Comparative study of complex N- and O-bearing molecules in hot molecular cores

F. Fontani\textsuperscript{1}, I. Pascucci\textsuperscript{2}, P. Caselli\textsuperscript{3,5}, F. Wyrowski\textsuperscript{4}, R. Cesaroni\textsuperscript{5}, and C.M. Walmsley\textsuperscript{5}

\textsuperscript{1} INAF, Istituto di Radioastronomia, CNR, Via Gobetti 101, I-40129 Bologna, Italy
\textsuperscript{2} Steward Observatory, The University of Arizona, Tucson, AZ 85721
\textsuperscript{3} Harvard-Smithsonian Center for Astrophysics, 60 Garden Street MS42, Cambridge, MA 02138, USA
\textsuperscript{4} Max-Planck-Institut fuer Radioastronomie, Auf dem Huegel 69, 53121 Bonn, Germany
\textsuperscript{5} INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

Received date; accepted date

ABSTRACT

Aims. We have observed several emission lines of two Nitrogen-bearing (C$_2$H$_5$CN and C$_2$H$_7$CN) and two Oxygen-bearing (CH$_3$OCH$_3$ and HCOOCH$_3$) molecules towards a sample of well-known hot molecular cores (HMCs) in order to check whether the chemical differentiation seen in the Orion-HMC and W3(H$_2$O) between O- and N-bearing molecules is a general property of HMCs.

Methods. With the IRAM-30m telescope we have observed 12 HMCs in 21 bands, centered at frequencies from 86250 to 258280 MHz.

Results. In six sources, we have detected a number of transitions sufficient to derive their main physical properties. The rotational temperatures obtained from C$_2$H$_5$CN, C$_2$H$_7$CN and CH$_3$OCH$_3$ range from \textasciitilde 100 to \textasciitilde 150 K in these HMCs. The total column densities of these molecules are of the order of \textasciitilde 10^{15} – 10^{17} cm$^{-2}$. Single Gaussian fits performed to unblended lines show a marginal difference in the line peak velocities of the C$_2$H$_5$CN and CH$_3$OCH$_3$ lines, indicating a possible spatial separation between the region traced by the two molecules. On the other hand, neither the linewidths nor the rotational temperatures and column densities confirm such a result. The average molecular abundances of C$_2$H$_5$CN, C$_2$H$_7$CN and CH$_3$OCH$_3$ are in the range \textasciitilde 10^{-9} – 10^{-10}, comparable to those seen in the Orion hot core. In other HMCs Bisschop et al. 2007 found comparable values for C$_2$H$_5$CN but values \textasciitilde 2.5 times larger for CH$_3$OCH$_3$. By comparing the abundance ratio of the pair C$_2$H$_5$CN/C$_2$H$_7$CN with the predictions of theoretical models, we derive that the age of our cores ranges between 3.7 and 5.9×10^4 yrs.

Conclusions. The abundances of C$_2$H$_5$CN and C$_2$H$_7$CN are strongly correlated, as expected from theory which predicts that C$_2$H$_7$CN is formed through gas phase reactions involving C$_2$H$_5$CN. A correlation is also found between the abundances of C$_2$H$_5$CN and CH$_3$OCH$_3$, and C$_2$H$_7$CN and CH$_3$OCH$_3$. In all tracers the fractional abundances increase with the H$_2$ column density while they are not correlated with the gas temperature. On average, the chemical and physical differentiation between O- and N-bearing molecules...
seen in Orion and W3(H$_2$O) is not revealed by our observations. We believe that this is partly due to the poor angular resolution of our data, which allows us to derive only average values over the sources of the discussed parameters.

**Key words.** Stars: formation – Radio lines: ISM – ISM: molecules

1. Introduction

The formation process of massive stars ($M \geq 8M_\odot$) is still poorly understood. This is mainly due to the observational limitations that hinder the study of early-type stars, i.e. their shorter evolutionary timescales, larger distances and stronger interaction with their environment. Despite this, a growing effort has been devoted to investigate this process, and important results have been obtained both from the observational and the theoretical point of view (see e.g. Garay & Lizano 1999; Tan & McKee 2002; Yorke 2004; Beuther et al. 2007; Cesaroni et al. 2007).

It is well known that when a high-mass star reaches the ZAMS, an ultracompact (UC) H II region, i.e. an ionized region with diameter smaller than a few $\sim 0.1$ pc, becomes observable at radio wavelengths due to the emission of free–free radiation. This has led to using UC H IIs as “signposts” of massive star formation (e.g. Wood and Churchwell 1989). Various authors have shown that UC H IIs are embedded in molecular clumps of a few thousand solar masses, diameters $\sim 1$ pc, and average H$_2$ volume density of $\sim 10^5$ cm$^{-3}$ (Cesaroni et al. 1991; Hofner et al. 2000; Fontani et al. 2002). Observations at higher angular resolution have also identified hot ($\geq 100$ K), dense ($\geq 10^7$ cm$^{-3}$) and compact ($\leq 0.1$ pc) molecular condensations in these clumps, called “hot molecular cores” (HMCs) from the name of their prototype, the Orion Hot Core (see Genzel & Stutzki 1989; Walmsley & Schilke 1992). These HMCs are often associated with outflows, water masers, and in some of them an UC H II region has been detected, suggesting that they represent the environment in which high-mass stars were recently born (see e.g. Kurtz et al. 2000; Cesaroni 2005). Their chemical composition is peculiar and very different from that of the surrounding molecular clump, showing higher abundances of saturated species (e.g. H$_2$O, NH$_3$, CH$_3$OH) and complex organic H–rich molecules (see e.g. Caselli 2005).

Since most of the observed H–rich molecules are difficult to form in gas-phase reactions, grain-surface chemistry is often invoked to explain their formation. One possible scenario is the following: during the collapse of a pre-stellar core, molecules freeze out onto dust grains, react with atoms or other molecules on the grain surface and, as the core is heated by the young star, some of them evaporate and return to the gas phase. Based on this scenario, one can distinguish three types of molecules (see Charnley 1995):
those formed in cold gas through ion-molecule reactions, frozen onto dust grains and then released into the gas phase when the core is heated up by the central star. Their abundances should hence reflect those of the initial early cold phase;

– those formed on the grain surfaces through reactions of frozen species, and then evaporated during the HMC phase;

– those formed in hot gas through reactions of evaporated molecules.

Several studies have been made to investigate the chemistry of HMCs (Macdonald et al. 1995; Gibb et al. 2000; Nomura & Millar 2004; Garrod & Herbst 2006). Charnley et al. (1992) showed that initial differences in the chemical composition and gas phase reactions subsequent to evaporation from dust grains can explain the existence of many of the complex O- and N-bearing species. Interestingly, Blake et al. (1987) found that N-bearing species are more abundant than O-bearing ones in the Orion-HC, while the opposite is observed in the Compact Ridge. The chemical model by Caselli et al. (1993) explains such a chemical difference as being due to the different physical properties of the two regions. The model also predicts a relation between the core evolutionary stage and the abundance ratio of molecular species like \( \text{C}_2\text{H}_3\text{CN} \) and \( \text{C}_2\text{H}_5\text{CN} \). Therefore, the relative abundance of these species can be used as a ‘chemical clock’ to estimate the HMC age.

In this work we present the results of the first survey of 4 complex molecules, \( \text{C}_2\text{H}_3\text{CN} \), \( \text{C}_2\text{H}_5\text{CN} \), \( \text{CH}_3\text{OCH}_3 \) and \( \text{HCOOCH}_3 \), towards 12 well-known HMCs, all of them associated with UC H\( \alpha \) regions and already observed in several molecular tracers (Hatchell et al. 1998; Hofner et al. 2000; Fontani et al. 2002). In Sect. \ref{sec:observations} we describe the observations and we present our sample. The methods used to analyse the data and the immediate results are presented in Sect. \ref{sec:results}. In Sect. \ref{sec:discussion} we discuss our results, and give an estimate of the chemical ages of the HMCs. Conclusions are drawn in Sect. \ref{sec:conclusions}.

\section{Observations and Data Reduction}

\subsection{Observations}

The observations were carried out with the IRAM 30-m telescope during two observing runs: in July 1996, and August 1997. The observed sources are listed in Table \ref{tab:source_list} inCols. 2 and 3 we give the equatorial (J2000) coordinates; LSR source velocities (\( V_{\text{LSR}} \)) and kinematic distances (\( d \)) are given inCols. 4 and 5, respectively. The numbers listed in Col. 6 will be used in the following to identify the source. We observed simultaneously at 3, 2, and 1.3 mm. The half power beam width (HPBW) of the telescope was \( \sim 22'' \), \( \sim 16'' \), and \( \sim 12'' \), respectively. We obtained spectra of vinyl cyanide (\( \text{C}_2\text{H}_3\text{CN} \)), ethyl cyanide (\( \text{C}_2\text{H}_5\text{CN} \)), methyl formate (\( \text{HCOOCH}_3 \)) and dimethyl ether (\( \text{CH}_3\text{OCH}_3 \)). The central frequencies of the observed bands and the sources observed in each band are listed in Table \ref{tab:source_list}.

System temperatures for both observing runs were 300–450 K, 500–900 K, and 700–3000 K for the 3 mm, 2 mm, and 1.3 mm receivers, respectively. The given temperature ranges depend
Table 1. List of the observed sources. The distances are taken from Table 1 of Kurtz et al. (2000) except when differently specified.

| Source        | R.A.(J2000) | Dec.(J2000) | V\(_{\text{LSR}}\) | d    | code |
|---------------|-------------|-------------|---------------------|------|------|
|               | (h m s)     | (° ′ ′′)    | (km s\(^{-1}\))    | (kpc)|      |
| W3(H\(_2\)O) | 02 27 04.7  | +61 52 24.5 | −45.0              | 1.95 | a    |
| G5.89−0.39    | 18 00 30.4  | −24 04 00.5 | 10.0               | 2.0  | b    |
| G9.62+0.19    | 18 06 15.0  | −20 31 42.2 | 4.4                | 5.7  | 3    |
| G10.47+0.03   | 18 08 38.2  | −19 51 49.7 | 67.8               | 5.8  | 4    |
| G10.62−0.38   | 18 10 28.7  | −19 55 49.7 | −3.1               | 4.8  | 5    |
| G19.61−0.23   | 18 27 38.1  | −11 56 38.5 | 41.6               | 12.6 | 6    |
| G29.96−0.02   | 18 46 04.0  | −02 39 21.5 | 98.0               | 7.4  | 7    |
| G31.41+0.31   | 18 47 34.4  | −01 12 46.0 | 97.0               | 7.9  | 8    |
| G34.26+0.15   | 18 53 18.5  | +01 14 57.7 | 58.0               | 3.7  | 9    |
| G45.47+0.05   | 19 14 25.6  | +11 09 25.9 | 62.0               | 8.3  | 10   |
| W51D          | 19 23 39.9  | +14 31 08.1 | 60.0               | 8.0  | 11   |
| IRAS20126+4104| 20 14 26.0  | +41 13 32.5 | −3.5               | 1.7  | 12   |

R.A.(J2000)= right ascension
Dec.(J2000)= declination
V\(_{\text{LSR}}\)= Local standard of rest velocity

\(^{a}\) Xu et al. (2006)
\(^{b}\) Acord et al. (1998)
\(^{c}\) Fish et al. (2003)
\(^{d}\) Kolpak et al. (2003)
\(^{e}\) Kuchar & Bania (1994)

on weather conditions and source elevation. The receivers alignment was checked through continuum cross scans on planets and found to be accurate to within 2″ for the 3 mm, 2 mm, and the first 1.3 mm receiver. A misalignment of up to 5″ was observed for the second 1.3 mm receiver, which however is negligible with respect to the beam size. Our spectrometers were an autocorrelator with bandwidth ∼ 523 MHz and 0.32 MHz resolution, and two filter-banks with 512 MHz bandwidth and 1 MHz resolution. The wobbling secondary mirror was used with a beam throw of 240″ and a frequency of 0.5 Hz resulting in linear baselines of the spectra. The focus was checked at the beginning of each night on Jupiter or Saturn. Since the two 1.3 mm receivers had somewhat different foci, we selected in these cases a focus position giving a compromise between the different receivers more weighted to the 1.3 mm G1 receiver that had the same focus as the 3 and 2 mm receivers. The resulting gain loss is smaller than 10%. Pointing was checked hourly by cross scans on planets. The observations were made in wobbler switching mode, with
the wobbling secondary reflector switching in azimuth at a rate of 0.5 Hz between the source position and a reference position offset by 4 arcmin.

The data were reduced and analysed using the software package CLASS. An advanced version of the package, XCLASS, was used to fit the transitions with blending problems (see e.g. Comito et al. 2005 for details on the XCLASS fitting procedure).

2.2. Line Identification

Line identification was done using several catalogues of line frequencies: the Lovas\(^1\) and JPL\(^2\) catalogues, as well as the compilations of Anderson et al. (1987, 1988a, 1988b, 1990a, 1990b, 1992), Bettens et al. (1999), Groner et al. (1998), Herbst (1999), Klisch et al. (1996), Pan et al. (1998), Pearson et al. (1991, 1994, 1997), Plummer et al. (1986, 1987), Wyrowski et al. (1999), Yamada et al. (1986). Predicted vibrational transitions of C\(_2\)H\(_5\)CN were taken from Pearson (2002). We have considered as identified those lines in the spectra within ∼1 MHz from the expected line position in the catalogues. We have considered as detected the lines above the 3σ level in the spectra.

In Fig. 1 we show a sample spectrum at 3 mm for the source G34.26+0.15, with identified and unidentified lines.

3. Results

In this Section we report on and analyse the results for the 6 sources of our sample which show a number of transitions sufficient to derive the physical parameters of our interest (column density, temperature, abundance). They are listed in Col. 1 of Table 3. All spectra observed towards these sources are shown in Figures A-1 – A-11 of Appendix A. Hereafter, we will use the source name G10.47 for G10.47+0.03, G10.62 for G10.62–0.38, G19.61 for G19.61–0.23, G29.96 for G29.96–0.02, G31.41 for G31.41+0.31 and G34.26 for G34.26+0.15.

We will concentrate on the study of C\(_2\)H\(_3\)CN, C\(_2\)H\(_5\)CN, and CH\(_3\)OCH\(_3\). We discuss separately the results of the study of HCOOCH\(_3\) in Sect. 3.3 because most of the transitions of this molecule appear in multiplets with nearly the same upper energies, and they are blended with lines of other molecular species much more than the lines of C\(_2\)H\(_5\)CN, C\(_2\)H\(_3\)CN and CH\(_3\)OCH\(_3\).

