Chemical differentiation in regions of high-mass star formation – II. Molecular multiline and dust continuum studies of selected objects

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ABSTRACT
The aim of this study is to investigate systematic chemical differentiation of molecules in regions of high-mass star formation (HMSF). We observed five prominent sites of HMSF in HCN, HNC, HCO\(^+\), their isotopes, C\(^{18}\)O, C\(^{34}\)S and some other molecular lines, for some sources both at 3 and 1.3 mm and in continuum at 1.3 mm. Taking into account earlier obtained data for N\(^2\)H\(^+\), we derive molecular abundances and physical parameters of the sources (mass, density, ionization fraction, etc.). The kinetic temperature is estimated from CH\(_3\)C\(_2\)H observations. Then, we analyse correlations between molecular abundances and physical parameters and discuss chemical models applicable to these species. The typical physical parameters for the sources in our sample are the following: kinetic temperature in the range \(\sim 30–50\) K (it is systematically higher than that obtained from ammonia observations and is rather close to dust temperature), masses from tens to hundreds solar masses, gas densities \(\sim 10^5\) cm\(^{-3}\) and ionization fraction \(\sim 10^{-7}\). In most cases, the ionization fraction slightly (a few times) increases towards the embedded young stellar objects (YSOs). The observed clumps are close to gravitational equilibrium. There are systematic differences in distributions of various molecules. The abundances of CO, CS and HCN are more or less constant. There is no sign of CO and/or CS depletion as in cold cores. At the same time, the abundances of HCO\(^+\), HNC and especially N\(^2\)H\(^+\) strongly vary in these objects. They anticorrelate with the ionization fraction and as a result decrease towards the embedded YSOs. For N\(^2\)H\(^+\) this can be explained by dissociative recombination to be the dominant destroying process. N\(^2\)H\(^+\), HCO\(^+\) and HNC are valuable indicators of massive protostars.

Key words: astrochemistry – stars: formation – ISM: clouds – ISM: molecules – radio lines: ISM.

1 INTRODUCTION
It is now well established that the central parts of dense low-mass cloud cores suffer strong depletion of molecules onto dust grains. Best studied is CO, which has been shown to be depleted in, e.g. L1544 (Caselli et al. 1999), IC 5146 (Kramer et al. 1999), L1498 (Willacy, Langer & Velusamy 1998) and L1689B (Jessop & Ward-Thompson 2001). Species related to CO, such as HCO\(^+\), are also expected to disappear at gas densities above \(\sim 10^5\) cm\(^{-3}\) (Caselli et al. 2002). Moreover, Tafalla et al. (2002) and Bergin et al. (2001) have shown that CS also depletes out in the central parts of dense cores, suggesting that CS (so far considered a high-density tracer) does not actually probe the central core regions. On the other hand, N\(^2\)H\(^+\) is an excellent tracer of dust continuum emission (Caselli et al. 2002), implying that this species does not deplete out (due to the volatility of the parent species N\(_2\)).

In more massive cores, depletion is probably active in dense regions away from star forming sites where dust temperatures may be low enough (\(T < 20\) K) for CO and CS abundances to drop and cause chemical differentiation (Fontani et al. 2006).

Several years ago, we mapped several tens of dense cores towards water masers in CS(2–1) with the Swedish-ESO Submillimetre Telescope (SEST) 15-m and Onsala 20-m radio telescopes (Zinchenko, Mattila & Toriseva 1995; Zinchenko, Pirogov & Toriseva 1998). In 2000, many of them were mapped in N\(^2\)H\(^+\) (Pirogov et al. 2003). The goal was to identify dense clumps as local maxima in N\(^2\)H\(^+\) maps and to further investigate their properties. However, large differences between the N\(^2\)H\(^+\) and CS distributions have been found.

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In this situation, it is important to understand which species better trace the total gas distribution: is it N$_2$H$^+$ as in low-mass cores? What is the reason for this differentiation in warm clouds, where freeze-out is hardly effective? To answer these questions, we observed dust continuum emission and several additional molecular lines towards selected sources which show significant differences between the CS and N$_2$H$^+$ maps. The results for the southern sources (where we observed only N$_2$H$^+$ $J = 1 - 0$, CS $J = 2 - 1$ and $J = 5 - 4$ and dust continuum) have been published separately (Pirogov et al. 2003; Zinchenko et al. 1998; Zinchenko, Henkel & Mao 2000; Pirogov et al. 2003). We present the results for the northern sample where we observed also HCN, HNC, HCO$^+$, their isotopes C$^{18}$O and some other molecular lines, for some sources both at 3 and 1.3 mm. These data help to understand better the chemical differentiation in these objects. In addition, they give important information on their physical properties.

2 OBSERVATIONS

2.1 Sources

The main criterion for this selection was a presence of significant differences in the CS and N$_2$H$^+$ maps. Two possible explanations were mentioned: an accelerated collapse model suggested by Lintott et al. (2005) and dissociative recombination of N$_2$H$^+$. We have shown in that paper that the differences in the CS and N$_2$H$^+$ maps cannot be explained by molecular excitation and/or line opacity effects, but are caused by chemical differentiation of these species. We found that N$_2$H$^+$ abundance in many cases drops significantly towards embedded luminous YSOs. However, the reasons for this behaviour were not clear. Here, we present and discuss the results for the northern sample where we observed also HCN, HNC, HCO$^+$, their isotopes C$^{18}$O and some other molecular lines, for some sources both at 3 and 1.3 mm. These data help to understand better the chemical differentiation in these objects. In addition, they give important information on their physical properties.

2.2 Instruments and frequencies

The observations were performed with a superconductor-insulator-superconductor (SIS) receiver in a single-sideband (SSB) mode using either dual beam switching with a beam throw of 11.5 arcmin or frequency switching. As a back end, the filter bank with 250-kHz resolution and a 512-channel filterbank with 1-MHz resolution. Since 2000, we used mainly the autocorrelator spectrometer tuned to 50-kHz resolution. Pointing was checked periodically by observations of nearby SiO masers; the pointing accuracy was typically $\lesssim 5$ arcsec. The half-power beam width (HPBW) was from about 35 arcsec at the highest frequencies to about 40 arcsec at the lowest frequencies.

The standard chopper-wheel technique was used for the calibration. The system temperature varied in a wide range depending on the weather and observing frequency, from $\sim 200$ K at lower frequencies in good weather to $\sim 1000$ K and more at higher frequencies and under cloudy conditions.

2.2.1 Onsala observations

The observations were performed with a superconductor-insulator-superconductor (SIS) receiver in a single-sideband (SSB) mode using either dual beam switching with a beam throw of 11.5 arcmin or frequency switching. As a back end, the filter bank with 250-kHz resolution and a 512-channel filterbank with 1-MHz resolution. Since 2000, we used mainly the autocorrelator spectrometer tuned to 50-kHz resolution. Pointing was checked periodically by observations of nearby SiO masers; the pointing accuracy was typically $\lesssim 5$ arcsec. The half-power beam width (HPBW) was from about 35 arcsec at the highest frequencies to about 40 arcsec at the lowest frequencies.

2.2.2 NRAO 12-m observations

At the NRAO 12-m telescope, only two sources from those listed in Table 1 were observed: S187 and S255 (in the C$^{18}$O, CS, C$^{13}$S, SiO and methanol lines at 1.3 mm). As a result, the data sets for these sources are the most complete ones.

