MOLECULAR LINES IN BOK GLOBULES
AND AROUND HERBIG Ae/Be STARS

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This paper is intended as part of a more extensive molecular line survey in star forming regions along the evolutionary track of a collapsing cloud toward a young stellar object.

We have studied a sample of seven small dark clouds (Bok globules) and eight Herbig Ae/Be stars in the $J=1\rightarrow0$ transition of HCO$^+$, H$^{13}$CO$^+$, HCN and H$^{13}$CN. The choice of these molecules is determined by the simple chemistry and the predicted high abundance of the reactants leading to their formation. The isotopically substituted species (isotopomers), H$^{13}$CO$^+$ and H$^{13}$CN, were observed in order to determine, whenever possible, the optical thickness of the main species. The most abundant isotopomers were found in almost all the sources (detection rate 70-90%). Those sources which exhibited the strongest signals were also searched for the $^{13}$C isotopomers. H$^{13}$CO$^+$ was found in one dark cloud and around three Herbig Ae/Be stars, while H$^{13}$CN around only one star. The column densities for each species and the physical conditions of the objects were derived whenever the observational data allowed it.
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I. INTRODUCTION

Molecular line observations are the most versatile probes of the internal properties of star forming regions. Molecular transitions can provide close investigations of the mechanisms which govern star formation processes. Thus, the composition, morphology and kinematics of the high density gas, which are relevant to the understanding of the phenomena associated with star formation, can be studied through observations of molecular tracers (Hartquist et al., 1993). The physical processes that accompany the birth and early evolution of a star modify the chemistry in the surrounding medium through increases in density and temperature and through very energetic mass ejection. Bipolar outflows of material in the neighbourhood of young stars, shock fronts with associated Herbig-Haro objects, maser emissions (H$_2$O, OH, SiO, CH$_3$OH, etc.) and highly excited rotational molecular lines of many species are only a few of the typical manifestations of newly-born stars interacting with their parental molecular clouds (Lada, 1985).

In order to contribute data to the understanding of the star forming processes we have measured HCO$^+$ and HCN millimeter-wave emissions in two different sample regions: (i) Bok globules and (ii) Herbig Ae/Be stars.

Bok globules, also called Barnard objects, are nearby (150-600 pc) dense interstellar clouds ($n(H_2)=10^3$-$10^5$ cm$^{-3}$) of gas and dust. In this sense they have to be considered a subsample of small dark clouds. They appear visibly as well defined dark patches with typical sizes of $\sim 1$ pc against the general background of stars. While most globules appear to be gravitationally bound and in virial equilibrium, recent infrared and radio observations suggest that low-mass (1 - 2 M$\odot$) star formation is taking place in some of them (Clemens and Barvainis, 1988, hereafter CB; Yun and Clemens, 1992, hereafter YC).

The Herbig Ae/Be stars are objects of intermediate mass ($\sim 3$ M$\odot$) in their pre-main sequence stage of evolution. Some of these stars show evidence of mass ejection. Because of their youth they are still embedded in the dark clouds which have originated them (Herbig, 1960; Finkenzeller and Mundt, 1984).

These two classes of objects represent a wide scenario of situations. Bok globules range from quiescent to star forming clouds and Herbig Ae/Be stars are already pre-main sequence objects still in some dynamical interactions with the environment. The study of molecular spectra from these regions should allow us to characterize the chemical and physical conditions of the different stages along the evolution sequence of a small molecular cloud toward star formation.

In this paper we report results of selected molecular line observations in seven Bok globules and in the cloud material surrounding eight Herbig Ae/Be stars. The number of objects and lines have been limited by telescope time allocation and frequency bands availability. We searched for the $J=1\rightarrow0$ rotational transitions of HCO$^+$, H$^{13}$CO$^+$, HCN, and H$^{13}$CN using the 20m radiotelescope at Onsala. These molecules have been chosen in view of the simple chemistry that leads to their formation and to the predicted abundance of the precursor species, CO, H$_3^+$, C$^+$, N, etc. (Hartquist et al., 1993). The isotopically substituted species, H$^{13}$CO$^+$ and H$^{13}$CN, have been searched for in order to determine, if detected, the optical
thickness of the main species. In paragraph II observations at the telescope are described. In paragraph III the criteria adopted to select the two observed samples are illustrated; for each source a brief description is given. Results are summarized in paragraph IV and the source physical properties derived. A summary of the paper is given as conclusion.