3.1. Masses and H\(_2\) Column Densities of the cores

To derive the abundances of the observed molecules relative to H\(_2\) we need first to estimate the total gas mass, \(M_{\text{gas}}\). We have computed \(M_{\text{gas}}\) and the corresponding H\(_2\) total column density, \(N(\text{H}_2)\), assuming the clumps to be Gaussian and in virial equilibrium. Under the further hypoth-

\(^1\) http://physics.nist.gov/PhysRefData/Micro/Html/contents.html
\(^2\) http://spec.jpl.nasa.gov
Table 2. Observed frequency bands

| Observing run | Band name      | $\nu_c^a$ (MHz) | observed sources$^b$ |
|---------------|----------------|-----------------|---------------------|
| BAND3–HCN     | 86250          | 1,4,8           |
| BAND3–HNCO    | 87800          | 1,4,7,8         |
| BAND3–109     | 109410         | 4,8             |
| BAND3–110     | 110095         | 1,4,5,7-9       |
| BAND2–NH3     | 140300         | 4,8             |
| July          | BAND2–154      | 154230          | 1,4,7,8             |
| 1996          | BAND2–155      | 154850          | 1,4,5,7-9           |
|               | BAND1–215      | 215250          | 1,4,5,7-9           |
|               | BAND1–218      | 218970          | 1,4,8               |
|               | BAND1–HNCO     | 219580          | 1,4,7,8             |
|               | BAND1–228      | 228100          | 4,8                 |
|               | BAND1–HCN      | 258280          | 1,4,8               |
|               | BAND2MM–1      | 147370          | 1-12                |
| August        | BAND2MM–2      | 161463          | 4,9,11,12           |
| 1997          | BAND2MM–3      | 173150          | 6-9,11              |
|               | BAND1MM–1      | 209580          | 6-9,11              |
|               | BAND1MM–2      | 224237          | 1-12                |
|               | BAND1MM–3      | 237460          | 4,9,11,12           |
|               | BAND3MM–1      | 98600           | 4-9,11,12           |
|               | BAND3MM–2      | 104360          | 6-9,11              |
|               | BAND3MM–3      | 111600          | 1-12                |
|               | BAND2MM–1      | 147370          | 1-12                |

$^a$ band central frequency

$^b$ source identification numbers as in Table I

esis that the lines are not broadened by high optical depth, one can demonstrate that $M_{\text{gas}}$ and $N_{\text{H}_2}$ are given by:

$$M_{\text{gas}}(M_\odot) = 125 \Delta \nu^2 (\text{km s}^{-1}) D(\text{pc}),$$

(1)

$$N_{\text{H}_2} = \frac{4 \ln 2}{\pi D^2 m_{\text{H}_2}} M_{\text{gas}},$$

(2)

where $\Delta \nu$ is the observed full line width at half maximum, $D = d\theta_s$ is the HMC linear diameter ($\theta_s$ is the source angular diameter) and $m_{\text{H}_2}$ is the mass of the $\text{H}_2$ molecule.

The results are summarised in Table I. HMC angular and linear diameters (obtained from the literature) are listed in Cols. 2 and 3, respectively; line widths, core masses and $\text{H}_2$ total column densities are given in Cols. 4, 5 and 6, respectively. The source linear diameters have been computed from the distances in Table I. The line widths are the average values of isolated
The identified and unidentified (U) lines are marked.

Table 3. Source angular ($\theta_s$) and linear ($D$) diameters, linewidths at half of the maximum of the C$_2$H$_5$CN transitions ($\Delta v$), core masses ($M_{\text{gas}}$) and H$_2$ total column densities ($N(\text{H}_2)$). The diameters are derived from mm interferometric data, except when otherwise specified. Masses and column densities are computed assuming sources in virial equilibrium and with Gaussian distribution of the gas.

| Source      | Diameter | $\Delta v$ | $M_{\text{gas}}$ | $N(\text{H}_2)$ |
|-------------|----------|------------|------------------|-----------------|
|             | $\theta_s$ | $D$        | ($\text{km s}^{-1}$) | ($M_\odot$) | ($\text{cm}^{-2}$) |
| G10.47+0.03 | 1.3$^a$  | 0.036      | 7.89             | 286             | 1.2$\times 10^{25}$ |
| G10.62−0.38 | 1.7$^b$  | 0.039      | 5.18             | 133             | 4.8$\times 10^{24}$ |
| G19.61−0.23 | 1.9$^c$  | 0.112      | 9.34             | 1239            | 5.4$\times 10^{24}$ |
| G29.96−0.02 | 1.4$^d$  | 0.050      | 6.01             | 228             | 5.1$\times 10^{24}$ |
| G31.41+0.31 | 1.1$^e$  | 0.042      | 8.52             | 385             | 1.2$\times 10^{25}$ |
| G34.26+0.15 | 3.6$^f$  | 0.066      | 6.55             | 358             | 4.5$\times 10^{24}$ |

$^a$ Olmi et al. (1996)
$^b$ Keto et al. (1988, from NH$_3$ interferometric observations)
$^c$ Kurtz et al. (2000)
$^d$ Cesaroni et al. (1998, from NH$_3$ interferometric observations)
$^e$ Beltrán et al. (2005)
$^f$ Akeson & Carlstrom (1996, from CH$_3$CN interferometric observations)

 transitions of C$_2$H$_5$CN. We decided to use this molecule because it is the species for which we have the largest number of unblended lines in each source.

The angular diameters of the HMCs have been taken from previous interferometric observations and require a detailed discussion. Most of the cores of our sample have been already
observed at high angular resolution in several molecular tracers, such as e.g. NH$_3$, CH$_3$CN and CH$_3$OH. These observations have shown that different molecular species can probe distinct regions of the core. Beuther et al. (2005) have observed at high angular resolution the Orion-HC in several molecular tracers, and reported significant spatial separation among the regions traced by O-, N- and S-bearing species (see also Fig. 2 of Wright et al. 1996). Notwithstanding this, at present high angular resolution observations of complex molecules in the HMCs of our sample are poor; Beltrán et al. (2005) have detected one line of C$_2$H$_5$CN and HCOOCH$_3$ in G31.41, and found that their integrated emission maps are fairly well overlapping with that of the 1.4 mm continuum, even though the two species do not peak exactly at the same position (see their Fig. 26). Similarly, Mookerjea et al. (2007) have detected few lines of C$_2$H$_5$CN, HCOOCH$_3$ and CH$_3$OCH$_3$ in G34.26, showing a separation between the emission peaks of O- and N-bearing species of $\sim0.8$, but a substantial overlap between their emission maps and that of the 2.8 mm continuum. Additionally, Remijan et al. (2004) have found that in G19.61, HCOOCH$_3$ and C$_2$H$_5$CN approximately peak at the same position. Given these results, as zero-order assumption we will suppose that the emission of all the observed molecules arises from the region seen in the mm continuum.

The angular diameters listed in Table 3 are hence derived from mm continuum interferometric maps with the exception of three sources: G10.62, G29.96 and G34.26. We decided to use the diameter inferred from CH$_3$CN for G34.26 and from NH$_3$ for G29.96, respectively, instead of that from the mm continuum, because the mm continuum position does not agree with that of the molecular emission (see Akeson & Carlstrom 1996 and Carral & Welch 1992 for G34.26; Olmi et al. 2003 for G29.96). Also, in G34.26 60% of the mm flux is due to the free-free continuum emission of an associated H$\alpha$ region (Akeson & Carlstrom 1996). For G10.62, angular diameters from mm continuum interferometric data are not available. Therefore, we have assumed the diameter from NH$_3$ inversion transitions measurements.

The total H$_2$ column density has been derived in our sources also from C$^{17}$O by Hofner et al. (2000) and from CH$_3$C$_2$H by Fontani et al. (2002). In both works the authors used Eq. (1), adopting the diameters and the virial masses they derive from the molecular lines that they observed. These estimates are $\sim 2$ orders of magnitude lower than those obtained from C$_2$H$_5$CN, consistently with the fact that the C$^{17}$O and CH$_3$C$_2$H transitions trace the parsec-scale molecular clump in which the HMC is embedded.

### 3.2. Rotational temperatures, total column densities and fractional abundances

#### 3.2.1. Derivation of the parameters

We derive rotational temperatures and total column densities applying the population diagram method described by Goldsmith & Langer (1999, hereafter GL99). The main assumptions in this method are: (i) optically thin lines; (ii) local thermodynamic equilibrium (LTE) conditions.
Under assumption (i), one can compute the column density $N_u$ of the upper level, $u$, of each transition from its integrated intensity according to the relation:

$$\frac{N_u}{g_u} = \frac{3k}{8\pi^2} \frac{W}{\nu \mu^2 S} \tag{3}$$

where $g_u$ is the statistic weight of the upper level, $k$ the Boltzmann constant, $W$ the integrated line intensity (in K km s$^{-1}$), $\nu$ the line rest frequency, $\mu$ the molecule’s dipole moment and $S$ the line strength. Then, under assumption (ii), we can use Eq. (21) of GL99 to derive rotational temperatures and total column densities of the molecules from least square fits to the data. The validity of assumptions (i) and (ii) will be discussed in detail in Sect. 3.2.4. The parameters derived from the XCLASS fitting procedure for the lines identified and used in the rotation diagrams are given for each source in Tables 1–11 of Appendix B. The rotation diagrams for all sources are shown in Figs. 1–6 of Appendix C.

The nuclear spin degeneracy and the partition functions used in Eq. (21) of GL99 have been taken from Blake et al. (1987) and Turner et al. (1991) for C$_2$H$_5$CN, C$_2$H$_3$CN, and HCOOCH$_3$, and from Groner et al. (1998) for CH$_3$OCH$_3$. Partition functions are calculated analytically in the approximation of high temperatures (i.e. $hA \ll kT$ for asymmetric top species, where $A$ is the Einstein coefficient). For the vibrational transitions, we computed the partition function following the approximation of Nummelin & Bergman (1999). In the rotation diagrams, the column density of each level observed at 2 mm and 1.3 mm has been normalized to the telescope beam at 3 mm (≈ 23″) assuming a source diameter negligible with respect to the beam size, thus obtaining beam-averaged total column densities. Then, source-averaged total column densities have been inferred by multiplying the beam-averaged values by $(23/\theta_s)^2$.

The molecule’s fractional abundance, $X$, is given by the source-averaged total column density divided by the H$_2$ total column density listed in Col. 5 of Table 3

$$X = \frac{N(\text{molecule})}{N(\text{H}_2)}$$

### 3.2.2. Temperatures and column densities

Rotational temperatures ($T$), beam- and source-averaged total column densities ($N_b$ and $N_s$) are given in Cols. 3, 4 and 5 of Tab. 3 respectively.

The rotational temperatures typically range from ~ 100 to ~ 150 K in all tracers. In each source, the estimates obtained from C$_2$H$_5$CN, C$_2$H$_3$CN and CH$_3$OCH$_3$ are in good agreement among them, with the exception of G34.26 and G10.62. For G34.26, the estimate from C$_2$H$_3$CN is a factor of 2 lower than those derived from CH$_3$OCH$_3$ and C$_2$H$_5$CN, but this is likely due to the fact that in the rotation diagram there are no points above ~ 200 K. In G10.62, the temperature from CH$_3$OCH$_3$ is much lower (~ 16 K) than the other two estimates, but it has been obtained from only few line detections and is thus less accurate.

The temperatures derived from C$_2$H$_5$CN and CH$_3$OCH$_3$ are in agreement both with those obtained by Bisschop et al. (2007) in other HMCs, and with those derived from other HMC tracers by Kurtz et al. (2000, see their Table 1), further attesting they are tracing the hot gas of the cores. The column densities of C$_2$H$_5$CN are in good agreement with the values of Bisschop et
al. (2007) in similar objects, while for CH$_3$OCH$_3$ we find column densities one order of magnitude smaller. In computing source-averaged column densities Bisschop et al. (2007) assume a source diameter corresponding to that of the region where the temperature is higher than ~ 100 K, that is comparable to those of our objects (~ 1\arcsec). Since masses and luminosities of the cores are comparable as well, the observed difference might reflect a different CH$_3$OCH$_3$ chemistry in the HMCs of our sample and those of Bisschop et al. (2007).

Only three transitions of C$_2$H$_5$CN have been identified towards G29.96. In this case the column densities have been estimated fixing the rotation temperature to that found from C$_2$H$_5$CN. The assumption of equal rotational temperature for C$_2$H$_5$CN and C$_2$H$_4$CN is justified both by observations (Schilke et al. 1997), which have shown that these molecules trace a very similar region, and by chemical models (Charnley et al. 1992; Caselli et al. 1993), which predict that C$_2$H$_5$CN forms in gas phase reactions involving C$_2$H$_5$CN.

Table 4. Rotational temperatures ($T$), beam and source averaged total column densities ($N_b$ and $N_s$) and abundances ($X$) with respect to H$_2$ of C$_2$H$_5$CN, C$_2$H$_3$CN and CH$_3$OCH$_3$.

| Molecule     | Source | $T$ (K) | $N_b$ (cm$^{-2}$) | $N_s$ (cm$^{-2}$) | $X$ |
|--------------|--------|---------|------------------|------------------|-----|
| C$_2$H$_5$CN | G10.47 | 103±12  | 3.6±0.9×10$^{14}$ | 1.1±0.3×10$^{17}$ | 9.6×10$^{-9}$ |
|              | G10.62 | 89±13   | 2.5±0.9×10$^{15}$ | 4.6±1.6×10$^{15}$ | 9.5×10$^{-10}$ |
|              | G19.61 | 116±12  | 1.5±0.2×10$^{14}$ | 2.2±0.3×10$^{16}$ | 4.1×10$^{-9}$   |
|              | G29.96 | 121±17  | 5.4±1.3×10$^{13}$ | 1.5±0.3×10$^{16}$ | 3.0×10$^{-9}$   |
|              | G31.41 | 118±13  | 2.3±0.5×10$^{14}$ | 1.0±0.2×10$^{17}$ | 8.3×10$^{-9}$   |
|              | G34.26 | 130±13  | 1.9±0.3×10$^{14}$ | 8.4±1.3×10$^{15}$ | 1.9×10$^{-9}$   |
| C$_2$H$_3$CN | G10.47 | 176±35  | 2.0±0.6×10$^{14}$ | 6.1±1.7×10$^{16}$ | 5.1×10$^{-9}$   |
|              | G10.62 | 123±24  | 6.5±2.1×10$^{13}$ | 9.7±3.2×10$^{15}$ | 1.8×10$^{-9}$   |
|              | G19.61 | 123±24  | 6.5±2.1×10$^{13}$ | 9.7±3.2×10$^{15}$ | 1.8×10$^{-9}$   |
|              | G29.96 | 67±15   | 5.6±2.5×10$^{13}$ | 2.4±1.0×10$^{15}$ | 5.3×10$^{-10}$  |
| CH$_3$OCH$_3$| G10.47 | 156±37  | 1.2±0.3×10$^{14}$ | 3.9±1.0×10$^{16}$ | 3.3×10$^{-9}$   |
|              | G10.62 | 16±1    | 1.4±0.2×10$^{13}$ | 2.6±0.4×10$^{15}$ | 5.4×10$^{-10}$  |
|              | G19.61 | 158±17  | 1.3±0.1×10$^{13}$ | 2.0±0.2×10$^{15}$ | 3.7×10$^{-10}$  |
|              | G29.96 | 141±26  | 2.3±0.4×10$^{13}$ | 6.2±1.0×10$^{15}$ | 1.2×10$^{-9}$   |
|              | G31.41 | 127±25  | 7.9±1.9×10$^{13}$ | 3.5±1.0×10$^{16}$ | 2.9×10$^{-9}$   |
|              | G34.26 | 116±25  | 7.6±2.3×10$^{13}$ | 3.3±1.0×10$^{15}$ | 7.3×10$^{-10}$  |
3.2.3. Molecular fractional abundances

Molecular fractional abundances are listed in Col. 6 of Table 4. The average abundances of $\text{C}_2\text{H}_5\text{CN}$, $\text{C}_2\text{H}_3\text{CN}$ and $\text{CH}_3\text{OCH}_3$ are $\sim 4.6 \times 10^{-9}$, $2.4 \times 10^{-9}$ and $\sim 1.5 \times 10^{-9}$, respectively. These values are comparable to those found in the Orion Hot Core (Sutton et al. 1995) and in Sgr B2 (Nummelin et al. 2000). $\text{C}_2\text{H}_5\text{CN}$ abundances are also comparable to the values obtained by Bisschop et al. (2007) in a similar sample of HMCs, while for $\text{CH}_3\text{OCH}_3$ we find a discrepancy of $\sim 2$ orders of magnitude with respect to the estimates of Bisschop et al. (2007). Again, we have to consider that in deriving their $\text{H}_2$ column densities Bisschop et al. (2007) use a model with a power-law density profile in the HMC of the type $n \propto r^{-1.5}$. Since we derive $\text{H}_2$ total column densities directly from observational measurements, the observed difference might be due to some assumptions in the model used by Bisschop et al. (2007) which cannot be applied to our sources.