The observations were performed in 2000 with the SIS receiver and two back ends in parallel: the filter bank with the 0.5-MHz resolution and The Millimeter Autocorrelator (MAC) autocorrelator with the 100-kHz resolution. We used frequency switching and position switching observing modes. The pointing and focus were checked periodically by observations of planets. The HPBW was 26–27 arcsec. The system temperature varied from $\sim 300$ K in good weather conditions to $\sim 1500$ K with increasing humidity.

2.2.3 IRAM 30-m observations

At the IRAM 30-m telescope, we obtained maps of the continuum emission from our sources at 1.2 mm and their maps in several components of the CH$_3$C$_2$H $J = 13 - 12$ transition. The continuum observations were performed with the MAMBO bolometer array (the details of this instrument are available at the IRAM web site) and reduced with the MOPIC package. The spectral line observations were done with the Heterodyne Receiver Array (HERA) and VESPA autocorrelator back end. The pointing and focus were checked periodically on nearby strong continuum sources. The antenna HPBW is about 12 arcsec at these frequencies. The typical system temperatures for HERA observations were in the range $\sim 200–400$ K.

3 OBSERVATIONAL RESULTS

We present the observational results in the form of maps and tables where the line parameters at selected positions are given. These

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Table 1. Source list.

| Source | $\alpha$(J2000) | $\delta$(J2000) | $D$ |
|--------|----------------|----------------|-----|
|        | (h m s)       | (° arcmin arcsec) | (kpc) |
| S187   | 01 23 15.0     | 61 48 47       | 1.0$^a$ |
| W3     | 02 25 28.2     | 62 06 58       | 2.1$^b$ |
| S255   | 06 12 53.3     | 17 59 22       | 2.5$^b$ |
| DR-21 NH$_3$ | 20 39 00.4 | 42 22 53       | 3.0$^c$ |
| S140   | 22 19 18.2     | 63 18 49       | 0.9$^b$ |

$^a$Fich & Blitz (1984), $^b$Blitz, Fich & Stark (1982) and
$^c$Harvey, Campbell & Hoffmann (1977).
positions correspond to different emission peaks in the sources which are identified in the maps of molecular emission, and in most cases can be seen in the continuum maps presented in Fig. 1. These maps are plotted using logarithmic scale for intensity in order to emphasize weak features. The continuum brightness, fluxes and angular sizes of the emission clumps towards selected positions are summarized in Table 2. The sources are rather extended in continuum. In order to provide a better comparison with the molecular data, most of which were obtained with ~30-arcsec (HPBW) beams, we give the fluxes integrated over 1-arcmin circles centred at the selected positions. These positions are labelled as 'CS' and 'N$_2$H$^+$' emission peaks according to our previous CS and N$_2$H$^+$ surveys (Zinchenko et al. 1998; Pirogov et al. 2003) and other available data. The sizes are derived from these fluxes and brightness as $\theta = \sqrt{4BF/\pi B}$. For Gaussian brightness distribution, this corresponds to size at the $1/e$ level which is about 20 per cent larger than the size at the half maximum level ($\theta_{0.5}$). In S140, it is hard to see a distinct continuum clump at the N$_2$H$^+$ emission peak, one can see rather an extended filament here. Nevertheless, we provide brightness and flux for this position too. The specific features of every source are briefly described below. The spectral data reduction was performed with the GILDAS and xspec (Onsala data) software packages.

Table 2. Results of the continuum observations: brightness ($B$), fluxes ($F$) and angular sizes ($\theta$) of the emission clumps towards selected positions.

| Source | $\Delta\alpha$ (arcsec) | $\Delta\delta$ (arcsec) | $B$ (Jy/beam) | $F$ (Jy) | $\theta$ (arcsec) | Peak          |
|--------|--------------------------|--------------------------|----------------|---------|------------------|--------------|
| S187   | 0                        | 0                        | 0.15           | 2.1     | 45               | CS           |
| W3     | 20                       | -40                      | 2.03           | 19      | 38               | N$_2$H$^+$   |
| S255   | 0                        | 160                      | 0.70           | 2.23    | 22               | N$_2$H$^+$   |
| S140   | 0                        | 60                       | 1.24           | 6.4     | 28               | N$_2$H$^+$   |
|        | +40                      | +20                      | 1.58           | 15.9    | 39               | CS           |

Figure 1. Maps of the sample sources in continuum at 1.2 mm obtained at the IRAM 30-m telescope. The sources are (from left to right and from top to bottom): S187, W3, S255 and S140. The intensity scale is logarithmic. The triangles mark water masers, the stars indicate point IR sources (IRAS point sources for S187, S255 and W3; IRS1, IRS2 and IRS3 for S140). The circle corresponds to the submillimetre source SMA1 in the S255 N clump area (Cyganowski et al. 2007).
3.1 Molecular maps and line parameters

3.1.1 S187

Maps of S187 in various lines overlaid on the grey-scale map of the 1.2-mm continuum emission are presented in Fig. 2. The CS(2–1) and N$_2$H$^+$(1–0) maps have been published earlier (Zinchenko et al. 1998; Pirogov et al. 2003). There is a striking difference between the various maps. Two separated clumps are clearly seen in N$_2$H$^+$(1–0), which peaks north-west of the IRAS 01202+6133 source. The two peaks are still visible in the HNC(1–0) map, although they are not as well separated as in the N$_2$H$^+$(1–0) map. All the other maps have a cometary or more irregular morphology, with peaks all shifted from the continuum peak. The Gaussian line parameters at the CS and N$_2$H$^+$ emission peaks are summarized in Table 3. In C$^{18}$O $J = 1 - 0$ and $J = 2 - 1$ emission towards the CS peak, there is an additional narrow ($\sim 0.7$ km s$^{-1}$) component at about $-15.5$ km s$^{-1}$. However, it is not pronounced in the lines of other high-density tracers and we do not include it in Table 3.

The molecular data indicate the presence of at least three clumps in the area. There are several IRAS point sources and molecular masers here. The strongest IRAS point source, IRAS 01202+6133, is located at about 2 arcmin to the east from our central position and coincides with the main 1.2-mm continuum peak. Here, an OH maser and ultracompact (UC) H II region are present (Argon, Reid & Menten 2000). The secondary N$_2$H$^+$ peak coincides with this IRAS position. Also a weaker CS clump is located here as is clearly seen from the CS $J = 5 - 4$ data. The main CS, HCO$^+$ and HCN emission peaks are shifted by about 1 arcmin further to the east. No infrared (IR) sources or masers are known in this area. It is worth noting that the methanol emission peak is shifted still further to the east. At the same time C$^{18}$O emission peaks near IRAS 01202+6133.

The strongest N$_2$H$^+$ peak coincides with a relatively weak 1.2-mm continuum clump. It is shifted by about 0.5 arcmin from the strong near IR source NIRS 60 (Salas, Cruz-Gonzalez & Porras 1998).

3.1.2 W3

The molecular line maps of W3 are shown in Fig. 3 overlaid with the 1.2-mm continuum emission map. The CS(2–1) and N$_2$H$^+$(1–0) maps have been published earlier (Zinchenko et al. 1998; Pirogov et al. 2003). The brightest continuum peak is attributed to free–free emission from a compact H II region (e.g. Tieftrunk et al. 1997).

