm ⁻²
N28	4.67±0.79	6.68±0.86	3.39±0.37	—	—	1.92±0.59
N3	7.28±1.03	10.50±2.07	40.70±6.85	—	1.32±0.39	5.55±0.57
N30	—	15.80±2.78	115.00±13.60	—	—	18.90±1.92
N31	2.70±1.10	10.50±1.66	72.40±10.80	—	—	8.41±0.86
N32	6.89±1.29	8.72±1.50	56.20±9.46	—	—	8.06±0.81
N36A	5.66±0.46	22.80±1.87	8.91±2.07	—	—	18.30±2.29
N36B	—	—	21.40±6.31	—	—	—
N37	3.75±0.33	9.01±0.67	41.70±26.10	—	1.43±0.26	5.45±0.55
N38A	0.22±0.32	0.83±1.10	51.30±29.90	—	0.19±0.52	0.94±1.82
N38B	—	—	24.00±2.56	—	—	—
N39	3.35±0.27	5.10±0.41	4.79±1.11	—	—	—
N40	0.28±0.36	0.77±0.91	81.30±52.40	—	0.16±0.67	0.52±0.83
N41A	3.99±0.36	18.60±1.45	34.70±19.80	—	0.63±0.20	15.10±1.52
N41B	—	—	13.50±1.74	—	—	—
N42A	—	—	36.30±4.30	—	—	20.00±2.01
N42B	3.07±0.30	20.70±1.61	14.50±1.71	5.28±1.85	3.54±0.55	—
N43	0.20±0.22	0.41±0.44	55.00±30.00	0.11±0.64	0.20±0.38	0.32±0.46
N44A	4.64±0.36	14.00±1.05	55.00±7.62	—	0.72±0.20	16.60±1.76
N45	2.67±0.23	6.86±0.53	7.76±1.00	—	2.50±0.31	3.99±0.42
N47	1.63±0.18	7.66±0.64	37.20±5.88	9.66±1.49	1.69±0.30	9.31±0.94
N48	2.94±0.28	20.00±1.70	79.40±11.00	—	3.59±0.48	20.40±2.05
N49	3.30±0.27	6.13±0.48	5.01±0.89	—	—	1.92±0.23
N5	—	7.45±1.31	3.89±0.34	—	—	—
N50	3.15±0.27	9.89±0.73	12.30±3.69	—	1.08±0.32	5.37±0.55
N51	0.30±0.40	0.74±0.98	38.90±9.04	0.29±0.93	0.15±0.37	0.56±1.04
N52	7.66±0.58	18.70±1.38	11.50±1.82	—	—	13.40±2.19
N53	6.64±0.51	17.40±1.34	45.70±9.89	—	0.73±0.37	12.30±1.98
N54	0.27±0.34	0.67±0.82	50.10±21.70	—	0.10±0.51	0.48±0.80
N56	4.31±1.67	12.70±2.40	22.90±7.05	5.82±1.58	—	—
N58	—	21.20±3.22	1.38±0.27	—	1.42±0.29	—
N6	—	7.24±1.31	5.25±0.46	—	—	—
N61	18.20±2.55	11.80±2.05	2.75±0.49	—	—	—
N63	17.20±2.03	13.10±2.09	18.60±1.64	—	0.50±0.16	—
N64	7.17±0.91	8.08±0.97	3.16±0.34	—	—	2.83±0.88
N65	11.40±1.59	11.50±1.87	9.12±0.80	—	—	—
N66	8.69±1.03	8.71±1.22	9.33±1.48	—	0.40±0.16	4.28±1.31
N67	14.80±2.03	14.20±1.91	9.12±1.70	—	—	13.30±3.13
N68-8	—	7.52±2.02	1.82±0.23	—	—	—
N69	7.51±0.94	14.80±1.71	22.90±16.70	—	—	—
N71	1.99±0.53	3.56±0.83	2.19±0.41	—	—	—
N72	—	7.35±2.22	3.80±0.53	—	—	—
W75N-6	5.34±0.90	5.35±1.03	2.75±0.66	—	—	—

Table E.3: Same as Table E.1 for HCO, HCO⁺, HCOOH, HNC, HNCO and N₂D⁺.

Clump	HCO ⁺ 10 ¹⁴ cm ⁻²	HCOOH 10 ¹⁴ cm ⁻²	HCO 10 ¹⁴ cm ⁻²	HNCO 10 ¹³ cm ⁻²	HNC 10 ¹⁴ cm ⁻²	N ₂ D ⁺ 10 ¹² cm ⁻²
C09-1	7.95±1.05	—	7.85±0.85	—	5.68±1.39	—
DR21-12	5.64±0.60	—	1.59±0.17	2.43±0.55	4.35±0.67	0.79±0.09
DR21-19	4.12±0.46	—	2.15±0.17	3.64±0.50	1.40±0.46	—
N03-2	0.13±0.44	—	0.06±0.31	—	—	—
N05-6	4.19±0.54	—	3.99±0.48	—	6.26±1.17	—
N1	10.50±1.08	—	1.42±0.20	2.37±0.63	11.90±1.35	—
N10	14.20±1.46	—	3.96±0.38	5.44±1.05	9.36±1.26	—
N11	6.13±0.86	—	—	5.39±1.65	9.32±1.46	—
N12	0.76±1.33	—	—	0.82±1.75	1.53±2.73	—
N12-4	3.05±0.45	—	—	—	5.09±0.86	—
N12-6	3.62±0.46	—	—	—	3.41±0.68	—
N12-7	0.20±0.52	—	0.07±0.29	—	0.40±1.25	0.32±1.15
N13	8.29±0.93	—	3.21±0.49	8.20±1.36	16.20±1.87	—
N14	8.74±0.96	1.05±0.53	4.63±0.45	5.75±1.43	7.02±0.99	—
N16	2.26±0.36	—	—	—	5.85±0.88	—
N18	4.95±0.59	—	1.63±0.36	—	4.15±0.79	—
N2	13.00±1.31	—	1.42±0.25	4.44±0.73	16.40±1.73	—
N20	3.29±0.42	—	—	—	3.90±0.60	—
N21	4.76±0.54	—	0.65±0.20	—	3.96±0.84	—
N22	7.08±0.74	—	1.33±0.35	—	6.70±0.89	3.11±0.68
N23	4.67±0.72	—	2.90±0.51	6.19±1.70	—	—
N24	8.21±0.87	—	0.52±0.23	—	8.51±1.09	5.01±0.79
N25	4.24±0.45	—	0.98±0.11	—	2.43±0.50	—
N26	1.32±0.31	—	0.99±0.20	—	2.08±0.63	—
N27	8.51±0.87	—	—	3.22±0.54	10.10±1.13	—
N28	5.82±0.60	0.49±0.27	—	—	4.32±0.62	—
N3	16.40±1.65	—	1.47±0.23	6.62±0.93	19.60±2.04	—
N30	45.50±4.62	2.65±0.98	—	33.00±4.08	24.50±3.05	—
N31	23.70±2.39	—	1.01±0.31	10.80±1.43	15.50±1.71	—
N32	19.70±2.00	—	1.59±0.35	10.30±1.44	11.20±1.39	—
N36A	48.80±4.88	—	—	—	44.20±4.59	2.33±0.21
N36B	—	—	3.08±0.23	12.80±1.43	—	—
N37	18.50±1.85	—	2.23±0.18	7.97±0.95	18.60±1.92	1.89±0.15
N38A	1.97±3.51	—	—	1.05±1.98	2.00±3.62	0.13±0.20
N38B	—	—	8.22±0.62	—	—	4.59±1.08
N39	6.05±0.65	—	1.78±0.18	2.61±0.67	3.36±0.62	1.09±0.12
N40	1.58±2.54	—	0.21±0.27	0.90±1.59	1.58±2.59	0.13±0.17
N41A	45.10±4.52	—	9.74±1.28	33.00±3.51	41.30±4.30	1.16±0.16
N41B	—	—	9.63±0.86	—	—	—
N42A	—	—	—	—	—	—
N42B	42.20±4.24	—	5.95±0.56	18.00±2.38	50.10±5.16	2.65±1.51
N43	0.88±1.26	—	0.06±0.07	0.25±0.39	0.86±1.25	0.10±0.19

Continued from previous page.

Clump	HCO ⁺ 10 ¹⁴ cm ⁻²	HCOOH 10 ¹⁴ cm ⁻²	HCO 10 ¹⁴ cm ⁻²	HNCO 10 ¹³ cm ⁻²	HNC 10 ¹⁴ cm ⁻²	N ₂ D ⁺ 10 ¹² cm ⁻²
N44A	32.80±3.27	—	3.01±0.23	15.00±1.56	27.00±2.72	1.06±0.27
N45	14.00±1.42	—	2.03±0.20	4.54±0.57	10.70±1.22	—
N47	16.90±1.71	—	2.08±0.23	4.59±0.75	20.20±2.11	0.83±0.18
N48	40.20±4.03	—	7.04±0.59	29.90±3.37	48.10±4.92	2.57±0.38
N49	7.52±0.78	—	1.48±0.16	2.73±0.62	6.00±0.80	1.16±0.10
N5	6.76±0.72	—	1.25±0.22	—	6.75±0.89	—
N50	17.10±1.73	—	1.86±0.21	4.80±0.80	16.00±1.73	0.70±0.17
N51	1.43±2.62	—	0.09±0.15	0.50±1.03	1.25±2.33	0.12±0.17
N52	26.80±2.72	—	4.04±0.45	14.80±2.19	25.30±2.83	2.66±0.23
N53	36.50±3.66	6.85±1.13	4.28±0.48	23.40±2.71	33.00±3.53	2.71±0.23
N54	1.41±2.32	0.16±0.46	0.11±0.22	0.61±1.17	1.15±1.99	0.14±0.19
N56	9.84±1.18	—	2.53±1.11	9.49±1.92	17.40±2.13	2.90±1.48
N58	—	—	4.34±0.97	—	—	—
N6	7.82±0.83	—	0.98±0.19	—	7.69±1.07	1.91±0.80
N61	8.88±1.01	—	—	—	—	—
N63	14.10±1.46	—	—	8.01±1.49	12.30±1.74	2.26±1.15
N64	6.66±0.69	—	0.82±0.12	2.13±0.48	4.08±0.55	1.64±0.54
N65	16.50±1.70	—	1.57±0.39	5.64±1.50	9.92±1.41	—
N66	8.48±0.87	—	1.09±0.17	2.46±0.56	4.74±0.69	1.95±0.62
N67	16.60±1.72	—	2.98±0.56	7.80±1.81	12.00±1.65	—
N68-8	4.63±0.94	—	5.69±0.81	—	7.20±1.46	—
N69	6.83±0.70	—	2.06±0.20	4.63±0.70	7.94±1.04	—
N71	2.48±0.33	—	1.28±0.16	1.29±0.53	2.42±0.50	—
N72	5.42±0.77	—	5.62±0.61	11.20±2.52	8.67±1.31	—
W75N-6	4.03±0.47	—	—	4.52±0.79	6.08±0.85	2.55±0.83

Table E.4: Same as Table E.1 for N₂H⁺, NH₂D, OCS, SiO, SO₂ and SO.

Clump	N ₂ H ⁺ 10 ¹³ cm ⁻²	NH ₂ D 10 ¹⁴ cm ⁻²	OCS 10 ¹⁴ cm ⁻²	SiO 10 ¹³ cm ⁻²	SO ₂ 10 ¹⁴ cm ⁻²	SO 10 ¹⁴ cm ⁻²
C09-1	2.10±0.24	—	—	—	—	0.95±0.36
DR21-12	1.77±0.20	1.52±0.23	—	—	0.53±0.32	1.04±0.17
DR21-19	0.39±0.07	0.39±0.17	—	—	—	0.47±0.12
N03-2	—	—	—	0.01±0.08	—	—
N05-6	3.44±0.48	—	—	0.17±0.10	—	—
N1	2.84±0.29	—	1.41±0.30	0.93±0.12	1.63±0.42	1.88±0.32

Continued from previous page.

Clump	N_2H^+ 10^{13} cm^{-2}	NH_2D 10^{14} cm^{-2}	OCS 10^{14} cm^{-2}	SiO 10^{13} cm^{-2}	SO_2 10^{14} cm^{-2}	SO 10^{14} cm^{-2}
N10	3.87±0.40	2.36±0.49	—	0.83±0.12	—	1.43±0.28
N11	3.12±0.39	—	—	—	—	—
N12	0.26±0.43	—	—	0.21±0.37	0.19±0.95	—
N12-4	1.24±0.17	—	—	—	—	—
N12-6	2.27±0.27	—	—	—	—	—
N12-7	0.08±0.20	—	—	—	—	—
N13	2.61±0.27	—	—	2.28±0.25	—	—
N14	1.58±0.17	—	—	0.79±0.14	—	1.90±0.27
N16	1.97±0.26	—	—	—	—	—
N18	2.94±0.35	—	—	—	—	—
N2	3.41±0.34	—	—	0.92±0.11	—	1.36±0.28
N20	1.53±0.21	—	—	—	—	—
N21	2.36±0.29	1.74±0.26	—	—	—	0.77±0.18
N22	3.72±0.39	3.48±0.37	—	—	—	0.96±0.19
N23	1.84±0.33	—	—	—	1.69±0.76	1.82±0.28
N24	4.45±0.47	3.70±0.40	—	0.37±0.07	—	1.58±0.23
N25	2.34±0.24	2.14±0.25	—	—	—	0.31±0.10
N26	1.72±0.25	—	—	0.20±0.07	1.41±0.37	—
N27	4.30±0.43	—	—	—	0.72±0.21	1.15±0.15
N28	2.45±0.25	2.23±0.27	—	—	—	0.39±0.11
N3	4.37±0.44	—	—	1.41±0.16	2.03±0.40	2.36±0.36
N30	5.23±0.52	—	5.39±0.95	6.28±0.66	20.80±2.31	15.90±1.62
N31	3.52±0.35	—	2.41±0.43	2.27±0.26	6.47±0.79	7.31±0.76
N32	2.88±0.29	—	2.59±0.55	1.47±0.18	6.13±0.85	7.18±0.74
N36A	14.60±1.46	19.70±2.21	2.16±0.52	4.30±0.45	9.01±1.07	4.94±0.55
N36B	—	—	—	—	—	—
N37	6.63±0.66	4.47±0.50	—	0.86±0.11	2.29±0.36	2.15±0.27
N38A	0.92±1.63	0.12±0.41	—	0.29±0.53	0.43±0.89	0.66±1.15
N38B	—	—	5.62±0.71	—	—	—
N39	1.99±0.23	1.03±0.17	—	0.18±0.06	—	0.73±0.16
N40	0.69±1.11	0.52±1.00	0.12±0.37	0.11±0.19	0.36±0.70	0.28±0.49
N41A	10.60±1.06	13.00±1.73	1.75±0.45	4.22±0.43	7.94±1.06	5.17±0.55
N41B	—	—	—	—	—	—
N42A	—	—	—	—	3.60±1.00	—
N42B	8.20±0.84	—	—	4.70±0.50	—	6.57±0.70
N43	0.28±0.40	0.08±0.15	0.02±0.12	0.03±0.06	0.09±0.20	0.12±0.20
N44A	—	—	2.34±0.34	5.37±0.54	6.23±0.66	10.60±1.05
N45	3.76±0.38	1.36±0.20	—	—	—	1.14±0.17
N47	5.05±0.51	—	—	0.86±0.10	1.77±0.41	3.35±0.38
N48	21.30±2.13	—	2.38±0.56	5.55±0.56	7.97±1.09	10.10±1.03
N49	3.79±0.40	2.84±0.34	—	—	2.14±0.40	1.13±0.17
N5	3.69±0.39	4.14±0.59	0.66±0.17	—	—	—

Continued from previous page.