3.2.4. LTE conditions and optical depth of the lines

Our results have been derived assuming LTE conditions. The critical densities of the observed transitions are of the order of $10^6 - 10^7$ cm$^{-3}$ (see Genzel 1991 for the collisional coefficients), and always $\leq 10^8$ cm$^{-3}$. Assuming spherical and homogeneous cores, from the linear diameters and gas column densities listed in Cols. 3 and 6 of Tab. 5 respectively, we find that all of our HMCs have $\text{H}_2$ volume densities larger than $10^7$ cm$^{-3}$. This makes us confident that the LTE approximation is correct.

The other fundamental assumption of the rotation diagram method is that of optically thin lines. If the lines are optically thick, the expression for the column density of the upper levels given in Eq. 2 has to be multiplied by the factor $\tau/(1-\exp(-\tau))$ (see e.g. Eq. 16 of GL99), where $\tau$ is the line opacity. Such a correction modifies the results of the rotation diagrams: large optical depths are expected to affect mostly the low-excitation transitions, thus causing a flattening of the plots at lower energies. In this case, the temperatures estimated assuming optically thin lines have to be taken as upper limits.

Line opacities can be derived from the line intensity ratio of two isotopologues of the same species. With the help of the JPL catalogue, we checked whether rotational transitions of isotopologues of the molecules of interest fall in the observed frequency bands. We have not found lines of the $\text{C}_2\text{H}_3\text{CN}$ isotopologues: this is likely due to the fact that not all of the line frequencies have been determined yet in the laboratory. On the other hand, the observed bandwiths cover 7 lines of $\text{C}_2\text{H}_3\text{CN}$ isotopologues (5 $\text{CH}_3\text{C}^{13}\text{H}_2\text{CN}$ lines and 2 $\text{CH}_3\text{CH}_2\text{C}^{13}\text{N}$ lines), but they are all undetected. Therefore, we can derive only upper limits on their optical depth: assuming a $^{12}\text{C}/^{13}\text{C}$ ratio of 10, the minimum upper limit turns out to be $\tau = 1.7$ which is not sufficient to conclude that the $\text{C}_2\text{H}_3\text{CN}$ lines are optically thin. Nevertheless, the good agreement between the data and the linear fits indicates that the assumption of optically thin lines is reasonable in our sources.
3.3. HCOOCH$_3$

As pointed out in Sec. 3, many HCOOCH$_3$ transitions are blended with other lines. Therefore, we used the software XCLASS to solve this problem (see Sect. 2). The spectra in BAND1-HCN offer the only opportunity in our data sets to fit simultaneously many HCOOCH$_3$ lines with energy of the upper level from about 150 to 300 K. In Fig. 2 we show an example spectrum at 258500 MHz with highly blended lines fitted by XCLASS. The rotation diagrams of only two sources, G10.47 and G31.41, give reliable fit results. Although the temperature is not well determined by the fit, the total column density is quite accurate since it accounts mainly for the total intensity of the blended feature. We derive source averaged total column densities of $3.7 \times 10^{17}$ cm$^{-2}$ for G10.47 and $5.3 \times 10^{17}$ cm$^{-2}$ for G31.41. The HCOOCH$_3$ fractional abundances are therefore $\sim 3.1 \times 10^{-8}$ and $\sim 4.4 \times 10^{-8}$ for G10.47 and G31.41, respectively. Both column densities and abundances are consistent with the values found by Bisschop et al. (2007) in similar HMCs.

3.4. Vibrationally excited C$_2$H$_3$CN in G10.47

Several lines of vibrationally excited C$_2$H$_3$CN have been identified at 218 GHz (see Fig. 3) towards the source G10.47. The main line parameters are given in Table 5. These lines have been identified for the first time by Nummelin et al. (1998) in the Sagittarius B2 molecular cloud. The frequencies for the in-plane CCN bend $v_{11}$ at 342 K and the CCN out-of-plane bend $v_{15}$ at 486 K are taken from the JPL catalogue (Poynter & Pickett 1985, Pickett et al. 1996).

---

**Fig. 2.** Sample spectrum of HCOOCH$_3$ in BAND1-HCN towards the source G10.47. We used the XCLASS software to solve the blending problem in this frequency band.
Fig. 3. Vibrationally excited vinyl cyanide in G10.47 at 218 GHz. The lines are marked with their vibrational mode and upper energies are given.

Table 5. Rest frequency ($\nu$), energy of the upper level ($E_u$) and integrated intensity ($\int T_{MB}dv$) of 9 unblended vibrational lines of C$_2$H$_3$CN detected towards G10.47.

| $\nu$ (MHz) | $E_u$ (K) | $\int T_{MB}dv$ (K km s$^{-1}$) |
|-------------|-----------|-------------------------------|
| 218719.6    | 756       | 3.23                          |
| 218728.9    | 671       | 4.15                          |
| 218830.5    | 835       | 3.57                          |
| 218841.6    | 651       | 3.31                          |
| 218878.6    | 651       | 3.28                          |
| 219027.1    | 574       | 5.68                          |
| 219077.1    | 642       | 4.71                          |
| 219099.1    | 523       | 5.81                          |
| 219125.8    | 682       | 3.46                          |

We also have found two "weak" C$_2$H$_3$CN transitions (i.e. transitions with low $\mu^2S$, at $E_u < 100$ K, see Fig. 1). Both vibrational and “weak” lines are unlikely to be optically thick. Therefore, we combine them to derive both temperature and column density. We obtain a rotational temperature of 135 ± 13 K and a source averaged total column density of 1.3±0.6×10$^{18}$ cm$^{-2}$. The temperature is equal, within the error bar, to that given in Tab. 4 but the density is about a factor of 20 higher. Note that it is also a factor of 10 higher than C$_2$H$_5$CN column den-
Table 6. Rest frequency (ν), energy of the upper level (E_u) and integrated intensity (\( \int T_{MB}dv \)) of 12 unblended vibrational lines of C_2H_5CN detected towards G10.47 and G31.41.

| Source | ν   | E_u | \( \int T_{MB}dv \) |
|--------|-----|-----|---------------------|
|        | (MHz) | (K) | (K km s\(^{-1}\)) |
| G10.47 |       |     |                     |
|        | 98464 | 410 | 2.0466              |
|        | 98539 | 409 | 0.85978             |
|        | 98619 | 361 | 5.3485              |
|        | 98672 | 377 | 1.9452              |
|        | 161338 | 422 | 3.4767              |
|        | 224380 | 342 | 2.9466              |
|        | 224396 | 616 | 2.1549              |
|        | 224409 | 542 | 2.8934              |
|        | 224480 | 522 | 2.7522              |
| G31.41 |       |     |                     |
|        | 98464 | 410 | 0.64                |
|        | 98619 | 361 | 1.83                |
|        | 98672 | 377 | 1.27                |
|        | 98737 | 342 | 1.90                |
|        | 161338 | 422 | 2.35                |
|        | 224378 | 577 | 4.28                |
|        | 224408 | 542 | 3.63                |
|        | 224479 | 522 | 2.06                |

The presence of both "weak" rotational and vibrational lines suggest that some "strong" rotational transitions can suffer from high optical depth. Therefore, correcting the data following the method described in Sect. 3.2.4, we obtain a best fit for the following parameters: \( N_\text{i} = (2.3 \pm 0.4) \times 10^{18} \text{cm}^{-2} \), \( T = 133 \pm 3 \text{ K} \), and \( \theta \sim 1.6'' \).

3.5. Vibrationally excited C_2H_5CN in G10.47 and G31.41

Using the compilation of Pearson (2002), we have searched for vibrationally excited C_2H_5CN transitions. We have identified 9 lines in G10.47 and 8 in G31.41. In Fig. 4 and Fig. 5 we show the 3 bands in which vibrationally excited lines of C_2H_5CN have been identified. The main parameters of the identified lines are listed in Table 6. Vibrationally excited C_2H_5CN was firstly identified by Mehriger et al. (2004) in Sgr B2.

4. Discussion

4.1. Comparison between N-bearing and O-bearing molecules

A different spatial distribution between N-bearing and O-bearing molecules has been observed in some HMCs (see Blake et al. 1987, Wright et al. 1992, 1996, and Beuther et al. 2005 for Orion;
Fig. 4. Bands in which vibrationally excited C$_2$H$_5$CN transitions have been identified (solid line) towards the source G10.47.

Wyrowski et al. 1999 for W3(H$_2$O)). Caselli et al. (1993) interpreted the difference seen in Orion as being due to the fact that N-bearing and O-bearing species trace regions of the HMCs with different physical properties. Charnley et al. (1992) simply use different grain mantle compositions for the Orion-HC and Compact Ridge to reproduce the observed differentiation.
Fig. 5. Bands in which vibrationally excited C$_2$H$_5$CN transitions have been identified (solid line) towards the source G31.41.

In order to see if such a differentiation is observable in the HMCs of our sample, we compare in each source the main physical properties (velocity, column density, temperature and abundance) obtained from N- and O-bearing species.
4.1.1. Line velocities and widths at half maximum

Peak velocities, $V_{\text{LSR}}$, and line widths at half maximum, $\Delta V$, of the unblended lines detected in each source are listed in Cols. 3 and 4, respectively, of Table 7. Both $V_{\text{LSR}}$ and $\Delta V$ have been obtained from single Gaussian fits to the lines. In Cols. 2 and 3 of Table 8 we report the average values of $V_{\text{LSR}}$ for the unblended lines of C$_2$H$_5$CN, $V_N$, and CH$_3$OCH$_3$, $V_O$, respectively, and their difference ($V_N - V_O$) is given in Col. 4. In Cols. 5, 6 and 7 of the same Table we also list the average value of the linewidths for C$_2$H$_5$CN, $\Delta V_N$, and CH$_3$OCH$_3$, $\Delta V_O$, and their ratio ($\Delta V_N / \Delta V_O$), respectively.

The velocity differences $V_N - V_O$ and line width ratios $\Delta V_N / \Delta V_O$ found in each source are then plotted in Fig. 6. $V_N - V_O$ shows that on average the C$_2$H$_5$CN lines have different velocities from the CH$_3$OCH$_3$ lines, in agreement with the idea that they are tracing different regions. The largest difference is for G10.62, for which however we stress that $V_N$ has been derived from 3 lines only, and one of these (the line at 224045 MHz) has a very uncertain velocity. On the other hand, no systematic differences are present in the line widths, except for G19.61 for which the C$_2$H$_5$CN lines are more than $\sim 1.5$ times larger than the CH$_3$OCH$_3$ lines. We point out that the values plotted in Fig. 6 are average values between lines observed at different wavelengths, and this can influence a lot the discussion of these quantities. In fact, the higher excitation lines, which trace the denser and hotter portion of the HMC, are also expected to have highest linewdths. Therefore, the number of unblended lines detected in each band, which are different for each source, may influence the average values both of velocities and linewidths. Also, each rotational transition of CH$_3$OCH$_3$ is split into four components coming from torsional motions of the molecule. The separation of these components in velocity is much smaller than the spectral resolution of our data, so that they are not resolved. Even though the software can derive the intrinsic $\Delta V$ and $V_{\text{LSR}}$ from the theoretical separation of the different components, we believe that $\Delta V$ and $V_{\text{LSR}}$ from these lines are less accurate than those derived from C$_2$H$_5$CN. For these reasons, we stress that the quantities plotted in Fig. 6 have to be interpreted carefully.

4.1.2. Abundance correlations

The abundances relative to H$_2$ of C$_2$H$_5$CN, C$_2$H$_3$CN and CH$_3$OCH$_3$ are compared in Figure 7. For each pair of tracers, we have performed a least square fit to the data to check a possible correlation between the different abundances. The left panel of Figure 7 shows that the abundances of the two N-bearing molecules, C$_2$H$_5$CN and C$_2$H$_3$CN, are strongly correlated (correlation coefficient $r \sim 0.96$). This result agrees with the theoretical prediction that C$_2$H$_3$CN is produced through gas-phase reactions involving C$_2$H$_5$CN (Caselli et al. 1993). On the other hand, central and right panels of Figure 7 show that there is correlation also between the abundances of C$_2$H$_5$CN and C$_2$H$_3$CN, and that of CH$_3$OCH$_3$ (correlation coefficients $\sim 0.90$ and $\sim 0.86$, respectively). CH$_3$OCH$_3$ is thought to form both through reactions on grain surfaces (CH$_3$ + CH$_3$O $\rightarrow$ CH$_3$OCH$_3$, Allen & Robinson 1977), and in the gas phase through reactions between
methanol and protonated methanol (Garrod & Herbst 2006), but both formation processes are not expected to involve species containing nitrogen. Furthermore, Bisschop et al. (2007) have indeed shown that in their HMCs the CH$_3$OCH$_3$ abundance does not correlate with that of other N-bearing species (see their Table 8). Nevertheless, based on considerations about abundance ratios and temperatures, they suggest that the O- and N-bearing molecules observed in their work may have experienced a common formation scheme.

