

Understanding the early stages of star formation in Perseus using CS and N_2H^+ tracers

Sebastien GUILLOT

September 17, 2006

Harvard-Smithsonian Center For Astrophysics
Work Term supervisors: Pr. Paola Caselli, Pr. Alyssa Goodman

Physics COOP workterm # 4. Summer 2006
In partial fulfillment of the requirement of the Physics COOP Program

Abstract

We present in this report the spectroscopic study of two molecules in the Perseus molecular cloud. As part of the COMPLETE project for star-forming regions, radio observations of CS and N_2H^+ were performed on pre-selected potential proto-stellar cores. The data, from the FCRAO 14m-telescope, have been reduced in order to be properly analyzed. Unlike optical images, the reduction of spectroscopic data is quite simple and only includes a baseline deletion. One also mapped out the data in order to visualize the distribution of the chemicals throughout the cloud. The following part of the analysis corresponded to the calculation of the column density from the fitting of the spectra. However, fitting the spectra is not a simple process and it required several trials before figuring out the proper method (especially for N_2H^+).

Contents

1	Introduction	5
2	Theory	5
2.1	Star Formation	5
2.2	Astrochemistry of Star-Forming regions	7
2.2.1	Generality about dense cores	7
2.2.2	Typical structure of a dense core	7
2.2.3	The Carbon-Sulfure molecule, CS	8
2.2.4	The diazenylium molecule, N_2H^+	8
2.2.5	Other Lines	8
2.3	The Doppler effect and spectroscopic lines	8
3	Data collection	10
3.1	Observation	10
3.2	Quality of the Data	11
4	Data Reduction	12
5	Mapping the Perseus regions	14
5.1	Footprints Maps	14
5.2	Channel Maps	16
6	Spectral line Analysis	18
6.1	Molecular line fitting	18
6.1.1	Fitting the CS line	18
6.1.2	Fitting the N_2H^+ line	19
6.1.3	Obtaining the column density	20
6.2	Results	21
7	Conclusion	21
8	Acknowledgements	22
9	References	22

List of Figures

1	Bipolar flows from few protostellar cores in L1448	6
2	Protostellar infall and spectroscopic data	9
3	Footprints observed in Perseus	10
4	Comparison between FCRAO and IRAM data	11
5	Baseline reduction with CLASS	13
6	Absorption spectrum	14
7	CS and N ₂ H ⁺ map of L1448	15
8	Channel map bands	16
9	CS channel map of PSC02	17
10	CS line fit	18
11	N ₂ H ⁺ line fit	20

1 Introduction

Scientists know how stars burn and evolve but it is, however, still quite obscure how they form. Many studies have been conducted to explore giant molecular clouds in which star forms. The most popular way of investigating those giant clumps of gases and dust is the spectroscopic analysis of the molecules present in the clouds. The COMPLETE (COordinated Molecular Probe Line Extinction Thermal Emission) survey for Star-Forming regions was created in 2001. Three targets were chosen among the numerous molecular clouds in the sky: Perseus, Ophiuchus and Serpens. During the first two years, an overall observation phase was performed in order to localize small areas with probable stars in formation. The second phase consisted in the high-resolution observation of the targets detected during the first phase. Several radio telescopes were used to observe these regions. The first section will briefly describe the theory of star formation, of the chemistry of molecular clouds and the basics of the theory of spectroscopic studies. Thereafter, the data collection and the data reduction will be detailed. Then, it will be explained how the regions observed in Perseus were mapped with the molecule used. Finally, the spectral analysis procedure is going to be examined.

2 Theory

This section will shortly described the processes involved in star formation and will give some inputs on the chemistry observed in molecular clouds.

2.1 Star Formation

In our galaxy, stars tend to form in well-defined regions. It has been discovered that Giant Molecular Clouds, composed of coalesced gaseous material, are the birth places of stars. These stellar nurseries are numerous throughout the galactic disks and many

of them are studied carefully like the Orion Nebula, the Ophiuchus molecular cloud and the Perseus molecular cloud which will be of interest here.

Within the deepest parts of a Giant molecular cloud, the density is high enough to engender new stars from the self-gravity of the cloud. Each forming star lies within a dense core called *protostellar* or *starless* core which is itself surrounded by slightly lower-density structures. Protostellar cores are confined within a disk, and altogether, they often produce an impressive bipolar flow of matter perpendicular to the disk like in figure (1).

