HCN Hyperfine Ratio Analysis of Massive Molecular Clumps

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Abstract. The CHaMP project has identified a uniform sample of 303 massive (20–8000 $M_\odot$), dense (200–30,000 cm^{-3}) molecular clumps in a large sector of the southern Milky Way that includes much of the Carina Arm. These are the kinds of clumps that are likely to be the precursors to IRDCs, large stellar clusters, and massive stars. We report new results of the physical conditions in these clouds based on the $J=1\rightarrow0$ emission at 3mm from the HCN molecule. Analysis of the HCN emission from these clumps reveals that the physical conditions in the gas (i.e., the excitation temperature, optical depth, and column density) do not follow the molecular line emissivity in a straightforward way. This means that large fractions of the molecular material involved in massive cluster formation, while not completely "dark", are under-luminous and easily missed in certain studies.

Keywords. Molecular clouds, cluster formation, star formation

1. Data & Analysis

We started with a sample of clumps from the full Mopra HCN data set, BYF 40a–g in Region 6 of CHaMP at an adopted distance of 6.6 kpc (see Fig. 1), and used the same data reduction techniques as described by Barnes *et al.* (2011) for HCO^+. For comparison with the HCO^+ results, we compiled the same observed clump properties in the HCN maps of BYF 40, such as clump positions, sizes, brightness, etc., as shown in Table 1. However, because of the HCN line's hyperfine structure, we used the PySpecKit package (Ginsburg & Mirocha 2000) to perform an LTE analysis of the emission, in order to obtain a self-consistent set of maps of the HCN's optical depth τ, excitation temperature T_{ex}, systemic velocity V_{LSR}, and velocity dispersion σ_V.
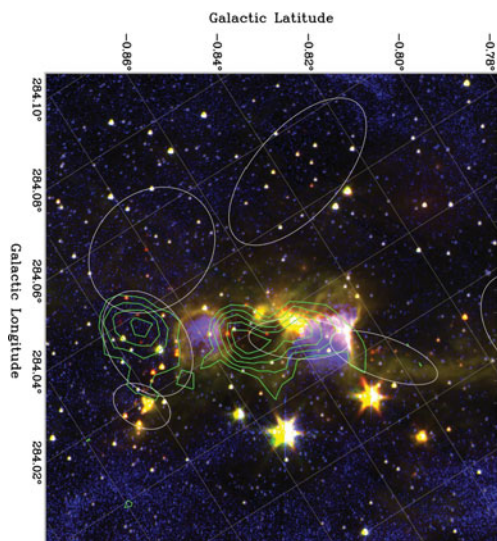

Figure 1. Three-color composite (red = IRAC2, green = IRAC1, blue = Brackett-γ) of the BYF 40 area, with the N_2H^+ contours shown in green and HCO^+ clumps' HPW shown by ellipses. The scale bar is for an assumed distance of 6.6 kpc. Note the mix of molecular and ionised gas in the area.

Table 1. HCN clump properties

Clump	l [deg]	b [deg]	I [K km s^{-1}]	$\mathbf{T}_{ex}$ [K]	R [pc]	$\mathbf{V}_{LSR}$ [km s^{-1}]	σ_V [km s^{-1}]	N_{HCN} [m^{-2}]
40a	284.012	−0.859	28.80	3.72	0.51	9.02	2.10	8.6e17
40b	284.032	−0.893	10.52	2.04	0.38	9.25	1.66	6.9e17
40c	284.019	−0.903	3.83	1.26	1.21	9.14	1.41	—
40d	283.996	−0.839	4.18	1.27	0.51	8.41	1.85	—
40e	284.056	−0.876	2.39	0.99	1.52	9.62	1.71	1.5e17
40f	284.049	−0.833	1.89	1.14	1.63	8.09	1.41	4.1e17
40g	283.986	−0.816	0.76	0.97	1.33	9.63	1.37	—

Having obtained spatially resolved maps of τ and T_{ex}, we then used

$$N(\text{HCN}) = 9 \times 10^{15}\,\text{m}^{-2}\,\frac{Q(T_{\text{ex}})e^{E_{\text{u}}/kT_{\text{ex}}}}{(1 - e^{-h\nu/kT_{\text{ex}}})} \int \tau dV \;, \qquad (1.1)$$

to compute a spatially resolved map of the HCN column density, including formal error propagation. Illustrative column density values at the clumps' peak emission positions are also given in Table 1.

2. Results

From the computed column densities, we can now compare them with the integrated intensities to explore the relationship (Fig. 2). Neither a linear nor a power-law does a good job of fitting the low-brightness (low-T_{ex}), high-N_{col} (high-τ) points. Using either of these laws to convert from integrated intensity to column density (with an assumed HCN abundance relative to H$_2$), we obtain a total clump mass around 24,000–37,000 M$_\odot$. Integrating the N_{col} map directly gives a total mass of 57,000 M$_\odot$ instead. Therefore, such laws substantially underestimate the amount of subthermally excited, dense, molecular gas available for (but not yet engaged in) star formation.

3. Implications

The integrated intensity of "dense gas tracers" like HCO$^+$ (Barnes *et al.* 2013)

Figure 2. Comparison of HCN integrated intensity with HCN column density, computed by PySpecKit from hyperfine ratio analysis in the BYF 40 area. The straight red line is a least-squares linear fit to the data, while the blue line is a least-squares power-law (index 0.7) fit. The green error bars show typical uncertainties.

and now HCN do not trace dense gas, but rather a combination of τ and T_{ex}. Physically-based column density calculations show instead that the molecular mass of dense clumps may be underestimated by substantial factors, which would also imply a correspondingly longer gas depletion timescale, for a given star formation rate. This means that the calibration of Kennicutt-Schmidt-type scaling relations may need to be re-examined.

References

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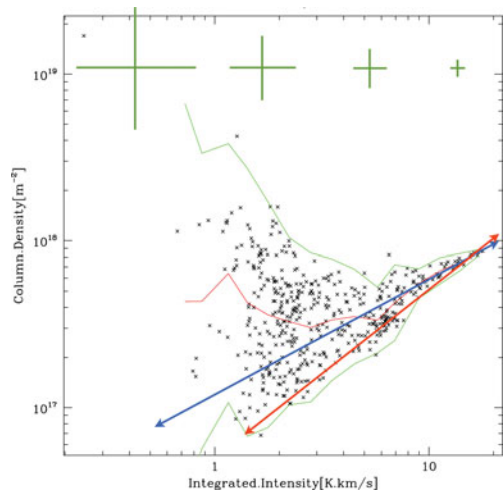Ginsburg, A. & Mirocha, J. 2000, *Astrophysics Source Code Library*, 1109.001