The JCMT dense gas survey in Gould Belt Molecular Clouds: an HCO^+/HCN comparison

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CAVENDISH ASTROPHYSICS

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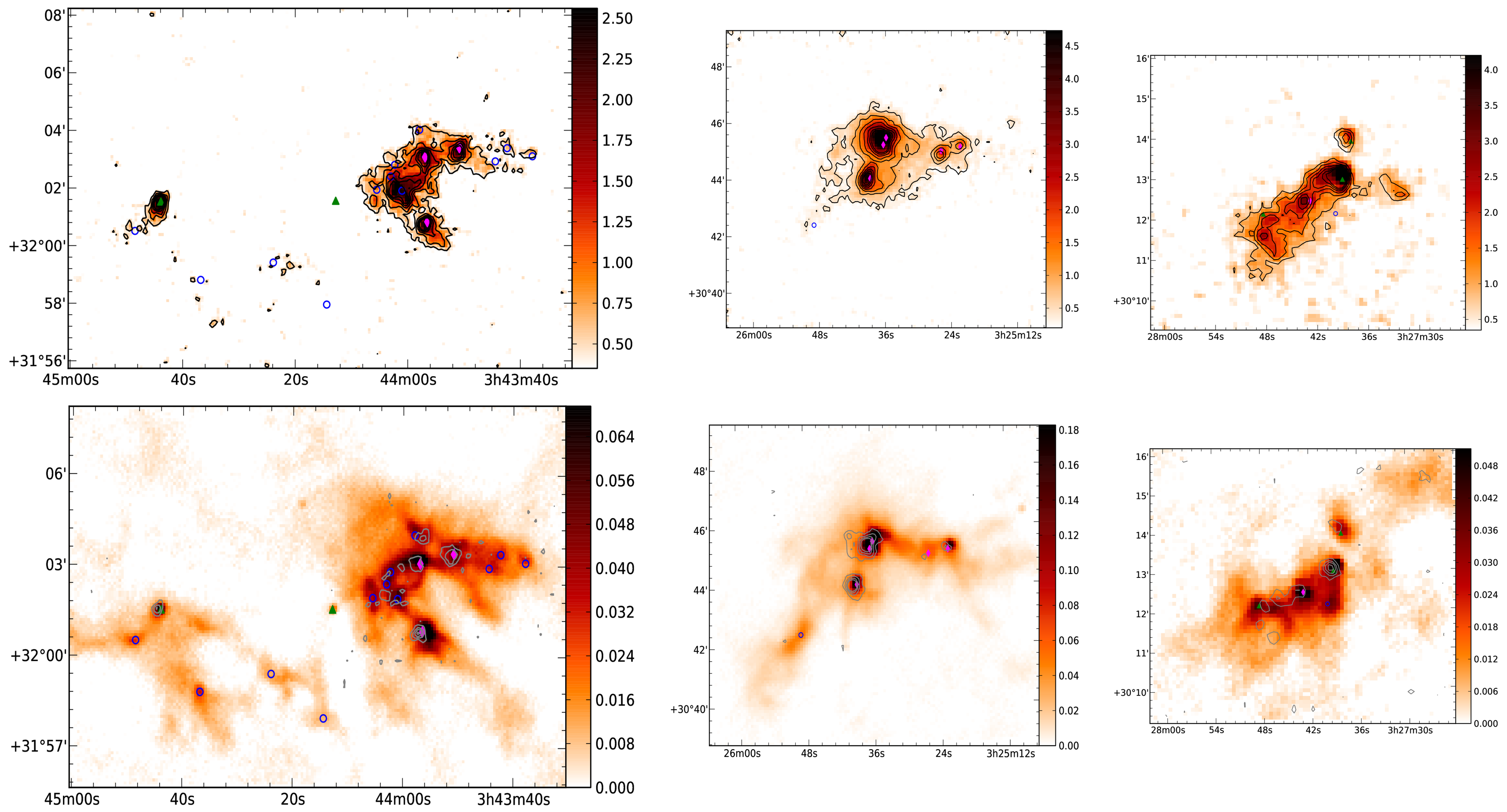
Abstract

We present the results of a large-scale survey of the very dense gas in molecular clouds in our Galaxy using HCO^+ and HCN (J = 4 - 3) rotational transitions. We have used this emission to trace gas at the extremely high densities found in pre- and protostellar cores; as well as outflows powered by these early star-forming cores. We present an analysis of the outflow properties in Perseus that we derive from this tracer; we find that our results are comparable to those obtained from similar outflow analyses using ^{12}CO. We present a comparison of the HCO^+/HCN emission, highlighting regions where there is a marked discrepancy in the spectra of the two emission lines. In particular, we examine the protostellar core IRAS 2, where the HCN abundance is greatly enhanced in the linewings in comparison with HCO^+.