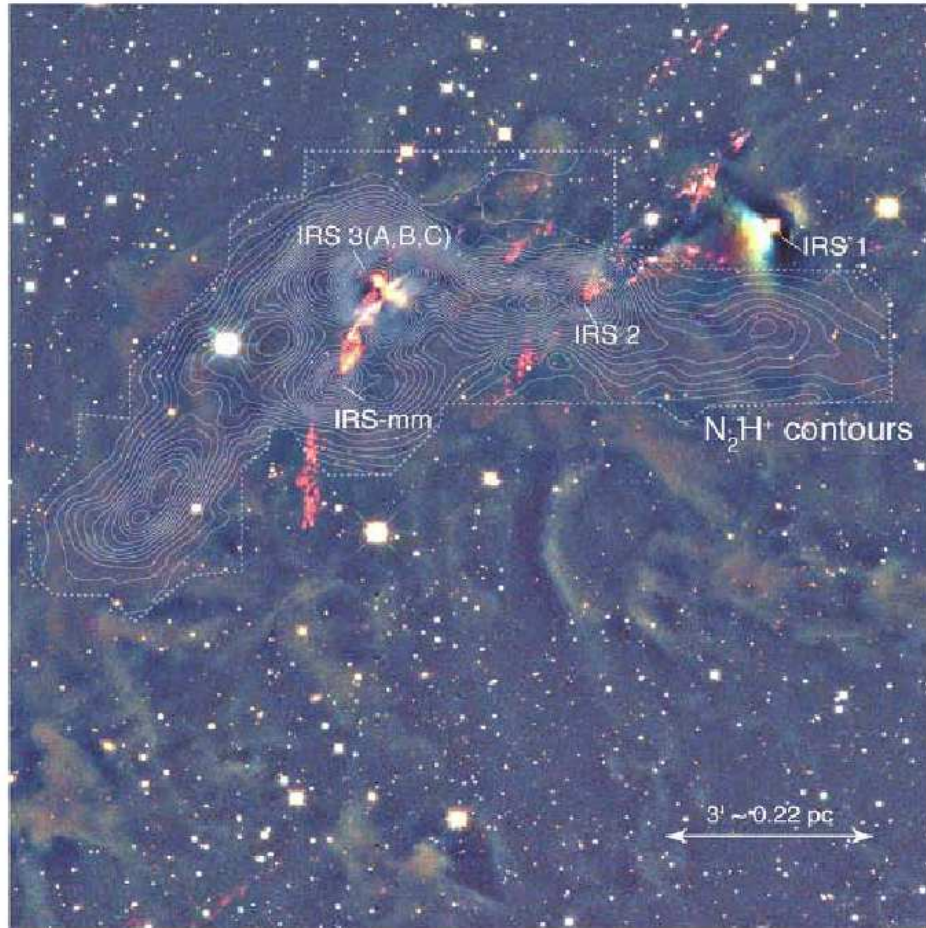


Figure 1: In cloud L1448, the collimated bipolar flows (red/yellow filaments) are expelled by the starless cores (IRS). (Foster and Goodman, 2006)

2.2 Astrochemistry of Star-Forming regions

2.2.1 Generality about dense cores

Probing the protostellar cores in molecular clouds requires some knowledge of the chemistry involved. The core is composed of dust and gases of low temperature ($\sim 10\text{K}$) but fairly high densities ($\sim 10^5 \text{ cm}^{-3}$). These conditions are very favorable to the accretion of gaseous species onto dust grains (P. Caselli, astro-ph/0504298 v1). Regarding time scales comparison, the freezing-out time scale is smaller than the free fall time: 10^4 years compared to 10^5 . Therefore, the gas phase is very likely to freeze onto dust grains during the evolution of the starless core. Consequently, this is a very useful tool to detect protostellar core since a strong localized depletion in a gas species observed would imply the presence of a starless core. Indeed, this feature has been confirmed by observations in molecular cloud cores (Caselli et al. 1999, Tafalla et al. 2004)

2.2.2 Typical structure of a dense core

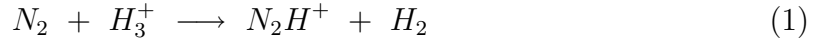
Protostellar cores are likely to be very unstable. In other words, they are in the state preceding the star formation. Consequently, understanding the initial conditions of star formation requires the understanding of the chemistry involved in these pre-stellar cores. Their molecular structures are thought to be differentiated. At outer radii (7,000 to 15,000 AU), CO and CS are mainly in the gas phase and HCO^+ is the main molecular ion. At smaller radii (2,000 to 7,000 AU), the density is about 10^5 cm^{-3} and therefore CO and CS are likely to be condensed onto dusts. This is where the depletion in CO and CS is observed. However, N_2H^+ and NH_3 , being lighter, still exist in the gas phase. Hence, N_2H^+ is a good tracer of the inner regions of the core. Finally, below 2,500 AU at densities around 10^6 cm^{-3} , molecules heavier than He are froze out onto dust grains leaving out H^+ , H_2D^+ (the best tracer of the inner core) and other light molecular ions.

2.2.3 The Carbon-Sulfure molecule, CS

As said before, the CS line traces the outer shell of the dense core since at higher densities, this molecule freezes-out on dusts. It is a single emission line which frequency is 97980.9533 MHz. It is fairly easy to detect and analyze and the data obtained are generally good.

2.2.4 The diazenylium molecule, N_2H^+

The N_2H^+ molecule, present in starless cores is formed by the following chemical reaction:



The N_2H^+ transition $J = 1 \rightarrow 0$ of interest for molecular clouds has seven hyperfine components due to interactions between the molecular electric field gradient and the electric quadrupole moment of the two nitrogen nuclei. The seven emission lines have frequencies ranging between 93176 and 93178 MHz. N_2H^+ is generally observable deeper in the cloud than CS.

2.2.5 Other Lines

Other molecules are also generally used for the study of molecular clouds. The $C_{16}O$ line, a 2.6 mm line, is always optically thick in giant molecular clouds and therefore, it emanates from surface layers but it is quite frequently used. N_2D^+ is also a good tracer, often used for inner dense regions of molecular clouds.

2.3 The Doppler effect and spectroscopic lines

When observing a molecular cloud in the radio part of the light spectrum, one is dealing with spectral lines. A lot of information can be deduced from the intensity and shape of these molecular lines. First of all, a shift of the whole line away from the laboratory line frequency (reference for the zero velocity) indicates if the cloud is

moving toward or away from the observer. On many of the spectra studied here, the line is right shifted from the zero velocity. If the line is shifted to higher velocity (to the right of the rest velocity), the cloud is moving away from the Earth since a higher velocity means a lower frequencies (eq. (2)) and therefore this corresponds to a redshift.

$$v_r = \frac{c(\nu_0 - \nu)}{\nu_0} \quad (2)$$

Here, v_r is the radial velocity and ν_0 is the reference (laboratory) frequency of the line. So, the argument corresponds to $v_r > 0$ which implies $\nu < \nu_0$.