Figure 2. Maps of S187 in various molecular lines (contours) overlaid on the map of 1.2-mm dust continuum emission (grey-scale). The contour levels span from 20 to 100 per cent of the peak intensity in steps of 10 per cent.
Table 3. Molecular line parameters at the CS and $N_2H^+$ emission peaks in S187.

| Line            | $(+160$ arcsec, 0) |                     | $(0, +80$ arcsec) |                     |
|-----------------|-------------------|---------------------|------------------|---------------------|
|                 | $T_{mb}$ (K)      | $V_{LSR}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $T_{mb}$ (K)      | $V_{LSR}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) |
| $^{15}$CO(1–0) | 5.47 (18)         | −13.92 (03)         | 1.71 (09)        | 3.24 (18)          | −13.78 (04)         | 1.67 (10) |
| $^{15}$CO(1–0) | 5.85 (19)         | −14.05 (02)         | 1.69 (05)        |                     |                     |            |
| CS(1–0)         | 4.29 (10)         | −14.26 (03)         | 2.30 (07)        | 1.20 (20)          | −13.63 (27)         | 3.24 (70) |
| $^{13}$CS(2–1)  | 1.00 (04)         | −14.05 (04)         | 2.25 (11)        |                     |                     |            |
| $^{13}$CS(5–4)  | 3.58 (06)         | −14.09 (01)         | 1.86 (03)        |                     |                     |            |
| $^{13}$CS(5–4)  | <0.4              |                     |                  |                     |                     |            |
| HCN(1–0)        | 5.14 (07)         | −14.31 (02)         | 2.33 (04)        | 1.92 (08)          | −13.81 (04)         | 1.63 (07) |
| H$_{13}$CN(1–0)| 0.50 (05)         | −14.17 (10)         | 1.83 (21)        |                     |                     |            |
| HCO$^+$ (1–0)   | 5.54 (08)         | −14.49 (02)         | 2.22 (04)        | 2.41 (08)          | −14.03 (03)         | 1.85 (08) |
| H$_{13}$CO$^+$ (1–0) | 0.58 (07) | −14.15 (09)         | 1.56 (22)        | 1.28 (10)          | −13.51 (03)         | 0.83 (07) |
| HNC(1–0)        | 5.44 (12)         | −14.29 (02)         | 2.27 (06)        | 5.70 (15)          | −13.58 (02)         | 1.39 (04) |
| HN$_{13}$C(1–0)| 0.33 (04)         | −13.88 (09)         | 1.66 (20)        | 0.63 (05)          | −13.35 (03)         | 0.76 (07) |
| $N_2H^+$ (1–0)  | 0.61 (08)         | −14.09 (07)         | 1.45 (20)        | 1.59 (12)          | −13.33 (03)         | 0.90 (06) |

There are two main molecular emission peaks in this area associated with two dust clumps. As in the S187 case, the $N_2H^+$ map looks very different from most other maps. The $N_2H^+$ peak coincides with a relatively weak south-east (SE) clump at the approximately $(160, −160$ arcsec) position. The Gaussian line parameters at the CS and $N_2H^+$ emission peaks are summarized in Table 4. Some spectra clearly show non-Gaussian features: broad wings at the CS peak position and red-shifted self-absorption in HCO$^+$ at the $N_2H^+$ peak.
Chemical differentiation in HMSF regions

3.1.3 S255

For S255, we have the most complete data set. In addition to the common set of molecular transitions, it includes SO($3_2 - 2_1$), SiO (2–1) and (5–4), several methanol 2–1 and 5–4 series lines. Earlier we mapped it also in ammonia (1,1) and (2,2) (Zinchenko, Henning & Schreyer 1997). The molecular maps overlaid on the grey-scale map of the 1.2-mm continuum emission are presented in Fig. 4. This source was mapped at 1.2 mm in continuum at the IRAM 30-m telescope by Mezger et al. (1988). Our observations with the new array receiver provide a better sensitivity and a wider map area, although the basic features of our map are consistent with those previous results.

The maps show two main peaks of molecular and dust continuum emission, around the (0,0) and (0, +60 arcsec) positions. The commonly accepted names for these clumps are S255IR and S255N. There is also a third (southern) peak at about (+20, −40 arcsec) notable in the continuum map and in several molecular maps, at least in N$_2$H$^+$ (1–0) and HCO$^+$ (1–0). N$_2$H$^+$ and ammonia are significantly stronger at the northern peak (S255N) while most other species are either stronger at the central position (S255IR) or comparable at both central and northern clumps. The dust emission is almost equal for these clumps. The nature of these two components is different. The central one is associated with a luminous cluster of IR sources, whereas towards the northern one an ultracompact H II region (G192.58-0.04) was detected. Recently, several compact submillimetre continuum clumps were detected there with SMA (Cyganowski, Brogan & Hunter 2007). This object is extremely red in the mid-IR band (Crowther & Conti 2003). Mezger et al. (1988) derived almost exactly the same dust masses and temperatures for both components from their 1.2-mm and 350-μm observations. The Gaussian line parameters at the central and northern emission peaks are summarized in Table 5.

3.1.4 DR-21 NH$_3$

This is another well known site of active star formation. The CS, HCN and HCO$^+$ spectra here suffer from a very strong red-shifted
Table 5. Molecular line parameters at the CS (central) and N$_2$H$^+$ (northern) emission peaks in S255.

| Line          | $T_{mb}$ (K) | $V_{LSR}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $T_{mb}$ (K) | $V_{LSR}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) |
|---------------|-------------|-----------------|------------------|-------------|-----------------|------------------|
| C$^{18}$O(1–0) | 1.99 (12)   | 1.67 (13)       | 3.71 (34)        | C$^{18}$O(2–1) | 6.45 (08)       | 5.89 (08)        |
| CS(2–1)       | 13.36 (09)  | 9.08 (08)       | 3.16 (03)        | CS(5–4)     | 10.94 (12)     | 8.55 (02)        |
| C$^{34}$S(2–1) | 1.93 (11)   | 1.33 (10)       | 3.20 (29)        | C$^{34}$S(5–4) | 1.13 (06)      | 0.75 (08)        |
| CS(5–4)       | 10.94 (12)  | 8.40 (12)       | 3.60 (03)        | HCN(1–0)    | 13.36 (09)     | 9.08 (08)        |
| C$^{34}$S(5–4)| 1.13 (06)   | 0.75 (08)       | 3.20 (29)        | HCO$^+$ (1–0)| 7.34 (10)      | 11.27 (11)       |
| HN$^{13}$C(1–0) | 1.41 (07)  | 1.37 (07)       | 2.12 (11)        | H$^{13}$CN(1–0) | 7.34 (11)     | 8.91 (06)        |
| HCN$^+$ (1–0) | 0.74 (10)   | 1.39 (08)       | 3.21 (04)        | H$^{13}$CO$^+$ (1–0) | 0.74 (10)   | 8.97 (07)        |
| HNC(1–0)      | 11.87 (18)  | 11.30 (17)      | 3.32 (06)        | HN$^{13}$C(1–0) | 0.18 (02)    | 8.83 (02)        |
| N$_2$H$^+$ (1–0) | 1.46 (06)  | 2.58 (05)       | 2.61 (06)        | N$_2$H$^+$ (1–0) | 1.46 (06)   | 2.12 (11)        |
| SiO(2–1)      | 0.18 (06)   | 0.20 (05)       | 5.24 (144)       | N$_2$H$^+$ (1–0) | 1.46 (06)   | 8.91 (06)        |

self-absorption (Fig. 5), which makes an analysis of corresponding maps almost senseless. For this reason, we present here and discuss only rarer isotopologue and N$_2$H$^+$ (1–0) maps (Fig. 6). We did not map the dust continuum emission in this area, given that it has been already observed by Chandler, Gear & Chini (1993). It is easy to see that the N$_2$H$^+$ and HN$^{13}$C peaks are shifted by about 0.5 arcmin to the south from the emission peaks of other species. The latter peaks practically coincide with the main dust emission peak DR-21(OH)M in the notation introduced by Mangum, Wootten & Mundy (1991). The N$_2$H$^+$ and HN$^{13}$C peaks lie near a weaker dust peak DR-21(OH)S. The Gaussian line parameters are given in Table 6.