II. OBSERVATIONS

Observations were made in February and May 1990 with the 20m radiotelescope at Onsala. The half-power beamwidth of the telescope was 45’ at 90 GHz. The spectrometer used was a 256-channel filter-bank with 250 kHz resolution (0.83 km s$^{-1}$). The SSB-tuned SIS receiver was operated in a dual beam switching mode and a chopper wheel calibration technique was used. The main beam efficiency ($\eta_{mb}$) was determined to be 0.43. We position switched, with one on-source per off-source measurement and 90s integration time on each position. The pointing error, checked every three hours, was found to be better than 4” rms on all occasions.

III. DESCRIPTION OF THE SAMPLE

In Table 1 we present a tabulation of the sources, consisting of seven Bok globules and eight Herbig Ae/Be stars. The source name is followed by the location of the central position in 1950 equatorial coordinates. The presence of water maser emission is also indicated, whenever detected.

Bok globules are dense condensations and possible sites of star formation (CB). They have optical sizes between 1’ and 10’. Frerking and Langer (1982) and Wootten et al. (1982) detected in them different molecular species. Recent IRAS observations have confirmed that many of these dark clouds have internal heat sources (Beichman, 1986), some of which have infrared colours corresponding to T-Tauri stars. For the choice of the Bok globules to be observed we adopted the following criteria: (i) to be IRAS point sources, (ii) these point sources have infrared colours corresponding to those of Beichman (1986) and Emerson (1987) samples for T-Tauri stars and cores. The selected objects in a colour/colour diagram show the following distribution: $-0.86 \leq \log (F_{12}/F_{25}) \leq -0.17$, $-1.44 \leq \log (F_{25}/F_{60}) \leq -0.29$, and $-0.55 \leq \log (F_{60}/F_{100}) \leq -0.03$ ($F_{12}$, $F_{25}$, $F_{60}$, and $F_{100}$ are the infrared fluxes at 12,25,60, and 100 $\mu$m, respectively). Finally, (iii) to have quite large CO linewidths. The above selection criteria clearly privilege active star forming clouds.

Ae/Be stars were originally selected by Herbig (1960) as Ae or Be stars embedded in nebulosities and later found to be young stellar objects in the pre-main sequence phase (Finkenzeller and Mundt, 1984). Our selection criteria are: (i) they have optical outflows and (ii) P-Cygni profiles ($H\alpha$ lines).

In the following a brief description of each source is given together with its present observational situation.
**LBN594.** Optical dimensions 6.7' × 5.6' and IRAS source 00259+5625. It has been observed in CO (CB). Recently Scappini et al., (1991) have detected maser emission 1 arcmin south of the cloud center. CO outflow has been discovered by YC.

**LBN613.** Optical dimensions 9' × 3.4' and IRAS source 00465+5028. It has been observed in CO (CB).

**L1534.** Also called TMC-1A, dark cloud in the Taurus cloud complex, IRAS source 04365+2535. The area, 0.87 square degrees, is larger than that of the other dark clouds of our sample (Lynds, 1962). It has been observed in CO by Heyer et al. (1987) and in NH$_3$ by Benson and Myers (1989).

**CB34.** Optical dimensions 4.5' × 2.2' and IRAS source 05440+2059 (CB). It showed CO outflow (YC).

**L810.** Optical dimensions 10.1' × 6.7' and IRAS source 19433+2743 (CB). It has been observed in HCO$^+$, in NH$_3$ and in H$_2$CO by Wootten et al., 1982. A near infrared source about at the center of the cloud has been discovered by Nekel et al., (1985), together with a nearby $6_{16}$$\rightarrow$$5_{23}$ water maser emission. More recently Harju (1989) has mapped the dark cloud in HCN(J=1$\rightarrow$0) and measured the ratio of the integrated intensities HNC/HCN towards the cloud center to be 0.4±0.1. CO outflow has been first discovered by Xie and Goldsmith (1990).

**L797.** Optical dimensions 6.7' × 4.5' and IRAS source 20037+2317 (CB). CO outflow has been discovered (YC).

**L1262.** Optical dimensions 11.2' × 5.6' and IRAS source 23238+7401 (CB). First observed in CO by Parker et al. (1988), showing evidence of outflow associated with the embedded IRAS source. A millimeter-wave interferometry map in CO by Tereby et al. (1989) has confirmed the presence of a spatially compact low-velocity outflow. The $^{12}$C/$^{13}$C abundance ratio was obtained by measurements of the optically thin species $^{12}$C$^{18}$O and $^{13}$C$^{18}$O to be 75±8(1σ), close to the solar value 89. Similarly, the $^{18}$O/$^{17}$O and $^{16}$O/$^{18}$O ratios were measured.