Clump	N_2H^+ 10^{13} cm^{-2}	NH_2D 10^{14} cm^{-2}	OCS 10^{14} cm^{-2}	SiO 10^{13} cm^{-2}	SO_2 10^{14} cm^{-2}	SO 10^{14} cm^{-2}
N50	4.48±0.46	—	—	0.20±0.08	—	1.26±0.25
N51	0.74±1.35	0.53±1.00	0.03±0.21	0.06±0.12	0.15±0.39	0.21±0.41
N52	11.90±1.19	15.30±1.72	—	1.90±0.23	5.60±0.95	2.27±0.34
N53	16.60±1.66	18.60±2.14	—	4.47±0.52	8.94±1.31	4.38±0.52
N54	0.65±1.07	0.73±1.25	—	0.11±0.22	0.35±0.73	0.26±0.46
N56	2.70±0.28	—	—	1.45±0.25	—	0.86±0.26
N58	—	—	—	0.49±0.17	—	4.86±0.62
N6	3.48±0.36	2.16±0.42	0.52±0.26	—	—	0.83±0.20
N61	2.62±0.33	—	—	0.92±0.18	—	—
N63	4.49±0.45	—	—	1.89±0.24	—	1.10±0.29
N64	2.10±0.23	4.18±0.53	—	0.14±0.05	—	0.89±0.13
N65	4.92±0.52	5.04±1.05	—	0.69±0.12	—	2.46±0.30
N66	2.68±0.28	1.14±0.12	—	0.70±0.10	—	0.84±0.17
N67	4.63±0.49	3.93±0.51	—	1.87±0.21	6.36±1.16	1.47±0.30
N68-8	1.81±0.40	—	—	—	—	—
N69	2.91±0.30	2.26±0.42	—	—	1.52±0.39	1.10±0.18
N71	1.86±0.23	—	—	—	—	—
N72	2.61±0.40	—	—	—	—	—
W75N-6	3.30±0.38	—	—	—	—	—

E.2 Radial density profiles of the clumps

The density profiles of high-mass star-forming clumps are an important property that influences the embedded star-forming cores as well as the chemical properties. For each clumps modeled with MUSCLE (Sect. 6.3.1) we inferred the radial density profile using the GBT/MUSTANG2 continuum maps at 3 mm wavelengths.

The density power-law index p can be inferred from the slope of the radial intensity profile, m (Adams, 1991; Motte and André, 2001):

$$p = m + 1 - Qq - \epsilon_f, \quad (\text{E.1})$$

with temperature power-law index q and deprojection factor $\epsilon_f = 0.1 \pm 0.1$. The correction factor Q , with $x = \frac{h\nu}{kT}$ (Adams, 1991), is calculated as follows:

$$Q(x) = \frac{xe^x}{(e^x - 1)} \quad (\text{E.2})$$

and is 1.07 at 90 GHz (3 mm) and $T=30$ K (Beuther et al., 2002) and we assume an uncertainty of $\Delta Q = 0.1$. For the temperature power-law index q we assume a value of $q = 0.4 \pm 0.1$ as derived in observations of high-mass star-forming regions (Gieser et al., 2021; Gieser et al., 2023). The uncertainty of the power-law index, Δp , assuming Gaussian error propagation, is calculated as

$$\Delta p = \sqrt{(\Delta m)^2 + (q\Delta Q)^2 + (Q\Delta q)^2 + (\Delta\epsilon_f)^2}. \quad (\text{E.3})$$

The continuum maps of all clumps covered by CASCADE are shown in Fig. E.2, where each panel is centered on a clump (Table B.1). Some clumps do not show a clear clumpy morphology in the 3 mm continuum data. For example, clumps N1 and N2 are too close to the bright clump N3 to be distinguished. A few cores are not detected in the 3 mm data at all (e.g., N58-1 and C09-2). In both cases, we cannot estimate the radial intensity profile from the continuum maps, and the clumps are marked in lightgrey. For most of the clumps, though, we were able to estimate the radial intensity profile. These are marked in red with the outer fit radii indicated by circles. However, the peak position in the 3 mm continuum might be slightly offset, and is marked by the $\star$.

For each clump with a clear detection in the 3 mm data (marked red in Fig. E.2), we extract the azimuthally averaged intensity profiles up to a radius of 0.8 pc from the 3 mm continuum peak position binned in half a beam size ($4.5''$). The radial intensity profiles of all clumps are presented in Fig. E.8 by grey data points. A linear fit to the log-log data provides the slope m , which is related to the density power-law index p (Eq. E.1). In the linear fit, we ignore the first two data points (one beam size) since these can be diluted by the beam. For each clump, we manually define the outer fit radius to avoid overlap with nearby clumps (e.g., N5 and N6). For each clump, the data points included in the fit are highlighted in black in Fig. E.8. The linear fit and its $\pm 1\sigma$ uncertainties are indicated by the red solid and dashed lines, respectively.

The fit results for m (and corresponding p) are shown in each panel in Fig. E.8 and are summarized in Table E.5. A histogram of the density power-law index is presented in Fig. E.1 in blue. The spread in p ranges from 0.6 to 2.4.

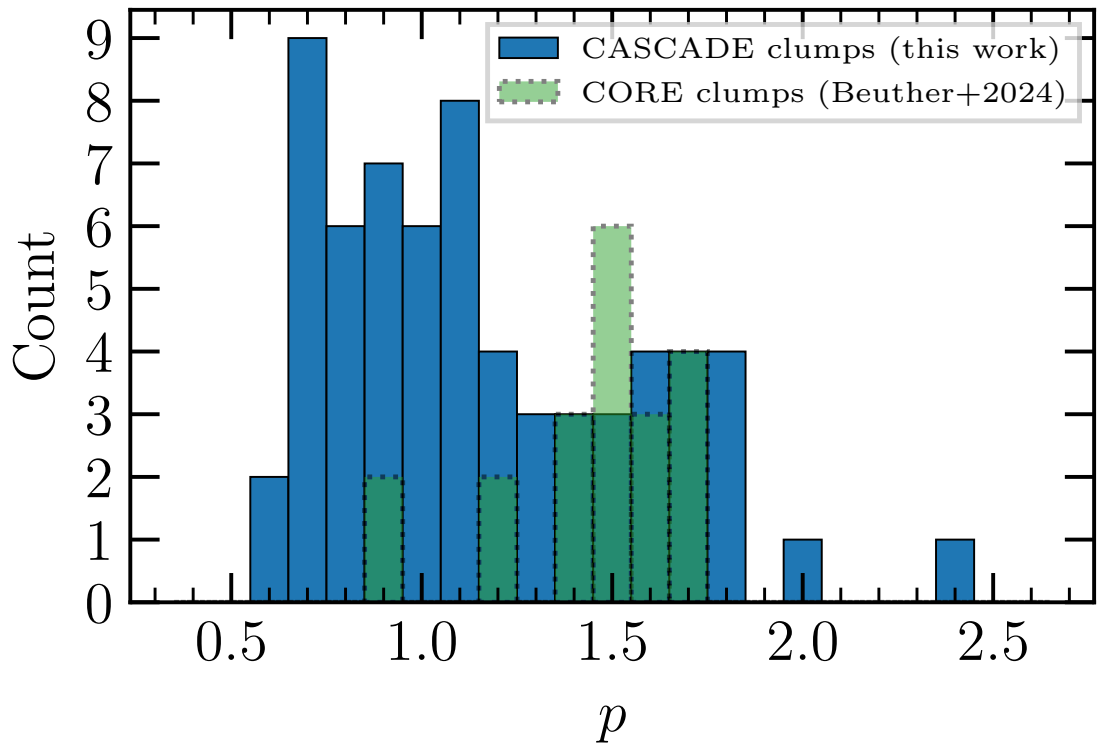


Figure E.1: Histogram of the density power-law index p of the CASCADE clumps (this work, blue) in comparison with the clumps of the CORE sample (Beuther et al., 2024, green).

E.2 Radial density profiles of the clumps

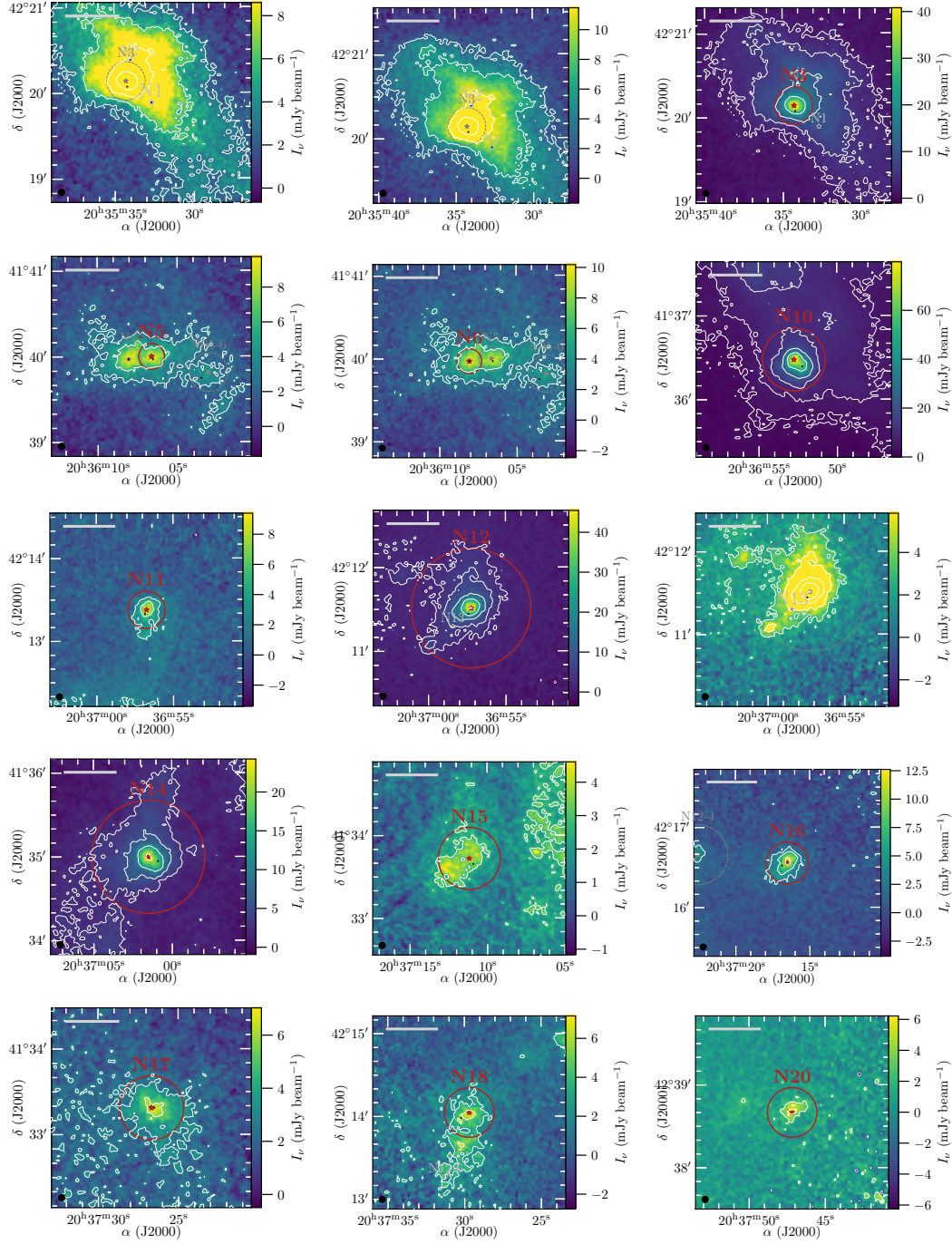


Figure E.2: Continuum maps of the Cygnus-X clumps covered by CASCADE. In color and white contours the GBT/MUSTANG2 3 mm continuum emission is shown (contour steps $-5, 5, 10, 20, 40, \dots \times \sigma_{\text{cont}}$). In the center of each panel, the position of the clump is shown. A clump with a clear detection in the 3 mm data is highlighted in red, whereas clumps that show now clear clump sturcture or are not detected are highlighted in lightgrey. The position of the clumps are marked by a dot, whereas the peak position in the 3 mm data is shown by a star. Nearby clumps are marked in dark grey. The fit radii of the radial intensity profiles are indicated by circles. In the bottom left corner the beam size is shown and a linear bar in the top left corner indicates a spatial scale of 0.5 pc.

Appendix E Molecules in the clumps of Cygnus X

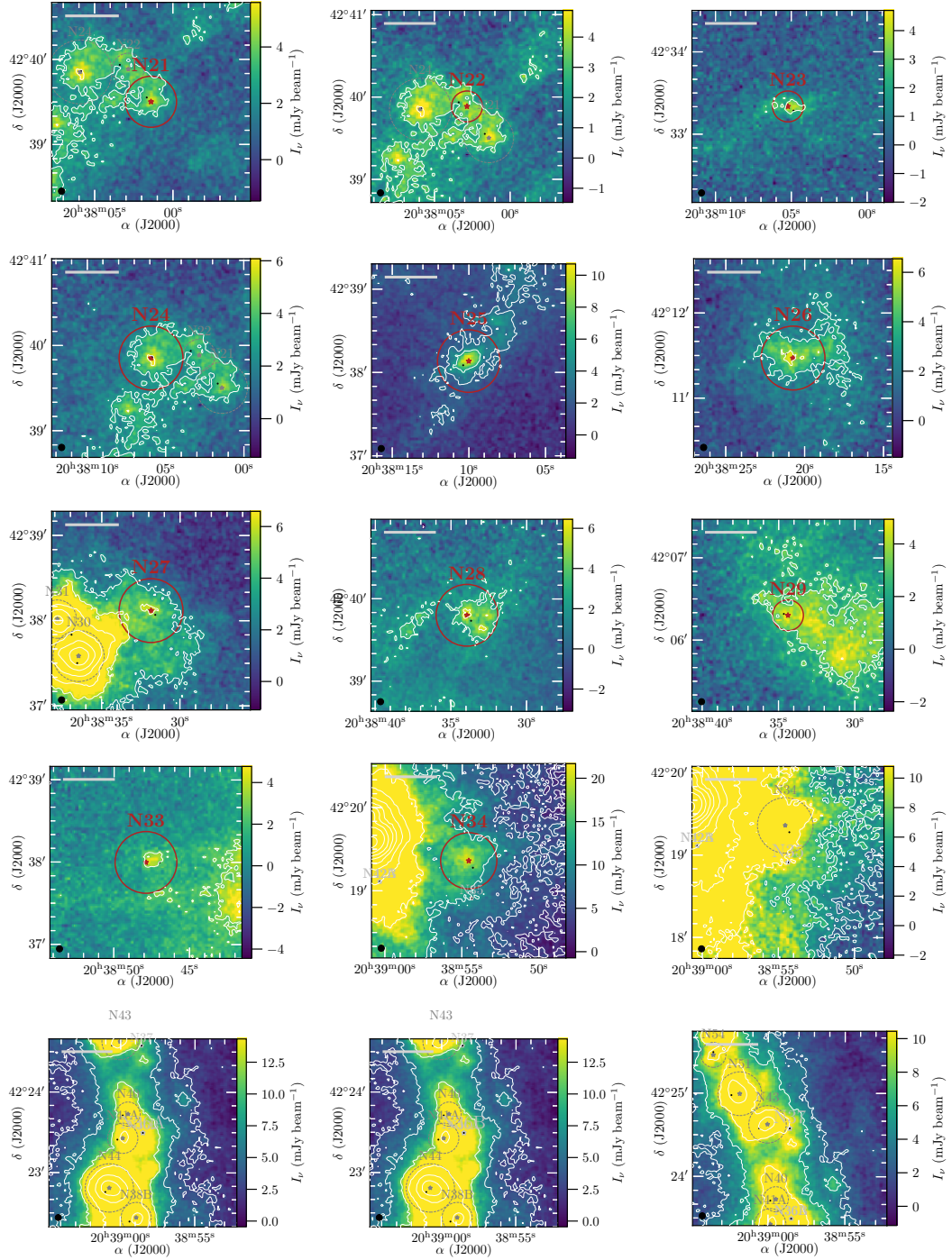


Figure E.3: continued.