3.1.5 S140

S140 is one of the best studied sites of active star formation. In particular, it was observed at various instruments in the HCN, HCO$^+$ and CO isotopic lines (e.g. Park & Minh 1995). Nevertheless, we present here our own data on these lines too, to better compare with other molecular maps (all maps have been obtained at Onsala). The N$_2$H$^+$ results have been published earlier (Pirogov et al. 2003).

The maps (Fig. 7) clearly show that HCN and HCO$^+$ emissions peak near the (0,0) position while the N$_2$H$^+$ peak is shifted to about (+50, +20 arcsec). A multitransitional CS study (Zhou et al. 1994) shows that CS emission peak is near the (0,0) position. HNC is an intermediate case and there is a secondary HNC peak near the N$_2$H$^+$ peak. These differences in emission distributions are not caused by opacity effects because the maps in the lines of rarer isotopic modifications of these molecules show the same features (the N$_2$H$^+$ optical depth is rather small, $\sim$0.4, as shown by Pirogov et al. 2003). The Gaussian line parameters are presented in Table 7.

4 PHYSICAL PARAMETERS OF THE SOURCES AND MOLECULAR ABUNDANCES

4.1 Kinetic temperatures

The kinetic temperatures of the sources have been estimated from the CH$_3$C$_2$H observations. As shown, for example, by Bergin et al. (1994), this symmetric top molecule is a good ‘thermometer’ for gas densities $n \gtrsim 10^4$ cm$^{-3}$. Our main goal is to compare the temperatures at the peaks of the CS and N$_2$H$^+$ emission. At first,
Chemical differentiation in HMSF regions

Figure 6. Maps of DR-21 NH$_3$ in various molecular lines. The contour levels span from 20 to 100 per cent of the peak intensity in steps of 10 per cent. The cross marks the position of DR-21 (OH).

Table 6. Molecular line parameters at the CS and N$_2$H$^+$ emission peaks in DR-21 NH$_3$.

| Line       | $(0, -20 \text{ arcsec})$ | $(0, -40 \text{ arcsec})$ |
|------------|---------------------------|---------------------------|
|            | $T_{mb}$ (K)               | $V_{LSR}$ (km s$^{-1}$)   | $\Delta V$ (km s$^{-1}$) | $T_{mb}$ (K)               | $V_{LSR}$ (km s$^{-1}$)   | $\Delta V$ (km s$^{-1}$) |
| C$^{18}$O(1–0) | 4.99 (14)                | −2.99 (05)                | 3.84 (13)               | 4.69 (15)                | −3.37 (05)                | 3.28 (12)               |
| C$^{34}$S(2–1) | 2.62 (06)                | −3.04 (05)                | 4.68 (12)               | 2.89 (06)                | −3.01 (04)                | 3.83 (10)               |
| H$^3$CN(1–0)    | 2.34 (06)                | −3.24 (06)                | 4.07 (10)               | 2.34 (06)                | −3.47 (05)                | 3.58 (09)               |
| H$^3$CO$^+$ (1–0) | 3.17 (07)               | −3.46 (04)                | 3.67 (09)               | 2.73 (07)                | −3.57 (04)                | 3.25 (10)               |
| HN$^3$C(1–0)    | 1.34 (09)                | −3.05 (14)                | 4.38 (32)               | 1.70 (09)                | −3.25 (10)                | 3.56 (23)               |
| N$_2$H$^+$ (1–0) | 4.99 (04)               | −3.11 (02)                | 4.04 (03)               | 6.93 (04)                | −3.25 (01)                | 3.51 (02)               |

we derived the temperatures from the CH$_3$C$_2$H $J = 6 - 5$ data obtained at Onsala. These measurements were done only at the peak positions. Later the CH$_3$C$_2$H $J = 13 - 12$ emission was mapped at IRAM with the multibeam receiver. The details of the temperature estimates are published elsewhere (Malafeev et al. 2005; Zinchenko et al., in preparation). Here we present the main results. In S187, the CH$_3$C$_2$H emission was too weak.

The kinetic temperatures at the CS and N$_2$H$^+$ peaks, derived from the Onsala and IRAM CH$_3$C$_2$H data, are listed in Table 8. It is easy to see that in most cases there is no significant temperature difference between the CS and N$_2$H$^+$ emission peaks, although on average the N$_2$H$^+$ peaks are somewhat colder than the CS ones. CH$_3$C$_2$H maps of sufficiently high quality were obtained at IRAM for DR-21, S140 and the CS peak in W3. The IRAM data indicate somewhat higher peak temperatures than obtained from the Onsala data, as expected due to a higher angular resolution and higher excitation requirements for the $J = 13 - 12$ transition if temperature increases towards an embedded heating source. Our data do show such temperature gradients consistent with theoretical expectations (Zinchenko et al. 2005), but we do not discuss them here. At the same time the IRAM data confirm our main conclusion that there is no significant temperature difference between the CS and N$_2$H$^+$ peaks in most cases, although the N$_2$H$^+$ peaks are somewhat colder than the CS ones on average.

It is interesting to compare our estimates of kinetic temperature with other available data for these sources. Most of them have been actively studied. Such comparison was made by Malafeev et al. (2005) and here we repeat the main points.

4.1.1 W3

Based on NH$_3$(1,1) and (2,2) lines, Tieftrunk et al. (1998) derived kinetic temperatures of 44 and 25 K towards our CS and N$_2$H$^+$ peaks, respectively. A comparison with Table 8 shows that these temperatures are somewhat lower than those obtained from the CH$_3$C$_2$H data, although the relation is the same.

4.1.2 S255

From our ammonia observations (Zinchenko et al. 1997), the kinetic temperature at the $(0, +80 \text{ arcsec})$ position (near the NH$_3$ and N$_2$H$^+$...
peaks) is 23 ± 1 K. At the central position, the uncertainty in the kinetic temperature is too high. Schreyer et al. (2000) obtained the kinetic temperature in the centre from their ammonia data of 30.8 K and the dust temperature from the IRAS data of 31.1 K. Mezger et al. (1988) derived almost the same dust temperatures (∼30 K) for the two peaks discussed here from their 1.3-mm and 350-μm continuum observations.

4.1.3 DR-21 NH$_3$

This source was observed (without mapping) in the CH$_3$C$_2$H lines at the 11-m NRAO telescope (Kuiper et al. 1984). They observed the same $J = 6 - 5$ transition and derived practically the same kinetic temperature at the centre as in our present work, 33.0 K. There are Very Large Array (VLA) ammonia observations by Mangum, Wootten & Mundy (1992). They derived kinetic temperatures of 32 K at the (0,0) position and 25 K near the (0, −40 arcsec) position. This is rather close to our estimates.