**LkHα198.** Ae star embedded in an anonymous dark cloud in Cassiopea. It exhibits molecular outflow (Cantò et al. 1984; Levreault 1988). The outflow has been found to be quite large extending asymmetrically to about 1.6 pc from the star with a total extent of 2 pc. As pointed out by Ho et al. (1982) an asymmetric bipolar outflow such as this can easily be explained by the presence of density gradients in the ambient cloud. The outflow mass is 3.7 M$_\odot$ (Levreault, 1988) and its velocity 6.7 km/s for the blue and 5.9 km/s for the red emission. A number of molecular line observations were carried out, besides those in CO and $^{13}$CO, by different authors (Loren 1977; Loren 1981; Kogure 1988; Levreault 1988). Data
concerning the column density of HCO$^+$ and HCN were not specifically reported, even if these molecules were detected.

**RRTau.** A spectral type classification as A6 was given to this star by Cohen and Kuhi (1979). A 3′× 3′ map in CO shows no outflow (Cantò et al., 1984).

**HD250550.** The star is classified as B6 by Cohen and Kuhi (1979). P-Cygni profiles in the Balmer lines were observed by Herbig (1960) and more recent CO mapping (Cantò et al. 1984) showed evidence of peculiar activity in the direction of the NE arc-shaped associated nebulosity.

**BD463471.** The H$\alpha$ lines have P-Cygni profiles with absorption at about -200 Km/s (Herbig, 1960). A bipolar outflow was observed (Levreault, 1988) as well as infrared emission in the 1.5 - 2.3 $\mu$m range (Harvey, 1984). The interpretation of this emission is that it arises from recombination in a HII region around the star.

**V645Cyg.** Known from radio-observations to be associated with high velocity molecular gas (Bally and Lada, 1983). The $6_{16}\rightarrow5_{23}$ water maser emission was, in fact, found at -46.1 kms$^{-1}$ (Lada et al., 1981).

**LkH$\alpha$234.** Ae star contained in the bright nebulosity NGC 7129 together with the Be star BD 651637 (Loren, 1977). Both stars were classified by Herbig (1960) as young massive stars. However the star BD 651637 is in a more advanced stage of evolution and has had more time to disperse the circumstellar gas (Strom et al., 1972). It has been shown that the maximum of the $T_A^{\ast}$(CO) in the NGC 7129 cloud is associated with LkH$\alpha$234 rather than with BD 651637 (Loren, 1977). The $6_{16}\rightarrow5_{23}$ water maser emission was observed at -14.9 kms$^{-1}$ (Rodriguez et al., 1980). Besides having been mapped in CO, other species, such as CS, SO, HCN, H$_2$CO, and HCO$^+$ were detected in the surrounding molecular cloud. However the somewhat limited angular resolution (2.6′ beamwidth) prevented detailed information on the molecular distribution (Loren et al., 1977).

**LkHa233.** The spectral type is estimated as A7 (Herbig, 1960). Carbon monoxide emission in both the CO and $^{13}$CO J=1→0 lines has been observed from the region surrounding the star (Loren et al. 1973). From H$_2$CO observations the density of the cloud core was estimated to be about 5x10$^3$ cm$^{-3}$ and the kinetic temperature 28K (Loren, 1981). The star excites the NGC 1788 nebula, which is embedded in a small dust cloud (Loren, 1981).

**MWC1080.** Classified as B0 by Cohen and Kuhi (1979). The CO outflow map shows that the regions of blueshifted and redshifted emission are concentric and centered on the star. This indicates either an isotropic outflow or a bipolar outflow observed along its axis (Cantò et al., 1984; Levreault, 1988). A more detailed map by Yoshida et al. (1991) suggests that the outflow is not exactly isotropic but bipolar. Herbig-Haro emission east of the star
and poorly collimated has been found by Poetzel et al. (1992). HCO\(^+\) (J=1→0) has been observed by Koo (1989).

**IV. RESULTS**

*a) The Survey Data*

The transition frequencies of the J=1→0 lines of HCO\(^+\), H\(^{13}\)CO\(^+\), HCN and H\(^{13}\)CN, together with the electric dipole moments and the N-nuclear quadrupole coupling constants are to be found in De Lucia and Gordy (1969), Pearson et al. (1976) and Bogey et al. (1981).

It is worth summarizing the dominant reactions which produce the observed species. For HCO\(^+\),

\[
\begin{align*}
H_3^+ + CO & \rightarrow HCO^+ + H_2 \\
N_2H^+ + CO & \rightarrow HCO^+ + N_2 \\
CH_3^+ + O & \rightarrow HCO^+ + H_2
\end{align*}
\]

Among these the most important is the reaction with the abundant species H\(_3^+\) (Huntress and Anicich, 1976). For HCN,

\[
\begin{align*}
CH_3^+ + N & \rightarrow H_2CN^+ + H \\
NH_3 + C^+ & \rightarrow H_2CN^+ + H \\
HNC + HCO^+ & \rightarrow H_2CN^+ + CO \\
HNC + H_3^+ & \rightarrow H_2CN^+ + H_2
\end{align*}
\]

\(H_2CN^+\) which has three isomeric forms, leads by dissociative recombination to HCN and HNC in a ratio which seems to depend very much upon the ambient conditions (Walmsley, 1993).