E.2 Radial density profiles of the clumps

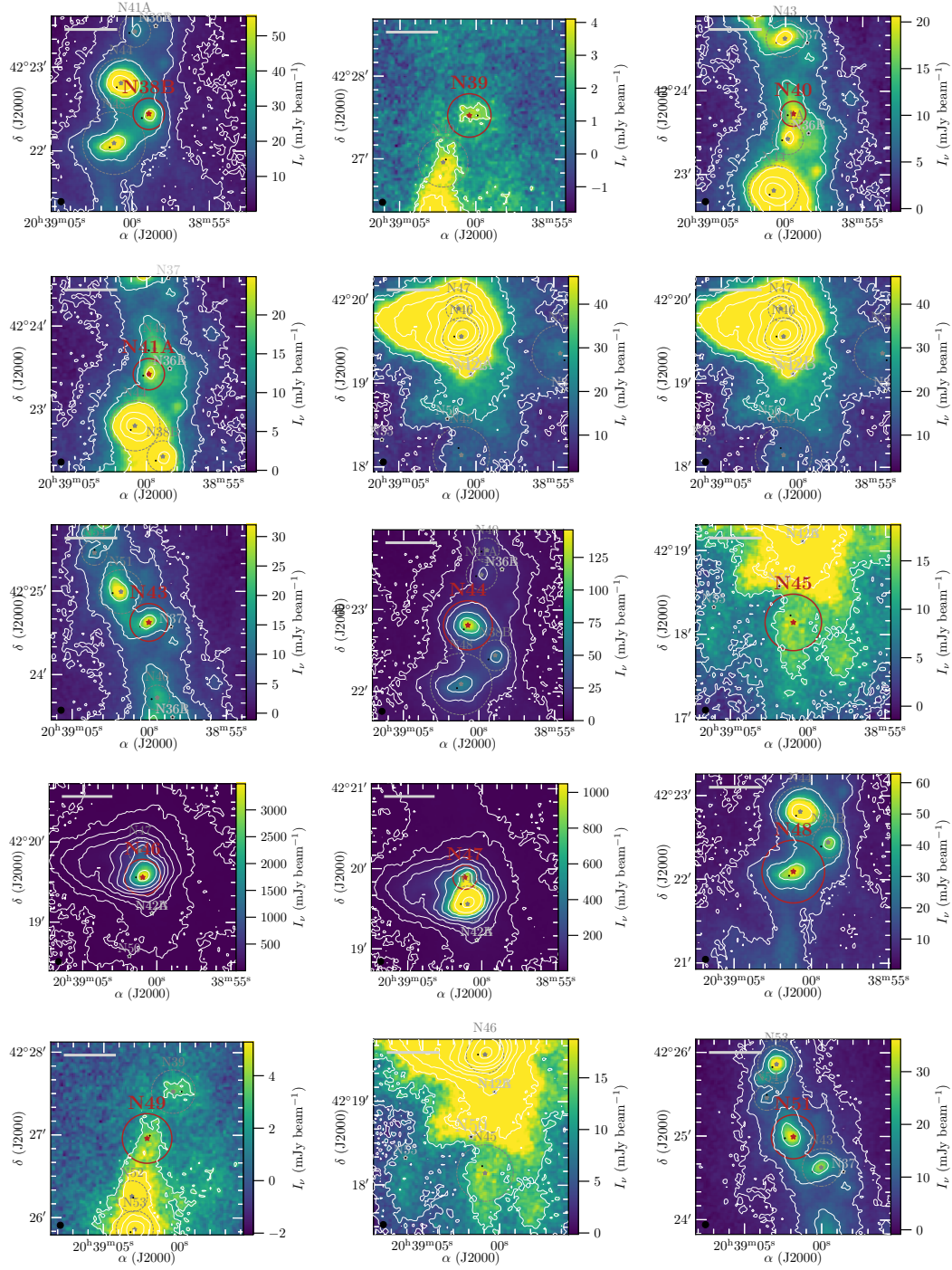


Figure E.4: continued.

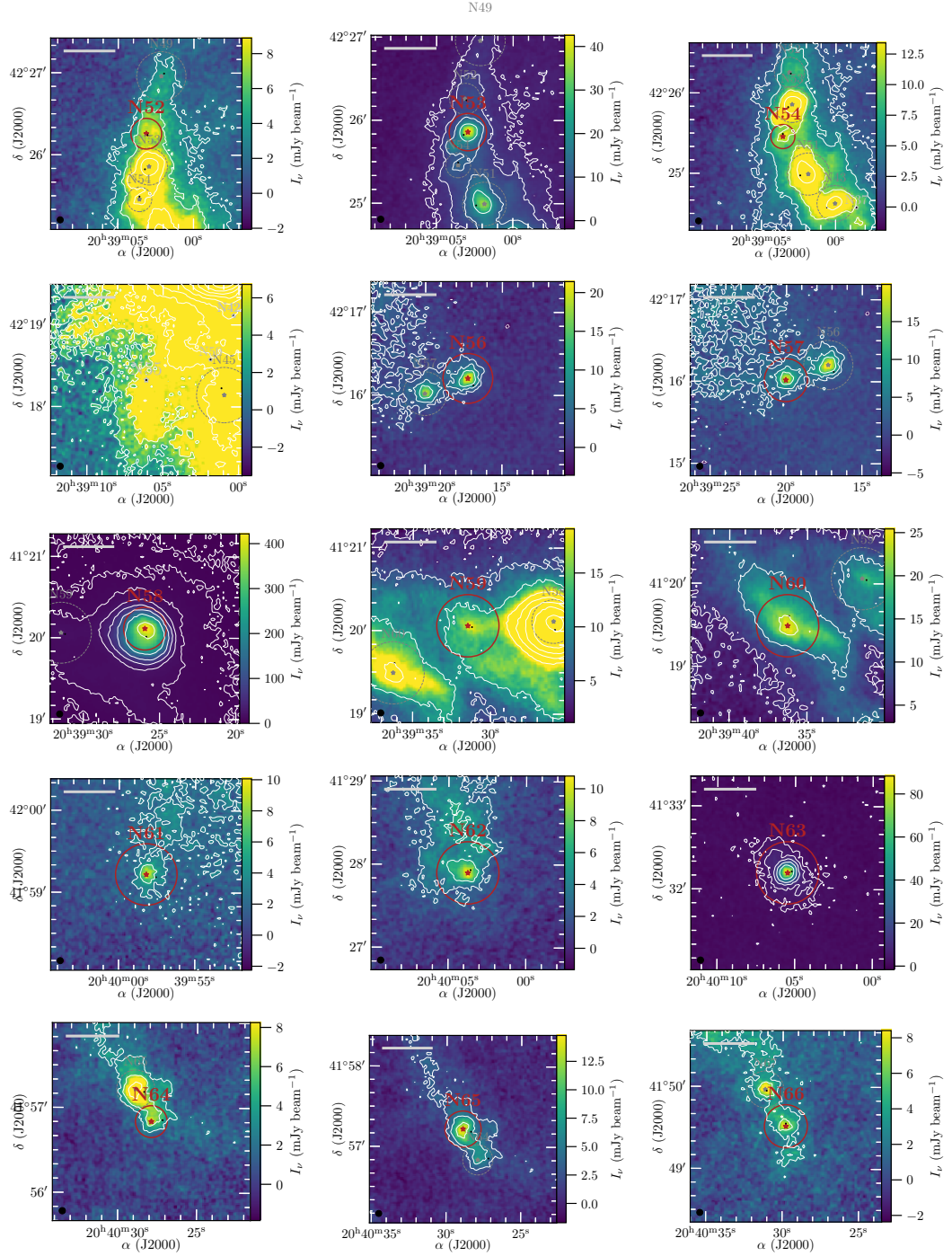


Figure E.5: continued.

E.2 Radial density profiles of the clumps

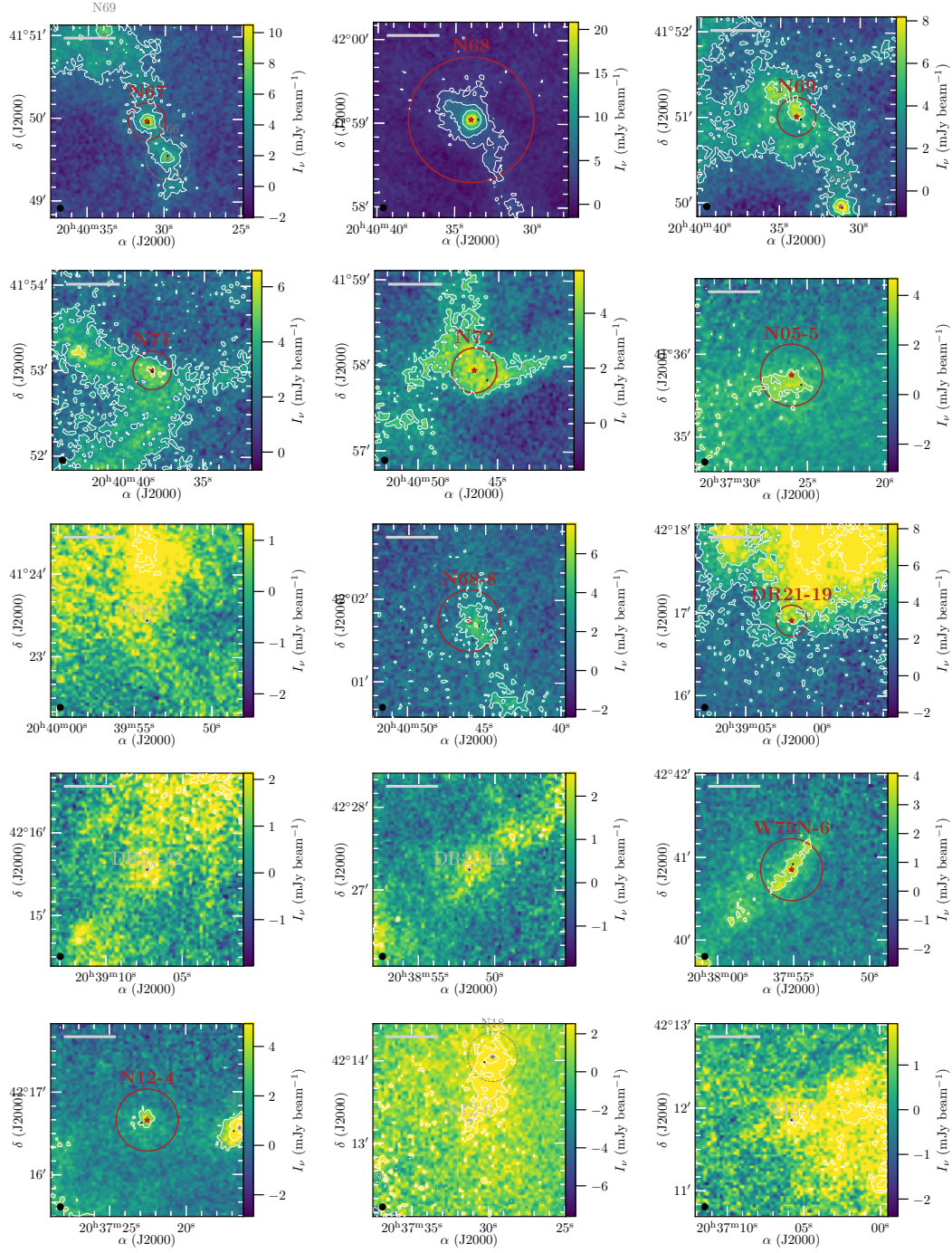


Figure E.6: continued.

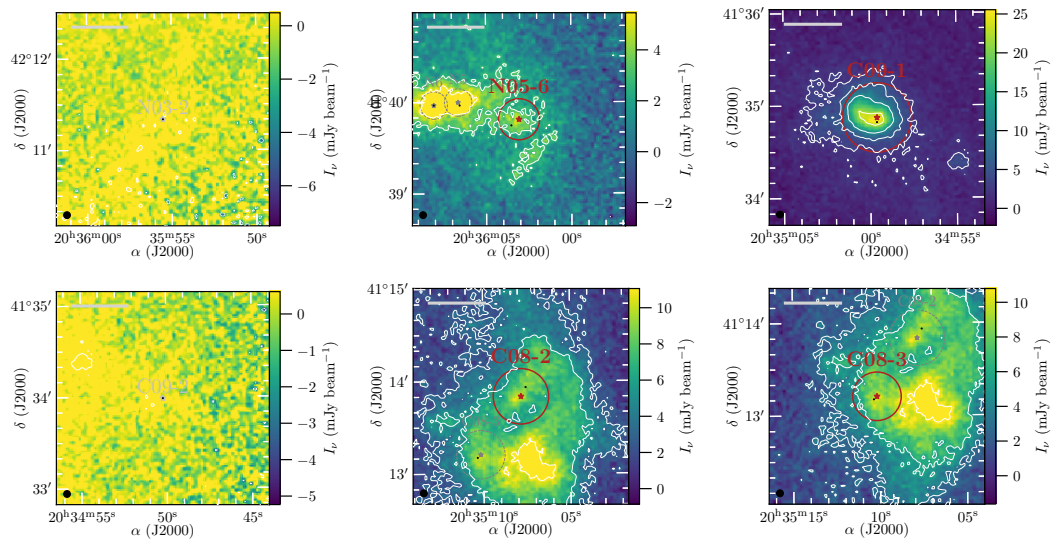


Figure E.7: continued.

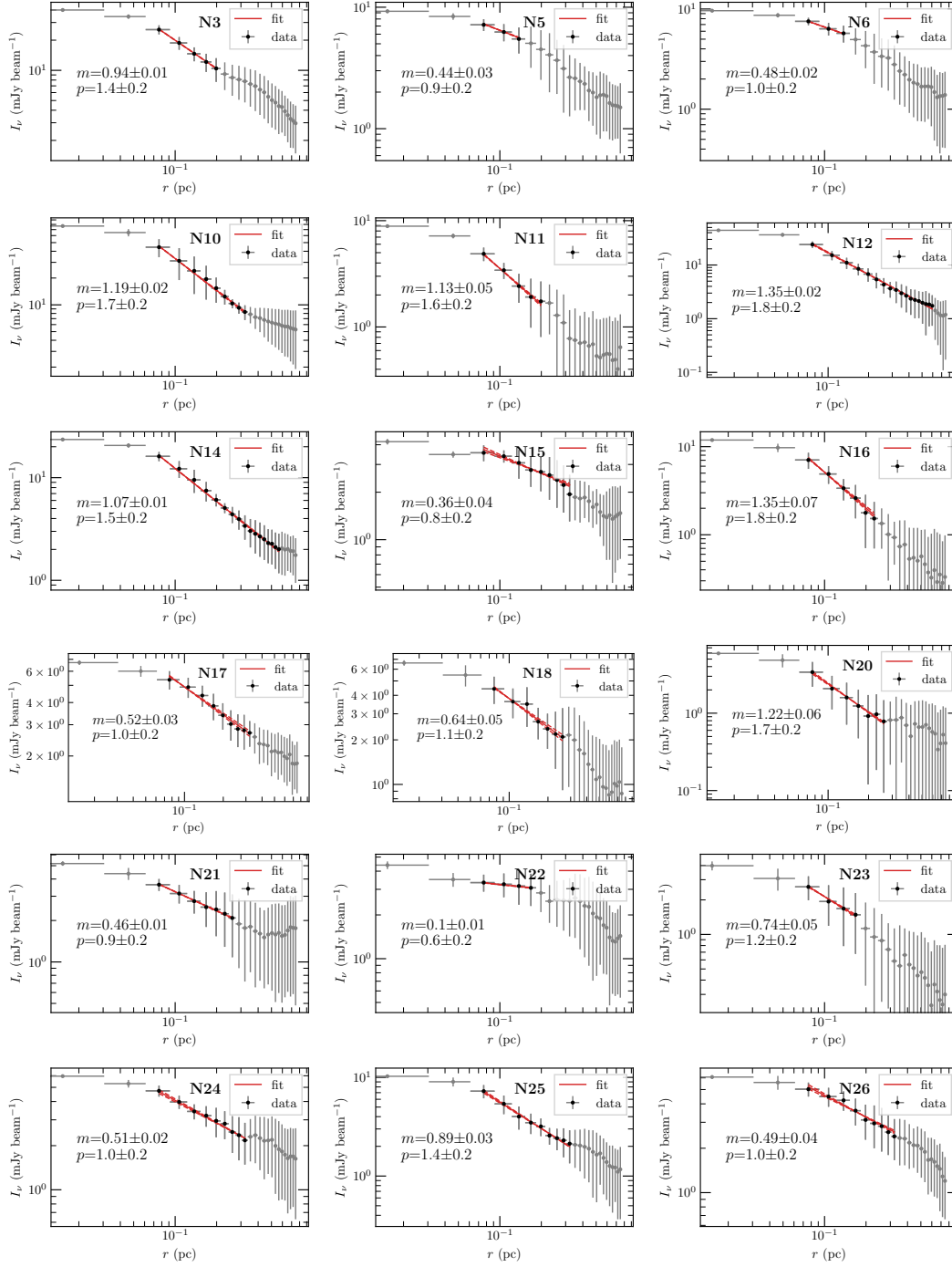


Figure E.8: Radial intensity profiles of the Cygnus-X clumps covered by CASCADE. The 3 mm radial intensity profile up to 0.8 pc is shown by the grey data points, whereas data points included in the fit are highlighted in black. The fit and uncertainties are shown by the red solid and dashed lines, respectively. The slope m and corresponding density power-law index p are shown in each panel.