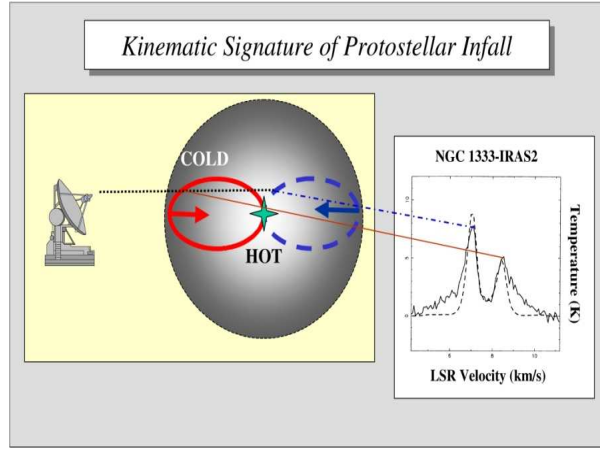


Figure 2: This diagram shows an infalling cloud and the corresponding line asymmetry observed.

In addition to that, the Doppler effect may also be used to figure out internal motion to the cloud like contraction or extension. Indeed, this will affect the shape of the emission line by broadening it. The back of the cloud will be blue-shifted while the front end will be red-shifted causing the broadening. Moreover, the line might be separated into two components creating what is called a line asymmetry. For a perfectly transparent cloud, the line would only be broadened but with a somewhat opaque gas, the light from the far side is blocked by the hot gas as it comes toward the observer causing a drop in the intensity (figure (2)). This kind of feature is therefore important to understand the dynamics in place within the molecular cloud observed.

3 Data collection

3.1 Observation

The data set used here comes from the FCRAO 14m telescope (Amherst, MA, USA). It is composed of 35 square regions (also called footprints) of 10 arcmin or 16 arcmin. 10 of these regions are called 'PSC' which stands for 'Perseus Starless Core'. 20 regions are labeled 'TAR' used for 'Target'. The last 5 regions are adjacent and cover the whole NGC1333 cloud. All of them have been observed within the CS and N_2H^+ lines frequency range. The figure (3) shows the whole perseus cloud with the observed footprints. As seen on this figure, some of the regions overlap and therefore the same characteristics should be observed.

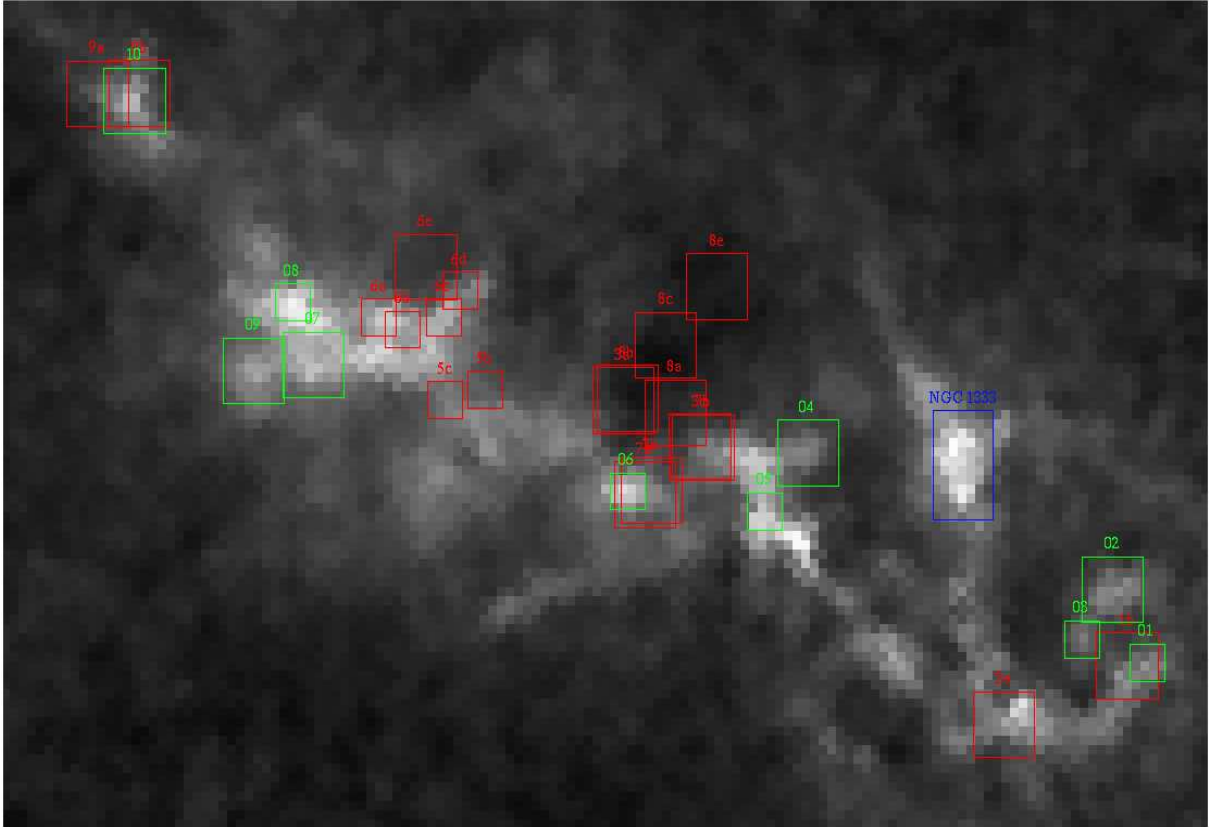


Figure 3: The Perseus molecular cloud and the regions observed. In green, the PSC regions. In red, the TAR regions. In blue, NGC1333

3.2 Quality of the Data

A good way to check the validity of the data set is to compare it with data of the same region from another telescope. Fortunately, the region L1448 (PSC02) and two other regions have been observed with the 30m telescope at the IRAM observatory (Pico Veleta, Spain). Spectra of the same position from the two telescopes should be similar in shape and intensity. However, since the beam efficiencies of the FCRAO telescope and the IRAM telescope differ, the data cannot be simply compared. The beam efficiency of the FCRAO is 50 arcsec while the one of the 30m telescope is 27 arcsec. This problem can be solved by convolving the IRAM data to 50 arcsec. After these modifications, the spectra from the two different telescopes actually match almost perfectly (figure (4)). This validity check has been done for the 3 available IRAM footprints at the intensity peaks and also for the average spectrum of the available regions.