4.1.4 S140

S140 was also observed in CH$_3$C$_2$H at the 11-m NRAO telescope by Kuiper et al. (1984). They obtained for the cloud centre the kinetic temperature of 32.1 ± 6.7 K which coincides with our $J = 6 - 5$ estimate within the uncertainties. From ammonia observations at Effelsberg, Ungerechts, Walmsley & Winnewisser (1986) found a temperature of about 20 K, once again a value significantly lower than found with CH$_3$C$_2$H. The dust temperature from IRAS data is 34 K (Zhou et al. 1994), more similar to our findings. Thus, CH$_3$C$_2$H appears to better trace the dust.
Table 9. Estimates of the gas column densities, average volume densities and masses from the continuum observations. In the last column estimates of the virial masses are given.

| Source | Peak | \(N_l \times 10^{-23}\) (cm\(^{-2}\)) | \(\bar{n} \times 10^{-5}\) (cm\(^{-3}\)) | \(M\) (M\(_\odot\)) | \(M_{vir}\) (M\(_\odot\)) |
|--------|------|---------------------------------|----------------|----------------|-----------------|
| S187   | CS   | 0.4                             | 0.7            | 30             | 50              |
|        | \(\text{N}_2\text{H}^+\) | 0.5                             | 1.0            | 14             | 10              |
| W3     | CS   | 2.0                             | 1.6            | 405            | 310             |
|        | \(\text{N}_2\text{H}^+\) | 1.2                             | 1.5            | 74             | 90              |
| S255   | CS   | 2.0                             | 1.9            | 290            | 210             |
|        | \(\text{N}_2\text{H}^+\) | 1.9                             | 1.6            | 280            | 220             |
| S140   | CS   | 2.8                             | 3.9            | 86             | 90              |
|        | \(\text{N}_2\text{H}^+\) | 0.6                             | 0.7            | 32             | 70              |

4.2 Masses and densities

There are several ways to estimate masses and densities of interstellar clouds. Here, we derive the source masses and column densities primarily from the dust continuum observations. This is considered to be one of the most reliable methods, partly due to the fact that dust/gas mass ratio is rather constant. At the same time, the uncertainties in the dust opacities are still rather high. Additional uncertainties are related to uncertainties in the dust temperature. Here, we use the temperature estimates obtained from our methyl acetylene observations, found to be similar to the dust temperature. It is known that at the typical densities of dense cores, the dust and gas kinetic temperatures are close to each other. The results of these estimates are presented in Table 9. It is worth noting that the masses here are not really total masses of the sources because they are derived from the fluxes integrated over 1-arcmin diameter circle around the indicated positions. The dust opacities were adopted from Ossenkopf & Henning (1994). The gas/dust mass ratio was assumed to be equal to 100. In addition, we present also estimates of the average volume density along the line of sight obtained as \(\bar{n} = N_l / L\), where the size \(L\) is derived from the angular size (Table 2) and distance to the source (Table 1).

In the last column, we give estimates of the virial masses of the clumps based on these sizes and widths of optically thin lines at these positions. These estimates are rather uncertain, at least by a factor of 2 due to large uncertainties in the parameters. Nevertheless, within this factor they agree well with the masses derived from continuum observations. This shows that the clumps are close to gravitational equilibrium.

The average gas volume densities are \(\bar{n} \sim 10^5\) cm\(^{-3}\) in all cases. However, it is well known that such mean densities can be significantly lower than densities found from molecular excitation analysis (e.g. Zinchenko et al. 1998). This discrepancy is most probably explained by small-scale gas clumpiness. Such clumpiness is indicated by many studies (e.g. Bergin, Snell & Goldsmith 1996). At the same time, our data do not provide sufficient material for excitation analysis in most cases. Only for S255, we have 3- and 1.3-mm data in C\(^{18}\)O, CS, C\(^{34}\)S and methanol transitions towards both CS and \(\text{N}_2\text{H}^+\) peaks which can be used for modelling. In particular, our Large Velocity Gradient (LVG) estimates of gas density from the C\(^{34}\)S data give values of about \(n \sim 5 \times 10^5\) cm\(^{-3}\) for both components. Methanol data modelling gives \(n \sim 3 \times 10^5\) cm\(^{-3}\) also for both peaks (S. Sali, private communication). Estimates based on C\(^{18}\)O are highly uncertain but are consistent with these values and show similar densities for both components because the line intensity ratios are similar. These estimates are rather close to the average densities presented in Table 9, although somewhat higher as expected. This shows that the volume filling factor in this density range is rather high. The continuum data also indicate practically equal mean gas densities for the components.

4.3 Abundances

We derive here abundances of several species which were observed in all our sources and are the most informative ones for our purposes: \(^{18}\)O, H\(^3\)CN, H\(^2\)CO\(^+\), H\(^N\)\(^3\)C, \(\text{N}_2\text{H}^+\) and C\(^{34}\)S. In most cases, we use only rare isotopic data which are presumably not affected by optical depth effects. The optical depth in the \(\text{N}_2\text{H}^+\) lines is also small or moderate as shown by Pirogov et al. (2003). The column densities are estimated from integrated line intensities in the Local Thermodynamic Equilibrium (LTE) approximation assuming the excitation temperatures equal to the kinetic temperatures as given in Table 8 (approximate values close to \(T_{\text{kin}}^{12}\) and \(T_{\text{kin}}^{13}\) were used). For S187, we assume \(T_{\text{kin}}\) of 20 K for the CS peak and \(T_{\text{kin}}\) of 10 K for the \(\text{N}_2\text{H}^+\) peak (taking into account narrow line widths and very weak CH\(_3\)C\(_2\)H emission). Then, we derive abundances from comparison of the molecular column densities and total gas column densities obtained from dust continuum observations (Table 9). In order to take into account different beam sizes, we correct the abundance estimates assuming Gaussian beams and Gaussian brightness distributions. For DR-21, where we do not have our own dust continuum data, the abundances were derived assuming \(X(\text{C}^{18}\text{O}) = 2 \times 10^{-7}\). The results are summarized in Table 10. Pirogov et al. (2003) derived \(\text{N}_2\text{H}^+\) abundances in a different way: from the \(\text{N}_2\text{H}^+\) column densities and virial masses of the clouds. Nevertheless, their estimates are very close to those presented in Table 10 when the positions coincide (within a factor of 2).

Non-LTE modelling for some clumps in our sample using the LVG approximation or the RADIEx code (based on the escape probability method; van der Tak et al. 2007) gives systematically lower (by a factor of 1.5–2) column densities for all species considered here, except C\(^{18}\)O, assuming temperature and density as described above. This is a natural result because C\(^{18}\)O is practically thermalized at these conditions while the other species are still far from equilibrium and population of lower levels exceeds that expected in LTE. Nevertheless, we believe that non-LTE modelling is not justified here due to the absence of the necessary data for most of the sources. One can bear in mind that the abundances derived here are somewhat overestimated.

4.4 Ionization fraction

The ionization fraction can be estimated from the HCO\(^+\) abundance using the results of relevant chemical models. It is known that in dense clouds HCO\(^+\) is formed mainly from H\(_3^+\) (e.g. Turner 1995):

\[
\text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2.
\] (1)

and is destroyed by dissociative recombination:

\[
\text{HCO}^+ + e \rightarrow \text{CO} + \text{H}.
\] (2)

In addition, one has to take into account HCO\(^+\) recombination onto negatively charged dust grains (e.g. Caselli et al. 2008). The rate of this reaction is given by the product \(k_g X_g\) where the rate coefficient \(k_g\) and the fractional abundance of dust grains \(X_g\) are determined by grain size distribution and gas kinetic temperature (Draine & Sutin 1987). For the typical temperatures in our objects (\(~30\) K) and MRN (Mathis, Rumpl & Nordsieck 1977) grain size distribution \(k_g X_g \approx 3 \times 10^{-15}\) s\(^{-1}\) cm\(^3\).