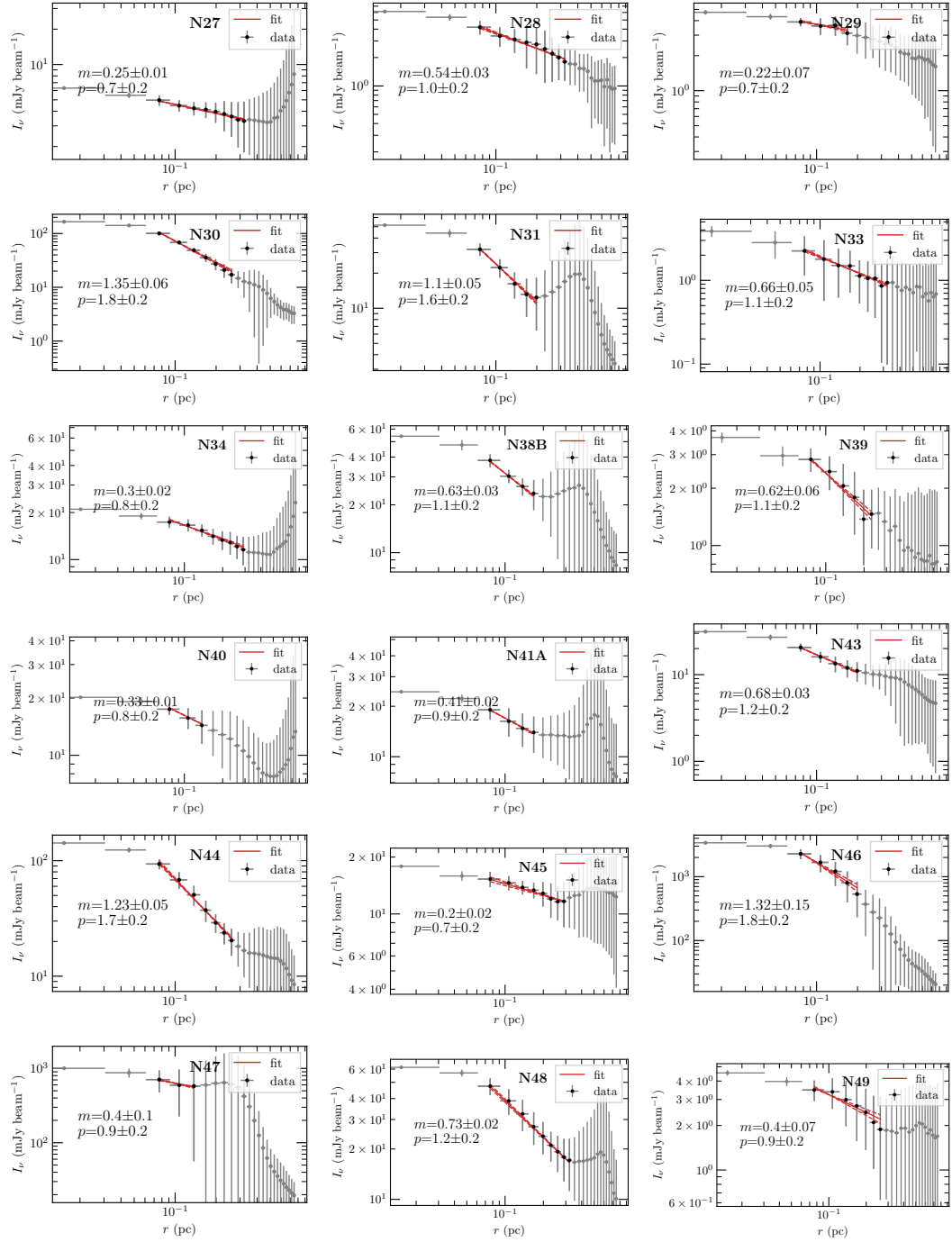


Figure E.9: continued.

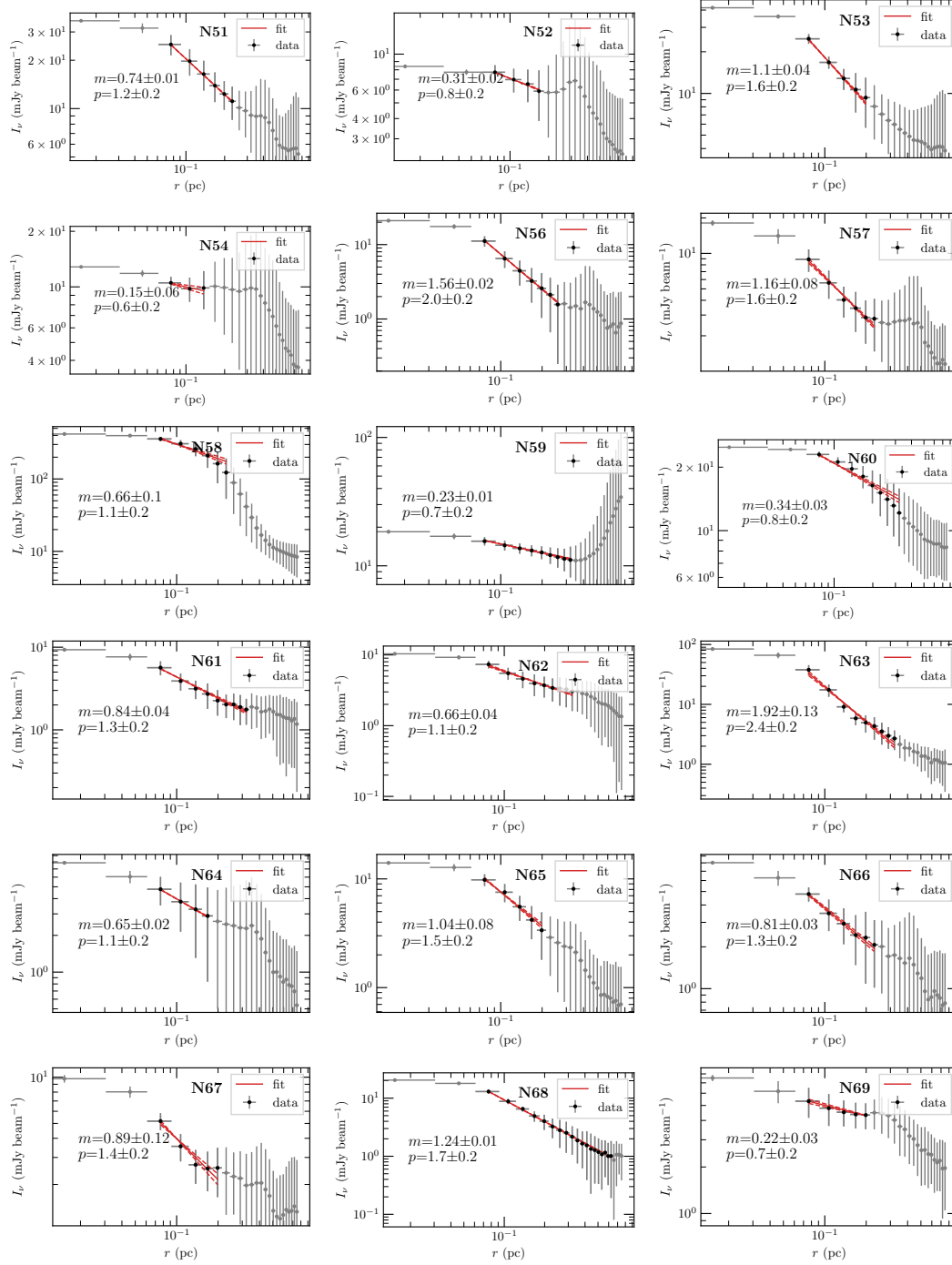


Figure E.10: continued.

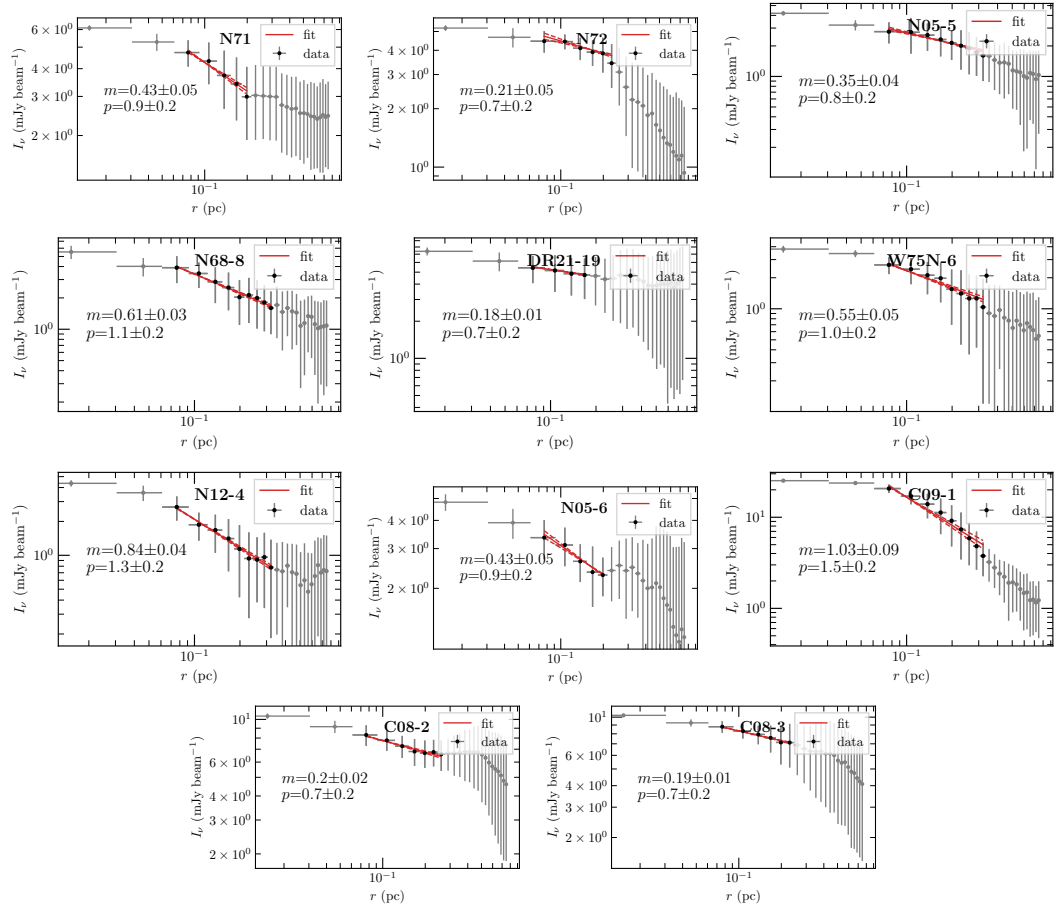


Figure E.11: continued.

E.3 MUSCLE results

The parameters of the MUSCLE modeling are summarized in Table E.5.

Table E.5: Parameters obtained with the MUSCLE in Cygnus-X clumps.

Source	p	$\#N_{\text{tot}}$	$\#N_{\text{best fit}}$	$T_{0.1 \text{ pc}}$ [K]	$M_{0.5 \text{ pc}}$ [$M_{\odot}$]	ζ s^{-1}	$S_{\text{peak}}/S_{\text{int}}$ ^a	τ_{chem} [yr]	Best fit model
C09-1	1.5	12	10	61.7	441.6	1.8×10^{16}	–	16913	HMPO
DR21-12	0.5	21	16	52.5	443.7	1.8×10^{15}	–	17432	HMPO
DR21-19	0.7	16	12	46.8	367.7	1.8×10^{17}	–	16510	HMPO
N03-2	0.5	9	8	29.5	627.2	1.8×10^{17}	–	906720	HMPO
N05-6	0.9	11	8	60.3	706.4	1.8×10^{17}	–	83510	UCHII
N1	0.5	19	15	50.2	1890.9	1.8×10^{16}	0.38	20729	HMPO
N10	1.7	20	16	63.1	236.0	1.8×10^{16}	0.39	98699	UCHII
N11	1.6	11	10	66.1	365.3	1.8×10^{17}	0.53	83510	UCHII
N12	1.8	16	13	28.2	528.3	1.8×10^{17}	0.45	212800	HMPO
N12-4	1.3	10	9	33.9	628.1	1.8×10^{17}	–	47039	HMPO
N12-6	0.5	9	9	43.7	737.0	1.8×10^{17}	–	65126	HMPO
N12-7	0.5	13	10	30.9	554.8	1.8×10^{17}	–	171780	HMC
N13	0.5	15	14	49.0	656.7	1.8×10^{15}	0.9	17330	HMPO
N14	1.5	18	14	70.8	306.3	1.8×10^{16}	0.53	16683	HMPO
N16	1.8	9	8	49.0	480.5	1.8×10^{17}	0.38	50805	HMPO
N18	1.1	13	12	38.9	567.6	1.8×10^{16}	0.26	21836	HMPO
N2	0.5	18	15	52.5	1458.8	1.8×10^{17}	0.29	83510	UCHII
N20	1.7	9	9	35.5	342.1	1.8×10^{17}	0.67	50805	HMPO
N21	0.9	15	13	41.7	352.6	1.8×10^{16}	0.26	20729	HMPO
N22	0.6	18	14	42.7	352.6	1.8×10^{16}	0.21	21250	HMPO
N23	1.2	12	11	60.3	473.8	1.8×10^{16}	0.32	16913	HMPO
N24	1.0	19	15	37.2	178.0	1.8×10^{17}	0.22	50805	HMPO
N25	1.4	15	12	45.7	484.8	1.8×10^{16}	0.38	24064	HMPO
N26	1.0	12	10	43.7	691.9	1.8×10^{17}	0.29	77859	HMPO
N27	0.7	18	16	42.7	484.3	1.8×10^{16}	0.45	21250	HMPO
N28	1.0	15	12	42.7	761.1	1.8×10^{17}	0.27	85426	HMPO
N3	1.4	20	15	35.5	3134.5	1.8×10^{16}	0.46	753980	HMC

References. ^a; Motte et al. (2007).

Table E.6: Continued from previous page.

Source	p	$\#N_{\text{tot}}$	$\#N_{\text{best fit}}$	$T_{0.1 \text{ pc}}$	$M_{0.5 \text{ pc}}$	ζ	$S_{\text{peak}}/S_{\text{int}}$	τ_{chem}	Best fit model
N30	1.8	18	14	67.7	2584.0	1.8×10^{16}	0.34	21836	HMPO
N31	1.6	20	15	46.8	2483.6	1.8×10^{16}	0.92	21836	HMPO
N32	0.5	20	15	36.3	6567.4	1.8×10^{17}	0.33	77859	HMPO
N36A	0.5	19	16	75.9	789.6	1.8×10^{16}	0.43	24997	HMPO
N36B	0.5	6	6	50.2	1171.4	1.8×10^{15}	0.43	17330	HMPO
N37	0.5	23	20	39.8	672.4	1.8×10^{15}	1.0	16827	HMPO
N38A	1.1	20	14	30.2	900.8	1.8×10^{17}	0.32	191250	HMPO
N38B	1.1	8	7	70.8	3193.2	1.8×10^{15}	0.32	16540	HMPO
N39	1.1	18	16	41.7	253.5	1.8×10^{16}	0.35	21250	HMPO
N40	0.8	23	16	27.6	799.4	1.8×10^{17}	0.2	514200	HMPO
N41A	0.9	22	17	93.4	90.6	1.8×10^{16}	1.0	58045	HMC
N41B	0.9	5	5	70.8	1729.1	1.8×10^{15}	1.0	16591	HMPO
N42A	0.5	5	5	75.9	5986.4	1.8×10^{16}	0.9	23234	HMPO
N42B	0.5	21	18	61.7	1402.1	1.8×10^{15}	0.9	16614	HMPO
N43	1.2	24	17	25.1	1496.5	1.8×10^{17}	0.3	103475	HMPO
N44A	1.7	21	18	47.9	1836.4	1.8×10^{16}	0.35	21250	HMPO
N45	0.7	20	16	40.8	1214.9	1.8×10^{16}	0.43	19851	HMPO
N47	0.9	22	15	46.8	5460.4	1.8×10^{16}	0.75	24997	HMPO
N48	1.2	22	17	57.6	1797.2	1.8×10^{17}	0.31	83510	UCHII
N49	0.9	19	16	37.2	443.5	1.8×10^{16}	0.5	20729	HMPO
N5	0.9	15	11	47.9	1647.0	1.8×10^{16}	0.46	22494	HMPO
N50	0.5	20	17	37.2	1374.4	1.8×10^{16}	0.33	20264	HMPO
N51	1.2	25	15	30.9	3431.7	1.8×10^{17}	0.29	103475	HMPO
N52	0.8	21	19	55.0	564.8	1.8×10^{15}	0.29	17330	HMPO
N53	1.6	24	19	53.7	1059.2	1.8×10^{15}	0.37	17676	HMPO
N54	0.6	23	17	28.2	2072.9	1.8×10^{17}	0.33	126250	HMPO
N56	2.0	18	13	91.3	631.5	1.8×10^{16}	0.45	26045	HMPO
N58	1.1	10	8	112.3	606.3	1.8×10^{17}	0.16	16510	HMPO
N6	1.0	15	12	41.7	1415.3	1.8×10^{16}	0.2	21836	HMPO
N61	1.3	10	9	58.9	225.3	1.8×10^{17}	0.43	83510	UCHII
N63	2.4	18	14	91.3	323.5	1.8×10^{16}	0.68	26045	HMPO
N64	1.1	20	14	43.7	837.3	1.8×10^{16}	0.45	1016500	HMPO
N65	1.5	19	15	55.0	725.9	1.8×10^{16}	0.29	83759	UCHII
N66	1.3	21	17	50.2	360.4	1.8×10^{16}	0.44	30030	HMPO
N67	1.4	20	16	53.7	249.4	1.8×10^{15}	0.67	17085	HMPO
N68-8	1.1	9	8	66.1	359.2	1.8×10^{17}	–	83540	UCHII
N69	0.7	18	15	40.8	124.7	1.8×10^{16}	0.59	16867	HMPO
N71	0.9	13	11	47.9	321.2	1.8×10^{16}	0.35	21836	HMPO
N72	0.7	13	12	61.7	526.6	1.8×10^{17}	0.19	84676	UCHII
W75N-6	1.0	12	11	37.2	302.6	1.8×10^{16}	–	24997	HMPO