In Figure 8 we plot the molecular abundances against the total H$_2$ column densities. Even though the uncertainties on these quantities are large, Figure 8 shows that on average cores with higher H$_2$ column density have also larger column densities of C$_2$H$_5$CN, C$_2$H$_3$CN and CH$_3$OCH$_3$, without any substantial difference between O- and N-bearing species. We have also checked if a correlation is present between the observed abundances and the gas temperature: none of the sources show a correlation between these two parameters. In summary, we do not see

**Fig. 6.** Top panel: difference between the average velocities of unblended transitions of C$_2$H$_5$CN ($V_N$) and CH$_3$OCH$_3$ ($V_O$). Bottom panel: ratio between the average line widths at half maximum of C$_2$H$_5$CN ($\Delta V_N$) and CH$_3$OCH$_3$ ($\Delta V_O$). Source code number is taken from Table 1.
Fig. 7. Comparison between the molecular abundances of C$_2$H$_5$CN and C$_2$H$_3$CN (left panel), C$_2$H$_5$CN and CH$_3$OCH$_3$ (central panel) and C$_2$H$_5$CN and CH$_3$OCH$_3$ (right panel). All abundances are relative to H$_2$. The solid lines correspond to the best-fits. The upper limit for the C$_2$H$_3$CN abundance in G10.62 is indicated by an arrow. Errorbars representing the typical uncertainties are shown in the lower right corners.

Fig. 8. Comparison between the H$_2$ total column density and the molecular abundances of C$_2$H$_5$CN (left panel), C$_2$H$_3$CN (central panel) and CH$_3$OCH$_3$ (right panel). The upper limit for the C$_2$H$_3$CN abundance in G10.62 is indicated by an arrow. Errorbars representing the typical uncertainties are shown in the lower right corners.

any difference between CH$_3$OCH$_3$ and the two N-bearing species when comparing their abundances both to the gas temperature and density of the cores.

4.1.3. Beam-averaged column densities and rotational temperatures

Figure 9 shows the ratios between the beam averaged column densities (top panel) and those between the rotational temperatures derived from C$_2$H$_5$CN and CH$_3$OCH$_3$ (see Tab. 4). The plot indicates that the column densities obtained from C$_2$H$_5$CN are on average marginally higher (a factor of $\sim 2.5$) than those derived from CH$_3$OCH$_3$, suggesting that C$_2$H$_5$CN may indeed trace a region marginally denser than that traced by CH$_3$OCH$_3$. We note a significant (a factor of $\sim 11$) difference in G19.61, which is the source in which there is also the largest difference in linewidths between C$_2$H$_5$CN and CH$_3$OCH$_3$, suggesting that C$_2$H$_5$CN is actually associated with a denser and more turbulent sub-region of the HMC. On the other hand, no systematic difference is found in the rotational temperatures, with the significant exception of G10.62, for which we find a value more than 5 times higher from C$_2$H$_5$CN. However, for this source the temperature from CH$_3$OCH$_3$ is less accurate because it is derived from three transitions only.
Figs. 6, 7 and 9 do not allow to conclude that the O- and N-bearing species observed in this work trace different HMC regions. However, when discussing these results one has to bear in mind that the angular resolution of our data is much larger than the size of the HMC. High angular resolution observations have demonstrated that the environment of some of our HMCs, and in general of massive YSOs, has a complex structure, and may be fragmented in objects with different masses and in different evolutionary stages (see e.g. Garay et al. 1998 for G19.61; Avalos et al. 2006 and Mookerjea et al. 2007 for G34.26), whose angular separation is comparable to or even smaller than the angular resolution of the observations. The observed emission is hence affected both by the emission of other molecular condensations close to the main one and, less likely, by the emission of the cooler molecular gas of the envelope surrounding the HMC. Therefore, it is difficult to reveal a clear differentiation between O- and N-bearing species since the observed line parameters represent average values in the whole source.

Table 7: Line velocities ($V_{\text{LSR}}$) and widths at half maximum ($\Delta V$) derived from single Gaussian fits to unblended lines for the sources G10.47, G10.62 and G19.61. The errors of the Gaussian fits to the lines are given between brackets.

| Molecule | frequency (MHz) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) |
|----------|----------------|-------------------------------|-------------------------|
| G10.47   |                |                               |                         |
| C$_2$H$_5$CN | 98701.1090 67.249 (0.15) | 8.411 (0.36) |
|          | 161581.2030 66.782 (0.48) | 13.001 (1.37) |
|          | 161367.344 67.564 (0.37) | 9.842 (0.86) |
|          | 224458.8590 66.546 (0.26) | 10.180 (0.73) |
|          | 224419.8120 66.952 (0.35) | 11.136 (1.12) |
| C$_2$H$_3$CN | 147561.719 66.866 (0.49) | 9.277 (1.09) |
| CH$_3$OCH$_3$ | 111783.241 66.745 (0.14) | 9.939 (0.36) |
|          | 111782.596 66.754 (0.14) | 9.555 (0.22) |
|          | 147456.863 66.940 (0.54) | 13.100 (1.19) |
|          | 237620.371 65.184 (0.43) | 11.751 (1.07) |
| G10.62   |                |                               |                         |
| C$_2$H$_5$CN | 161581.203 -1.667 (0.82) | 5.934 (1.51) |
|          | 224045.750 0.395 (0.35) | 4.703 (0.78) |
|          | 224419.812 -1.409 (0.40) | 6.208 (0.83) |
| C$_2$H$_3$CN | – – – – | – – – – |
| CH$_3$OCH$_3$ | 111783.241 -3.440 (0.28) | 7.852 (0.58) |
|          | 111782.596 -3.429 (0.28) | 7.357 (0.38) |
|          | 147210.732 -2.726 (0.27) | 2.730 (0.57) |
| G19.61 |   |
|-------|---|
| C₂H₅CN | 98701.109 | 39.665 (0.40) | 10.119 (0.95) |
|        | 161581.203 | 40.198 (0.52) | 12.758 (1.57) |
|        | 161367.344 | 43.908 (0.72) | 9.451 (2.02) |
|        | 224045.750 | 39.835 (0.43) | 6.861 (1.06) |
|        | 224419.812 | 40.334 (0.39) | 7.634 (1.25) |
| C₂H₃CN | – | – | – |
| CH₃OCH₃ | 111783.241 | 41.429 (0.53) | 5.955 (0.99) |
|        | 111782.596 | 41.427 (0.53) | 5.264 (0.66) |

| G29.96 |   |
|-------|---|
| C₂H₅CN | 98701.109 | 97.792 (0.29) | 4.721 (0.91) |
|        | 161581.203 | 97.413 (0.73) | 7.728 (2.19) |
|        | 161367.344 | 98.110 (1.47) | 11.032 (4.69) |
|        | 224045.750 | 98.124 (0.73) | 6.617 (1.53) |
|        | 224419.812 | 97.169 (0.24) | 2.854 (0.59) |
|        | 224458.859 | 96.595 (0.60) | 5.633 (1.39) |
| C₂H₃CN | – | – | – |
| CH₃OCH₃ | 111783.241 | 97.929 (0.34) | 5.675 (0.88) |
|        | 111782.596 | 97.976 (0.32) | 4.919 (0.58) |
|        | 147210.732 | 105.190 (1.13) | 10.947 (3.52) |

| G31.41 |   |
|-------|---|
| C₂H₅CN | 98701.109 | 97.711 (0.26) | 8.289 (0.58) |
|        | 161581.203 | 97.179 (0.38) | 8.365 (1.07) |
|        | 161367.344 | 97.006 (1.02) | 8.245 (2.25) |
|        | 224458.859 | 96.673 (0.50) | 9.998 (1.67) |
|        | 224419.812 | 97.140 (0.36) | 9.065 (0.93) |
| C₂H₃CN | 147561.719 | 97.316 (0.46) | 9.643 (1.10) |
| CH₃OCH₃ | 111783.241 | 98.104 (0.06) | 7.181 (0.15) |
|        | 111782.596 | 98.125 (0.06) | 6.617 (0.10) |
|        | 147210.732 | 97.580 (0.18) | 5.502 (0.49) |
|        | 173293.064 | 98.255 (0.36) | 5.641 (0.83) |
|        | 237620.371 | 96.334 (0.20) | 7.338 (0.46) |

| G34.26 |   |
|-------|---|
| C₂H₅CN | 98701.109 | 57.333 (0.26) | 7.449 (0.66) |
|        | 161581.203 | 57.511 (0.34) | 8.542 (0.93) |
|        | 161367.344 | 57.103 (0.53) | 8.368 (1.46) |
|        | 224045.750 | 57.610 (0.39) | 3.691 (0.92) |
Table 8. Average line velocities and widths computed from the unblended lines of \( \text{C}_2\text{H}_3\text{CN} \) (\( V_N \) and \( \Delta V_N \), respectively) and \( \text{CH}_3\text{OCH}_3 \) (\( V_O \) and \( \Delta V_O \), respectively). Velocity differences (\( V_N - V_O \)) and linewidth ratios (\( \Delta V_N / \Delta V_O \)) are also given.

| Source | \( V_N \) | \( V_O \) | \( V_N - V_O \) | \( \Delta V_N \) | \( \Delta V_O \) | \( \Delta V_N / \Delta V_O \) |
|--------|-----------|-----------|----------------|-------------|-------------|----------------|
| G10.47 | 67.0      | 66.4      | 0.6            | 10.5        | 11.1        | 0.94           |
| G10.62 | –0.9      | –3.1      | –2.2           | 5.6         | 5.9         | 0.95           |
| G19.61 | 40.8      | 41.4      | –0.6           | 9.4         | 5.6         | 1.68           |
| G29.96 | 97.5      | 97.9      | –0.4           | 6.4         | 7.2         | 0.89           |
| G31.41 | 97.1      | 97.7      | –0.6           | 8.9         | 6.5         | 1.37           |
| G34.26 | 57.4      | 58.9      | –1.5           | 6.8         | 7.0         | 0.97           |

4.2. Hot core chemical ages

When comparing the observed abundance of different molecular species (see Sect. 3.2) from predictions of theoretical models, we can get some insights into the evolutionary stage of HMCs.

H-rich species are thought to form in icy mantles of dust grains and then released into the gas phase when the central massive (proto)star begins to heat up the surroundings. A following gas phase chemistry transforms many of the grain mantle products into other species. In particular, \( \text{C}_2\text{H}_3\text{CN} \), formed onto dust grains and then evaporated, is expected to form \( \text{C}_2\text{H}_3\text{CN} \) through gas-phase reactions (Caselli et al. 1993). The occurrence of these reactions, as well as those which destroy \( \text{C}_2\text{H}_3\text{CN} \), depends on the core physical parameters, which are thought to change with the core evolution. Therefore, the abundance ratio of \( \text{C}_2\text{H}_3\text{CN} \) and \( \text{C}_2\text{H}_3\text{CN} \) is correlated to the core evolutionary stage, and can be used as a 'chemical clock' for the HMC.

In Col. 2 of Tab. 9 we list the observational values for the abundance ratio \( R = X(\text{C}_2\text{H}_3\text{CN})/X(\text{C}_2\text{H}_3\text{CN}) \), derived from the molecule’s abundances given in Col. 6 of Table 4. We also plot these ratios in Fig. 10 together with the predictions of the chemical models of Caselli et al. (1993) for the Orion-HC and Compact Ridge. The physical and chemical properties of these two regions can be considered as 'extrema' for our HMCs, so that we will use them to constrain
Fig. 9. Top panel: ratio between the beam averaged total column densities ($N_b$ in Tab. 4) derived from $\text{C}_2\text{H}_5\text{CN}$ and $\text{CH}_3\text{OCH}_3$. Bottom panel: ratio between the rotational temperatures derived from $\text{C}_2\text{H}_5\text{CN}$ and $\text{CH}_3\text{OCH}_3$. The numbers on the x-axis indicate the identification number of each source as in Tab. 1. The dashed line represents equal column density or rotational temperature from $\text{C}_2\text{H}_5\text{CN}$ and $\text{CH}_3\text{OCH}_3$.

the chemical ages of our sample. Chemical models predict a sharp decrease in the abundances of many complex molecules, among which are $\text{C}_2\text{H}_3\text{CN}$ and $\text{C}_2\text{H}_5\text{CN}$, in HMCs after $\sim 10^5$ yrs (see Fig. 10). Therefore, the detection of several lines of both $\text{C}_2\text{H}_3\text{CN}$ and $\text{C}_2\text{H}_5\text{CN}$ suggest that all of our HMCs are likely younger than $\sim 10^5$ yrs. In fact, we find ages in the range from $\sim 3.7 \times 10^4$ to $\sim 5.9 \times 10^4$ yrs, with the HMC in G34.26 being the youngest and that in G29.96 the oldest. We point out that this procedure does not take into account the errors in the model predictions.

In Fig. 11 we also plot $R$ against the $\text{C}_2\text{H}_5\text{CN}$ fractional abundance and we compare it with the theoretical curve predicted for the Orion HC. From Fig. 11 we deduce that the model underestimates the observed ratio by a factor greater than 10. This could be due to a missing reaction
Fig. 10. Comparison between the observed abundance ratio of the daughter/parent pair \( \text{C}_2\text{H}_5\text{CN} / \text{C}_2\text{H}_3\text{CN} \) and the predictions of the chemical models of Caselli et al. (1993). The observed abundance ratio of each source is plotted as a horizontal line (see the top right corner for the source identification). The curves correspond to the predictions of the models by Caselli et al. (1993) for the Orion-HC (corresponding to \( T = 200 \text{ K} \) and \( n_{\text{H}_2} = 10^7 \text{ cm}^{-3} \)) and Compact Ridge (corresponding to \( T = 100 \text{ K} \) and \( n_{\text{H}_2} = 10^6 \text{ cm}^{-3} \)).

in the chemical network between \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{H}_3\text{O}^+ \). In fact, the hydronium ion is quite abundant in the HMC phase and could destroy some of the \( \text{C}_2\text{H}_5\text{CN} \) molecules, thus increasing the observed \( \text{C}_2\text{H}_3\text{CN}/\text{C}_2\text{H}_5\text{CN} \) abundance ratio (see e.g. Caselli et al. 1993). Another possibility is that additional \( \text{C}_2\text{H}_5\text{CN} \) forms in gas phase reactions as suggested by Charnley et al. (1992) and Rodgers & Charnley (2001).

4.3. Comments on individual sources

In this Section we describe the main properties of each source on the basis of the results obtained both in this work and from previous observations.