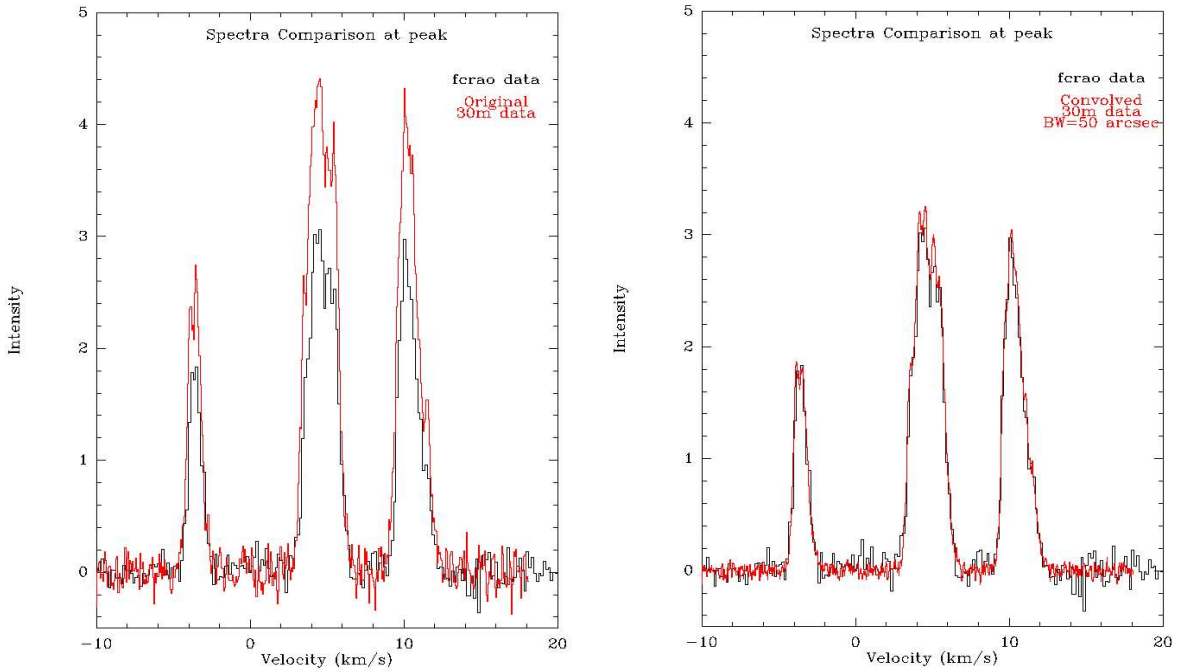


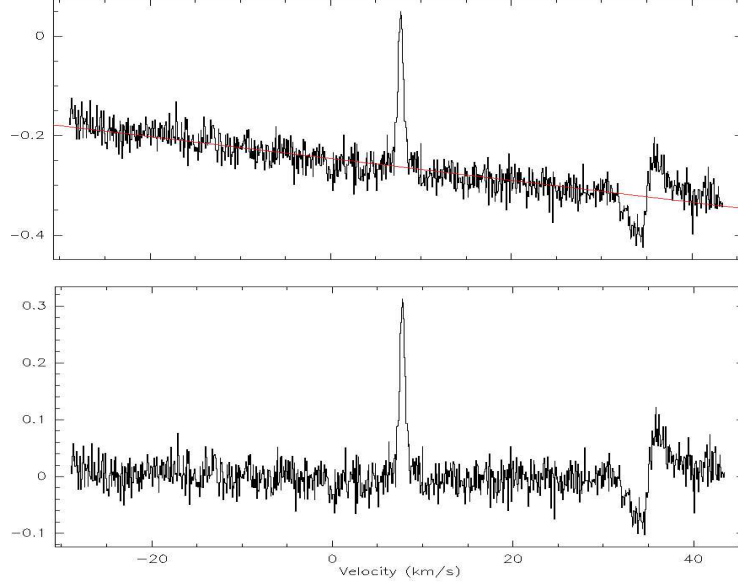
Figure 4: The graph on the left shows the comparison before the IRAM data has been convolved. The graph on the right shows that the two spectra match (here, at the peak). In red, the spectrum from the IRAM telescope and in black, the spectrum from the FCRAO.