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Table 10. Estimates of molecular and electron abundances towards selected positions in the sample sources. For C$^{18}$O, abundances derived from the $J = 1 - 0$ and $J = 2 - 1$ transitions are shown separately.

| Source | $\Delta \alpha$ (arcsec) | $\Delta \delta$ (arcsec) | X(C$^{18}$O)$_{10}$ | X(C$^{18}$O)$_{21}$ | X(H$^{13}$CN) | X(H$^{13}$CO$^+$) | X(HN$^{13}$C) | X(C$^{14}$S) | X(N$_2$H$^+$) | $X_2$ |
|--------|-----------------|-----------------|-----------------|-----------------|---------------|-----------------|---------------|---------------|-----------------|----------------|
| S187   | 160             | 0               | 4.2E−07         | 1.5E−07         | 1.0E−10       | 5.8E−11        | 6.5E−11       | 6.0E−10       | 6.5E−11         | 1.7E−07         |
|        | 0               | 80              | 2.5E−07         | 7.6E−11         | 6.2E−11       | 1.2E−10        | 1.3E−10       |                |                |                |
| W3     | 0               | −40             | 2.9E−07         | 4.8E−10         | 8.6E−11       | 7.6E−11        | 6.5E−11       | 1.2E−07       |                |                |
| S255   | 160             | −160            | 2.0E−07         | 1.9E−10         | 8.8E−11       | 2.7E−10        | 5.4E−08       |                |                |                |
| DR-21  | 0               | −20             | 2.2E−10         | 1.6E−10         | 1.5E−10       | 6.3E−10        | 3.2E−10       | 6.3E−08       |                |                |
| S140   | 0               | 0               | 3.4E−07         | 1.0E−10         | 1.2E−10       | 7.1E−11        | 1.5E−10       | 8.4E−08       | 9.1E−10         | 3.4E−08         |

In this model for HCO$^+$ abundance in steady state we can write

$$X(\text{HCO}^+) = \frac{k_1 X(H_2^+) X(\text{CO})}{\alpha(\text{HCO}^+) X_e + k_g X_e},$$

where $k_1$ is the rate of reaction (1) and $\alpha(\text{HCO}^+)$ is the HCO$^+$ dissociative recombination rate.

$H_2^+$ is formed by cosmic-ray ionization of molecular hydrogen and is destroyed in dense clouds primarily by reaction (1) (e.g. Black 2000). For regions where CO is not frozen onto dust grains, recombination onto negatively charged grains is a negligible $H_2^+$ destruction process compared with this reaction. Therefore, for $H_2^+$ abundance in this regime we obtain

$$X(H_2^+) = \frac{\xi/n}{k_1 X(\text{CO})},$$

where $\xi$ is the cosmic-ray ionization rate and $n$ is the total gas density. Now combining equations (3) and (4) we come to the following simple expression:

$$X(\text{HCO}^+) = \frac{\xi/n}{\alpha(\text{HCO}^+) X_e + k_g X_e}.$$  

Estimates of the electron abundances based on this formula are presented in the last column of Table 10. The cosmic-ray ionization rate was assumed to be equal to $\xi = 3 \times 10^{-17}$ s$^{-1}$, $\alpha(\text{HCO}^+) = 7.5 \times 10^{-7}$ s$^{-1}$ cm$^{-3}$ (Turner 1995). The gas density was assumed to be $n = 10^4$ cm$^{-3}$ and [HCO$^+$]/[H$^{13}$CO$^+$] = 40. The $k_g X_e$ term leads to corrections less than 10 per cent in the $X_e$ values and we neglected it. Strictly speaking, in this way we derive more reliably the parameter $n X_e$, i.e. the electron density, not abundance. However, for a better comparison with other results, we will discuss further the $X_e$ values.

5 DISCUSSION

5.1 Variations of molecular abundances

An inspection of the observational results and estimates of the physical parameters presented above leads to several important conclusions:

(1) There are strong variations of the relative intensities in the lines of different molecular tracers across the investigated high-mass star forming regions. In Paper I, we mentioned already striking differences between N$_2$H$^+$ and CS maps and the fact that the CS distribution follows that of the dust emission while N$_2$H$^+$ does not. Now we see that C$^{18}$O and HCN, like CS, are good tracers of the dust emission which presumably shows the total mass distribution. At the same time the behaviour of HCO$^+$ and HNC resembles that of N$_2$H$^+$. Significant differences in distributions of various species in particular sources have been noticed in some other studies (e.g. Ungerechts et al. 1997), but here we see systematic effects common for the sources in the sample.

(2) There is no sign of CO and/or CS depletion in these objects (in contrast to cold dark clouds). The abundances derived for C$^{18}$O from the $J = 1 - 0$ and $J = 2 - 1$ transitions more or less agree with each other. They are practically constant within each source and among the whole sample (with small deviations which can be caused, for example, by temperature uncertainties) and are close to the ‘canonical’ values derived earlier [e.g. X(C$^{18}$O) $\approx 1.7 \times 10^{-7}$ obtained by Freking, Langer & Wilson 1982].

(3) The N$_2$H$^+$ and HNC abundances significantly decrease with increasing ionization fraction (Fig. 8). The best fit gives X(N$_2$H$^+$) $\propto X_e^{-1.3\pm0.3}$ and X(HN$^{13}$C) $\propto X_e^{-0.8\pm0.2}$ with the correlation coefficients of [|$\rho$] $\approx 0.85$ for both dependences. At the same time the HCN abundance does not show significant variations. It is interesting that the data for N$_2$H$^+$ and $X_e$ presented by Bergin et al. (1999) are in excellent agreement with the X(N$_2$H$^+$) $\propto X_e$ relation obtained here, as one can see in Fig. 8, where the open symbols are the X(N$_2$H$^+$) values derived from the N$_2$H$^+$ and C$^{18}$O column densities presented by Bergin et al. (1999), and assuming X(C$^{18}$O) $= 1.7 \times 10^{-7}$ (Freking et al. 1982).

These correlations should not be affected much by the uncertainties in the abundances due to the LTE approximation, given that both variables scale in a similar way if the non-LTE approach is adopted.

(4) The derived ionization fraction in these objects in general increases towards the strong embedded IR sources which coincide with the main peaks of the dust and CS emission (by a factor of 2−3). The N$_2$H$^+$, HCO$^+$ and HNC abundances decrease correspondingly in these areas. This is consistent with our results in Paper I where we found that the N$_2$H$^+$ abundance is systematically lower towards the CS/dust emission peaks which coincide with strong IR sources. However, it is important to emphasize that estimates of the electron abundance were performed under the assumption of a constant gas density. Our estimates of the gas density towards S255 IR and N give practically the same values. At the same time, it is not unreasonable to expect density variations which can smooth the derived variations of the ionization fraction.

It is worth noting that these variations of the ionization fraction refer to the values averaged over the line of sight and an increase of the electron abundance in vicinities of a young star can be
The kinetic (and dust) temperatures at the CS and N$_2$H$^+$ peaks are similar in most cases and rather high, $\geq 30$ K, which probably makes freeze-out ineffective. This is confirmed by the absence of any indication of the CO and CS depletion as mentioned above.

One possible explanation for the observed chemical differentiation was proposed by Lintott et al. (2005). They suggested that the enhancement of CS and reduction in N$_2$H$^+$ abundance found in regions of high-mass star formation (HMSF) may be related to the high dynamical activity in these regions which could enhance the rate of collapse of cores above the free-fall rate. Consequently, high gas densities would be achieved before freeze-out had removed the molecules responsible for N$_2$H$^+$ loss, while the high densities promote CS formation.