Bibliography

- Adams, F. C. (1991), *Asymptotic Theory for the Spatial Distribution of Protostellar Emission*, [ApJ 382 544](#).
- Aikawa, Y. et al. (2012), *From Prestellar to Protostellar Cores. II. Time Dependence and Deuterium Fractionation*, [ApJ 760, 40 40](#).
- Akabane, K. et al. (1974), *Detection of Interstellar Lines of Para-Formaldehyde and OCS and Searches for Other Molecular Lines at 73GHz*, *PASJ* 26 1.
- Albertsson, T. et al. (2013), *New Extended Deuterium Fractionation Model: Assessment at Dense ISM Conditions and Sensitivity Analysis*, [ApJS 207, 27 27](#).
- Anderson, I. M. et al. (1999), *Deuterium fractionation and the degree of ionization in the R Coronae Australis molecular cloud core*, *A&A* 347 983.
- André, P. et al. (2014), “From Filamentary Networks to Dense Cores in Molecular Clouds: Toward a New Paradigm for Star Formation”, *Protostars and Planets VI*, ed. by H. Beuther et al. 27.
- André, P. J. et al. (2022), *The typical width of Herschel filaments*, [A&A 667, L1 L1](#).
- Ao, Y. et al. (2013), *The thermal state of molecular clouds in the Galactic center: evidence for non-photon-driven heating*, [A&A 550, A135 A135](#).
- Arzoumanian, D. et al. (2019), *Characterizing the properties of nearby molecular filaments observed with Herschel*, [A&A 621, A42 A42](#).
- Bacmann, A. et al. (2003), *CO Depletion and Deuterium Fractionation in Prestellar Cores*, [ApJL 585 L55](#).
- Battersby, C. et al. (2025), *3D CMZ. I. Central Molecular Zone Overview*, [ApJ 984, 156 156](#).
- Beerer, I. M. et al. (2010), *A Spitzer View of Star Formation in the Cygnus X North Complex*, [ApJ 720 679](#).
- Belloche, A. et al. (2013), *Complex organic molecules in the interstellar medium: IRAM 30 m line survey of Sagittarius B2(N) and (M)*, [A&A 559, A47 A47](#).
- Bernath, P. F. (2005), *Spectra of Atoms and Molecules*, Oxford University Press, ISBN: 9780195177596.
- Bertin, M. et al. (2016), *UV Photodesorption of Methanol in Pure and CO-rich Ices: Desorption Rates of the Intact Molecule and of the Photofragments*, [ApJL 817, L12 L12](#).

- Beuther, H. et al. (2002), *High-Mass Protostellar Candidates. II. Density Structure from Dust Continuum and CS Emission*, [ApJ 566 945](#).
- Beuther, H. et al. (2007a), “The Formation of Massive Stars”, *Protostars and Planets V*, ed. by B. Reipurth et al. 165.
- Beuther, H. et al. (2007b), “The Formation of Massive Stars”, *Protostars and Planets V*, ed. by B. Reipurth et al. 165.
- Beuther, H. et al. (2014), *Carbon in different phases ([CII], [CI], and CO) in infrared dark clouds: Cloud formation signatures and carbon gas fractions*, [A&A 571, A53 A53](#).
- Beuther, H. et al. (2018), *Fragmentation and disk formation during high-mass star formation. IRAM NOEMA (Northern Extended Millimeter Array) large program CORE*, [A&A 617, A100 A100](#).
- Beuther, H. et al. (2022), *The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE. Overview and first results toward DR20 from the Max Planck IRAM Observatory program (MIOP)*, [A&A 665, A63 A63](#).
- Beuther, H. et al. (2024), *Density distributions, magnetic field structures, and fragmentation in high-mass star formation*, [A&A 682, A81 A81](#).
- Bonne, L. et al. (2023), *Unveiling the Formation of the Massive DR21 Ridge*, [ApJ 951, 39 39](#).
- Brinkmann, N. et al. (2020), *An imaging line survey of OMC-1 to OMC-3. Averaged spectra of template regions*, [A&A 636, A39 A39](#).
- Brunthaler, A. et al. (2021), *A global view on star formation: The GLOSTAR Galactic plane survey. I. Overview and first results for the Galactic longitude range $28^\circ < l < 36^\circ$* , [A&A 651, A85 A85](#).
- Burbidge, E. M. et al. (1957), *Synthesis of the Elements in Stars*, [Reviews of Modern Physics 29 547](#).
- Burkhardt, A. M. et al. (2019), *Modeling C-shock Chemistry in Isolated Molecular Outflows*, [ApJ 881, 32 32](#).
- Burkhardt, A. M. et al. (2021), *Discovery of the Pure Polycyclic Aromatic Hydrocarbon Indene (c-C₉H₈) with GOTHAM Observations of TMC-1*, [ApJL 913, L18 L18](#).
- Busch, L. A. et al. (2024), *Shocking Sgr B2 (N1) with its own outflow. A new perspective on segregation between O- and N-bearing molecules*, [A&A 681, A104 A104](#).
- Cao, Y. et al. (2019), *Surveys of Clumps, Cores, and Condensations in Cygnus X. I. A New Catalog of ~ 0.1 pc Massive Dense Cores*, [ApJS 241, 1](#).
- Cao, Y. et al. (2021), *Core Mass Function of a Single Giant Molecular Cloud Complex with 10,000 Cores*, [ApJL 918, L4 L4](#).
- Cao, Y. et al. (2022), *The DR21(OH) Trident-Resolving the Massive Ridge into Three Entangled Fibers as the Initial Condition of Cluster Formation*, [ApJ 927, 106 106](#).
- Carey, S. J. et al. (2009), *MIPSGAL: A Survey of the Inner Galactic Plane at 24 and 70 μ m*, [PASP 121 76](#).

-
- Carey, S. J. et al. (1998), *The Physical Properties of the Midcourse Space Experiment Galactic Infrared-dark Clouds*, [ApJ 508 721](#).
- Carter, M. et al. (2012), *The EMIR multi-band mm-wave receiver for the IRAM 30-m telescope*, [A&A 538, A89 A89](#).
- Caselli, P. et al. (1998), *The Ionization Fraction in Dense Cloud Cores*, [ApJ 499 234](#).
- Caselli, P. et al. (2002), *Molecular Ions in L1544. II. The Ionization Degree*, [ApJ 565 344](#).
- Caselli, P. and C. Ceccarelli (2012), *Our astrochemical heritage*, [A&AR 20, 56 56](#).
- Chen, H.-R. et al. (2010), *Deuterium Fractionation as an Evolutionary Probe in the Infrared Dark Cloud G28.34+0.06*, [ApJL 713 L50](#).
- Christensen, I. B. et al. (2024), *The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE. III. The large scale distribution of DCO⁺, DNC, and DCN in the DR21 filament*, [A&A 688, A215 A215](#).
- Christensen, I. B. (2020), *Universet fra Arktis*, Tidsskriftet Grønland 3 108 -110.
- Churchwell, E. et al. (2009), *The Spitzer/GLIMPSE Surveys: A New View of the Milky Way*, [PASP 121 213](#).
- Coletta, A. et al. (2025), *ALMAGAL: III. Compact source catalog: Fragmentation statistics and physical evolution of the core population*, [A&A 696, A151 A151](#).
- Combes, F. et al. (1985), *Detection of interstellar CCD.*, [A&A 147 L25](#).
- Contreras, Y. et al. (2013), *ATLASGAL - compact source catalogue: $330^\circ < \ell < 21^\circ$* , [A&A 549, A45 A45](#).
- Cooke, R. J. et al. (2018), *One Percent Determination of the Primordial Deuterium Abundance*, [ApJ 855, 102 102](#).
- Crapsi, A. et al. (2005), *Probing the Evolutionary Status of Starless Cores through N₂H⁺ and N₂D⁺ Observations*, [ApJ 619 379](#).
- Cruz-Diaz, G. A. et al. (2016), *Negligible photodesorption of methanol ice and active photon-induced desorption of its irradiation products*, [A&A 592, A68 A68](#).
- Csengeri, T. et al. (2014), *The ATLASGAL survey: a catalog of dust condensations in the Galactic plane*, [A&A 565, A75 A75](#).
- Cummins, S. E. et al. (1983), *The kinetic temperature and density of the Sagittarius B2 molecular cloud from observations of methyl cyanide.*, [ApJ 266 331](#).
- Cuppen, H. M. et al. (2017), *Grain Surface Models and Data for Astrochemistry*, [Space Sci. Rev. 212 1](#).
- Dalgarno, A. (2008), *A serendipitous journey.*, [ARA&A 46 1](#).
- Dame, T. M. et al. (2001), *The Milky Way in Molecular Clouds: A New Complete CO Survey*, [ApJ 547 792](#).

- Damiani, F. et al. (2017), *The Gaia-ESO Survey: dynamics of ionized and neutral gas in the Lagoon nebula (M 8)*, [A&A 604, A135 A135](#).
- Daniel, F. et al. (2007), *The Excitation of N_2H^+ in Interstellar Molecular Clouds. II. Observations*, [ApJ 667 980](#).
- Dib, S. et al. (2020), *The structure and characteristic scales of molecular clouds*, [A&A 642, A177 A177](#).
- Dickel, J. R. et al. (1978), *The detailed structure of CO in molecular cloud complexes. II. The W75-DR21 region.*, [ApJ 223 840](#).
- Dicker, S. R. et al. (2014), *MUSTANG 2: A Large Focal Plane Array for the 100 m Green Bank Telescope*, [Journal of Low Temperature Physics 176 808](#).
- Dobbs, C. L. et al. (2006), *The formation of molecular clouds in spiral galaxies*, [MNRAS 371 1663](#).
- Dokara, R. et al. (2021), *A global view on star formation: The GLOSTAR Galactic plane survey. II. Supernova remnants in the first quadrant of the Milky Way*, [A&A 651, A86 A86](#).
- Dokara, R. et al. (2023), *A global view on star formation: The GLOSTAR Galactic plane survey. VII. Supernova remnants in the Galactic longitude range $28^\circ < l < 36^\circ$* , [A&A 671, A145 A145](#).
- Douglas, A. E. and G. Herzberg (1941), *Note on CH^+ in Interstellar Space and in the Laboratory.*, [ApJ 94 381](#).
- Downes, D. and R. Rinehart (1966), *Microwave Observations of the Cygnus X Region*, [ApJ 144 937](#).
- Downes, D. et al. (1980), *H110alpha and H2CO survey of galactic radio sources.*, [A&AS 40 379](#).
- Draine, B. T. and H. M. Lee (1984), *Optical Properties of Interstellar Graphite and Silicate Grains*, [ApJ 285 89](#).
- Draine, B. T. (2011), *Physics of the Interstellar and Intergalactic Medium*.
- Druard, C. and V. Wakelam (2012), *Polysulphanes on interstellar grains as a possible reservoir of interstellar sulphur*, [MNRAS 426 354](#).
- Emprechtinger, M. et al. (2009), *The N_2D^+/N_2H^+ ratio as an evolutionary tracer of Class 0 protostars*, [A&A 493 89](#).
- Favre, C. et al. (2015), *Evidence for DCO^+ as a Probe of Ionization in the Warm Disk Surface*, [ApJL 802, L23 L23](#).
- Fehér, O. et al. (2025), *Dense gas tracers in and between spiral arms: from Giant Molecular Filaments to star-forming clumps*, [MNRAS 540 3441](#).
- Feng, S. et al. (2016), *Inferring the evolutionary stages of the internal structures of NGC 7538 S and IRS1 from chemistry*, [A&A 593, A46 A46](#).
- Fontani, F. et al. (2011), *Deuteration as an evolutionary tracer in massive-star formation*, [A&A 529, L7 L7](#).

-
- Fontani, F. et al. (2014), *DNC/HNC and N_2D^+/N_2H^+ ratios in high-mass star-forming cores*, [MNRAS 440 448](#).
- Fontani, F. et al. (2015), *Deuteration and evolution in the massive star formation process. The role of surface chemistry*, [A&A 575, A87 A87](#).
- Gaia Collaboration et al. (2016), *The Gaia mission*, [A&A 595, A1 A1](#).
- Garrod, R. T. and E. Herbst (2006), *Formation of methyl formate and other organic species in the warm-up phase of hot molecular cores*, [A&A 457 927](#).
- Garrod, R. T. (2013), *A Three-phase Chemical Model of Hot Cores: The Formation of Glycine*, [ApJ 765, 60 60](#).
- Garrod, R. T. et al. (2008), *Complex Chemistry in Star-forming Regions: An Expanded Gas-Grain Warm-up Chemical Model*, [ApJ 682 283](#).
- Gerin, M. et al. (2009), *HCO mapping of the Horsehead: tracing the illuminated dense molecular cloud surfaces*, [A&A 494 977](#).
- Gerin, M. (2013), “The Molecular Universe”, *Astrochemistry and Astrobiology*, ed. by I. W. M. Smith et al., Berlin, Heidelberg: Springer Berlin Heidelberg 35, ISBN: 978-3-642-31730-9.
- Gerner, T. et al. (2014), *Chemical evolution in the early phases of massive star formation. I*, [A&A 563, A97 A97](#).
- Gerner, T. et al. (2015), *Chemical evolution in the early phases of massive star formation. II. Deuteration*, [A&A 579, A80 A80](#).
- Giannetti, A. et al. (2014), *ATLASGAL-selected massive clumps in the inner Galaxy. I. CO depletion and isotopic ratios*, [A&A 570, A65 A65](#).
- Giannetti, A. et al. (2017), *ATLASGAL-selected massive clumps in the inner Galaxy. V. Temperature structure and evolution*, [A&A 603, A33 A33](#).
- Giannetti, A. et al. (2019), *A timeline for massive star-forming regions via combined observation of $o\text{-H}_2D^+$ and N_2D^+* , [A&A 621, L7 L7](#).
- Gieser, C. et al. (2019), *Chemical complexity in high-mass star formation. An observational and modeling case study of the AFGL 2591 VLA 3 hot core*, [A&A 631, A142 A142](#).
- Gieser, C. et al. (2021), *Physical and chemical structure of high-mass star-forming regions. Unraveling chemical complexity with CORE: the NOEMA large program*, [A&A 648, A66 A66](#).
- Gieser, C. et al. (2022), *Clustered star formation at early evolutionary stages. Physical and chemical analysis of the young star-forming regions ISOSS J22478+6357 and ISOSS J23053+5953*, [A&A 657, A3 A3](#).
- Gieser, C. et al. (2023), *Physical and chemical complexity in high-mass star-forming regions with ALMA. I. Overview and evolutionary trends of physical properties*, [A&A 674, A160 A160](#).
- Ginsburg, A. et al. (2011), *Galactic H_2CO Densitometry. I. Pilot Survey of Ultracompact H II Regions and Methodology*, [ApJ 736, 149 149](#).