4 Data Reduction

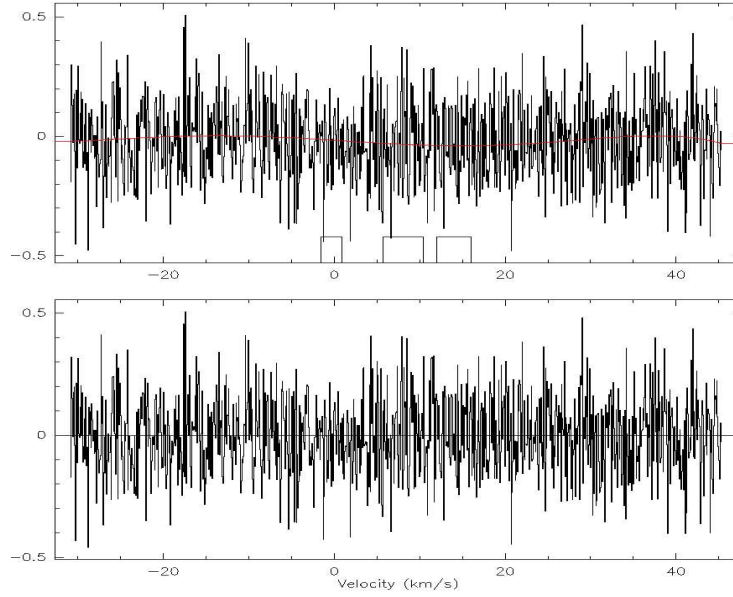
Having raw data always required some reduction to improve the quality and diminish the noise level. Spectroscopic observations often contain some artificial distortions on the baseline. In few words, the baseline is the zero level of the spectra. Therefore, a distorted baseline modifies the real spectrum and has to be removed. It can be either a straight line or a higher degree polynomial. CLASS has a simple command that subtract the baseline from the plot: *base x* where *x* is the degree of the polynomial. However, a window containing the emission lines(s) has to be defined preliminarily in order to avoid *base x* to include the line(s) in the polynomial fitting. In addition to that, this window is also used by CLASS to determine the integrated intensity. In order to select the window, the average spectrum is utilized to determine the velocity range of the emission line(s). The integrated intensity is simply the integrated area under the spectral line between the boundaries delimited by the window. It is used to map out the intensity of an emission line since, for each position in the footprint, the integrated intensity indicates how much of the molecule is present.

For the CS data, a straight line fitting has been used to remove the baseline. Concerning N_2H^+ , a degree 5 polynomial usually better suits the baseline. Then, while the window for CS was simple (since CS has a single emission line), for N_2H^+ , the window was composed of 3 separated parts since all the hyperfine component are not grouped together. The effect of the baseline removal can be seen on figures (5a) and (5b).

For some of the regions, an absorption line appears instead of the usual emission line. This is due to some problems during the observation. Unfortunately, these regions are useless until a proper solution is found (figure (6)).



(a)



(b)

Figure 5: (a) Baseline reduction of a CS spectral line. Top: before the baseline removal. The baseline is the straight inclined red line. Bottom: after the baseline removal. (b) Baseline reduction of a N_2H^+ spectral line. Top: Before the baseline removal. The baseline is the degree 5 polynomial. Bottom: After the baseline removal. The 3 boxes show the 3 windows containing the hyperfine components. Note: a noisy spectrum has been used here, i.e. no emission lines are visible.

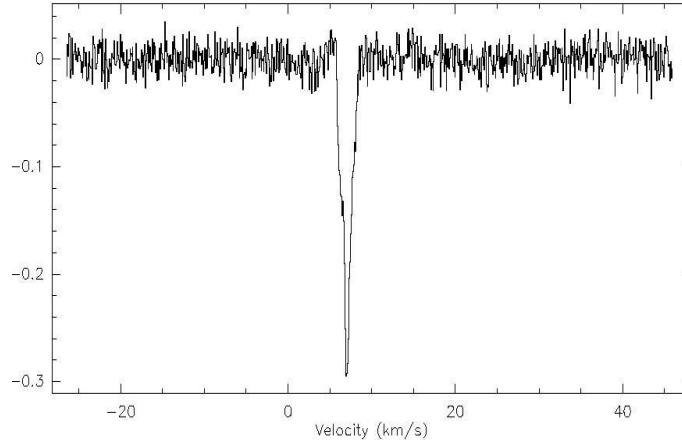


Figure 6: This kind of spectrum is useless since one expects an emission line instead of the absorption line. Note: this figure shows the average spectrum of the footprint PSC04.

5 Mapping the Perseus regions

5.1 Footprints Maps

Using the integrated area data, the map of each of the regions can be plotted. Indeed, in a given region, the coordinates of a single spectrum are given as an offset with respect to the center of the region in equatorial coordinates. Therefore, one can easily plot the intensity at each point of the map in term of the offset or in term of the real positions. On these maps, the N_2H^+ tracer has been mapped overlapping the CS tracer.

In order to plot these maps, only the spectrum with a good signal will be taken into account. Indeed, there is no point to plot noise. This selection is done using the RMS integrated area given with the integrated intensity when removing the baseline (section 4). The first step is to remove spectra for which the RMS value is larger than 2 times the mean RMS of the whole footprint. Then, the remaining noisy spectra will not be plotted depending on the contour level chosen. Indeed, the lowest contour level is expressed as a percentage of the maximum value of the intensity. It is determined using the peak value in the region and the mean error on the integrated area, σ_A . Therefore,

if σ_A is large, the spectra will not be plotted. σ_A is deduced from the calculated RMS of the position with the relation:

$$\sigma_{Area} = RMS \times \Delta_v \times \sqrt{NBchannel} \quad (3)$$

Then the lowest contour percent is given by:

$$\%_{lowest\ contour} = 3 \times \frac{\sigma_{Area}}{Area_{max}} \times 100 \quad (4)$$

This criterion permits to omit spectra for which the RMS is too high. In other words, one removes spectra for which $3 \times \overline{RMS} \geq A$. Once the lowest level has been determined, the other levels are chosen. For comparison purposes with other regions, it is better to have contour levels at regular intervals and to include the 50% contour level in order to locate the half maximum contour line. The figure (7) shows one of the maps obtained.