G10.47+0.03 In this region three UC H\( \alpha \)s are associated with a HMC (see e.g. Gibb et al. 2004). Observations of CH\( \text{CN} \) (13–12) and (19–18) (Hatchell et al. 1998) show that the temperature increases from \( \sim 87 \text{ K} \) at a distance of \( \sim 2.3'' \) from the centre, to \( \sim 134 \text{ K} \) at 0.8” from the centre, indicating a temperature gradient. This is confirmed by observations of the NH\( \text{3} \) (4,4) inversion transition (Cesaroni et al. 1998), that show temperature and velocity gradients, which can be interpreted in terms of a rotating structure with temperature increasing towards the centre. Our
Table 9. Hot cores chemical ages

| Source | $R$     | $t_{\text{min}}$ | $t_{\text{max}}$ |
|--------|---------|------------------|------------------|
|        | (×10$^4$ yr) |
| G10.47 | 0.5±0.2 | 5.0              | 5.4              |
| G19.61 | 0.4±0.2 | 4.7              | 5.0              |
| G29.96 | 0.5±0.1 | 4.7              | 5.9              |
| G31.41 | 0.4±0.1 | 4.3              | 4.7              |
| G34.26 | 0.3±0.1 | 3.7              | 4.2              |

$R = X(C_2H_3CN)/X(C_2H_5CN)$

Fig. 11. Observed abundance ratio $R = X(C_2H_3CN)/X(C_2H_5CN)$ against $C_2H_5CN$ fractional abundance. The solid line represents the prediction of the model by Caselli et al. (1993) for the Orion-HC ($T = 200$ K, $n = 10^7$ cm$^{-3}$). The numbers identify the sources as in Table 1.

Fig. 6 indicates a small difference in the line velocities of O- and N-bearing molecules, suggesting that they are likely arising from marginally different regions. This result agrees with that of Olmi et al. (1996), who found a displacement between HCOOCH$_3$ and CH$_3$CN of ~0.5″. The most surprising property of this source is the high $C_2H_3CN$ column density. The presence of both vibrationally excited (see Sect. 3.4) and "weak" b-type lines (see Sect. 3.2.4) suggest that temperature measurements agree with the estimates obtained by Hatchell et al. (1998) at ~ 1″ from the core centre.
C$_2$H$_3$CN is about 10 times more abundant than C$_2$H$_5$CN. If we use in the rotation diagram all our data ("strong", "weak" and vibrationally excited lines) and we correct for the optical depth (see Wyrowski et al. 1999 for the procedure) we obtain the following best fit parameters: $N_s \sim 1.7 \times 10^{18}$ cm$^{-2}$, $T_{\text{rot}} \sim 140$ K and $\theta \sim 1''$. A previous study of vibrationally excited HC$_3$N also showed anomalous high abundance for this molecule, a column density of $\sim 4 \times 10^{18}$ cm$^{-2}$, comparable with that from C$_2$H$_3$CN. This result is in agreement with the model predictions of Caselli et al. (1993), who showed that the abundances of HC$_3$N and C$_2$H$_3$CN, after evaporation from dust grains, vary in a very similar way both in the Orion-HC for $t > 100$ yrs (see their Fig. 4) and in the Compact Ridge for $t \geq 10^4$ yrs (see their Fig. 5), while those of C$_2$H$_5$CN and HC$_3$N are very different between them. In fact, the destruction of C$_2$H$_5$CN by molecular ions (in particular H$_3^+$) leads to the production of both C$_2$H$_3$CN and HC$_3$N via dissociative recombination of C$_3$H$_4$N$^+$ (formed in the reaction with H$_3^+$).

**G10.62–0.38** This star forming region consists of a cluster of OB stars embedded in a dense, collapsing molecular cloud (Ho & Haschick 1986, Keto et al. 1987, 1988, Sollins et al. 2005). Keto et al. (1987) find an average temperature of 95 K for the absorption components at -3.0 and -0.5 km s$^{-1}$ and 140 K at 1.9 km s$^{-1}$, while the average temperature for the gas seen in emission, away from the UC H$_2$O, is 54 K; they suggest a temperature decreasing from the HMC center with a power-law of the type $R^{-0.5}$. The temperature derived from C$_2$H$_5$CN (see Table 4) indicates that this molecule traces a region at about 0.1 pc from the centre of the core, which also coincides with the centre of the continuum emission of the UC H$_2$O region. The C$_2$H$_5$CN and CH$_3$OCH$_3$ line velocities in Fig. 6 show that these molecules are spatially separated, with the latter more distant from the UC H$_2$O. This is also suggested by the temperature derived from CH$_3$OCH$_3$, even though the statistics are very poor because only three lines at $E_u < 100$ K have been identified. We find only one blended transition of C$_2$H$_3$CN in all our spectra so we cannot estimate rotational temperature and column density for this molecule.

**G19.61–0.23** This is a complex region with an irregular structure both of the ionized gas (Wood & Churchwell 1990), and of the molecular emission from the associated molecular clumps. Garay et al. (1998) found five distinct UC H$_2$O regions excited by individual stars from VLA observations of the ionized and molecular gas (NH$_3$(2,2) inversion line): the cometary-like and most compact of them is associated with the densest ammonia clump, called Middle clump to distinguish it from the Northern and the Southwestern clumps. The Middle clump exhibits very broad line widths ($\sim 9.5$ km s$^{-1}$) and is characterized by a $V_{\text{LSR}}$ of $39.3 \pm 0.1$ km s$^{-1}$ in the main NH$_3$(2,2) line: these values are similar to those we find for C$_2$H$_5$CN. The Southwestern clump shows lower $\Delta V$ and higher $V_{\text{LSR}}$ equal to those for CH$_3$OCH$_3$. This seems to suggest that N- and O-bearing molecular emission originates from separate regions. This is confirmed by the column density ratio between C$_2$H$_5$CN and CH$_3$OCH$_3$, much higher than those of the other sources (see Fig. 7), suggesting that C$_2$H$_5$CN indeed traces a region denser than that traced by O-bearing species.
In spite of this, high angular resolution observations of two rotational lines of $\text{C}_2\text{H}_5\text{CN}$ and HCOOCH$_3$, performed with BIMA (Remijan et al. 2004), indicate that these molecules seem to trace the same region.

G29.96–0.02 G29.96 is an example of UC H$\upalpha$ cometary region. High angular resolution VLA observations in the ammonia (4,4) inversion transition (Cesaroni et al. 1998) show that the HMC has a nearly symmetric profile, and is not affected by the presence of the embedded UC H$\upalpha$ region. Our rotational temperatures agree with those obtained by Hatchell et al. (1998) from CH$_3$CN (13–12) and (19–18) and are higher than the estimate that they derive from CH$_3$OH ($T_{\text{rot}} \sim 48$ K). This could indicate that O-bearing molecules map colder and extended gas. Nevertheless, Fig. 6 does not show any displacement between the location of O- and N-bearing molecules: both their $\Delta V$ and $V_{\text{LSR}}$ are, in fact, equal within the error bars. This is supported by high angular resolution observations (Olmi et al. 2003) which have shown that some lines of HCOOCH$_3$ and the N-bearing molecule CH$_3$CN trace approximately the same region. Our $V_{\text{LSR}}$ also agrees with those of C$^{17}$O (2-1) and (3-2) measured by Hofner et al. (2000).

G31.41+0.31 The region is made of a core-halo UC H$\upalpha$ region, offset by $\sim 5''$ from a hot core in which Beltrán et al. (2005) have revealed a rotating toroidal structure. Also, as already mentioned in Sect. 3.1 they serendipitously detected the $\text{C}_2\text{H}_5\text{CN}$ (25$_{2,24}$ – 24$_{2,23}$) and HCOOCH$_3$-A (25$_{11,15}$ – 26$_{9,18}$) lines, and found from their high-angular resolution maps that, even though the two tracers peak at slightly different positions, their integrated emissions and that of the 1.4 mm continuum are fairly well overlapping. Interferometric observations of CH$_3$CN lines (Olmi et al. 1996; Beltrán et al. 2005) and of the NH$_3$(4,4) main and satellite inversion lines (Cesaroni et al. 1998) show that both the column density and the temperature increase towards the HMC center. This hot and dense gas has also been detected through HC$_3$N (17-16) in its $v_7$ and $v_6$ vibrationally excited states (Wyrowski et al. 1999). The ratio between the intensity of these two lines point to temperatures of $\sim 250$ K.

Lower angular resolution maps of the CH$_3$CN (19-18) and (13-12) transitions (Hatchell et al. 1998) give a temperature in agreement with the estimate that we derive from our molecules (see Tab. 4). The $\Delta V$ of the CH$_3$CN lines are comparable to those measured by us from C$_2$H$_5$CN. CH$_3$OCH$_3$ and HCOOCH$_3$ have lower $\Delta V$, but the difference in $V_{\text{LSR}}$ between the O- and N-bearing molecules is small.

G34.26+0.15 This is a complex massive star formation region located at a distance of 3.7 kpc (Kuchar & Bania 1994) extensively studied both in radio continuum (Wood & Churchwell 1989; Avalos et al. 2006) and in molecular lines (e.g. Garay & Rodríguez 1990; Hatchell et al. 1998; Sewilo et al. 2004). VLA observations of the NH$_3$ (2,2) and (3,3) inversion transitions (Garay & Rodríguez 1990) reveal the presence of three distinct regions of the molecular gas:
– a low density \( n(\text{H}_2) \approx 10^4 \text{ cm}^{-3} \), low-temperature \( T_{\text{rot}} \approx 18 \text{ K} \) gas in front of a bright cometary UC H\( \alpha \) region.

– a warm gas \( T_{\text{rot}} \approx 70 \text{ K} \) in a molecular disk-like structure \( \approx 7.3'' \times 2.8'' \) in size, mapped by the main hyperfine component of the (3,3) transition, seen in absorption.

– an ultracompact region \( \approx 1.6'' \) in size, \( \approx 2'' \) to the east of the bright cometary UC H\( \alpha \) region, traced by the satellite hyperfine lines of the (2,2) and (3,3) transitions. It is characterized by a rotational temperature of \( 185^{+75}_{-45} \text{ K} \) and by a \( \text{H}_2 \) density of \( \approx 7 \times 10^7 \text{ cm}^{-3} \).

The \( \text{H}_2 \) density and temperatures estimated from the tracers studied in this paper agree with those given by Garay & Rodríguez (1990). Mookerjea et al. (2007) have observed with \( \sim 1'' \) resolution two transitions of \( \text{C}_2\text{H}_5\text{CN} \), and one transition of \( \text{CH}_3\text{OCH}_3 \) and \( \text{HCOOCH}_3 \), but all of them fall out of the bands observed in this work. From these maps and those of other molecular species, Mookerjea et al. (2007) have concluded that O- and N-bearing species peak at different positions, separated by \( \sim 0.8' \), with a spatial separation similar to that observed in Orion. Given the low angular resolution of our data and the complexity of the region, such a differentiation is not shown from our observations. Hatchell et al. (1998) found evidence for temperature and density gradient in this source: the high excitation \( \text{CH}_3\text{CN} \) (19-18) transitions trace a smaller, hotter and denser region than that traced by \( \text{CH}_3\text{CN} \) (13-12). Our \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{CH}_3\text{OCH}_3 \) temperatures agree with those of the higher excitation lines, indicating that they trace the same hot gas.

5. Conclusions

We have surveyed rotational transitions of 4 complex O- and N-bearing molecules, \( \text{C}_2\text{H}_3\text{CN} \), \( \text{C}_2\text{H}_5\text{CN} \), \( \text{CH}_3\text{OCH}_3 \) and \( \text{HCOOCH}_3 \), with the IRAM-30m telescope towards a selected sample of 12 well-known HCs, all of them associated with UC H\( \alpha \) regions. For 6 sources of our sample, we have detected a sufficient number of transitions to derive the main physical properties of the cores. We focus our analysis on the 3 species \( \text{C}_2\text{H}_3\text{CN} \), \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{CH}_3\text{OCH}_3 \) only, because the \( \text{HCOOCH}_3 \) lines are usually blended. The main results of our study are summarised as follows:

– From the rotational lines of \( \text{C}_2\text{H}_3\text{CN} \), \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{CH}_3\text{OCH}_3 \), we have derived rotational temperatures from \( \sim 100 \) to \( \sim 150 \text{ K} \), and source averaged total column densities of order of \( 10^{15} - 10^{17} \text{ cm}^{-2} \). Temperatures and column densities derived from the three tracers are typically in good agreement among them in each source, indicating that they are tracing approximately the same dense and hot gas of the cores.

– The abundances relative to \( \text{H}_2 \) are of the order of \( \sim 10^{-9} - 10^{-10} \) for all species, and are comparable to the values found in the Orion-hot core and in Sgr B2. The \( \text{C}_2\text{H}_3\text{CN} \) abundances are also comparable to those derived in other HMCs by Bisschop et al. (2007), while for \( \text{CH}_3\text{OCH}_3 \) we find values a factor of \( \sim 2.5 \) lower. There is a strong correlation between the abundances of \( \text{C}_2\text{H}_3\text{CN} \) and \( \text{C}_2\text{H}_5\text{CN} \), as expected from theory that predicts that the latter is formed through gas phase reactions involving \( \text{C}_2\text{H}_3\text{CN} \). Interestingly, a correlation is present
also between the two N-bearing species and CH$_3$OCH$_3$, in disagreement with the results found by Bisschop et al. (2007) in similar sources.

- Single Gaussian fits to unblended lines reveal a small difference between the average peak velocity of C$_2$H$_5$CN and CH$_3$OCH$_3$ lines, suggesting a possible spatial separation of the two tracers, as seen in Orion and W3(H$_2$O). On the other hand, no systematic differences are found in the linewidths. We find a clear difference only in G19.61. We believe that this partly is due to the poor angular resolution of our observations, which allows us to derive only average values over the sources, which show a complex morphology.

- We have compared the abundance ratio of the daughter/parent pair C$_2$H$_5$CN/C$_2$H$_3$CN with the predictions of chemical models to constrain the HCs’ chemical ages. We find ages between 3.7-5.9×10$^4$ yrs. We also compared this ratio against C$_2$H$_5$CN fractional abundance, finding that chemical models underestimate even by a factor greater than 10 our observational results.

The chemical and physical differentiation between O- and N-bearing molecules seen in the Orion HC and W3(H$_2$O) is not revealed by our observations of other HMCs. We stress however that our data have beam size much larger than the diameters of the HMCs, providing only average values of the physical parameters of interest in the whole molecular clump hosting the cores, and may be affected by other objects embedded inside the clumps themselves. Follow-up observations with millimeter and sub-millimeter interferometers (in particular ALMA, available in the near future) will be fundamental to provide maps with resolution comparable or even smaller than the core sizes, thus allowing us to derive with better spatial accuracy the physical parameters of the HMCs.

Acknowledgements. We are grateful to the IRAM-30m telescope staff for their assistance. We thank Peter Schilke for providing us with the XCLASS program. Ilaria Pascucci would like to thank Thomas Henning for helpful discussions. Many thanks to Geoff Macdonald for his corrections and suggestions.
Fig. 1. Spectra obtained towards G10.47 with the IRAM-30m Telescope during the 1997 observing run.