Table 2 gives the results of the observations, that is the peak antenna temperature \(T^*_A\), corrected for atmospheric losses, the FWHM linewidth, and the LSR velocity of the peak emission. A Gaussian profile was numerically fitted to each line to obtain the peak antenna temperature \(T^*_A\), linewidth \(\Delta v\) (FWHM), and center frequency. In the case of HCN and H\(^{13}\)CN the nitrogen quadrupolar nucleus splits the J=1→0 line into three components corresponding to F=1-1, F=2-1, and F=0-1, with theoretical intensity ratios 33:56:11, respectively. These spectra were fitted simultaneously to the expected hyperfine pattern of three lines. The spectra of MWC1080 (J=1→0, HCO\(^+\)), LBN594 (J=1→0, HCN) and LkH\(\alpha\)233 (J=1→0, HCN) appear contaminated with extra features and/or noise. They were fitted using the above described procedure together with the known \(v_{LSR}\) of CO emission (see Table 1).

The quoted \(T^*_A\) for HCN and H\(^{13}\)CN in Table 2 is the sum of the peak temperatures of the three components. All errors in Table 2 are only 1\(\sigma\) fitting errors and all limits are 3\(\sigma\).
HCO$^+$ was detected in all seven Bok globules and around six Herbig Ae/Be stars. HCN was found in five globules and around five stars. In those sources where HCO$^+$ and HCN exhibited the strongest signals we searched also for H$^{13}$CO$^+$ and H$^{13}$CN. H$^{13}$CO$^+$ was found in one Bok globule and around three Herbig Ae/Be stars and H$^{13}$CN around one star. Typical spectra are presented in Figs. 1 to 10.

From the spectra of HCN and H$^{13}$CN it can be seen that the intensity ratios between the hyperfine components do not correspond to the theoretical ones. In fact, while the two strongest lines retain approximately their theoretical ratio, the third is more intense than it should. Cernicharo et al., 1984 have suggested that in cold dark clouds scattering in the surrounding envelope changes the HCN hyperfine ratios formed in the core so that the optically thinnest line, F=0→1, shows up enhanced relative to the other two hyperfine components.

In Table 3 we present the integrated line intensities $I(X) = \frac{1}{\eta_{mb}} \int T_A^* dv$ for the observed species (X = HCO$^+$, H$^{13}$CO$^+$, HCN, and H$^{13}$CN). The ratios $I$(HCO$^+)/I(H$^{13}$CO$^+$) and $I$(HCN)/I(H$^{13}$CN) are also given, whenever the corresponding intensities were measured.

HCO$^+$ and HCN have been mapped (9-10 points in steps of one beam size) in CB34 and in LkH$\alpha$234 and Figs. 11 and 12 show the corresponding integrated line intensity distribution. The position of the peak of the molecular emission coincides with the position of the center of the cloud or of the star within, at most, one beamwidth.

b) Physical properties

We derive estimates of the optical depth from the ratio of the $^{12}$C and $^{13}$C isotopomer line intensities, $I$(12C)/$I$(13C). Assuming that the lines of the isotopomers are at the same excitation temperature and that the beam filling factors are similar (here they are taken to be unity) one has,

$$\frac{I(12C)}{I(13C)} = \frac{1 - e^{-\tau_{12}}}{1 - e^{-\tau_{13}}}$$

(8)

where $\tau_{12}$ and $\tau_{13}$ are the optical depths of the $^{12}$C and $^{13}$C isotopomers, respectively. Adopting the solar isotopic abundance ratio $\tau_{12}/\tau_{13} = 89$, this expression can be solved for $\tau_{13}$. Table 4 reports the calculated optical depths for HCO$^+$ and HCN, whenever the ratio $I$(12C)/$I$(13C) has been determined.

The excitation temperature $T_{ex}$ can be calculated from the observed value of $T_A^*$ in the optically thick case,

$$T_{ex} = \frac{h \nu_{10}}{k} \left( \ln \left[ 1 + \frac{h \nu_{10}/k}{J_\nu(T_{bg}) + T_A^*/\eta_{mb}} \right] \right)^{-1}$$

(9)

where $h \nu_{10}/k \approx 4$ K at the frequency $\nu_{10}$ of the J=1→0 transition, the background temperature $T_{bg} = 2.7$ K and the function $J_\nu$ at background temperature is,

$$J_\nu(T_{bg}) = \frac{h \nu_{10}/k}{e^{h \nu_{10}/k T_{bg}} - 1}$$

(10)
Values of $T_{ex}$ derived in this manner, for the ascertained optically thick cases, are listed in Table 4. For the excitation temperature to be equal to the gas kinetic temperature $T_k$ the critical density is calculated to be $n(H_2) \approx 10^6 \text{ cm}^{-3}$ and this condition may not be always fulfilled for the objects under investigation.