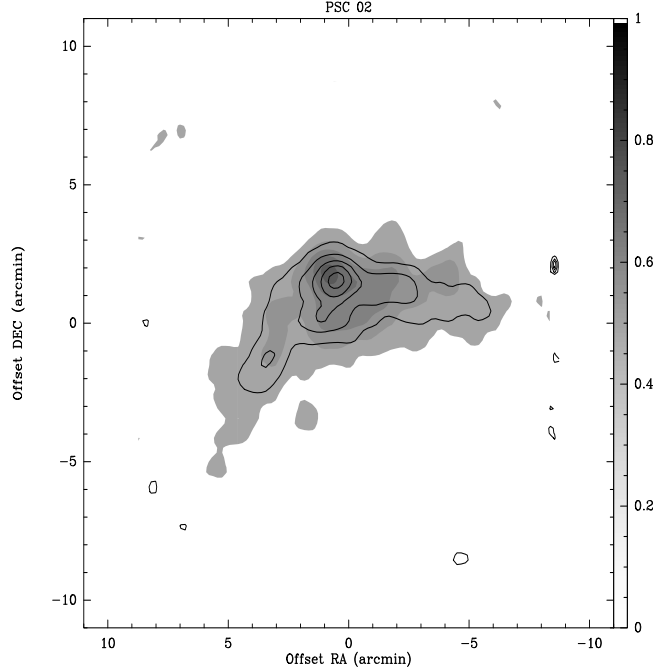


Figure 7: CS (grey scale) and N_2H^+ (black lines) in L1448. For this region, the CS and N_2H^+ tracers peak almost at the same location.

5.2 Channel Maps

A channel map consists in dividing the emission line in several bands (figure (8)), calculating the integrated intensity of each band and mapping each one separately. The bands all have the same width. Moreover, they are numerous enough in order to include only a single feature of the emission line (peak or depletion).

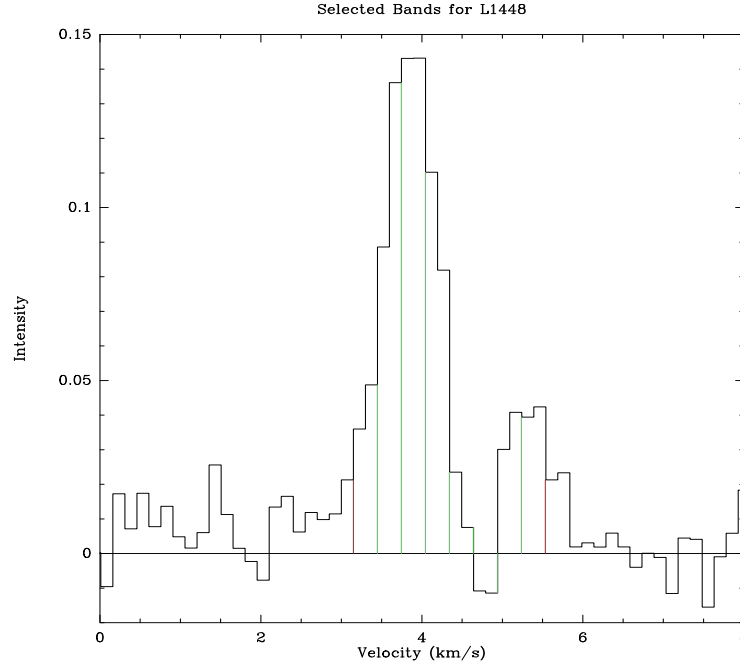


Figure 8: On this average spectrum for the regions PSC02, the several channels are chosen between the two red lines and the bands are delimited by the green lines. In other words, the integrated intensities are calculated in the several areas enclosed between the green lines.

Comparing the maps of the different channels is helpful to understand the dynamics within the cloud using the Doppler effect explained before in the theory part. In other words, one can visualize if the eventual gap between the two components (figure (2) and (8)) lies at a particular location in the cloud. It would permit to locate an area where there is a higher extinction. Therefore, it might be a way to situate a hot core.

On the figure (9), it is not really clear if there is an area with extinction. The 5th and 6th boxes are the maps of the bands that include the depletion seen on spectrum (8). There is no particular depletion in these boxes as one might expect from the spectrum. The fact that there is a drop in the emission line but no depletion in the channel map is probably a problem during the observation process. It might be an artificial feature. Other regions do not show any depletion either.