Appendix A: Observed spectra

Appendix B: Tables

Tables 1.11 list the molecular transitions used to derive the rotational temperatures and total column densities of the sources in Table 3. For each line we give: rest frequency, \( \nu \), in MHz (Col. 1, indicated with "b" if it is a b-type transition); the molecular species (Col. 2); the energy
Fig. 2. Spectra obtained towards G10.47 with the IRAM-30m Telescope during the 1996 observing run.

of the lower level, $E_l$, in cm$^{-1}$ (Col. 3); the line integrated emission, $\int T_{MB} \, dv$, in K km s$^{-1}$; (Col. 4); the quantity $\mu^2 S$, where $\mu$ (in Debye) is the molecule’s dipole moment and $S$ is the line strength (Col. 5). The CH$_3$OCH$_3$ lines are separated in four components not resolved in our spectra (see also Sect. 4.1). For this reason, for the CH$_3$OCH$_3$ transitions we give in Col. 4 the total integrated emission of the four components divided by the sum of the statistical weights of each component (for the statistical weights see Groner et al. 1998).
Fig. 3. Same as Fig. 1 for G10.62.

Table 1: Transitions observed towards G10.47 during the 1997 observing run.

| ν (MHz) | Molecule | $E_i$ (cm⁻¹) | $\int T_{MB} \, dv$ (K km s⁻¹) | $\mu^2 S$ (D²) |
|--------|----------|--------------|-------------------------------|----------------|
| 98399.6170 | C₂H₃CN | 66.0140 | 0.498 | 4.682 |
| Frequency | Species   | Mass 1 | Mass 2 | Mass 3 |
|-----------|-----------|--------|--------|--------|
| 98523.883 | C$_2$H$_3$CN | 44.251 | 3.33   | 113.939|
| 98524.664 | C$_2$H$_3$CN | 54.287 | 3.05   | 96.525 |
| 98532.070 | C$_2$H$_3$CN | 65.860 | 3.19   | 76.412 |
| 98533.984 | C$_2$H$_3$CN | 35.754 | 4.16   | 128.685|
| 98544.148 | C$_2$H$_3$CN | 78.967 | 2.78   | 53.615 |
| 98559.867 | C$_2$H$_3$CN | 93.604 | 1.64   | 28.149 |
| 98564.836 | C$_2$H$_3$CN | 28.801 | 4.11   | 140.761|
| 98566.797 | C$_2$H$_3$CN | 28.801 | 3.15   | 140.761|
| 98701.109 | C$_2$H$_3$CN | 23.398 | 4.38   | 150.140|
| b111574.625 | CH$_3$OCH$_3$ | 73.733 | 0.74   | 10.807 |
| b111783.241 | CH$_3$OCH$_3$ | 17.550 | 0.1439 | 27.2197|
| b111802.549 | CH$_3$OCH$_3$ | 42.142 | 0.0287 | 4.43093|
| b111813.417 | CH$_3$OCH$_3$ | 118.013 | 0.1204 | 96.5637|
| b147205.839 | CH$_3$OCH$_3$ | 22.082 | 0.2271 | 19.52177|
| b147456.863 | CH$_3$OCH$_3$ | 257.141 | 0.1097 | 145.57157|
| 147561.719 | C$_2$H$_3$CN | 38.491 | 4.70   | 232.515|
| 161261.141 | C$_2$H$_3$CN | 95.144 | 13.0   | 213.000|
| 161265.734 | C$_2$H$_3$CN | 108.253 | 12.5   | 199.066|
| b161281.953 | CH$_3$OCH$_3$ | 75.305 | 0.3944 | 49.41313|
| b161289.996 | CH$_3$OCH$_3$ | 333.668 | 0.1341 | 162.13361|
| 161303.484 | C$_2$H$_3$CN | 139.060 | 9.28   | 166.301|
| 161304.922 | C$_2$H$_3$CN | 73.536 | 11.3   | 235.930|
| 161367.344 | C$_2$H$_3$CN | 175.957 | 9.38   | 126.974|
| 161380.828 | C$_2$H$_3$CN | 101.33 | 15.13  | 246.2506|
| 161397.047 | CH$_3$OCH$_3$ | 97.114 | 6.92   | 217.164|
| 161441.2660 | C$_2$H$_3$CN | 139.0100 | 5.87   | 386.26|
| 161445.3910 | C$_2$H$_3$CN | 67.1130 | 7.04   | 234.339|
| 161450.3590 | C$_2$H$_3$CN | 67.1130 | 7.04   | 234.339|
| 161475.172 | C$_2$H$_3$CN | 52.712 | 19.70  | 258.004|
| 161502.266 | C$_2$H$_3$CN | 56.6050 | 9.00   | 240.337|
| 161516.7190 | C$_2$H$_3$CN | 58.1110 | 9.38   | 252.312|
| 161527.500 | C$_2$H$_3$CN | 192.6770 | 5.77   | 162.238|
| 161581.203 | C$_2$H$_3$CN | 58.115 | 14.3   | 252.312|
| 161582.047 | C$_2$H$_3$CN | 223.8800 | 3.37   | 144.202|
| 161643.250 | C$_2$H$_3$CN | 257.9690 | 4.50   | 124.459|
| 224002.109 | C$_2$H$_3$CN | 166.828 | 4.40   | 309.672|
| 224003.438 | C$_2$H$_3$CN | 152.185 | 6.00   | 320.879|
| 224045.750 | C$_2$H$_3$CN | 200.696 | 5.73   | 283.720|
| ν (MHz) | Molecule     | $E_i$ (cm$^{-1}$) | $\int T_{MB} dv$ (K km s$^{-1}$) | $\mu^2 S$ ($D^2$) |
|---------|--------------|------------------|----------------------------------|------------------|
| 224084.281 | C$_2$H$_5$CN | 219.912          | 5.20                             | 268.960          |
| 224088.2035 | C$_2$H$_5$CN | 127.510          | 6.00                             | 339.753          |
| 224131.516 | C$_2$H$_5$CN | 240.640          | 3.63                             | 253.034          |
| 224186.344 | C$_2$H$_5$CN | 262.876          | 3.27                             | 235.930          |
| 224206.609 | C$_2$H$_5$CN | 117.492          | 4.09                             | 347.406          |
| 224208.078 | C$_2$H$_5$CN | 117.492          | 4.09                             | 347.406          |
| b224231.688 | C$_2$H$_5$CN | 94.4160          | 2.05                             | 33.527           |
| 224248.016 | C$_2$H$_5$CN | 286.614          | 2.21                             | 217.645          |
| 224389.719 | C$_2$H$_5$CN | 338.567          | 2.25                             | 177.537          |
| 224419.812 | C$_2$H$_5$CN | 109.033          | 6.34                             | 353.894          |
| 224458.859 | C$_2$H$_5$CN | 109.036          | 8.10                             | 353.894          |
| b237360.891 | C$_2$H$_5$CN | 114.9850         | 2.33                             | 24.209           |
| 237396.9765 | C$_2$H$_5$CN | 168.5260         | 5.15                             | 336.209          |
| 237405.1880 | C$_2$H$_5$CN | 101.8870         | 13.71                            | 380.894          |
| 237456.2500 | C$_2$H$_5$CN | 216.3420         | 5.07                             | 635.06           |
| 237482.766 | C$_2$H$_5$CN | 132.5690         | 4.06                             | 350.218          |
| 237485.016 | C$_2$H$_5$CN | 132.5700         | 3.61                             | 350.218          |
| 237548.541 | CH$_3$OCH$_3$ | 447.259          | 0.200                            | 34.69413         |
| 237585.484 | C$_2$H$_5$CN | 275.8720         | 3.58                             | 294.183          |
| 237591.391 | C$_2$H$_5$CN | 108.5880         | 6.11                             | 359.528          |
| b237620.371 | CH$_3$OCH$_3$ | 32.291           | 0.551                            | 23.17836         |
| 237638.0160 | C$_2$H$_5$CN | 119.0860         | 6.74                             | 355.471          |
| 237668.766 | C$_2$H$_5$CN | 309.9800         | 4.29                             | 280.758          |

Table.2: Transitions observed towards G10.47 during the 1996 observing run.
| ν (MHz) | Molecule | $E_l$ (cm$^{-1}$) | $\int T_{MB} dv$ (K km s$^{-1}$) | $\mu^2 S$ ($D^2$) |
|--------|----------|----------------|-----------------|----------------|
| b111783.241 | CH$_3$OCH$_3$ | 17.550 | 0.0403 | 27.2197 |
| 111802.17 | CH$_3$OCH$_3$ | 42.141 | 0.016 | 2.53886 |
| 111802.93 | CH$_3$OCH$_3$ | 42.142 | 0.013 | 2.53886 |
| 111813.417 | CH$_3$OCH$_3$ | 118.013 | 0.016 | 96.5637 |
| b147205.839 | CH$_3$OCH$_3$ | 22.082 | 0.0478 | 19.52177 |
| 147456.863 | CH$_3$OCH$_3$ | 257.141 | 0.0196 | 145.57157 |
| 161261.141 | C$_2$H$_5$CN | 95.144 | 1.82 | 213.000 |
| 161265.734 | C$_2$H$_5$CN | 108.253 | 0.32 | 199.066 |
| 161281.953 | CH$_3$OCH$_3$ | 75.305 | 0.0572 | 49.41313 |
| 161289.996 | CH$_3$OCH$_3$ | 333.668 | 0.0572 | 162.13361 |
| 161475.172 | C$_2$H$_5$CN | 52.712 | 0.86 | 258.004 |
| 161581.203 | C$_2$H$_5$CN | 58.115 | 1.07 | 252.312 |
| 224002.109 | C$_2$H$_5$CN | 166.828 | 0.78 | 309.672 |
| 224003.438 | C$_2$H$_5$CN | 152.185 | 0.97 | 320.879 |
| 224045.750 | C$_2$H$_5$CN | 200.696 | 0.65 | 283.720 |
| 224084.281 | C$_2$H$_5$CN | 219.912 | 0.39 | 268.960 |
| 224088.2035 | C$_2$H$_5$CN | 127.510 | 1.16 | 339.753 |
| 224206.609 | C$_2$H$_5$CN | 117.492 | 1.05 | 347.406 |
Table 4: Transitions observed towards G10.62–0.38 during the 1996 July observing run.

| ν (MHz) | Molecule  | $E_i$ (cm$^{-1}$) | $\int T_{MB} dv$ (K km s$^{-1}$) | $\mu^2S$ (D$^2$) |
|---------|-----------|------------------|-------------------------------|----------------|
| 215040.8 | C$_2$H$_5$CN | 229.5 | 2.49 | 1199.4 |
| 215109.047 | C$_2$H$_5$CN | 183.46 | 3.25 | 651.1 |
| 215427.984 | C$_2$H$_5$CN | 156.88 | 1.67 | 340.332 |

Table 5: Transitions observed towards G19.61–0.23 during the 1997 observing run.

| ν (MHz) | Molecule  | $E_i$ (cm$^{-1}$) | $\int T_{MB} dv$ (K km s$^{-1}$) | $\mu^2S$ (D$^2$) |
|---------|-----------|------------------|-------------------------------|----------------|
| 98523.883 | C$_2$H$_5$CN | 44.251 | 1.24 | 113.939 |
| 98524.664 | C$_2$H$_5$CN | 54.287 | 0.87 | 96.525 |
| 98532.070 | C$_2$H$_5$CN | 65.860 | 0.75 | 76.412 |
| 98533.9845 | C$_2$H$_5$CN | 35.754 | 1.49 | 128.685 |
| 98544.148 | C$_2$H$_5$CN | 78.967 | 0.69 | 53.615 |
| 98564.836 | C$_2$H$_5$CN | 28.801 | 1.21 | 140.761 |
| 98566.797 | C$_2$H$_5$CN | 28.801 | 0.72 | 140.761 |
| 98701.109 | C$_2$H$_5$CN | 23.398 | 1.24 | 150.140 |
| b104177.000 | CH$_3$OCH$_3$ | 102.625 | 0.185 | 79.56847 |
| 104212.656 | C$_2$H$_5$CN | 23.4110 | 0.80 | 155.205 |
| 104419.312 | C$_2$H$_5$CN | 71.4640 | 0.80 | 112.653 |
| 104432.797 | C$_2$H$_5$CN | 30.9450 | 0.72 | 148.58 |
| 104437.516 | C$_2$H$_5$CN | 90.9290 | 0.94 | 95.507 |
| 104453.930 | C$_2$H$_5$CN | 30.9460 | 0.72 | 148.58 |
| 104490.168 | CH$_3$OCH$_3$ | 585.600 | 0.026 | 4.48006 |
| b111783.241 | CH$_3$OCH$_3$ | 17.550 | 0.017 | 27.2197 |
| b111813.417 | CH$_3$OCH$_3$ | 118.013 | 0.024 | 96.5637 |
| Mass (amu) | Formula | Abundance (u) | Width (u) | Molecular Weight (amu) |
|-----------|---------|---------------|-----------|-----------------------|
| 147205.839 | CH$_3$OCH$_3$ | 22.082 | 0.0376 | 19.52177 |
| 147456.863 | CH$_3$OCH$_3$ | 257.141 | 0.0376 | 145.57157 |
| 147561.719 | C$_2$H$_3$CN | 38.4910 | 2.46 | 232.515 |
| 161261.141 | C$_2$H$_3$CN | 95.144 | 5.56 | 213. |
| 161265.734 | C$_2$H$_5$CN | 108.253 | 4.72 | 199.066 |
| 161281.953 | CH$_3$OCH$_3$ | 75.305 | 0.0483 | 49.41313 |
| 161289.996 | CH$_3$OCH$_3$ | 333.668 | 0.0512 | 162.13361 |
| 161303.484 | C$_2$H$_5$CN | 139.060 | 3.33 | 166.301 |
| 161304.922 | C$_2$H$_5$CN | 73.536 | 3.89 | 235.93 |
| 161367.344 | C$_2$H$_5$CN | 175.957 | 2.78 | 126.974 |
| 161379.844 | C$_2$H$_5$CN | 65.047 | 2.79 | 244.939 |
| 161397.047 | C$_2$H$_5$CN | 97.1140 | 2.84 | 434.328 |
| 161441.266 | C$_2$H$_5$CN | 65.047 | 2.79 | 244.939 |
| 161445.391 | C$_2$H$_5$CN | 139.0100 | 2.21 | 193.130 |
| 161475.172 | C$_2$H$_5$CN | 52.712 | 5.04 | 258.004 |
| 161480.219 | C$_2$H$_5$CN | 164.3800 | 3.68 | 178.538 |
| 161527.500 | C$_2$H$_5$CN | 192.6770 | 1.10 | 162.238 |
| 161581.203 | C$_2$H$_5$CN | 58.115 | 4.78 | 252.312 |
| 209422.190 | CH$_3$OCH$_3$ | 136.101 | 0.1111 | 71.12975 |
| 209515.532 | CH$_3$OCH$_3$ | 41.221 | 0.1111 | 54.9886 |
| 209735.828 | C$_2$H$_5$CN | 86.7860 | 1.14 | 315.05 |
| 209812.329 | CH$_3$OCH$_3$ | 168.885 | 0.0864 | 64.85627 |
| 224002.109 | C$_2$H$_5$CN | 166.828 | 4.21 | 309.672 |
| 224003.438 | C$_2$H$_5$CN | 152.185 | 7.58 | 320.879 |
| 224045.750 | C$_2$H$_5$CN | 200.696 | 4.21 | 283.72 |
| 224084.281 | C$_2$H$_5$CN | 219.912 | 2.95 | 268.96 |
| 224088.203 | C$_2$H$_5$CN | 127.510 | 8.01 | 339.753 |
| 224186.344 | C$_2$H$_5$CN | 262.876 | 2.63 | 235.93 |
| 224206.609 | C$_2$H$_5$CN | 117.492 | 4.01 | 347.406 |
| 224208.078 | C$_2$H$_5$CN | 117.492 | 4.01 | 347.406 |
| 224419.812 | C$_2$H$_5$CN | 109.033 | 6.01 | 353.894 |
| 224458.859 | C$_2$H$_5$CN | 109.036 | 6.01 | 353.894 |
| 237261.970 | CH$_3$OCH$_3$ | 214.188 | 0.1533 | 66.88355 |
| 237396.976 | C$_2$H$_5$CN | 168.5260 | 3.14 | 336.209 |
| 237411.906 | C$_2$H$_5$CN | 149.0560 | 3.14 | 343.797 |
| 237415.359 | C$_2$H$_5$CN | 190.9600 | 2.62 | 327.453 |
| 237456.250 | C$_2$H$_5$CN | 216.3420 | 2.32 | 317.531 |
Table 6: Transitions observed towards G29.96–0.02 during the 1997 observing run.