However, this model has several drawbacks. In particular, its predictions for some species (e.g. SO) are not supported by observations. Then, it predicts a decrease in the abundance accompanied by CS enhancement. Our data show no sign of the CS abundance variations. Nothing to say that an accelerated collapse itself has no more or less advanced physical basement.

Our results presented in the previous section indicate that ionization fraction is probably more important in establishing the steady-state N$_2$H$^+$ and HNC abundance in massive cores. The only important process which forms N$_2$H$^+$ is (e.g. Turner 1995)

$$\text{H}_3^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2.$$  \hspace{1cm} (6)

There are two main processes which destroy N$_2$H$: the reaction with the CO molecule:

$$\text{N}_2\text{H}^+ + \text{CO} \rightarrow \text{HCO}^- + \text{N}_2$$  \hspace{1cm} (7)

and dissociative recombination

$$\text{N}_2\text{H}^+ + e^- \rightarrow \text{N}_2 + \text{H}$$  \hspace{1cm} (8)

and

$$\text{N}_2\text{H}^+ + e^- \rightarrow \text{NH} + \text{N}_2$$  \hspace{1cm} (9)

which mainly lead to the formation of N$_2$ (90 per cent of the total reaction), as recently found by Molek et al. (2007).

Then, we have to take into account N$_2$H$^+$ recombination onto negatively charged dust grains as in the case of HCO$^-$. The steady state N$_2$H$^+$ abundance in this model will be given by the formula

$$X(N_2H^+) = \frac{k_2 X(H_3^+) X(N_2)}{k_3 X(CO) + \sigma(N_2H^+) X_e + k_4 X_g},$$  \hspace{1cm} (10)

where $k_2$ is the rate of the reaction (6), $k_3$ is the rate of the reaction (7) which is $8.8 \times 10^{-10}$ cm$^3$ s$^{-1}$ according to the University of Manchester Institute of Science and Technology (UMIST) data base and $\sigma(N_2H^+)$ is the summary rate of the reactions (8) and (9).

Its value is significantly different in the UMIST and Ohio State University (OSU) data bases. We accept the value of $8 \times 10^{-7}$ cm$^3$ s$^{-1}$ at 30 K (E. Herbst, private communication). This means that the dissociative recombination will dominate at $X_e \gtrsim 10^{-3}$ X(CO), i.e. at $X_e \gtrsim 10^{-7}$ for the standard CO abundance X(CO) $\sim 10^{-4}$. This is close to an average electron abundances derived in this work. Therefore, in principle, it is possible that the dissociative recombination of N$_2$H$^+$ can dominate at least in part of our objects. Then, if the H$_3^+$ and N$_2$ abundances are more or less constant (as can be expected), we obtain for $X(N_2H^+)$ the dependence on $X_e$ similar to that presented in Fig. 8.

It is less clear how to explain the behaviour of the HCN and HNC abundances. Their formation pathways are very different. HCN definitely forms from the neutral–neutral processes (Turner, Pirogov & Minh 1997):

$$\text{N} + (\text{CH}_2, \text{CH}_3) \rightarrow \text{HCN}.$$  \hspace{1cm} (11)

Figure 8. Relative abundances of N$_2$H$, \text{HN}^{13} \text{C}$ and H$^{13} \text{CN}$ (from top to bottom) in dependence on the electron abundance. Our estimates are plotted by the filled symbols. The open symbols correspond to the data presented by Bergin et al. (1999).

significantly larger. Ungerechts et al. (1997) found similar variations of molecular abundances in the Orion molecular cloud and suggested that the abundances of molecular ions can be reduced by a higher electron abundance caused by UV radiation propagating in a clumpy photodissociation region. It is well known that in clumpy media UV photons can penetrate deep into dense clouds leading to significantly enhanced ionization (e.g. Bethell, Zweibel & Li 2007). At the same time, in their study of the ionization fraction in massive cores, Bergin et al. (1999) did not find any notable increase of the electron abundance from the edge to the centre of massive cores. This can be caused perhaps by insufficient luminosities of their sample sources.

Thus, we believe that UV radiation from young massive stars in clumpy media can be the primary cause of the observed ionized enhancement. In addition, X-rays detected already from many massive stars (e.g. Zhekov & Palla 2007) can also be responsible for this effect.

(5) We see no dependence of the relative abundances on the velocity dispersion, as derived from the observed line widths. In principle, such dependence could be expected in particular for N$_2$H$^+$ if it really escapes perturbed regions as suggested, for example, by Womack, Ziurys & Wyckoff (1992).

(6) There may be a trend for decreasing N$_2$H$^+$ and increasing H$^{13}$CN abundances with increasing temperature. However, this is based on only one point (W3 data) and cannot be considered reliable.

5.2 Chemical implications

Apparently the observed differences in molecular distributions cannot be explained by molecular freeze-out as in low-mass cores. 

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HNC forms via the distinctly independent sequence
\[ \text{C}^+ + \text{NH}_3 \rightarrow \text{H}_2\text{CN}^+ + e \rightarrow \text{HNC}. \] (12)

The main destruction processes for HNC are probably reactions with \( \text{C}^+ \) and \( \text{H}_3^+ \) (Turner et al. 1997). Calculations of steady state abundances of these species require additional chemical modelling. We note that the HNC formation is closely linked to \( \text{NH}_3 \). Given that \( \text{NH}_3 \) and \( \text{N}_2\text{H}^+ \) both form from \( \text{N}_2 \), thus they are chemically related, one expects similar morphologies of HNC and \( \text{N}_2\text{H}^+ \), as in fact we observe.

### 5.3 Chemical indicators of massive protostars

One of the most intriguing problems in studies of HMSF is the identification of massive protostars at the earliest phases of evolution. Some clumps from our sample represent probably such protostellar objects. For example, the SE clump in W3 area is associated with a water maser but has no embedded IR sources and/or UC \( \text{H} \alpha \) regions. The HCO\(^+\) line profile shows a red-shifted self-absorption feature typical for a collapsing cloud. The mass of this clump from continuum data is about 70\( M_{\odot} \) (Table 9). Therefore, it can be a massive protostar on a rather early evolutionary stage. It is also very pronounced in \( \text{N}_2\text{H}^+ \) emission. Another example of this kind is the \( \text{N}_2\text{H}^+ \) emission peak in S187 (although we did not see signs of contraction on the line profiles). In the S255 area, the northern component, which is dominant in \( \text{N}_2\text{H}^+ \), is apparently much younger than S255 IR. These examples show that a relatively strong \( \text{N}_2\text{H}^+ \) emission can be considered as an indicator of such objects. The species which correlate with \( \text{N}_2\text{H}^+ \) (HCO\(^+\) and HNC) can also be useful in this respect.

### 6 CONCLUSIONS

We presented and discussed here observations of five regions of active HMSF in various molecular lines (at 3 mm and at 1.3 mm) and in continuum at 1.3 mm. On the basis of these observations, we estimated physical parameters of the sources and molecular abundances. The main results of this study can be summarized as follows:

1. The typical physical parameters for the sources in our sample are: kinetic temperature in the range \( 30-50 \) K, masses from tens to hundreds solar masses, gas densities \( \sim 10^3 \text{ cm}^{-3} \) and ionization fraction \( \sim 10^{-7} \). In most cases, the ionization fraction slightly (a few times) increases towards the embedded YSOs. The observed clumps are close to gravitational equilibrium. Our temperature estimates are systematically lower (by a factor of about 1.5–2) compared to those obtained with \( \text{NH}_3 \) observations. However, temperatures measured with \( \text{CH}_3\text{C}^+ \) are similar to dust temperatures, suggesting that the observed methylene acetylene transitions better trace the dust than ammonia (1,1) and (2,2) lines.