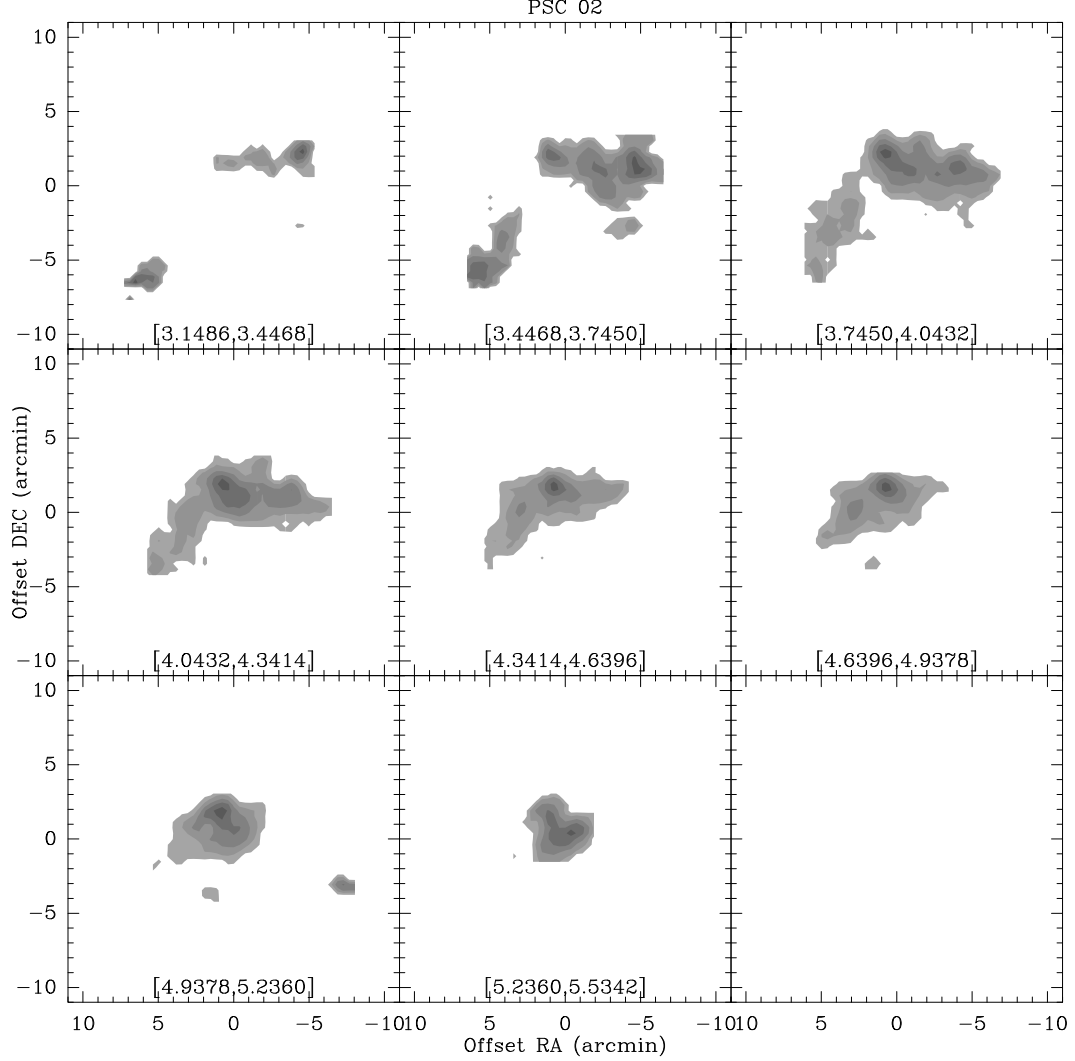


Figure 9: CS channel map of the region PSC02 (L1448). The interval in each boxes correspond to the velocity range of the band (from figure (8)). The third box shows the third band containing the peak of the emission line.

6 Spectral line Analysis

6.1 Molecular line fitting

In order to deduce more information on the star forming regions, each single emission line has to be fitted. After a fit, the CLASS package gives the line area, the width of the line, its position, and its intensity. From this, the LSR velocity can be deduced. The main point of having all these details is to determine the column density. It is basically, the projected density of the molecular cloud expressed in mass/area (column mass density) or in $1/\text{area}$ (column number density). But the fitting method differs depending on the molecule studied.

6.1.1 Fitting the CS line

Since the CS molecule has a single emission line, it can be fitted using a simple Gaussian fit method. The CLASS package contains a built-in Gaussian fit method which simplifies the analysis. The first step is to use the mean spectrum (for a given region) to determine the position of the mean emission line. Then, this is used as a parameter for the fit method. The figure (10) shows a CS spectrum with the corresponding obtained fit.

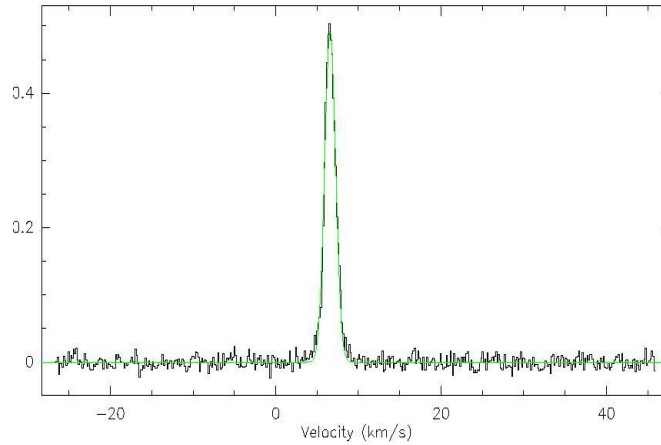


Figure 10: The green Gaussian curve is the fit to the CS emission line of this spectrum.

6.1.2 Fitting the N_2H^+ line

Unlike the CS line, the N_2H^+ has seven components and the Gaussian fit method cannot be used. However, the CLASS package has another method for hyperfine structure molecule (HFS method), but it is not as straight forward as the Gaussian method. Indeed, it requires a text file containing the velocity offset of each component with their relative intensities (table (1)).

Δv	I_{rel}
6.9360	0.03704
5.9842	0.18519
5.5452	0.11111
0.9560	0.18519
0.0000	0.25926
-0.6109	0.11111
-8.0064	0.11111

Table 1: The first column gives the velocity offset and the second one gives the relative intensities. In this case, the reference frequency is the one of the 5th hyperfine component.

Nevertheless, the N_2H^+ data were not that easy to analyze. Depending on whether the line is optically thick or thin (opaque or not), the fitting method is changing. Indeed, among the fitting parameters is an opacity parameter. Before running the HFS method, the user has to enter its value and has to allow it to change or not as the fit is calculated. Unfortunately, the package was not always able to determine to proper opacity parameter and the line width. Moreover, the HFS method may require some iteration to obtain the proper fit. Therefore, the included fitting method had troubles to perform the right fit. Unfortunately, there was no possibilities to automate this process and for each spectrum, the parameter for the fit had to be manually determine. In other words, for each spectrum, one had to tell the package to iterate the fit (in order to improve fit) or whether the line was optically thin or thick. One finally obtained

spectra like the one on figure (11).