| ν (MHz) | Molecule | $E_l$ (cm$^{-1}$) | $\int T_{MB} \, dv$ (K km s$^{-1}$) | $\mu^2 S$ ($D^2$) |
|---------|----------|-------------------|--------------------------------------|------------------|
| 98523.883 | C$_2$H$_5$CN | 44.251 | 0.41 | 113.939 |
| 98524.664 | C$_2$H$_5$CN | 54.287 | 0.52 | 96.525 |
| 98532.070 | C$_2$H$_5$CN | 65.860 | 0.34 | 76.412 |
| 98533.9845 | C$_2$H$_5$CN | 35.754 | 0.55 | 128.685 |
| 98564.836 | C$_2$H$_5$CN | 28.801 | 0.19 | 140.761 |
| 98566.797 | C$_2$H$_5$CN | 28.801 | 0.40 | 140.761 |
| 98701.109 | C$_2$H$_5$CN | 23.398 | 0.69 | 150.140 |
| 104490.168 | CH$_3$OCH$_3$ | 102.625 | 0.021 | 79.56847 |
| 104437.5160 | CH$_3$OCH$_3$ | 585.600 | 0.027 | 4.48006 |
| 111802.17 | CH$_3$OCH$_3$ | 90.9290 | 0.353 | 191.014 |
| 111802.93 | CH$_3$OCH$_3$ | 42.141 | 0.024 | 2.53886 |
| 111802.93 | CH$_3$OCH$_3$ | 42.142 | 0.0183 | 2.53886 |
| b111813.417 | CH$_3$OCH$_3$ | 118.013 | 0.0368 | 96.5637 |
| b147205.839 | CH$_3$OCH$_3$ | 22.082 | 0.0458 | 19.52177 |
| 147456.863 | CH$_3$OCH$_3$ | 257.141 | 0.040 | 145.57157 |
| 161261.141 | C$_2$H$_5$CN | 95.144 | 2.14 | 258.004 |
| 161265.734 | C$_2$H$_5$CN | 108.253 | 1.16 | 199.066 |
| 161289.996 | CH$_3$OCH$_3$ | 333.668 | 0.0467 | 162.13361 |
| 161303.484 | C$_2$H$_5$CN | 139.060 | 2.14 | 166.301 |
| 161304.922 | C$_2$H$_5$CN | 73.536 | 1.43 | 235.930 |
| 161367.344 | C$_2$H$_5$CN | 175.957 | 1.79 | 126.974 |
| 161379.844 | C$_2$H$_5$CN | 65.047 | 1.34 | 244.939 |
| 161381.875 | C$_2$H$_5$CN | 65.047 | 1.34 | 244.939 |
| 161397.047 | C$_2$H$_5$CN | 97.1140 | 0.89 | 217.164 |
| 161475.172 | C$_2$H$_5$CN | 52.712 | 1.63 | 258.004 |
Table 7: Transitions observed towards G29.96-0.02 during the 1996 observing run.

| ν (MHz) | Molecule  | \(E_1\) (cm\(^{-1}\)) | \(\int T_{MB} dv\) (K km s\(^{-1}\)) | \(\mu^2 S\) (\(D^2\)) |
|---------|-----------|-----------------|-----------------|-----------------|
| b154311.469 | CH\(_3\)OCH\(_3\) | 185.5 | 0.0114 | 12.859 |
| b154456.5 | CH\(_3\)OCH\(_3\) | 62.92 | 0.063 | 21.739 |
| 215040.8 | C\(_2\)H\(_3\)CN | 229.5 | 5.22 | 1199.4 |
| 215088.203 | C\(_2\)H\(_3\)CN | 288.76 | 2.31 | 533.6 |
| 215109.047 | C\(_2\)H\(_3\)CN | 183.46 | 4.82 | 651.1 |
| 215119.203 | C\(_2\)H\(_3\)CN | 135.84 | 4.22 | 369.666 |
| 215126.703 | C\(_2\)H\(_3\)CN | 316.4 | 1.66 | 502.8 |
| 215173.234 | C\(_2\)H\(_3\)CN | 346.23 | 1.5 | 469.4 |
Table 8: Transitions observed towards G31.41+0.31 during the 1997 August observing run.

| ν (MHz) | Molecule | $E_1$ (cm⁻¹) | $\int T_{MB} \, dv$ (K km s⁻¹) | $\mu^2 S$ ($D^2$) |
|---------|----------|--------------|-------------------------------|-------------------|
| 98523.883 | C₂H₅CN | 44.251 | 1.60 | 113.939 |
| 98524.664 | C₂H₅CN | 54.287 | 2.00 | 96.525 |
| 98532.070 | C₂H₅CN | 65.860 | 1.80 | 76.412 |
| 98533.9845 | C₂H₅CN | 35.754 | 2.79 | 128.685 |
| 98544.148 | C₂H₅CN | 78.967 | 2.22 | 53.615 |
| 98559.867 | C₂H₅CN | 93.604 | 0.59 | 28.149 |
| 98564.836 | C₂H₅CN | 28.801 | 1.87 | 140.761 |
| 98566.797 | C₂H₅CN | 28.801 | 2.42 | 140.761 |
| 98701.109 | C₂H₅CN | 23.398 | 2.60 | 150.140 |
| b104177.000 | CH₃OCH₃ | 102.625 | 0.0843 | 79.56847 |
| 104212.656 | C₂H₅CN | 23.411 | 1.18 | 155.205 |
| 104419.312 | C₂H₅CN | 71.464 | 1.48 | 112.653 |
| 104432.7970 | C₂H₅CN | 30.9450 | 1.13 | 148.58 |
| 104453.930 | C₂H₅CN | 30.9460 | 1.62 | 148.580 |
| 104490.168 | CH₃OCH₃ | 585.600 | 0.0424 | 4.48006 |
| b 111574.6250 | C₂H₅CN | 73.7330 | 0.38 | 10.807 |
| b111742.636 | CH₃OCH₃ | 130.299 | 0.1514 | 103.90668 |
| b111783.241 | CH₃OCH₃ | 17.550 | 0.1647 | 27.2197 |
| b111801.945 | CH₃OCH₃ | 42.142 | 0.029 | 4.43093 |
| b111813.417 | CH₃OCH₃ | 118.013 | 0.1694 | 96.5637 |
| b147205.839 | CH₃OCH₃ | 22.082 | 0.3239 | 19.52177 |
| b147456.863 | CH₃OCH₃ | 257.141 | 0.0816 | 145.57157 |
| 147561.719 | C₂H₅CN | 38.4910 | 2.66 | 232.515 |
| 161261.141 | C₂H₅CN | 95.144 | 7.89 | 213. |
| 161265.734 | C₂H₅CN | 108.253 | 6.91 | 199.066 |
| b161281.953 | CH₃OCH₃ | 75.305 | 0.1839 | 49.41313 |
| b161289.996 | CH₃OCH₃ | 333.668 | 0.0667 | 162.13361 |
| 161303.484 | C₂H₅CN | 139.060 | 5.67 | 66.301 |
| 161304.922 | C₂H₅CN | 73.536 | 3.70 | 235.93 |
| 161367.344 | C₂H₅CN | 175.957 | 2.47 | 126.974 |
| Frequency (GHz) | Molecule   | J/K   | Intensity (K km/s) |
|----------------|------------|-------|--------------------|
| 161379.844     | C$_2$H$_5$CN | 65.047 | 3.86               |
| 161381.875     | C$_2$H$_5$CN | 65.047 | 4.12               |
| 161397.047     | C$_2$H$_3$CN | 58.115 | 5.92               |
|                | C$_2$H$_3$CN | 55.578 | 9.50               |
|                | C$_2$H$_3$CN | 54.772 | 11.2               |
| 161447.875     | C$_2$H$_5$CN | 67.113 | 5.4                |
|                | C$_2$H$_5$CN | 57.114 | 9.50               |
| 172998.766     | C$_2$H$_3$CN | 110.480| 0.3097             |
| 173083.162     | CH$_3$OCH$_3$| 149.025| 0.1542             |
| 173094.261     | CH$_3$OCH$_3$| 168.885| 0.1334             |
| 1731293.064    | CH$_3$OCH$_3$| 34.233 | 0.4182             |
| 1731561.532    | CH$_3$OCH$_3$| 41.221 | 0.479              |
| 209812.329     | CH$_3$OCH$_3$| 168.885| 0.1334             |
| 224002.109     | C$_2$H$_5$CN | 166.828| 5.36               |
| 224003.438     | C$_2$H$_5$CN | 152.185| 6.13               |
| 224045.75      | C$_2$H$_5$CN | 200.696| 6.72               |
| 224084.281     | C$_2$H$_5$CN | 219.912| 4.60               |
| 224088.2035    | C$_2$H$_5$CN | 127.510| 6.89               |
| 224131.516     | C$_2$H$_5$CN | 240.640| 3.82               |
| 224185.344     | C$_2$H$_5$CN | 262.876| 3.73               |
| 224206.609     | C$_2$H$_5$CN | 117.492| 5.22               |
| 224208.078     | C$_2$H$_5$CN | 117.492| 5.22               |
| 224248.016     | C$_2$H$_5$CN | 286.614| 1.91               |
| 224419.812     | C$_2$H$_5$CN | 109.033| 7.66               |
| 224458.859     | C$_2$H$_5$CN | 109.036| 7.63               |
| 237396.9765    | C$_2$H$_5$CN | 168.526| 2.50               |
| 237405.1880    | C$_2$H$_5$CN | 101.8870| 8.49             |
| 237476.0470    | C$_2$H$_5$CN | 91.4820| 3.77               |
| 237456.250     | C$_2$H$_5$CN | 216.3420| 2.10             |
| 237485.016     | C$_2$H$_5$CN | 132.5700| 3.12             |
| 237548.541     | CH$_3$OCH$_3$| 447.259| 0.1445            |
| 237591.3910    | C$_2$H$_5$CN | 108.5880| 2.17             |
| 237620.371     | CH$_3$OCH$_3$| 32.291 | 0.452             |
| 237638.0160    | C$_2$H$_5$CN | 119.0860| 2.17             |
| 237668.7660    | C$_2$H$_5$CN | 309.9800| 2.03             |
Fig. 4. Same as Fig. 2 for G10.62.
Table 9: Transitions observed towards G31.41+0.31 during the 1996 July observing run.

| ν     | Molecule | $E_i$ | $\int T_{MB} \, dv$ | $\mu^2 S$ |
|-------|----------|-------|---------------------|------------|
| MHz   |          | (cm$^{-1}$) | (K km s$^{-1}$) | (Dº)       |
| b140226.172 | CH$_3$OCH$_3$ | 159.81 | 0.0686 | 9.896 |
| a140429.484  | C$_2$H$_3$CN   | 54.24  | 2.2   | 202.872 |
Table .10: Transitions observed towards G34.26+0.15 during the 1997 observing run.