The column densities, for optically thin emission ($\tau << 1$), are obtained with the relation,

$$N = \frac{8\pi k^2 \nu_{10}}{3h^2 c^2 A_{10} B_0} \frac{T_{ex} \exp \left(\frac{h \nu_{10}}{k T_{ex}}\right)}{1 - \left(\frac{J_\nu(T_{bg})}{J_\nu(T_{ex})}\right)} \eta_{mb} \int T_\nu^* d\nu$$

where $A_{10}$ is the Einstein coefficient for spontaneous emission, $B_0$ is the rotational constant, and $J_\nu(T_{ex})$ is the radiation temperature of a black body at temperature $T_{ex}$.

In the optically thick limit ($\tau >> 1$) the integrated line intensity has to be multiplied by the optical depth to obtain corrected column densities.

Table 5 reports the column densities for the observed species calculated using Eq.(11) in the optically thin limit and, assuming $T_{ex} = 10K$ for all sources (Myers, 1985). Only for those objects for which the optical depth was calculated, see Table 6, an optical depth correction factor was introduced. The column densities of HCO$^+$ and HCN calculated in the remaining objects may be underestimated. Moreover, the isotopomers $^{13}$CO$^+$ and $^{13}$CN are assumed to be optically thin in all the observed objects.

The assumed excitation temperature $T_{ex} = 10K$ in the Bok globules and in the gas around the Herbig Ae/Be stars is supported by the values obtained in Table 4. From this temperature a thermal linewidth, for the molecular observations reported here, is calculated to be $\Delta \nu \approx 0.13 \text{ km s}^{-1}$. The observations reported in Table 2 show linewidths much larger than thermal $\sim 1.1-3.1 \text{ km s}^{-1}$, implying bulk motions over some unknown length scale.

**SUMMARY**

In order to contribute molecular data on star forming regions we have measured several molecular transitions in Bok globules and Herbig Ae/Be stars. The selection criteria for the Bok globules were intended to include those with characteristic features of possible star formation. For the Herbig Ae/Be stars the criteria aimed at objects with outflows. Specifically, we have searched for the $J = 1 \rightarrow 0$ ground state transition of HCO$^+$, $^{13}$CO$^+$, HCN, $^{13}$CN in seven Bok globules and in eight Herbig Ae/Be stars. The detection rate was very high for the normal isotopes (HCO$^+$ $= 90\%$ and HCN $= 70\%$), and lower for the $^{13}$C isotopomers, but these have not been searched in all objects.

The HCO$^+$/HCN column density ratio distribution among the investigated Bok globules is $0.3 - 1.3$ and among the Herbig Ae/Be stars is $0.4 - 1.9$. This shows that there is a large overlapping density interval between the two categories of objects. Table 6 compares the HCO$^+$/HCN column density ratio, excitation temperature, density and linewidth of the present sample with those of other known regions. The chemical and physical scenario of the investigated objects looks similar to that found in cold regions, but linewidths are larger than thermal broadening alone. It is worth noting that in two Bok globules (LBN594 and
L810) as well as in two Herbig stars (V645Cyg and LkHα234) water emission was found (Scappini et al., 1991; Nekel et al., 1985; Lada et al., 1981; Rodriguez et al., 1980).

A few maps of the objects exhibiting the highest molecular abundance give an idea of the total line area and of the almost symmetric distribution around the object position.

Even if our results have to be considered very preliminary, still their analysis suggests a quite similar scenario of abundances and physical conditions in the observed Bok globules and in the gas around the Herbig stars. These similarities together with the already discussed features, such as embedded infrared sources, water maser emission, CO outflow, and large CO linewidths, suggest that the presently studied globules are likely to be sites of low-mass star formation.

As discussed in Section III, HCN is produced by dissociative recombination of H$_2$CN$^+$ with electrons, and this produces HNC as well. It would be interesting to search for HNC and the correlated species NH$_3$ in the same objects. In an investigation over twenty dark clouds cores Harju (1989) has found that the average HNC/HCN(J=1→0) intensity ratio is of the order of one. Furthermore the HNC distribution in L1551 is very similar to that of ammonia, while HCN behaves somewhat differently, supporting the idea of different chemical origin between the two isomers.