- Ginsburg, A. et al. (2015), *The dense gas mass fraction in the W51 cloud and its protoclusters*, [A&A 573, A106 A106](#).
- Girichidis, P. et al. (2020), *Physical Processes in Star Formation*, [Space Sci. Rev. 216, 68 68](#).
- Goldsmith, P. F. and W. D. Langer (1999), *Population Diagram Analysis of Molecular Line Emission*, [ApJ 517 209](#).
- Gong, Y. et al. (2023), *A global view on star formation: The GLOSTAR Galactic plane survey. VIII. Formaldehyde absorption in Cygnus X*, [A&A 678, A130 A130](#).
- Guilloteau, S. et al. (1992), *The IRAM interferometer on Plateau de Bure.*, [A&A 262 624](#).
- Gulkis, S. and I. de Pater (2003), “Radio Astronomy, Planetary”, *Encyclopedia of Physical Science and Technology (Third Edition)*, ed. by R. A. Meyers, Third Edition, New York: Academic Press 687, ISBN: 978-0-12-227410-7.
- Güsten, R. et al. (2006), *The Atacama Pathfinder EXperiment (APEX) - a new submillimeter facility for southern skies -*, [A&A 454 L13](#).
- Hacar, A. et al. (2013), *Cores, filaments, and bundles: hierarchical core formation in the L1495/B213 Taurus region*, [A&A 554, A55 A55](#).
- Hacar, A. et al. (2018), *An ALMA study of the Orion Integral Filament. I. Evidence for narrow fibers in a massive cloud*, [A&A 610, A77 A77](#).
- Hacar, A. et al. (2020), *HCN-to-HNC intensity ratio: a new chemical thermometer for the molecular ISM*, [A&A 635, A4 A4](#).
- Hacar, A. et al. (2023), “Initial Conditions for Star Formation: a Physical Description of the Filamentary ISM”, *Protostars and Planets VII*, ed. by S. Inutsuka et al., vol. 534, Astronomical Society of the Pacific Conference Series 153.
- Harju, J. et al. (2024), *Nuclear spin ratios of deuterated ammonia in prestellar cores. LAsMA observations of H-MM1 and Oph D*, [A&A 682, A8 A8](#).
- Heiner, J. S. et al. (2015), *Molecular cloud formation as seen in synthetic H I and molecular gas observations*, [MNRAS 452 1353](#).
- Hennemann, M. et al. (2012), *The spine of the swan: a Herschel study of the DR21 ridge and filaments in Cygnus X*, [A&A 543, L3 L3](#).
- Herbst, E. (1982), *The temperature dependence of the HCO⁺/DCO⁺ abundance ratio in dense interstellar clouds*, [A&A 111 76](#).
- Herbst, E. (1995), *Chemistry in the Interstellar Medium*, [Annual Review of Physical Chemistry 46 27](#).
- Herbst, E. et al. (2000), *Calculations on the rates, mechanisms, and interstellar importance of the reactions between C and NH₂ and between N and CH₂*, [MNRAS 311 869](#).
- Herbst, E. and E. F. van Dishoeck (2009), *Complex Organic Interstellar Molecules*, [ARA&A 47 427](#).
- Herbst, E. et al. (1987), *Ion-Molecule Calculation of the Abundance Ratio of CCD to CCH in Dense Interstellar Clouds*, [ApJ 312 351](#).

-
- Hernandez, A. K. and J. C. Tan (2015), *The Giant Molecular Cloud Environments of Infrared Dark Clouds*, [ApJ 809, 154 154](#).
- Heyer, M. and T. M. Dame (2015), *Molecular Clouds in the Milky Way*, [ARA&A 53 583](#).
- Hill, T. et al. (2011), *Filaments and ridges in Vela C revealed by Herschel: from low-mass to high-mass star-forming sites*, [A&A 533, A94 A94](#).
- Hoyle, F. (1946), *The synthesis of the elements from hydrogen*, [MNRAS 106 343](#).
- Hu, B. et al. (2021), *DR 21 South Filament: A Parsec-sized Dense Gas Accretion Flow onto the DR 21 Massive Young Cluster*, [ApJ 908, 70 70](#).
- Indriolo, N. et al. (2015), *Herschel Survey of Galactic OH^+ , H_2O^+ , and H_3O^+ : Probing the Molecular Hydrogen Fraction and Cosmic-Ray Ionization Rate*, [ApJ 800, 40 40](#).
- Jakob, H. et al. (2007), *The cooling of atomic and molecular gas in DR21*, [A&A 461 999](#).
- Jansky, K. G. (1933), *Radio Waves from Outside the Solar System*, [Nature 132 66](#).
- Johnson, J. A. (2019), *Populating the periodic table: Nucleosynthesis of the elements*, [Science 363 474](#).
- Jørgensen, J. K. et al. (2011), *Arcsecond resolution images of the chemical structure of the low-mass protostar IRAS 16293-2422. An overview of a large molecular line survey from the Submillimeter Array*, [A&A 534, A100 A100](#).
- Jørgensen, J. K. et al. (2016), *The ALMA Protostellar Interferometric Line Survey (PILS). First results from an unbiased submillimeter wavelength line survey of the Class 0 protostellar binary IRAS 16293-2422 with ALMA*, [A&A 595, A117 A117](#).
- Jørgensen, J. K. et al. (2020), *Astrochemistry During the Formation of Stars*, [ARA&A 58 727](#).
- Kahle, K. A. et al. (2024), *The effects of stellar feedback on molecular clumps in the Lagoon Nebula (M8)*, [arXiv e-prints, arXiv:2404.07920 arXiv:2404.07920](#).
- Kaifu, N. et al. (1975), *Distribution of 733-GHz para-formaldehyde line emission in the Orion nebula.*, [ApJ 196 719](#).
- Kelly, G. et al. (2017), *Molecular shock tracers in NGC 1068: SiO and HNCO*, [A&A 597, A11 A11](#).
- Khan, S. et al. (2024), *A global view on star formation: The GLOSTAR Galactic plane survey: X. Galactic H II region catalog using radio recombination lines*, [A&A 689, A81 A81](#).
- Kim, W. -. et al. (2020), *ATLASGAL-selected massive clumps in the inner Galaxy. VIII. Chemistry of photodissociation regions*, [A&A 644, A160 A160](#).
- Kim, W. -. et al. (2025), *The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE: IV. Unveiling the hidden structures in DR18*, [A&A 694, A30 A30](#).
- Kirk, H. et al. (2013), *Filamentary Accretion Flows in the Embedded Serpens South Protocluster*, [ApJ 766, 115 115](#).
- Koley, A. et al. (2021), *The magnetic field in the dense photodissociation region of DR 21*, [MNRAS 501 4825](#).

- König, C. et al. (2017), *ATLASGAL-selected massive clumps in the inner Galaxy. III. Dust continuum characterization of an evolutionary sample*, [A&A 599, A139 A139](#).
- Kraemer, K. E. et al. (2010), *Circumstellar Structure Around Evolved Stars in the Cygnus-X Star Formation Region*, [AJ 139 2319](#).
- Kroupa, P. et al. (2013), “The Stellar and Sub-Stellar Initial Mass Function of Simple and Composite Populations”, *Planets, Stars and Stellar Systems. Volume 5: Galactic Structure and Stellar Populations*, ed. by T. D. Oswalt and G. Gilmore, vol. 5 115.
- Krumholz, M. R. and I. A. Bonnell (2009), “Models for the formation of massive stars”, *Structure Formation in Astrophysics*, ed. by G. Chabrier 288.
- Kryukova, E. et al. (2014), *The Dependence of Protostellar Luminosity on Environment in the Cygnus-X Star-forming Complex*, [AJ 148, 11 11](#).
- Kumar, M. S. N. et al. (2007), *WFCAM, Spitzer/IRAC and SCUBA observations of the massive star-forming region DR21/W75 - II. Stellar content and star formation*, [MNRAS 374 54](#).
- Kumar, M. S. N. et al. (2020), *Unifying low- and high-mass star formation through density-amplified hubs of filaments. The highest mass stars ($>100 M_{\odot}$) form only in hubs*, [A&A 642, A87 A87](#).
- Larson, R. B. (1978), *Calculations of three-dimensional collapse and fragmentation.*, [MNRAS 184 69](#).
- Larson, R. B. (1981), *Turbulence and star formation in molecular clouds.*, [MNRAS 194 809](#).
- Larson, R. B. (2006), “Understanding the Stellar Initial Mass Function”, *Revista Mexicana de Astronomía y Astrofísica Conference Series*, vol. 26, Revista Mexicana de Astronomía y Astrofísica Conference Series 55.
- Lequeux, J. (2005), *The Interstellar Medium*.
- Li, A. and B. T. Draine (2001), *Infrared Emission from Interstellar Dust. II. The Diffuse Interstellar Medium*, [ApJ 554 778](#).
- Li, G.-X. et al. (2017), *Revealing a spiral-shaped molecular cloud in our galaxy: Cloud fragmentation under rotation and gravity*, [A&A 598, A96 A96](#).
- Li, G.-X. et al. (2021), *Network of Star Formation: Fragmentation Controlled by Scale-dependent Turbulent Pressure and Accretion onto the Massive Cores Revealed in the Cygnus-X GMC Complex*, [ApJ 916, 13 13](#).
- Lin, S.-J. et al. (2024), *Deuterium fractionation of the starless core L 1498*, [A&A 688, A118 A118](#).
- Lin, Y. et al. (2022), *The evolution of temperature and density structures of OB cluster-forming molecular clumps*, [A&A 658, A128 A128](#).
- Linsky, J. L. (1998), *Deuterium Abundance in the Local ISM and Possible Spatial Variations*, *Space Sci. Rev.* 84 285.
- Liu, B. and S. Yu (2020), “Flux calibration for single-dish radio telescopes”, *Big Data in Astronomy: Scientific Data Processing for Advanced Radio Telescopes*, ed. by L. Kong et al. 165.
- Mangum, J. G. and Y. L. Shirley (2015), *How to Calculate Molecular Column Density*, [PASP 127 266](#).

-
- Mangum, J. G. and A. Wootten (1993), *Formaldehyde as a Probe of Physical Conditions in Dense Molecular Clouds*, [ApJS 89 123](#).
- Mangum, J. G. et al. (1990), *Observations of the Formaldehyde Emission in Orion-KL: Abundances, Distribution, and Kinematics of the Dense Gas in the Orion Molecular Ridge*, [ApJ 348 542](#).
- Mangum, J. G. et al. (2008), *Formaldehyde Densitometry of Starburst Galaxies*, [ApJ 673 832](#).
- Mangum, J. G. et al. (2013), *Formaldehyde Densitometry of Starburst Galaxies: Density-independent Global Star Formation*, [ApJ 766, 108 108](#).
- Marston, A. P. et al. (2004), *DR 21: A Major Star Formation Site Revealed by Spitzer*, [ApJS 154 333](#).
- Martín-Pintado, J. et al. (1997), *SiO Emission from the Galactic Center Molecular Clouds*, [ApJL 482 L45](#).
- McGuire, B. A. et al. (2020), *Laboratory spectroscopy techniques to enable observations of interstellar ion chemistry*, [Nature Reviews Physics 2 402](#).
- McKee, C. F. and E. C. Ostriker (2007), *Theory of Star Formation*, [ARA&A 45 565](#).
- McKee, C. F. and J. C. Tan (2002), *Massive star formation in 100,000 years from turbulent and pressurized molecular clouds*, [Nature 416 59](#).
- McKee, C. F. and J. C. Tan (2003), *The Formation of Massive Stars from Turbulent Cores*, [ApJ 585 850](#).
- McKellar, A. (1940), *Evidence for the Molecular Origin of Some Hitherto Unidentified Interstellar Lines*, [PASP 52 187](#).
- Medina, S. -. X. et al. (2019), *GLOSTAR: Radio Source Catalog I. $28^\circ < \ell < 36^\circ$ and $|b| < 1^\circ$* , [A&A 627, A175 A175](#).
- Miettinen, O. et al. (2011), *Deuterium fractionation and the degree of ionisation in massive clumps within infrared dark clouds*, [A&A 534, A134 A134](#).
- Miranzo-Pastor, J. J. et al. (2025), *PRODIGE – envelope to disk with NOEMA: VI. The missing sulfur problem*, [A&A 700, A251 A251](#).
- Miyama, S. M. et al. (1984), *Criteria for collapse and fragmentation of rotating, isothermal clouds*, [ApJ 279 621](#).
- Molinari, S. et al. (2010), *Clouds, filaments, and protostars: The Herschel Hi-GAL Milky Way*, [A&A 518, L100 L100](#).
- Motte, F. and P. André (2001), *The circumstellar environment of low-mass protostars: A millimeter continuum mapping survey*, [A&A 365 440](#).
- Motte, F. et al. (2007), *The earliest phases of high-mass star formation: a 3 square degree millimeter continuum mapping of Cygnus X*, [A&A 476 1243](#).
- Motte, F. et al. (2010), *Initial highlights of the HOBYS key program, the Herschel imaging survey of OB young stellar objects*, [A&A 518, L77 L77](#).

- Motte, F. et al. (2018), *High-Mass Star and Massive Cluster Formation in the Milky Way*, [ARA&A 56 41](#).
- Mottram, J. C. et al. (2011), *The Red MSX Source survey: the bolometric fluxes and luminosity distributions of young massive stars*, [A&A 525, A149 A149](#).
- Müller, H. S. P. et al. (2005), *The Cologne Database for Molecular Spectroscopy, CDMS: a useful tool for astronomers and spectroscopists*, [Journal of Molecular Structure 742 215](#).
- Nguyen, H. et al. (2022), *A global view on star formation: The GLOSTAR Galactic plane survey. V. 6.7 GHz methanol maser catalogue*, [A&A 666, A59 A59](#).
- Nothnagel, A. et al. (2010), “Homologous Deformation of the Effelsberg 100 m Telescope determined with a Total Station”, *Sixth International VLBI Service for Geodesy and Astronomy. Proceedings from the 2010 General Meeting*, ed. by R. Navarro et al. 123.
- Öberg, K. I. et al. (2009), *Formation rates of complex organics in UV irradiated CH₃OH-rich ices. I. Experiments*, [A&A 504 891](#).
- Okoh, D. et al. (2014), *Formaldehyde and H110 α observations towards 6.7 GHz methanol maser sources*, [Ap&SS 350 657](#).
- Oliveira, C. M. et al. (2003), *Interstellar Deuterium, Nitrogen, and Oxygen Abundances toward GD 246, WD 2331-475, HZ 21, and Lanning 23: Results from the FUSE Mission*, [ApJ 587 235](#).
- Pagani, L. et al. (2011), *Ortho-H₂ and the Age of Interstellar Dark Clouds*, [ApJL 739, L35 L35](#).
- Panopoulou, G. V. et al. (2014), *¹³CO filaments in the Taurus molecular cloud*, [MNRAS 444 2507](#).
- Payne-Gaposchkin, C. H. (1925), *Stellar atmospheres: A contribution to the observational study of high temperature in the reversing layers of stars*, PhD thesis: Radcliffe College, United States.
- Pazukhin, A. G. et al. (2022), *H¹³CN-HN¹³C Intensity Ratio as a Temperature Indicator of Interstellar Clouds*, [Astronomy Reports 66 1302](#).
- Pazukhin, A. G. et al. (2023), *Variations of the HCO⁺, HCN, HNC, N₂H⁺, and NH₃ deuterium fractionation in high-mass star-forming regions*, [MNRAS 526 3673](#).
- Peretto, N. et al. (2013), *Global collapse of molecular clouds as a formation mechanism for the most massive stars*, [A&A 555, A112 A112](#).
- Peretto, N. et al. (2014), *SDC13 infrared dark clouds: Longitudinally collapsing filaments?*, [A&A 561, A83 A83](#).
- Perley, R. A. et al. (2011), *The Expanded Very Large Array: A New Telescope for New Science*, [ApJL 739, L1 L1](#).
- Petrashkevich, I. V. et al. (2024), *Deuterium fractionation in cold dense cores in the low-mass star-forming region L1688*, [MNRAS 528 1327](#).
- Pety, J. (2005), “Successes of and Challenges to GILDAS, a State-of-the-Art Radioastronomy Toolkit”, *SF2A-2005: Semaine de l’Astrophysique Française*, ed. by F. Casoli et al. 721.

-
- Pety, J. (2018), “GILDAS and CLASS”, *Submillimetre Single-dish Data Reduction and Array Combination Techniques* 11 11.
- Pickett, H. M. et al. (1998), *Submillimeter, millimeter and microwave spectral line catalog.*, *J. Quant. Spectr. Rad. Transf.* 60 883.
- Piddington, J. H. and H. C. Minnett (1952), *Radio-Frequency Radiation from the Constellation of Cygnus*, *Australian Journal of Scientific Research A Physical Sciences* 5 17.
- Pillai, T. et al. (2012), H_2D^+ in the High-mass Star-forming Region Cygnus X, *ApJ* 751, 135 135.
- Pineda, J. E. et al. (2023), “From Bubbles and Filaments to Cores and Disks: Gas Gathering and Growth of Structure Leading to the Formation of Stellar Systems”, *Protostars and Planets VII*, ed. by S. Inutsuka et al., vol. 534, Astronomical Society of the Pacific Conference Series 233.
- Pokhrel, R. et al. (2018), *Hierarchical Fragmentation in the Perseus Molecular Cloud: From the Cloud Scale to Protostellar Objects*, *ApJ* 853, 5 5.
- Potapov, A. and R. T. Garrod (2024), *Influence of the $C + H_2O \rightarrow H_2CO$ solid-state reaction on astrochemical networks and the formation of complex organic molecules*, *A&A* 692, A252 A252.
- Punanova, A. F. et al. (2025), *Correlation between formaldehyde and methanol in prestellar cores*, *MNRAS* 537 3686.
- Redaelli, E. et al. (2019), *High-sensitivity maps of molecular ions in L1544. I. Deuteration of N_2H^+ and HCO^+ and primary evidence of N_2D^+ depletion*, *A&A* 629, A15 A15.
- Reipurth, B. and N. Schneider (2008), “Star Formation and Young Clusters in Cygnus”, *Handbook of Star Forming Regions, Volume I*, ed. by B. Reipurth, vol. 4 36.
- Remijan, A. et al. (2004), *High-Resolution Observations of Methyl Cyanide (CH_3CN) toward the Hot Core Regions W51e1/e2*, *ApJ* 606 917.
- Riaz, B. and W.-F. Thi (2022), *Deuterium chemistry and D/H ratios in Class 0/I proto-brown dwarfs*, *MNRAS* 511 6110.
- Rice, T. S. et al. (2016), *A Uniform Catalog of Molecular Clouds in the Milky Way*, *ApJ* 822, 52 52.
- Rigby, A. J. et al. (2024), *The dynamic centres of infrared-dark clouds and the formation of cores*, *MNRAS* 528 1172.
- Roberts, H. and T. J. Millar (2000a), *Gas-phase formation of doubly-deuterated species*, *A&A* 364 780.
- Roberts, H. and T. J. Millar (2000b), *Modelling of deuterium chemistry and its application to molecular clouds*, *A&A* 361 388.
- Roberts, H. et al. (2004), *The chemistry of multiply deuterated species in cold, dense interstellar cores*, *A&A* 424 905.
- Roueff, E. et al. (2007), *Deuterium fractionation in warm dense interstellar clumps*, *A&A* 464 245.
- Rybarczyk, D. R. et al. (2023), *Shaken or Stirred: The Diffuse Interstellar Medium with Exceptionally High SiO Abundance*, *ApJ* 950, 52 52.