| ν      | Molecule | $E_1$ (cm$^{-1}$) | $\int T_{MB} dv$ (K km s$^{-1}$) | $\mu^2S$ ($D^2$) |
|--------|----------|-------------------|----------------------------------|------------------|
| 98523.883 | C$_2$H$_5$CN | 44.251 | 1.23 | 113.939 |
| 98524.664 | C$_2$H$_5$CN | 54.287 | 0.96 | 96.525  |
| 98532.070 | C$_2$H$_5$CN | 65.860 | 1.16 | 76.412  |
| 98533.9845 | C$_2$H$_5$CN | 35.754 | 1.64 | 128.685 |
| 98544.148 | C$_2$H$_5$CN | 78.967 | 0.68 | 53.615  |
| 98559.867 | C$_2$H$_5$CN | 93.604 | 0.24 | 28.149  |
| 98564.836 | C$_2$H$_5$CN | 28.801 | 1.10 | 140.761 |
| 98566.797 | C$_2$H$_5$CN | 28.801 | 1.35 | 140.761 |
| 98701.109 | C$_2$H$_5$CN | 23.398 | 1.37 | 150.140 |
| b104177.000 | CH$_3$OCH$_3$ | 102.625 | 0.1033 | 79.56847 |
| Transition | Species       | $J$ | $K_a$ | $K_c$ |
|------------|--------------|-----|-------|-------|
| 104419.312 | C$_2$H$_3$CN | 71.4640 | 0.57 | 112.653 |
| 104432.797 | C$_2$H$_3$CN | 30.9450 | 0.57 | 148.58 |
| 104437.516 | C$_2$H$_3$CN | 90.9290 | 0.71 | 95.507  |
| 104453.930 | C$_2$H$_3$CN | 30.9460 | 0.89 | 148.58 |
| 104461.516 | C$_2$H$_3$CN | 113.3510 | 0.425 | 151.236 |
| b111783.241 | CH$_3$OCH$_3$ | 17.550 | 0.1639 | 27.2197 |
| 111802.93 | CH$_3$OCH$_3$ | 42.142 | 0.0192 | 2.5386 |
| b111813.417 | CH$_3$OCH$_3$ | 118.013 | 0.1493 | 96.5637 |
| b147205.839 | CH$_3$OCH$_3$ | 22.082 | 0.2814 | 19.52177 |
| b147456.863 | CH$_3$OCH$_3$ | 257.141 | 0.0763 | 145.57157 |
| 161261.141 | C$_2$H$_5$CN | 95.144 | 9.19 | 213. |
| 161265.734 | C$_2$H$_5$CN | 108.253 | 6.32 | 199.066 |
| b161285.603 | CH$_3$OCH$_3$ | 75.305 | 0.279 | 12.35331 |
| 161289.996 | CH$_3$OCH$_3$ | 333.668 | 0.0566 | 162.13361 |
| 161303.484 | C$_2$H$_5$CN | 139.060 | 6.89 | 166.301 |
| 161304.922 | C$_2$H$_5$CN | 73.536 | 6.89 | 235.930 |
| 161367.344 | C$_2$H$_5$CN | 175.957 | 2.87 | 126.974 |
| 161379.844 | C$_2$H$_5$CN | 65.047 | 6.24 | 244.939 |
| 161381.875 | C$_2$H$_5$CN | 65.047 | 4.05 | 244.939 |
| 161397.047 | C$_2$H$_5$CN | 97.1140 | 2.31 | 217.164 |
| 161445.391 | C$_2$H$_5$CN | 67.1130 | 2.21 | 234.339 |
| 161450.359 | C$_2$H$_5$CN | 67.1130 | 2.21 | 234.339 |
| 161475.172 | C$_2$H$_5$CN | 52.712 | 7.47 | 258.004 |
| 161581.203 | C$_2$H$_5$CN | 58.115 | 5.75 | 252.312 |
| 172998.766 | C$_2$H$_5$CN | 55.578 | 5.92 | 293.998 |
| 173092.859 | C$_2$H$_5$CN | 54.7720 | 4.69 | 259.424 |
| b173293.064 | CH$_3$OCH$_3$ | 34.233 | 0.3016 | 46.73276 |
| b209515.532 | CH$_3$OCH$_3$ | 41.221 | 0.7994 | 54.9886 |
| b209812.329 | CH$_3$OCH$_3$ | 168.885 | 0.1865 | 64.85627 |
| 224002.109 | C$_2$H$_5$CN | 166.828 | 9.23 | 309.672 |
| 224003.438 | C$_2$H$_5$CN | 152.185 | 3.69 | 320.879 |
| 224045.75 | C$_2$H$_5$CN | 200.696 | 3.26 | 283.720 |
| 224084.281 | C$_2$H$_5$CN | 219.912 | 3.88 | 268.960 |
| 224088.2035 | C$_2$H$_5$CN | 127.510 | 6.79 | 339.753 |
| 224186.344 | C$_2$H$_5$CN | 262.876 | 2.43 | 235.930 |
| 224206.609 | C$_2$H$_5$CN | 117.492 | 4.95 | 347.406 |
| 224208.078 | C$_2$H$_5$CN | 117.492 | 4.95 | 347.406 |
| b224310.9220 | C$_2$H$_5$CN | 84.2220 | 5.83 | 2.17 |
Table .11. Transitions observed towards G34.26+0.15 during the 1996 observing run.

| ν (MHz) | Molecule   | $E_i$ (cm$^{-1}$) | $\int T_{MB} \, dv$ (K km/s) | $\mu^2 S$ (D$^2$) |
|---------|------------|-------------------|-------------------------------|------------------|
| 215040.8 | C$_2$H$_3$CN | 229.5             | 15.83                         | 1199.4           |
| 215088.203 | C$_2$H$_3$CN | 288.76           | 7.                           | 533.6            |
| 215109.047 | C$_2$H$_3$CN | 183.46           | 10.73                        | 651.1            |
| 215119.203 | C$_2$H$_3$CN | 135.84           | 11.35                        | 369.666          |
| 215126.703 | C$_2$H$_3$CN | 316.4            | 4.87                         | 502.8            |
| 215173.234 | C$_2$H$_3$CN | 346.23           | 4.37                         | 469.4            |
| 215400.797 | C$_2$H$_3$CN | 156.87           | 9.2                          | 340.336          |
| 215427.984 | C$_2$H$_3$CN | 156.88           | 11.88                        | 340.332          |

Appendix C: Boltzmann plots
Fig. 6. Same as Fig. 1 for G29.96.

References

Acord, J.M., Churchwell, E., Wood, D.O.S. 1998, ApJ 495, L107
Akeson R.L. & Carlstrom J.E. 1996, ApJ, 470, 528
Allen, M., & Robinson, G. W. 1977, ApJ, 212, 396
Anderson T., Herbst E., de Lucia F. C. 1987, ApJS, 64, 703
Anderson T., Crownover R. L., Herbst E., De Lucia F. C. 1988a ApJS, 67, 135
Anderson T., Herbst E., de Lucia F. C. 1988b, ApJS, 68, 821
Anderson T., de Lucia F. C., Herbst E. 1990a, ApJS, 72, 797
Anderson T., Herbst E., de Lucia F. C. 1990b, ApJS, 74, 647
Anderson T., Herbst E., de Lucia F. C. 1992, ApJS, 82, 405
Avalos, M., Lizano, S., Rodríguez, L.F., Franco-Hernández, R., Moran, J.M. 2006, ApJ, 641, 406
Beltrán, M.T., Cesaroni, R., Neri, R. et al., 2005, A&A, 435, 901
Bettens F. L., Sastry K. V. L. N., Herbst E., Albert S., Oesterling Lee C., de Lucia F. C. 1999, ApJ 510, 789
Beuther, H., Churchwell, E. B., McKee, C.F., Tan, J.C. 2007, Protostars and Planets V, ed. B. Reipurth, D. Jewitt, and K. Keil, University of Arizona Press, Tucson, p.165
Beuther, H., Zhang, Q., Greenhill, L. J., et al. 2005, ApJ, 632, 355
Bisschop, S.E., Jorgensen, J.K., van Dishoeck, E.F., de Wachter, E.B.M. 2007, A&A in press, astro-ph/0702066
Blake G. A., Sutton E. C., Masson C. R., Phillips T. G. 1987, ApJ, 315, 621
Carral P. & Welch W. J. 1992, ApJ, 385, 244
Caselli P., Hasegawa T. I., Herbst E. 1993, ApJ, 408, 548
Caselli, P. 2005, in “Cores to Clusters: Star Formation with Next Generation Telescopes. Ed. by M.S. Nanda Kumar, M. Tafalla and P. Caselli. Published by Springer, New York, NY USA, p. 47
Cesaroni, R., Walmsley C. M., Kömpe C., Churchwell E. 1991, A&A, 252, 278
Cesaroni, R., Hofner P., Walmsley C. M., Churchwell E. 1998, A&A, 331, 709
Cesaroni, R. 2005, Proceedings of the IAUSS227 "Massive Star Birth: A Crossroads of Astrophysics"
Cesaroni, R., Galli, D., Lodato, G., Walmsley, C.M. & Zhang, Q. 2007, Protostars and Planets V, ed. by B. Reipurth, D. Jewitt, and K. Keil, University of Arizona Press, Tucson, p. 197
Charnley S. B., Tielens A. G. G. M., Millar T. J. 1992, ApJ, 399, L71
Charnley S. B. 1995, Ap&SS 224, 251
Churchwell E., Walmsley C. M., Cesaroni R. 1990, A&AS, 83, 119
Comito, C., Schilke, P., Phillips, T.G., et al. 2005, ApJS, 156, 127
Fish, V.L., Reid, M.J., Wilner, D.J., Churchwell, E. 2003, ApJ, 587, 701
Fontani, F., Cesaroni, R., Caselli, P. et al. 2002, A&A, 389, 603
Garay G. & Rodríguez L.F. 1990, ApJ, 362, 191
Garay G., Moran J.M., Rodríguez L.F., Reid M.J. 1998, ApJ, 492, 635
Garay G., Lizano S. 1999, PASP, 111, 1049
Garrod, R.T. & Herbst, E. 2006, A&A, 457, 927
Genzel R., Stutzki J. 1989, Annu. Rev. Astron. Astrophys., 27, 41
Genzel R., "The galactic interstellar medium" Saas-Fee Advanced Course 21, 1991 ed. Springer-Verlag Berlin Heidelberg 1992
Gibb, E., Nummelin, A., Irvine, W.M., Whittet, D.C.B., Bergman, P. 2000, ApJ, 545, 309
Gibb, A.G., Wyrowski, F., Mundy, L.G. 2004, ApJ, 616, 301
Goldsmith P. F. & Langer W. D. 1999, ApJ, 519, 173
Groner P., Albert S., Herbst E., de Lucia F. C. 1998, ApJ, 500, 1059
Hatchell J., Thompson M. A., Millar T. J., Macdonald G. H. 1998, A&AS, 133, 29
Herbst E. 1999 "HCOOCH$_3$ transitions", private communication
Hofner P., Wyrowski F., Walmsley C. M., Churchwell E. 2000, ApJ, 536, 393
Ho P. T. P. & Haschick A. D. 1986, ApJ, 304, 501
Keto E. R., Ho P. T. P., Haschick A. D., Aubrey D. 1987, ApJ, 318, 712
Keto E. R., Ho P. T. P., Haschick A. D. 1988, ApJ, 324, 920
Klisch E., Klaus Th., Belov S. P., Dolgner A., Schieder R., Winnewisser G., Herbst E. 1996, ApJ, 473, 1118
Kolpak, M.A., Jackson, J.M., Bania, T.M., Clemens, D.P., Dickey, J.M. 2003, ApJ, 582, 756
Kuchar, T.A. & Bania, T.M. 1994, ApJ, 436, 117
Kurtz S., Cesaroni R., Churchwell E., Hofner P., Walmsley C. M. 2000, "Protostars and Planets IV", eds Mannings, V., Boss, A. P., Russel, S. S. (Tucson: Univ. Arizona Press), p. 299
Macdonald, G.H., Habing, R.J., Millar, T.J. 1995, Ap&SS, 224, 177
Mehringer, D.M, Pearson, J.C., Keene, J., Phillips, T.G. 2004, ApJ, 608, 306
Mookerjea, B., Casper, E., Mundy, L.G., Looney, L.W. 2007, ApJ, in press, astro-ph/0701827
Nomura, H., & Millar, T.J. 2004, A&A, 414, 409
Nummelin, A., Bergman, P., Hjalmarson, A. et al. 1998, ApJS, 117, 427
Nummelin, A. & Bergman, P. 1999, A&A, 341, 59L
Nummelin, A., Bergman, P., Hjalmarson, A. et al. 2000, ApJS, 128, 213
Olmi L., Cesaroni R., Neri R., Walmsley C.M. 1996, A&A, 315, 565
Olmi, L., Cesaroni, R., Hofner, P. et al. 2003, A&A, 407, 225
Pan J., Albert S., Sastry K. V. L. N., Herbst E., de Lucia F. C. 1998, ApJ 499, 517
Pearson J. C., Anderson T., Herbst E., de Lucia F. C., Helminger P. 1991, ApJ, 379, L41
Pearson J. C., Sastry K. V. L. N., Herbst E., de Lucia F. C. 1994, ApJS, 93, 589
Pearson J. C., Sastry K. V. L. N., Herbst E., de Lucia F. C. 1997, ApJ, 480,420
Pearson J. C. 2002, "C$_2$H$_5$CN transitions", personal communication
Plummer G. M., Herbst E., de Lucia F. C., Blake G. A. 1986, ApJS, 60, 949
Plummer G. M., Herbst E., de Lucia F. C. 1987, ApJ, 318, 873
Pickett H. M., Poynter R. L., Cohen E. A., Delitsky M. L., Pearson J. C., Müller H. S. P. "Submillimeter, millimeter and microwave line catalogue", JPL Publication 80-23, revision 4, Pasadena CA, 1996
Poynter R. L. & Pickett, H. M. 1985, Applied Optics, 24, 2235
Remijan, A., Shiao, Y.S., Friedel, D.N., Meier, D.S., Snyder, L.E. 2004, ApJ, 617, 384
Rodgers S. D. & Charnley S. B. 2001, ApJ, 546, 324
Schilke P., Groesbeck T. D., Blake G. A., Phillips T. G. 1997, ApJS, 108, 301
Sewilo, M., Churchwell, E., Kurtz, S., Goss, W.M., Hofner, P. 2004, ApJ, 605, 285
Sollins, P.K., Zhang, Q., Keto, E., Ho, P.T.P. 2005, ApJ, 624, L49
Sutton, E.C., Peng, R., Danchi, W.C. et al. 1995, ApJS, 97, 455
Tan, J.C., McKee, C.F 2002, in ASP Conf. Ser. 267, The Earliest Stages of Massive Star Birth, ed. P.A. Crowther (San Francisco: ASP), 267
Turner B.E. 1991, ApJS, 76, 617
Xu, Y., Reid, M. J., Zheng, X. W., Menten, K. M. 2006, Science, 311, 54
Walmsley C. M., Schilke, P. 1992, Proceedings of the 50th Symposium of the International Astronomical Union
Wright, M., Sandell, G., Wilner, D.J., Plambeck, R.L. 1992, ApJ, 393, 225
Wright M. C. H., Plambeck R. L., Wilner D. J. 1996, ApJ, 469, 216
Wood D. O. S., Churchwell E. 1989, ApJS, 69, 831
Wood D. O. S., Churchwell E. 1990, ApJS, 354, 247
Wyrowski F., Schilke P., Walmsley C.M., Menten, K.M. 1999, A&A, 514, L43
Yamada K. M. T., Creswell R. A. 1986, J.Mol.Spectr. 116, 384
Yorke, H.W. 2004, Proceedings of the IAU symposium 221, 141
Fig. 7. Same as Fig. 2 for G29.96.
Fig. 8. Same as Fig. 1 for G31.41.
Fig. 9. Same as Fig. 2 for G31.41.
Fig. 10. Same as Fig. 8 for G34.26.
g34.26

Fig. 11. Same as Fig. 2 for G34.26.
**Fig. 1.** Boltzmann plots for G10.47. $T_{\text{fit}}$ and $N_{\text{fit}}$ are the "best-fit" values for the rotational temperature and the total column densities (see Tab. 4). Filled circles indicate "strong" transitions; open circles correspond to "weak" transitions. Open triangles indicate upper limits for undetected lines, estimated from the $3\sigma$ level in the spectrum. The error on the quantity on the y-axis is about 20%, and it is due to calibration uncertainties.

**Fig. 2.** Same as Fig. 1 but for G10.62.

**Fig. 3.** Same as Fig. 1 but for G19.61.

**Fig. 4.** Same as Fig. 1 but for G29.96.
Fig. 5. Same as Fig. 1 but for G31.41.

Fig. 6. Same as Fig. 1 but for G34.26.
\[ N_{\text{fit}} = 19.5 \pm 5.6 \times 10^{13} \text{ cm}^{-2} \]
\[ T_{\text{fit}} = 176 \pm 35 \text{ K} \]
$N_{\text{fit}} = 12.4 \pm 3.3 \times 10^{13} \text{ cm}^{-2}$

$T_{\text{fit}} = 156 \pm 37 \text{ K}$

$\text{CH}_3\text{OCH}_3$
$N_{\text{fit}} = 1.4 \pm 0.2 \ E+13 \ \text{cm}^{-2}$

$T_{\text{fit}} = 16 \pm 1 \ \text{K}$