Future observations will be aimed at other molecular species and also at more quiescent globules in order to eventually detect composition differences between active and inactive regions.
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FIGURE CAPTIONS

Figs. 1 to 10 Line profiles of the J=1→0 transitions of HCO⁺, H¹³CO⁺, HCN and H¹³CN in a number of sources. The telescope pointing positions correspond to the coordinates given in Table 1.

Fig. 11 Contour maps of the integrated line intensity distribution of HCO⁺ (solid line) and of HCN (dashed line) in CB34. Levels are $\frac{1}{\eta_{mb}} \int T_A^* dv = 1,2,3,4,5 \text{ KKms}^{-1}$.

Fig. 12 Contour maps of the integrated line intensity distribution of HCO⁺ (solid line) and of HCN (dashed line) in LkHα234. Levels are $\frac{1}{\eta_{mb}} \int T_A^* dv = 3,5,7,9,11 \text{ KKms}^{-1}$.
### Table 1

**List of the Sources and of Their Physical Properties**

| Source name | \( \alpha_{1950} \) (hms) | \( \delta_{1950} \) (° ′ ″) | \( v_{LSR}^a \) (kms\(^{-1}\)) | Comments |
|-------------|-----------------|---------------------|-----------------|----------|
| Bok globules | | | | |
| LBN594\(^1\) | 00 25 | 59.0 | 56 25 32 | -38.3 | \( \text{H}_2\text{O maser}\)\(^b\) |
| LBN613\(^1\) | 00 46 | 34.0 | 50 28 25 | -12.5 |
| L1534\(^2\) | 04 36 | 31.6 | 25 35 56 | 6.1 |
| CB34\(^1\) | 05 44 | 03.0 | 20 59 07 | 0.7 |
| L810\(^3\) | 19 43 | 21.0 | 27 43 37 | 15.8 | \( \text{H}_2\text{O maser}\)\(^c\) |
| L797\(^1\) | 20 03 | 44.0 | 23 17 54 | 12.6 |
| L1262\(^1\) | 23 23 | 48.0 | 74 01 07 | 4.0 |
| Herbig Ae/Be stars | | | | |
| LkH\(\alpha\)198\(^4\) | 00 08 | 44.0 | 58 33 06 | -0.7 |
| RRTau\(^5\) | 05 36 | 23.3 | 26 20 56 | -5.4 |
| HD250550\(^4\) | 05 59 | 06.5 | 16 30 58 | 2.1 |
| V645Cyg\(^4\) | 21 38 | 10.6 | 50 00 43 | -44.6 | \( \text{H}_2\text{O maser}\)\(^d\) |
| LkH\(\alpha\)234\(^4\) | 21 41 | 57.0 | 65 53 09 | -7.8 | \( \text{H}_2\text{O maser}\)\(^e\) |
| BD463471\(^4\) | 21 50 | 38.5 | 46 59 34 | 7.0 |
| LkH\(\alpha\)233\(^6\) | 22 32 | 28.2 | 40 24 33 | 0.1 |
| MWC1080\(^4\) | 23 15 | 14.9 | 60 34 19 | -29.1 |

**References:**

- (1) Clemens and Barvainis 1988;
- (2) Meyer et al. 1987;
- (3) Neckel et al. 1985;
- (4) Lada 1985;
- (5) Loren 1981;
- (6) Levreault 1988.

\(^a\) From CO millimeter-wave measurements in the clouds (CB) and in the star environments (Cantó et al. 1984).

\(^b\) Scappini et al., 1991.

\(^c\) Neckel et al., 1985.

\(^d\) Lada et al., 1981.