2. There are systematic differences in distributions of various molecules in regions of HMSF. The abundances of CO, CS and HCN are more or less constant and optically thin lines of rare isotopes of these species are good tracers of the dense gas distribution in these regions. There is no sign of CO and/or CS depletion as in cold low-mass cores.

3. At the same time, the abundances of the high-density tracers HCO\(^+\), HNC and especially \( \text{N}_2\text{H}^+ \) strongly vary in these objects. They anticorrelate with the ionization fraction \( \propto X_{\text{e}}^{-1.3\pm0.3} \) and \( X(\text{HN}^1\text{C}) \propto X_{\text{e}}^{-0.8\pm0.2} \) and as a result decrease towards the embedded YSOs. For \( \text{N}_2\text{H}^+ \), this can be explained by dissociative recombination to be the dominant destroying process. This conclusion is more or less consistent with the data on chemical reaction rates. There is no correlation of these abundances with the line width.

4. The described variations of the HCO\(^+\), HNC and \( \text{N}_2\text{H}^+ \) abundances make them potentially valuable indicators of massive protostars. In our sample, there are some clumps which represent probably massive protostars at very early stages of evolution and they are very pronounced in the lines of these species, especially \( \text{N}_2\text{H}^+ \).

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### REFERENCES

Argon A. L., Reid M. J., Menten K. M., 2000, ApJS, 129, 159
Bergin E. A., Goldsmith P. F., Snell R. L., Ungerechts H., 1994, ApJ, 1994, 431, 674
Bergin E. A., Snell R. L., Goldsmith P. F., 1996, ApJ, 460, 343
Bergin E. A., Plume R., Williams J. P., Myers P. C., 1999, ApJ, 512, 724
Bergin E. A., Ciardi D. R., Lada C. J., Alves J., Lada E. A., 2001, ApJ, 557, 209
Bethell T. J., Zweibel E. G., Li P. S., 2007, ApJ, 667, 275
Black J. H., 2000, Phil. Trans. R. Soc. Lond. A, 358, 2359
Blitz L., Fich M., Stark A. A., 1982, ApJS, 49, 183
Caselli P., Walmsley C. M., Tafalla M., Dore L., Myers P. C., 1999, ApJ, 523, L165
Caselli P., Walmsley C. M., Zucconi A., Tafalla M., Dore L., Myers P. C., 2002, ApJ, 565, 331
Caselli P., Vastel C., Ceccarelli C., van der Tak F. S., Crapsi A., Bacmann A., 2008, A&A, 492, 703
Chandler C. J., Gear W. K., Chini R., 1993, MNRAS, 260, 337
Crowther P. A., Conti P. S., 2003, MNRAS, 343, 143
Cyganowski C. J., Brogan C. L., Hunter T. R., 2007, AJ, 134, 346
Draine B. T., Sutin B., 1987, ApJ, 320, 803
Fich M., Blitz L., 1984, ApJ, 279, 125
Fontani F., Caselli P., Crapsi A., Cesaroni R., Molinari S., Testi L., Brand J., 2006, A&A, 460, 709
Ferking M. A., Langer W. D., Wilson R. W., 1982, ApJ, 262, 590
Harvey P. M., Campbell M. F., Hoffmann W. F., 1977, ApJ, 211, 786
Jessop N. E., Ward-Thompson D., 2001, MNRAS, 323, 1025
Jijina J., Myers P. C., Adams F. C., 1999, ApJS, 125, 161
Kramer C., Alves J., Lada C. J., Lada E. A., Sievers A., Ungerechts H., Walmsley C. M., 1999, A&A, 342, 257
Kuiper T. B., Kuiper E. N. R., Dickinson D. F., Turner B. E., Zuckermain B., 1984, ApJ, 274, 211
Lintott C. J., Viti S., Rawlings J. M. C., Williams D. A., Hartquist T. W., Caselli P., Zinchenko I., Myers P., 2005, ApJ, 620, 795

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Chemical differentiation in HMSF regions

Malafeev S. Yu., Zinchenko I. I., Pirogov L. E., Johansson L. E. B., 2005, Astron. Lett., 31, 239
Mangum J. G., Wootten A., Mundy L. G., 1991, ApJ, 378, 576
Mangum J. G., Wootten A., Mundy L. G., 1992, ApJ, 388, 467
Mathis J. S., Rumpl W., Nordsieck K. H., 1977, ApJ, 217, 425
Mezger P. G., Chini R., Kreysa E., Wink J. E., Salter C. J., 1988, A&A, 191, 44
Molek C. D., McLain J. L., Poterya V., Adams N. G., 2007, J. Phys. Chem. A, 111, 6760
Ossenkopf V., Henning Th., 1994, A&A, 291, 943
Park Y., Minh Y., 1995, J. Korean Astron. Soc., 28, 255
Pirogov L., Zinchenko I., Caselli P., Johansson L. E. B., Myers P. C., 2003, A&A, 405, 639
Pirogov L., Zinchenko I., Caselli P., Johansson L. E. B., 2007, A&A, 461, 523 (Paper I)
Salas L., Cruz-Gonzalez I., Porras A., 1998, ApJ, 500, 853
Schreyer K., Henning T., Koenme P., Harjunpaa P., 1996, A&A, 306, 267
Tafalla M., Myers P. C., Caselli P., Walmsley C. M., Comito C., 2002, ApJ, 569, 815
Tieftrunk A. R., Gaume R. A., Claussen M. J., Wilson T. L., Johnston K. J., 1997, A&A, 318, 931
Tieftrunk A. R., Megeath S. T., Wilson T. L., Rayner J. T., 1998, A&A, 336, 991
Turner B. E., 1995, ApJ, 449, 635
Turner B. E., Pirogov L., Minh Y. C., 1997, ApJ, 483, 235
Ungerechts H., Walmsley C. M., Winnewisser G., 1986, A&A, 186, 157, 207
Ungerechts H., Bergin E. A., Goldsmith P. F., Irvine W. M., Schloerb F. P., Snell R. L., 1997, ApJ, 482, 245
Van der Tak F. F. S., Black J. H., Schoier F. L., Jansen D. J., van Dishoeck E. F., 2007, A&A, 468, 627
Willacy K., Langer W. D., Velusamy T., 1998, ApJ, 507, L171
Zhekov S. A., Palla F., 2007, MNRAS, 382, 1124
Zhou S., Butner H. M., Evans N. J., Guesten R., Kutner M. L., Mundy L. G., 1994, ApJ, 428, 219
Womack M., Ziurys L. M., Wyckoff S., 1992, ApJ, 387, 417
Zinchenko I., Mattila K., Toriseva M., 1995, A&S, 111, 95
Zinchenko I., Henning Th., Schreyer K., 1997, A&A, 124, 385
Zinchenko I., Pirogov L., Toriseva M., 1998, A&A, 133, 337
Zinchenko I., Henkel C., Mao R. Q., 1997, A&A, 361, 1079
Zinchenko I., Pirogov L., Caselli P., Johansson L. E. B., Malafeev S., Turner B., 2005, in Cesaroni R., Felli M., Churchwell E., Walmsley M., eds, Proc. IAU Symp. 227, Massive Star Birth: A Crossroads of Astrophysics. Cambridge Univ. Press, Cambridge, p. 92

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