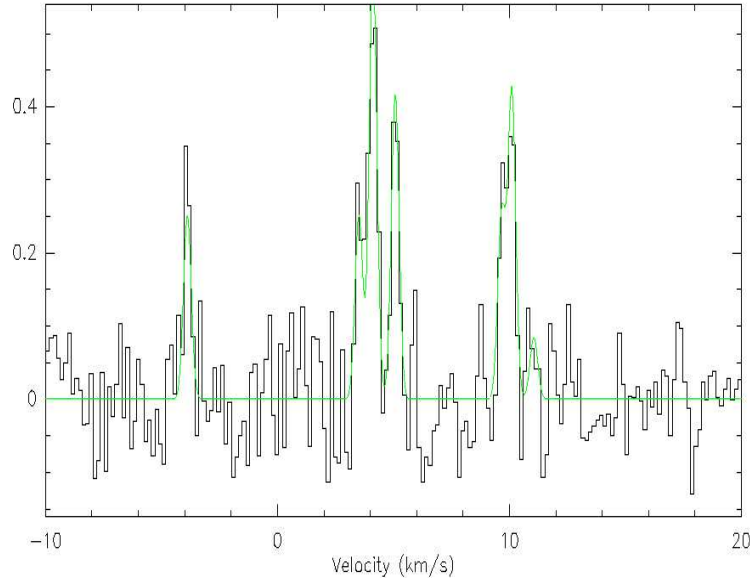


Figure 11: Despite an average signal to noise, the fit (green line) of the several component is pretty good and will permit an analysis of the N_2H^+ molecule in the molecular clouds.

6.1.3 Obtaining the column density

The column density calculation is different depending on the type of transition. For optically thick transition,

$$N_{tot} = \frac{8\pi^3/2 \Delta\nu}{2\sqrt{\ln 2} \lambda^3 A} \cdot \frac{g_l}{g_u} \cdot \frac{\tau}{1 - \exp(-h\nu/kT_{ex})} \cdot \frac{Q_{rot}}{g_l \exp(-E_l/kT_{ex})} \quad (5)$$

where $\Delta\nu$ is the line width, λ and ν are the wavelength and frequency of the observed transition. A is the Einstein coefficient, g_l and g_u are the statistical weight of the lower and upper levels of the transition. Then, τ is the optical depth, h is the Planck constant, k is the Boltzmann constant, T_{ex} is the excitation temperature, Q_{rot} is the partition function (equation (6)) and E_l is the energy of the lower level. For linear molecule (like CS and N_2H^+),

$$Q_{rot} = \sum_{J=0}^{\infty} (2J+1) \exp(-E_J/kT) \quad \text{and} \quad E_J = J(J+1)hB \quad (6)$$

Here, J is the rotational quantum number and B is the rotational constant.

For an optically thin line, the column density is a bit different and does not depend on the line width. It is given by:

$$N_{tot} = \frac{8\pi W}{\lambda^3 A} \cdot \frac{g_l}{g_u} \cdot \frac{1}{J_\nu(T_{ex}) - J_\nu(T_{bg})} \cdot \frac{1}{1 - \exp(-h\nu/kT_{ex})} \cdot \frac{Q_{rot}}{g_l \exp(-E_l/kT_{ex})} \quad (7)$$

T_{mb} is the main-beam brightness temperature, $J_\nu(T_{ex})$ and $J_\nu(T_{bg})$ are the equivalent Rayleigh-Jeans excitation and background temperatures. Finally, W is the integrated intensity on the line calculated by the package CLASS. It is given by:

$$W = \frac{\pi^{1/2} \Delta\nu T_{mb}}{2\sqrt{\ln 2}} \quad (8)$$

6.2 Results

Unfortunately, due to a lack of time, the column density calculation were not performed.

7 Conclusion

The starless cores in Perseus were observed with the FCRAO radiotelescope. The CS and N_2H^+ emission line were used to trace the outer shell (with CS) and the denser regions of the cores (with N_2H^+). The reduction of the data involved the baseline deletion on the spectra. Then, the reduced data are utilized to create the maps of the protostellar cores using the fact that each spectrum has an intensity and correspond to an offset position. The CS and N_2H^+ tracers usually match on the map. In other words, they display a peak at almost the same position as one would expect. The channel maps are an important tool to understand the dynamics of the cores but the results were not as expected. Finally, the fitting of the spectra was a very long and tedious process and therefore the column densities were not calculated.

8 Acknowledgements

I really would like to thank Paola Caselli for her guidance, patience and trust during this term. I am also really grateful toward Alyssa A. Goodman for offering me the opportunity to work with the COMPLETE team. I also want to thank all the COMPLETE members I met for the warm welcome I received.

9 References

1. 'Laboratory and radio-astronomical spectroscopy of the hyperfine structure of N₂D⁺', L. Dore et al. (2003)
2. 'Radio-Astronomical Spectroscopy of the Hyperfine Structure of N₂H⁺', Paola Caselli et al. (1995)
3. 'An Observational Perspective of Low-Mass Dense Cores I: Internal Physical and Chemical Properties', James Di Francesco et al. (2006)
4. 'The COMPLETE Survey of Star-Forming Regions on its Second Birthday', Alyssa A. Goodman (2004)
5. 'Molecular Ions in L1544 II: The Ionization Degree' Paola Caselli et al. (2001)
6. 'Chemical processes in star forming regions', Paola Caselli (2005)
7. 'Cloudshine: New Light on Dark Clouds', J. Foster and A. A. Goodman. (2006)
8. '<http://www.strw.leidenuniv.nl/vcgeers/sfcourse/>', Star Formation Course, University of Leiden, Netherlands.