\(^e\) Rodriguez et al., 1980.
| Source name | $T_A^*$ (K) | $\Delta v$ (kms$^{-1}$) | $v_{LSR}$ (kms$^{-1}$) | C-isotope |
|-------------|-------------|-------------------------|-------------------------|-----------|
| LBN594      | 0.48(5)     | 1.9                     | -39.4                   | 12        |
|             | <0.05       |                         |                         | 13        |
| LBN613      | 0.63(3)     | 1.1                     | -12.4                   | 12        |
| L1534       | 0.30(4)     | 2.0                     | 6.7                     | 12        |
| CB34        | 0.91(4)     | 2.0                     | 0.5                     | 12        |
|             | <0.07       |                         |                         | 13        |
| L810        | 1.75(6)     | 2.0                     | 15.9                    | 12        |
|             | 0.20(4)     |                         |                         | 13        |
| L797        | 0.13(2)     | 2.2                     | 12.2                    | 12        |
| L1262       | 0.47(4)     | 1.6                     | 4.4                     | 12        |
| LkHα198     | 0.99(3)     | 1.3                     | 0.0                     | 12        |
|             | 0.27(4)     |                         |                         | 13        |
| RRTau       | <0.09       |                         |                         | 12        |
| HD250550    | <0.11       |                         |                         | 12        |
| V645Cyg     | 1.63(5)     | 3.1                     | -43.9                   | 12        |
|             | 0.28(2)     |                         |                         | 13        |
| LkHα234     | 2.15(6)     | 2.5                     | -10.3                   | 12        |
|             | 0.16(2)     |                         |                         | 13        |
| BD463471    | 0.22(3)     | 1.7                     | 6.8                     | 12        |
| LkHα233     | 0.20(5)     | 1.4                     | -0.1                    | 12        |
| MWC1080     | 0.30(3)     | 2.4                     | -30.1                   | 12        |
|             | <0.18       |                         |                         | 13        |
| Object      | HCN  | FWHM | Inclination | RA   |
|-------------|------|------|-------------|------|
| LBN594      | 0.79(10) | 2.3 | -40.2       | 12   |
| LBN613      | 0.25(6)  | 1.3 | -12.4       | 12   |
| L1534       | <0.28    |     |             | 12   |
| CB34        | 0.83(5)  | 1.8 | 0.5         | 12   |
|             | <0.10    |     |             | 13   |
| L810        | 1.35(14) | 1.4 | 16.0        | 12   |
| L797        | <0.11    |     |             | 12   |
| L1262       | 0.55(4)  | 2.1 | 4.1         | 12   |
| LkHα198     | 0.60(9)  | 1.3 | 0.1         | 12   |
| RRTau       | <0.89    |     |             | 12   |
| HD250550    | <0.08    |     |             | 12   |
| V645Cyg     | 1.70(7)  | 2.7 | -43.9       | 12   |
|             | 0.09(1)  |     |             | 13   |
| LkHα234     | 1.56(6)  | 2.4 | -10.2       | 12   |
|             | <0.07    |     |             | 13   |
| BD463471    | <0.10    |     |             | 12   |
| LkHα233     | 0.23(7)  | 1.7 | 0.0         | 12   |
| MWC1080     | 0.43(4)  | 2.4 | -30.5       | 12   |

*Standard errors are in units of the last digit.*
TABLE 3

INTEGRATED LINE INTENSITIES $I(X)^a$ FOR THE OBSERVED SPECIES. RATIOS (R) OF THE INTENSITIES FOR THE $^{12}$C AND $^{13}$C ISOTOPOMERS

| Source name | $I$(HCO$^+$) (Kkms$^{-1}$) | $I$(H$^{13}$CO$^+$) (Kkms$^{-1}$) | R | $I$(HCN) (Kkms$^{-1}$) | $I$(H$^{13}$CN) (Kkms$^{-1}$) | R |
|-------------|-----------------|-----------------|---|-----------------|-----------------|---|
| LBN594     | 2.23(23)        | <0.51           | >4.4 | 4.50(16)        |                 |    |
| LBN613     | 1.88(17)        |                 | 0.79(18) |                 |                 |    |
| L1534      | 1.47(21)        |                 | <2.1 |                 |                 |    |
| CB34       | 4.83(21)        | <0.73           | >6.6 | 3.70(21)        | <0.61           | >6.8 |
| L810       | 8.86(30)        | 0.74(18)        | 12.0(29) | 4.79            |                 |    |
| L797       | 0.68(20)        |                 | <0.55 |                 |                 |    |
| L1262      | 2.22(23)        |                 | 2.98(23) |                 |                 |    |
| LkHa198    | 3.18(17)        | 0.68(12)        | 4.7(9) | 1.80(30)        |                 |    |
| RRTau      | <0.66           |                 | <0.65 |                 |                 |    |
| HD250550   | <0.83           |                 | <0.74 |                 |                 |    |
| V645Cyg    | 14.28(55)       | 1.69(18)        | 8.4(10) | 11.46(46)       | 0.52(8)         | 22.0(35) |
| LkHa234    | 12.66(30)       | 0.64(12)        | 19.8(35) | 9.46(24)        | <0.45           | >21 |
| BD463471   | 1.04(18)        |                 | <0.87 |                 |                 |    |
| LkHa233    | 0.70(16)        |                 | 0.98(32) |                 |                 |    |
| MWC1080    | 1.78(11)        | <1.07           | >1.7  | 2.55(11)        |                 |    |