- Rygl, K. L. J. et al. (2012), *Parallaxes and proper motions of interstellar masers toward the Cygnus X star-forming complex. I. Membership of the Cygnus X region*, [A&A 539, A79 A79](#).
- Sakai, T. et al. (2012), *DNC/HNC Ratio of Massive Clumps in Early Evolutionary Stages of High-mass Star Formation*, [ApJ 747, 140 140](#).
- Salpeter, E. E. (1955), *The Luminosity Function and Stellar Evolution.*, [ApJ 121 161](#).
- Schilke, P. et al. (2001), *Observations of SiO towards photon dominated regions*, [A&A 372 291](#).
- Schneider, N. et al. (2006), *A new view of the Cygnus X region. KOSMA ^{13}CO 2 to 1, 3 to 2, and ^{12}CO 3 to 2 imaging*, [A&A 458 855](#).
- Schneider, N. et al. (2010), *Dynamic star formation in the massive DR21 filament*, [A&A 520, A49 A49](#).
- Schneider, N. et al. (2015), *Understanding star formation in molecular clouds. II. Signatures of gravitational collapse of IRDCs*, [A&A 578, A29 A29](#).
- Schneider, N. et al. (2023), *Ionized carbon as a tracer of the assembly of interstellar clouds*, [Nature Astronomy 7 546](#).
- Schuller, F. et al. (2009), *ATLASGAL - The APEX telescope large area survey of the galaxy at 870 μm* , [A&A 504 415](#).
- Semenov, D. et al. (2010), *Chemistry in disks. IV. Benchmarking gas-grain chemical models with surface reactions*, [A&A 522, A42 A42](#).
- Semenov, D. et al. (2024), *PRODIGE - planet-forming disks in Taurus with NOEMA. I. Overview and first results for ^{12}CO , ^{13}CO , and C^{18}O* , [A&A 685, A126 A126](#).
- Shirley, Y. L. (2015), *The Critical Density and the Effective Excitation Density of Commonly Observed Molecular Dense Gas Tracers*, [PASP 127 299](#).
- Sipilä, O. et al. (2015), *Spin-state chemistry of deuterated ammonia*, [A&A 581, A122 A122](#).
- Skretas, I. M. et al. (2023), *The Cygnus Allscale Survey of Chemistry and Dynamical Environments: CASCADE. II. A detailed kinematic analysis of the DR21 Main outflow*, [A&A 679, A66 A66](#).
- Snyder, L. E. et al. (1969), *Microwave Detection of Interstellar Formaldehyde*, [Phys. Rev. Lett. 22 679](#).
- Steinicke, W. (2016), *William Herschel's 'Hole in the Sky' and the discovery of dark nebulae*, *Journal of Astronomical History and Heritage* 19 305.
- Swings, P. and L. Rosenfeld (1937), *Considerations Regarding Interstellar Molecules*, [ApJ 86 483](#).
- Tafalla, M. et al. (2004), *On the internal structure of starless cores. I. Physical conditions and the distribution of CO, CS, N_2H^+ , and NH_3 in L1498 and L1517B*, [A&A 416 191](#).
- Tang, X. D. et al. (2017), *Kinetic temperature of massive star-forming molecular clumps measured with formaldehyde. II. The Large Magellanic Cloud*, [A&A 600, A16 A16](#).
- Tang, X. D. et al. (2018), *ATLASGAL-selected massive clumps in the inner Galaxy. VI. Kinetic temperature and spatial density measured with formaldehyde*, [A&A 611, A6 A6](#).

-
- Tang, X. D. et al. (2021), *Kinetic temperature of massive star-forming molecular clumps measured with formaldehyde. IV. The ALMA view of N113 and N159W in the LMC*, [A&A 655, A12 A12](#).
- Taquet, V. et al. (2012), *Formaldehyde and Methanol Deuteration in Protostars: Fossils from a Past Fast High-density Pre-collapse Phase*, [ApJL 748, L3 L3](#).
- Taylor, A. R. et al. (2003), *The Canadian Galactic Plane Survey*, [AJ 125 3145](#).
- Tielens, A. G. G. M. (2005), *The Physics and Chemistry of the Interstellar Medium*.
- Tielens, A. (2021), *Molecular Astrophysics*.
- Tigé, J. et al. (2017), *The earliest phases of high-mass star formation, as seen in NGC 6334 by Herschel-HOBYS*, [A&A 602, A77 A77](#).
- Tiwari, M. et al. (2019), *Observational study of hydrocarbons in the bright photodissociation region of Messier 8*, [A&A 626, A28 A28](#).
- Tothill, N. F. H. et al. (2002), *The Structure and Evolution of the Lagoon Nebula. I. Submillimeter Continuum and CO Line Mapping*, [ApJ 580 285](#).
- Treviño-Morales, S. P. et al. (2014), *Deuteration around the ultracompact HII region Monoceros R2*, [A&A 569, A19 A19](#).
- Trofimova, E. A. et al. (2024), *A Survey of High-Mass Star Forming Regions in the Line of Singly Deuterated Ammonia NH₂D*, [Astronomy Reports 68 771](#).
- Turner, B. E. (2001), *Deuterated Molecules in Translucent and Dark Clouds*, [ApJS 136 579](#).
- Urquhart, J. S. et al. (2014), *ATLASGAL - towards a complete sample of massive star forming clumps*, [MNRAS 443 1555](#).
- Urquhart, J. S. et al. (2022), *ATLASGAL - evolutionary trends in high-mass star formation*, [MNRAS 510 3389](#).
- van der Walt, S. J. et al. (2021), *Protostellar Interferometric Line Survey of the Cygnus X region (PILS-Cygnus). First results: Observations of CygX-N30*, [A&A 655, A86 A86](#).
- van Dishoeck, E. F. (2014), *Astrochemistry of dust, ice and gas: introduction and overview*, [Faraday Discussions 168 9](#).
- van Dishoeck, E. F. (2018), “Astrochemistry: overview and challenges”, *Astrochemistry VII: Through the Cosmos from Galaxies to Planets*, ed. by M. Cunningham et al., vol. 332, IAU Symposium 3.
- Walmsley, C. M. and H. Ungerechts (1983), *Ammonia as a molecular cloud thermometer*, [A&A 122 164](#).
- Watanabe, N. and A. Kouchi (2002), *Efficient Formation of Formaldehyde and Methanol by the Addition of Hydrogen Atoms to CO in H₂O-CO Ice at 10 K*, [ApJL 571 L173](#).
- Watson, W. D. (1974), *Ion-Molecule Reactions, Molecule Formation, and Hydrogen-Isotope Exchange in Dense Interstellar Clouds*, [ApJ 188 35](#).

- Wienen, M. et al. (2012), *Ammonia from cold high-mass clumps discovered in the inner Galactic disk by the ATLASGAL survey*, [A&A 544, A146 A146](#).
- Wiesenfeld, L. and A. Faure (2013), *Rotational quenching of H_2CO by molecular hydrogen: cross-sections, rates and pressure broadening*, [MNRAS 432 2573](#).
- Wilson, T. L. and R. Mauersberger (1990), *The internal structure of molecular clouds. I. C1C180, C34S and NH3 maps of the DR 21/W 75S region.*, [A&A 239 305](#).
- Wilson, T. L. et al. (2009), *Tools of Radio Astronomy*.
- Woon, D. E. (2002), *Modeling Gas-Grain Chemistry with Quantum Chemical Cluster Calculations. I. Heterogeneous Hydrogenation of CO and H_2CO on Icy Grain Mantles*, [ApJ 569 541](#).
- Wootten, A. (1987), “Deuterated molecules in interstellar clouds.”, *Astrochemistry*, ed. by M. S. Vardya and S. P. Tarafdar, vol. 120 311.
- Yamagishi, M. et al. (2018), *Nobeyama 45 m Cygnus-X CO Survey. I. Photodissociation of Molecules Revealed by the Unbiased Large-scale CN and $C^{18}O$ Maps*, [ApJS 235, 9 9](#).
- Yamamoto, S. (2017), *Introduction to Astrochemistry: Chemical Evolution from Interstellar Clouds to Star and Planet Formation*.
- Yan, Y. T. et al. (2019), *A Systematic TMRT Observational Study of Galactic $^{12}C/^{13}C$ Ratios from Formaldehyde*, [ApJ 877, 154 154](#).
- Yang, K. et al. (2024), *Molecular Deuterations in Massive Starless Clump Candidates*, [ApJS 270, 35 35](#).
- Zhou, J. W. et al. (2023), *High-resolution APEX/LAsMA ^{12}CO and ^{13}CO (3-2) observation of the G333 giant molecular cloud complex. I. Evidence for gravitational acceleration in hub-filament systems*, [A&A 676, A69 A69](#).
- Zhou, J. W. et al. (2024), *High-resolution APEX/LAsMA ^{12}CO and ^{13}CO (3-2) observation of the G333 giant molecular cloud complex. II. Survival and gravitational collapse of dense gas structures under feedback*, [A&A 682, A128 A128](#).
- Zhou, J. W. et al. (2025), *High-resolution APEX/LAsMA ^{12}CO and ^{13}CO (3-2) observation of the G333 giant molecular cloud complex: III. Decomposition of molecular clouds into multi-scale hub-filament structures*, [A&A 699, A355 A355](#).
- Zinnecker, H. and H. W. Yorke (2007), *Toward Understanding Massive Star Formation*, [ARA&A 45 481](#).

List of Figures

- 1.1 The image of Cygnus-X with different tracers of the same field-of-view. *Top left image:* The *Spitzer* IRAC three-color composite image (Beerer et al., 2010). Red: 8.0 μm ; green: 4.5 μm ; blue: 3.6 μm . *Top right image:* 5.8 GHz GLOSTAR combination (Very Large Array D-configuration and Effelsberg; Brunthaler et al., 2021) with the zero-level intensities restored using the Urumqi 4.8 GHz continuum data (Dokara et al., 2023). *Bottom left:* The H_2 column density (HOBYS program; Motte et al., 2010; Bonne et al., 2023). *Bottom right:* mm-continuum image (IRAM 30-m telescope using MAMBO and MAMBO-2 cameras; Motte et al., 2007). 2
- 1.2 Schematic evolutionary sequence of high-mass star formation, adopted from Tigé et al. (2017), adapted by Motte et al. (2018). (1) Massive filaments and spherical clumps are hosts for massive dense cores, where high-mass stars are formed. (2) During the starless phase, the massive dense cores only harbor low-mass prestellar cores. (3) The IR-quiet massive dense cores become protostellar hosting a stellar embryo of low-mass, and as the protostellar cores collapse, the surrounding massive dense cores and filaments/spherical clumps also collapse. (4) High-mass protostars are formed as the protostellar envelopes are accreted in gravitationally driven inflows. (5) High-mass protostars become IR-bright for stellar embryos of $> 8 M_{\odot}$. (6) The accretion of the material stops when the UV of the star ionizes the protostellar envelope and an H II region develops. 5
- 1.3 Simplified image of the low- and high-mass stellar life cycle. All stars are formed in dense molecular clouds (“Star-forming nebula”), but their evolution differ. The low-mass star (“Sun-like star”) is in a steady state of hydrogen-to-helium fusion for several billion years. As the star exhaust the hydrogen in its core, the low-mass star evolves to a “Red giant”, where it increases in size and loses its mass through stellar winds. As the low-mass star cools down, it leaves its hot core (“White dwarf”), heating up and exciting the surrounding gas and dust (“Planetary nebula”). This gas and dust will later become part of a molecular clouds, forming the next generation of stars. The high-mass star has a much shorter lifetime (millions of years), where it ends its life as a “Supernova”. Depending on the initial mass of the star, the remnant is either a “Neutron star” (lower mass massive stars) or “Black hole” (higher mass massive stars). Image made by Ivalu Barlach Christensen. 8

1.4	The DR21 filament adopted from Bonne et al. (2023). <i>Top left</i> : integrated brightness map of ^{13}CO (1–0) toward the DR21 cloud. Overlaid on the map are the integrated intensity contours starting at 2 K km s^{-1} with increments of 10 K km s^{-1} . The subfilaments in the cloud are indicated with their names. <i>Top right</i> : same as the top left panel, but for HCO^+ (1–0) with increments of 5 K km s^{-1} . <i>Bottom left</i> : same as the top left panel, but for C^{18}O (1–0), with contour increments of 2 K km s^{-1} . <i>Bottom right</i> : same as the top left panel, but for H^{13}CO^+ (1–0), with contour increments of 2 K km s^{-1} . The locations of the DR21 radio continuum source (Downes and Rinehart, 1966) and the DR21(OH) and DR21–N massive clumps (e.g., Motte et al., 2007) are indicated with black triangles.	12
1.5	Periodic table of atoms, color-coded relevant to their nucleosynthesis sources, adopted from Johnson (2019). Black, purple, green, blue, orange, and yellow show the naturally occurring elements of our Solar System from Big Bang fusion, CR fission, exploding massive stars, exploding white dwarfs, merging neutron stars, dying low-mass stars, respectively. Gray show artificially made elements.	13
1.6	The Milky Way in optical (top) and radio wavelength (bottom).	14
2.1	Sketch of the 2-dimensional power pattern of an antenna. The width at half-power beam of the main lobe denotes the angular resolution of the telescopes.	18
2.2	The APEX telescope at Llano de Chajñator, Chile.	20
2.3	The IRAM 30-m telescopes close to Pico Veleta, Spanish Sierra Nevada.	21
2.4	The NOEMA telescope array at Plateau de Bure. Photo credit: IRAM/André, R.	21
2.5	The Green Bank Telescope in West Virginia. Photo credit: Jay Young.	22
2.6	The coverage of CASCADE towards Cygnus-X. The maps show the integrated intensity of HCO^+ . Credits to Dr. Friedrich Wyrowski.	24
2.7	The coverage of the follow-up observations towards the DR21 filament (tiles marked in red). The background emission shows the integrated intensity of $\text{DCO}^+ J = 1 - 0$	25
2.8	The Cygnus-X clumps on the <i>Herschel</i> $250 \mu\text{m}$ map. The clumps are colored based on the source velocity components, with multiple colors indicating more velocity components. The scalebar shows 0.5 pc at a distance of 1.5 kpc	26
2.9	Radio continuum image of the GLOSTAR pilot region, adopted from Brunthaler et al. (2021). The continuum image is a combination of VLA D-configuration and Effelsberg 100-m telescope observations.	26
2.10	The M8 region with the line-of-sight velocities of the clumps. The background shows the grey-scale of the $870 \mu\text{m}$ dust continuum flux. This image is adopted from Kahle et al. (2024).	27
3.1	Processes of emission and absorption in atoms and molecules.	32
3.2	Sketch of light traveling through a medium s . A dust particle partially absorbs the light I traveling through the medium, and a molecular line is emitted.	32
3.3	The rich spectrum $0.5''$ offset from the continuum peak of low-mass star-forming region IRAS 16293-2422B by Jørgensen et al. (2016).	37
3.4	Chemical network in the gas phase leading to atomic deuterium formation, adopted by Taquet et al. (2012). The atomic deuterium is marked in red “D”.	40

