Molecular Abundances in Low-Mass Protostellar Envelopes

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Abstract

A study of the chemical structure of the envelopes around a sample of protostars is introduced. Physical models for the envelopes derived using 1D radiative transfer modeling of their dust continuum emission are used as input for Monte Carlo modeling of single-dish line observations in order to establish the chemical inventories for the different sources. CO and HCO$^+$ abundances are found to be correlated with envelope mass: the sources with the most massive envelopes show the lowest abundances, supporting the idea that the depletion of these molecules is most efficient in the colder, denser environments. Other molecules like CS and HCN do not show a similar trend. Deuterated species like DCO$^+$ and DCN also show signs of correlations with envelope mass and temperature: the deuterium fractionation of HCO$^+$ is most prominent for the coldest and most massive envelopes in the sample and at the same time anti-correlated with the fractionation of HCN. This puts constraints on the low temperature gas-phase deuterium chemistry.

Key words: ISM: molecules – ISM: abundances – stars: formation – radiative transfer – astrochemistry

1. Introduction

Understanding the chemistry of protostellar environments is of great importance for addressing topics of star formation. It is directly related to processes regulating star formation, for example through the ionisation and the chemistry also potentially serves as an evolutionary clock against which physical models, e.g. for the protostellar collapse, can be compared (see e.g. van Dishoeck & Blake [1998] for an overview). Recent evidence suggests that many of the traditional molecular tracers of density and temperature may be subject to significant gradients in abundances. Examples are the freeze-out of molecules like CO onto dust grains both in pre-stellar cores (Caselli et al. 1999, Bacmann et al. 2002) and in the cold and dense parts of low-mass protostellar envelopes (Jørgensen et al. 2002) and enhancement of molecules due to liberation of ice mantles in regions of higher temperatures similar to “hot cores” or in regions subject to shocks driven by protostellar outflows (Bachiller & Pérez Gutiérrez 1997, Ceccarelli et al. 2000, Schöier et al. 2002).

In this paper a preliminary overview of the results from a large survey of the chemical properties of a sample of low-mass protostars is presented. For further details see Jørgensen et al. (2002) and Jørgensen et al. (2003; in prep.).

2. Sample, observations and modeling

The sample of objects in this study comprises 18 pre- and protostellar objects, including 11 class 0 objects, 5 class I objects and 2 pre-stellar cores; the full sample is presented in Jørgensen et al. (2002). These objects have been observed in a range of molecular transitions using the 15 m James Clerk Maxwell Telescope (JCMT), 20 m telescope at Onsala Space Observatory and the IRAM Pico Valeta 30 m telescope between 2000 and 2002.

The physical structure of each envelope is derived using 1D radiative transfer calculations. Power-law density profiles are assumed for a range of envelope parameters (e.g. density slope and optical thickness) and the corresponding temperature profiles calculated using the radiative transfer code, DUSTY (Ivezić et al. 1999) for a given central source of heating. For each model, images are constructed and compared to the observed SCUBA images (450 and 850 $\mu$m) and SEDs over the range from 60 $\mu$m to 1.3 mm. It is found that each protostellar envelope can successfully be modeled under these assumptions, whereas the pre-stellar cores can not, which is not unexpected since these sources per definition are characterized as not having central sources of heating.

The derived physical models are subsequently used as basis for calculating the molecular excitation and radiative transfer for the molecular lines using the Monte
Carlo code of Hogerheijde & van der Tak (2000). The fractional abundances (assumed to be constant) are constrained through comparisons with the integrated line intensities and it is found that the majority of the lines can successfully be accounted for with the presented models and assumptions. In Fig. 1, an overview of the average abundances for the class 0 and I objects are compared to the molecular cloud L134N (Dickens et al. 2000) and the abundances in the steady state or pre-collapse phase of the models of Bergin & Langer (1997). The abundances are, where possible, derived from the minor isotopic lines. The main isotopic lines of e.g. CS and HCO$^+$ are more sensitive to departures from spherical symmetry or the interaction of molecular outflows with the envelope material.

Figure 1. Comparisons between average abundances with respect to $\text{H}_2$ for different molecules for objects with envelope masses larger or smaller than $0.5 \, M_\odot$, and with the abundances towards the “C” position in the dark cloud L134N (Dickens et al. 2000) and the abundances in the stage before the collapse in the chemical models of Bergin & Langer (1997). All abundances normalized to the abundances of L134N. (From Jørgensen et al. 2003; in prep.)

3. Molecular depletion

As can be seen from Fig. 1 and 2 significant differences exist between the various molecules relative to the two comparison sets of abundances and also between the samples of class 0 and I objects for some molecules – in particular CO and HCO$^+$. CO is thought to be frozen out onto dust grains at low temperatures ($T \leq 30 \, \text{K}$; Jørgensen et al. 2002) and CO is indeed most depleted for the sources with the most massive envelopes (Fig. 2), i.e., the envelopes with a region in which the temperatures are low enough and densities high enough that the depletion can be effective. The primary formation route of HCO$^+$ is connected to the presence of CO through the reaction $\text{CO} + \text{H}_2 \rightarrow \text{HCO}^+ + \text{H}_2$, as is indeed illustrated by the data in Fig. 3.

Figure 2. CO (upper panel) and CS (lower panel) abundances as functions of mass. (From Jørgensen et al. 2002, 2003; in prep.)

Other molecules like CS and HCN do not show a similar trend with mass, which at first may seem unexpected (lower panel of Fig. 2): CS depletion is expected to occur at even lower densities than for CO and CS should stay bound to the dust grains to even higher temperatures than CO due to its larger binding energy to the dust grains. Comparison to the models of Bergin & Langer (1997) shows that the CS abundances observed in the protostellar environments are indeed lower by more than an order of magnitude, which could indicate that the observed lines only probe the region where CS is depleted. A detailed comparison with other sulfur-bearing species like SO will be needed to fully address this, and similarly
for the nitrogen-bearing species that also show interesting features – in particular the strikingly low HNC abundances for the protostars compared to other star-forming environments.

4. Deuterium fractionation

Another interesting aspect of the chemistry in the envelopes around protostars is the degree of deuterium fractionation. Gas-phase deuterium fractionation of molecules like HCO$^+$ is expected to be particularly efficient at low temperatures (e.g., [Roberts & Millar 2000]) due to small zero-point energy differences of reactions like HD$^+$ + H$_3^+$ → H$_2$D$^+$ + H$_2$. As illustrated in Fig. 4, the highest degree of deuterium fractionation is seen to occur in the pre-stellar cores and class 0 objects with low temperatures ($T \leq 20$ K) and high densities. Interestingly, the HCN deuterium fractionation seems to be anti-correlated with that of HCO$^+$ as shown in the lower panel of Fig. 4. For HCN deuterium fractionation through other species like CH$_3^+$ (i.e. forming CH$_2$D$^+$) could become increasingly important in producing DCN at temperatures $T \sim 30$ K (e.g., [Turner 2001]). Such a scenario could explain the observed anti-correlation between the deuteration of HCO$^+$ and HCN.

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Figure 3. HCO$^+$ abundance as a function of CO abundance. Symbols as in Fig. 2. (Jørgensen et al. 2003; in prep.)

Figure 4. [DCO$^+$/[HCO$^+$] ratio plotted against mass (upper panel) and [DCN]/[HCN] plotted against [DCO$^+$/[HCO$^+$] ratios (lower panel). Symbols as in Fig. 2. (Jørgensen et al. 2003; in prep.)

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