$^a I(X) = \frac{1}{\eta_{ab}} \int T_A dv$ for $X = \text{HCO}^+$, $\text{H}^{13}\text{CO}^+$, HCN, and $\text{H}^{13}\text{CN}$, respectively.
| Source name | $\tau_{13}$ | $\tau_{12}$ | $T_{ex}$ (K) |
|-------------|-------------|-------------|-------------|
| HCO$^+$     |             |             |             |
| LBN594      | $<0.26$     | $<22.9$     |             |
| CB34        | $<0.16$     | $<14.6$     |             |
| L810        | 0.09(2)     | 7.7(17)     | 7.0         |
| LkH$\alpha$198 | 0.24(4)    | 21.4(40)    | 5.1         |
| V645Cyg     | 0.13(2)     | 11.3(17)    | 6.7         |
| LkH$\alpha$234 | 0.05(1)     | 4.4(9)      | 7.8         |
| MWC1080     | $<0.89$     | $<79$       |             |
| HCN         |             |             |             |
| CB34        | $<0.16$     | $<2.2$      |             |
| V645Cyg     | 0.05(1)     | 4.1(8)      | 6.9         |
| LkH$\alpha$234 | $<0.05$     | $<4.3$      |             |

$^a\tau_{13}$ refers to the $^{13}$C isotopomer of H$^{13}$CO$^+$ or H$^{13}$CN.

$^b\tau_{12}$ refers to the $^{12}$C isotopomer of HCO$^+$ or HCN.
| Source     | N[HCO$^+$] $(\text{cm}^{-2} \times 10^{12})$ | N[H$^{13}$CO$^+$] $(\text{cm}^{-2} \times 10^{12})$ | N[HCN] $(\text{cm}^{-2} \times 10^{12})$ | N[H$^{13}$CN] $(\text{cm}^{-2} \times 10^{12})$ |
|------------|-------------------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
| LBN594     | 2.16(22)                                  | <0.51                                           | 7.96(24)                        |                                 |
| LBN613     | 1.82(16)                                  |                                                | 1.40(32)                        |                                 |
| L1534      | 1.43(20)                                  |                                                | <3.72                           |                                 |
| CB34       | 4.68(20)                                  | <0.71                                           | 6.55(37)                        | <1.15                           |
| L810       | 66.2(22)                                  | 0.74(18)                                        | 65.3(70)$^a$                    |                                 |
| L797       | 0.66(19)                                  |                                                | <1.50                           |                                 |
| L1262      | 2.15(22)                                  |                                                | 5.27(41)                        |                                 |
| LkH$\alpha$198 | 66.0(35)                              | 0.69(12)                                        | 68.2(11)$^a$                    |                                 |
| RRTau      | <0.64                                     |                                                | <1.15                           |                                 |
| HD250550   | <0.80                                     |                                                | <1.31                           |                                 |
| V645Cyg    | 156.5(60)                                 | 1.71(18)                                        | 83.2(32)                        | 0.98(15)                        |
| LkH$\alpha$234 | 54.0(13)                              | 0.65(12)                                        | 73.7(19)$^a$                    | <0.85                           |
| BD463471   | 1.01(17)                                  |                                                | <1.54                           |                                 |
| LkH$\alpha$233 | 0.68(15)                              |                                                | 1.73(57)                        |                                 |
| MWC1080    | 1.73(11)                                  | <1.08                                           | 4.51                            |                                 |

$^a$Assuming $\tau_{12}(\text{HCN}) \simeq \tau_{12}(\text{HCO}^+)$. 

TABLE 5
COLUMN DENSITIES OF HCO$^+$, H$^{13}$CO$^+$, HCN, AND H$^{13}$CN

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TABLE 6
THE HCO$^+$/HCN COLUMN DENSITY RATIO FOR DIFFERENT REGIONS TOGETHER WITH EXCITATION TEMPERATURE, DENSITY AND LINEWIDTH INFORMATION

| Source          | HCO$^+$/HCN | $T(K)$ | $n$(cm$^{-3}$) | $\Delta v$(kms$^{-1}$)$^a$ | Ref. |
|-----------------|-------------|--------|---------------|----------------|------|
| TMC-1           | 0.4         | 10-20  | $10^3$-$10^5$ | 0.2-0.9        | 1    |
| L134N(L183)     | 2.0         | 10-20  | $10^3$-$10^5$ | 0.2-0.9        | 1    |
| Orion ridge     | 0.15        | 50-100 | $10^4$-$10^6$ | 2.5-4          | 1    |
| Orion plateau   | 0.03        | 90-150 | $10^6$-$10^7$ | 20             | 1    |
| Bok globules    | 0.3-1.3     | 10     | $10^3$-$10^4$ | 1.1-2.2        | 2    |
| Herbig Ae/Be stars | 0.4-1.9 | 10     | $10^3$-$10^4$ | 1.3-3.1        | 2    |

$^a$FWHM linewidth.

1Irvine et al., 1985; Irvine et al., 1987.
2Present work. The density of the Bok globules is taken from Leung, 1985.
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