3.5	Chemical network of the successive hydrogenation forming H_2CO and CH_3OH on dust grain mantles, adopted by Taquet et al. (2012). Solid, dashed, and open arrows indicate addition, abstraction, and substitution reactions, respectively. Black arrows denote reactions involving hydrogen, while gray arrows represent reactions involving deuterium. Bold values show rates relative to the $\text{H} + \text{CO}$ reaction, and non-bold values indicate deduced relative rates by analogy with similar reactions.	43
4.1	Degrees of deuteration, $R(\text{DCO}^+)$ (left column), $R(\text{DNC})$ (middle column), and $R(\text{DCN})$ (right column), with dust temperature (top row) and H_2 column densities (middle row) (Bonne et al., 2023) and kinetic gas temperature (bottom row) in the DR21 filament. Each point corresponds to the pixel-wise deuteration derived from the $J = 1 - 0$ and $J = 2 - 1$ or $J = 3 - 2$ transitions of DCO^+ , DNC , and DCN where each of the species were detected at an rms noise level $\geq 4\sigma_{\text{tot}}$. The black line shows the running mean, while the purple range marks the standard deviation. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.	47
4.2	$R(\text{DCO}^+)$ with column density, where in gray are all the pixels measured in DR21, purple is $R(\text{DCO}^+)$ where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ was measured, orange is where $X(\text{SiO})$ was measured, and green is where $N(\text{HCO})/N(\text{H}^{13}\text{CO}^+)$ and $X(\text{SiO})$ intersect. The linear fit, where SiO and HCO are detected, is shown in dashed brown. The red and blue stars mark the surroundings of DR21 Main and DR21(OH), respectively.	48
4.3	Dust temperature as a function of integrated intensity ratio of DCN and DNC with a Pearson correlation of $r = 0.58$	49
5.1	Locations of clumps in Cygnus-X (top), the GLOSTAR pilot region (bottom left), and M8 (bottom right).	53
5.2	Difference between the gas kinetic temperature of sources in Cygnus-X (purple), the GLOSTAR pilot region (orange), and M8 (blue) using pyradex+emcee compared with the LTE gas kinetic temperature function presented in Tang et al., 2018. The green dashed line marks $n(\text{H}_2) = 10^{5.5} \text{ cm}^{-3}$	54
5.3	Comparison of volume densities in Cygnus-X (purple) and M8 (blue) obtained with pyradex+emcee and the 1.2-mm continuum emission by Motte et al., 2007 for Cygnus-X and Tothill et al., 2002 for M8. The grey dashed line shows $x = y$	55
5.4	Distribution of (left to right) the H_2 volume density, gas kinetic temperature, dust temperature, and H_2CO fractional abundance with evolutionary phases of our sample. The horizontal lines within the distribution mark the mean of our sub-sample, grey distributions in the H_2 volume density and dust temperature show the mean of the ATLASGAL sample by Urquhart et al., 2022.	56
6.1	Cumulative distribution function (CDF) of S-bearing (magenta), C-bearing (blue), O-bearing (green), D-bearing (orange), and N-bearing (red) in Cygnus-X clumps. The horizontal dashed lines mark the mean column densities.	61
6.2	Distribution of the modeled evolutionary phases of the clumps in Cygnus-X.	65
6.3	Distribution of model parameters across the evolutionary phases.	65

6.4	Rate of success (green) and fail (red) in reproducing the observed molecular column densities with the MUSCLE modeling. The number on top denotes the total number of clumps of which the molecule was detected.	66
6.5	Spatial distribution of the chemical age in clumps. On the left is the entire Cygnus-X region, with the red outlining the CASCADE coverage. On the right is the DR21 filament.	67
6.6	Relative detection rates of all 25 molecules in clumps in HMPO, HMC, and UCH _{II} evolutionary phase.	69
6.7	Heatmap table of the deuterated molecules in the regions covered with CASCADE with the total number of clumps in each regions shown in left. The parenthesis denotes the number of clumps the deuterated fraction was measured in, and the right y-axis denoted the total number of clumps in the region.	70
6.8	Spread of deuterated fraction in the evolutionary phases modeled with MUSCLE. The number of clumps of which the deuterated fraction is measured is written below each range. The grey boxes in $R(\text{DNC})$, $R(\text{DCN})$, $R(\text{DCO}^+)$, and $R(\text{N}_2\text{D}^+)$ are the deuterated fractions from Gerner et al. (2015).	72
B.1	Spectra of $^{13}\text{CS } J = 2 - 1$ towards the Cygnus-X sources. The green background indicated detection ($> 4\sigma$) and white background indicates no detection.	106
B.2	Same as Fig. B.1 for $\text{C}_2\text{D } N = 1 - 0$, $J = 3/2 - 1/2$, $F = 5/2 - 3/2^*$ towards the Cygnus-X sources.	107
B.3	Same as Fig. B.1 for $\text{C}_2\text{D } N = 1 - 0$, $J = 1/2 - 1/2$, $F = 3/2 - 3/2^*$ towards the Cygnus-X sources.	108
B.4	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 3/2 - 1/2$, $F = 1 - 1^*$ towards the Cygnus-X sources.	109
B.5	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 3/2 - 1/2$, $F = 2 - 1^*$ towards the Cygnus-X sources.	110
B.6	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 3/2 - 1/2$, $F = 1 - 0^*$ towards the Cygnus-X sources.	111
B.7	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 1/2 - 1/2$, $F = 1 - 1^*$ towards the Cygnus-X sources.	112
B.8	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 1/2 - 1/2$, $F = 0 - 1^*$ towards the Cygnus-X sources.	113
B.9	Same as Fig. B.1 for $\text{C}_2\text{H } N = 1 - 0$, $J = 1/2 - 1/2$, $F = 1 - 0^*$ towards the Cygnus-X sources.	114
B.10	Same as Fig. B.1 for $\text{C}_2\text{S } N = 6 - 5$, $J = 5 - 4$ towards the Cygnus-X sources.	115
B.11	Same as Fig. B.1 for $\text{C}_2\text{S } N = 11 - 10$, $J = 10 - 10$ towards the Cygnus-X sources.	116
B.12	Same as Fig. B.1 for $\text{CH}_3\text{CN } J = 4(1) - 3(1)$ towards the Cygnus-X sources.	117
B.13	Same as Fig. B.1 for $\text{CH}_3\text{CN } J = 4(0) - 3(0)$ towards the Cygnus-X sources.	118
B.14	Same as Fig. B.1 for $\text{CH}_3\text{CN } J = 5(0) - 4(0)$ towards the Cygnus-X sources.	119
B.15	Same as Fig. B.1 for $\text{DCN } J = 1 - 0$ towards the Cygnus-X sources.	120
B.16	Same as Fig. B.1 for $\text{DCO}^+ J = 1 - 0$, $F = 1 - 1$ towards the Cygnus-X sources.	121
B.17	Same as Fig. B.1 for $\text{DNC } J = 1 - 0$ towards the Cygnus-X sources.	122
B.18	Same as Fig. B.1 for $\text{H}^{13}\text{CN } J = 1 - 0$ towards the Cygnus-X sources.	123
B.19	Same as Fig. B.1 for $\text{H}^{13}\text{CO}^+ J = 1 - 0$ towards the Cygnus-X sources.	124

B.20	Same as Fig. B.1 for $\text{HC}_5\text{N } J = 27 - 26$ towards the Cygnus-X sources.	125
B.21	Same as Fig. B.1 for $\text{HC}^{13}\text{CCN } J = 8 - 7, F = 8 - 7$ towards the Cygnus-X sources.	126
B.22	Same as Fig. B.1 for $\text{HCO } 1(0, 1) - 0(0, 0), J = 3/2 - 1/2, F = 2 - 1^*$ towards the Cygnus-X sources.	127
B.23	Same as Fig. B.1 for $\text{HCO } 1(0, 1) - 0(0, 0), J = 3/2 - 1/2, F = 1 - 0^*$ towards the Cygnus-X sources.	128
B.24	Same as Fig. B.1 for $\text{HCO } 1(0, 1) - 0(0, 0), J = 1/2 - 1/2, F = 1 - 1^*$ towards the Cygnus-X sources.	129
B.25	Same as Fig. B.1 for $\text{HCOOH } J = 4(1, 4) - 3(1, 3)$ towards the Cygnus-X sources.	130
B.26	Same as Fig. B.1 for $\text{HN}^{13}\text{C } J = 1 - 0$ towards the Cygnus-X sources.	131
B.27	Same as Fig. B.1 for $\text{HNCO } J = 4(0, 4) - 3(0, 3)$ towards the Cygnus-X sources.	132
B.28	Same as Fig. B.1 for $\text{NH}_2\text{D } 1(1, 1)0_s - 1(0, 1)0_a$ towards the Cygnus-X sources.	133
B.29	Same as Fig. B.1 for $\text{N}_2\text{H}^+ J = 1 - 0$ towards the Cygnus-X sources.	134
B.30	Same as Fig. B.1 for $\text{N}_2\text{D}^+ J = 1 - 0$ towards the Cygnus-X sources.	135
B.31	Same as Fig. B.1 for $\text{OCS } J = 6 - 5$ towards the Cygnus-X sources.	136
B.32	Same as Fig. B.1 for $\text{SiO } J = 2 - 1, v = 0 - 0$ towards the Cygnus-X sources.	137
B.33	Same as Fig. B.1 for $\text{SO } J = 2(2) - 1(1)$ towards the Cygnus-X sources.	138
B.34	Same as Fig. B.1 for $\text{SO}_2 J = 6(0, 6) - 5(1, 5)$ towards the Cygnus-X sources.	139
B.35	Same as Fig. B.1 for $\text{DCO}^+ J = 3 - 2, F = 3 - 2$ towards the DR21 sources.	140
B.36	Same as Fig. B.1 for $\text{DCN } J = 3 - 2$ towards the DR21 sources.	140
B.37	Same as Fig. B.1 for $\text{DNC } J = 2 - 1$ towards the DR21 sources.	141
B.38	Same as Fig. B.1 for $\text{N}_2\text{D}^+ J = 2 - 1$ towards the DR21 sources.	141
B.39	Same as Fig. B.1 for $\text{N}_2\text{D}^+ J = 3 - 2$ towards the DR21 sources.	142
D.1	Spectra of $\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})$ towards the Cygnus-X sources. The green background indicated detection ($> 4\sigma$) and white background indicates no detection.	196
D.2	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ towards the Cygnus-X sources.	197
D.3	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,2} - 2_{2,1})$ towards the Cygnus-X sources.	198
D.4	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ towards the Cygnus-X sources.	199
D.5	Same as Fig. D.1 for $\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})$ towards the GLOSTAR sources.	200
D.6	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ towards the GLOSTAR sources.	200
D.7	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,2} - 2_{2,1})$ towards the GLOSTAR sources.	200
D.8	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ towards the GLOSTAR sources.	201
D.9	Same as Fig. D.1 for $\text{H}_2\text{CO } (1_{0,1} - 0_{0,0})$ towards the M8 sources. Red indicates no observed spectrum.	201
D.10	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{0,3} - 2_{0,2})$ towards the M8 sources.	202
D.11	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,2} - 2_{2,1})$ towards the M8 sources.	203
D.12	Same as Fig. D.1 for $\text{H}_2\text{CO } (3_{2,1} - 2_{2,0})$ towards the M8 sources.	204
E.1	Histogram of the density power-law index p of the CASCADE clumps (this work, blue) in comparison with the clumps of the CORE sample (Beuther et al., 2024, green).	214

E.2	Continuum maps of the Cygnus-X clumps covered by CASCADE. In color and white contours the GBT/MUSTANG2 3 mm continuum emission is shown (contour steps $-5, 5, 10, 20, 40, \dots \times \sigma_{\text{cont}}$). In the center of each panel, the position of the clump is shown. A clump with a clear detection in the 3 mm data is highlighted in red, whereas clumps that show now clear clump sturcture or are not detected are highlighted in lightgrey. The position of the clumps are marked by a dot, whereas the peak position in the 3 mm data is shown by a star. Nearby clumps are marked in dark grey. The fit radii of the radial intensity profiles are indicated by circles. In the bottom left corner the beam size is shown and a linear bar in the top left corner indicates a spatial scale of 0.5 pc.	215
E.3	continued.	216
E.4	continued.	217
E.5	continued.	218
E.6	continued.	219
E.7	continued.	220
E.8	Radial intensity profiles of the Cygnus-X clumps covered by CASCADE. The 3 mm radial intensity profile up to 0.8 pc is shown by the grey data points, whereas data points included in the fit are highlighted in black. The fit and uncertainties are shown by the red solid and dashed lines, respectively. The slope m and corresponding density power-law index p are shown in each panel.	221
E.9	continued.	222
E.10	continued.	223
E.11	continued.	224

List of Tables

1.1	Physical properties of the ISM, adopted from Table 1.3 in Draine (2011).	4
1.2	Physical properties of the HMSF, adopted from Motte et al. (2018); Table 1.	9
2.1	Overview of surveys used in this thesis.	22
2.2	H ₂ CO transitions observed with the IRAM 30-m and the APEX 12-m telescopes. . .	29
2.3	Parameters of the IRAM and APEX observations.	29
3.1	Gas-phase bond formation, destruction, and rearrangement.	38
6.1	Frequencies and spectroscopic properties of the transitions used to determine the column densities and utilized for the chemical modeling.	59
6.2	MUSCLE input parameters, table adopted from Gieser et al. (2021).	64
6.3	Number of clumps' evolutionary phase classified with SED or the MUSCLE model. .	68
B.1	Central position of clumps in Cygnus-X adopted from Motte et al. (2007) and Cao et al. (2019). and the corresponding integrated line intensities and linewidths measured of this work.	143
B.2	Continued.	144
B.3	Continued.	145
B.4	Continued.	146
B.5	Continued.	147
B.6	Continued.	148
B.7	Continued.	149
B.8	Continued.	150
B.9	Continued.	151
B.10	Continued.	152
B.11	Continued.	153
B.12	Continued.	154
B.13	Continued.	155
B.14	Continued.	156
B.15	Continued.	157
B.16	Continued.	158
B.17	Continued.	159
B.18	Continued.	160
B.19	Continued.	161

List of Tables

B.20 Continued.	162
B.21 Continued.	163
B.22 Continued.	164
B.23 Continued.	165
B.24 Continued.	166
B.25 Continued.	167
B.26 Continued.	168
B.27 Continued.	169
E.1 Beam-averaged column densities of C_2D , C_2H , C_2S , CH_3CN , CS and DCN towards clumps in Cygnus-X.	205
E.2 Same as Table E.1 for DCO^+ , DNC , H_2CO , HC_3N , HC_5N and HCN	207
E.3 Same as Table E.1 for HCO , HCO^+ , $HCOOH$, HNC , $HNCO$ and N_2D^+	209
E.4 Same as Table E.1 for N_2H^+ , NH_2D , OCS , SiO , SO_2 and SO	210
E.5 Parameters obtained with the MUSCLE in Cygnus-X clumps.	225
E.6 Continued from previous page.	226

Acknowledgements

As I approach the final stages of my PhD, I find myself reflecting on the path that has led me here, and on the many people whose support and mentorship have been invaluable along the way.

First, I would like to thank Dr. Nimesh Patel, who first introduced me to the world of radio astronomy and sparked my curiosity about the chemistry of space, and in particular, in star-forming regions. I'm deeply grateful for his encouragement, guidance, and for the trust he placed in me to work independently during the early stages of my research journey.

I would also like to thank Dr. Friedrich Wyrowski and Prof. Karl M. Menten for giving me the opportunity to work in this exciting field. Thank you to Prof. Serena Viti for taking over as my main supervisor in the last year.

This thesis would not be possible without the support of my friends and family. From the day I began my bachelor's degree in physics, I have been profoundly grateful to have had my best friend's, Jane Lund Plesner, support and encouragement at every stage of my academic journey. Although the path has not always been easy, her confidence in me and unwavering support have been a constant source of strength and motivation. To Tukummeq Olsen (Kristensen), thank you for reminding me not to take everything too seriously and for always finding humor in my mistakes. Your presence has given me a space to unwind, laugh, and truly be myself, providing balance and lightness throughout this journey. To my parents, I extend my deepest gratitude for instilling in me the belief that the sky is the limit and that I can achieve whatever I set my mind to. Your unwavering faith in me has given me the confidence to pursue my own path and to explore the world with curiosity and determination.

I am deeply grateful to Dr. Manali Jeste, not only for her friendship but also for helping me stay grounded throughout this journey. Thank you for reading my drafts, assisting with seemingly endless paperwork, and reminding me that my emotions and struggles are an inherent part of the PhD experience. Lastly, thank you for the many shared laughs, and for granting me a (well-deserved) citation for my sense of humor. To the friends I made throughout my PhD in the sub-mm group: Sarwar, Anahat, Hans, Rohit, Dat, and Sree. Thank you for making my time at the MPIfR truly memorable. From shared lunches and dinners to spirited discussions about reality TV and other wonderfully questionable topics, your company brought energy and laughter to everyday life. I am especially grateful for indulging my enthusiasm for the latest celebrity gossip.

Lastly, I would like to express my gratitude to the people from my home, Greenland. Your support and encouragement have meant the world to me, and I have truly felt as though I had my own team of cheerleaders celebrating each step of this journey.

I would also like to acknowledge the AI tool, perplexity, for improving the language and grammar of this thesis.