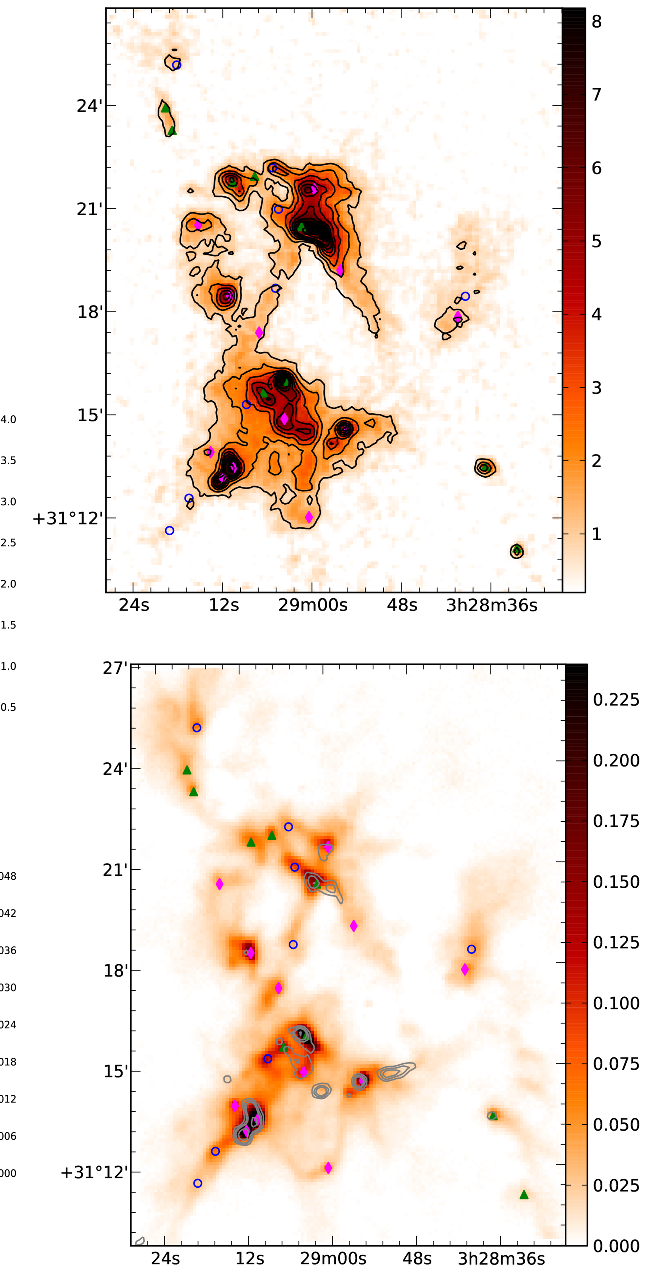


Figure 1: Comparison of HCO^+ integrated intensity (top row) and SCUBA-2 dust emission obtained as part of the GBS S2 project (bottom row) for four regions in Perseus (left to right): IC 348, L 1448, L 1455 and NGC 1333. The HCN integrated intensity is overlaid on the SCUBA-2 maps as grey contours, and previously identified core positions (Hatchell et. al., 2007) are indicated with magenta diamonds (Class 0), green triangles (Class I) and blue circles (starless). The colour scales for the top and bottom rows are in K kms^{-1} and Jy per 6" pixel respectively.

1. The dense gas survey

- Mapping of several northern Gould Belt clouds in HCO^+ and HCN (J = 4 – 3): Orion A, Orion B, and Perseus.
- Mapping of Serpens and Ophiuchus in HCO^+ only (due to time constraints, and hence not included in this analysis).
- Observations were carried out using HARP on the JCMT at Mauna Kea, Hawaii.

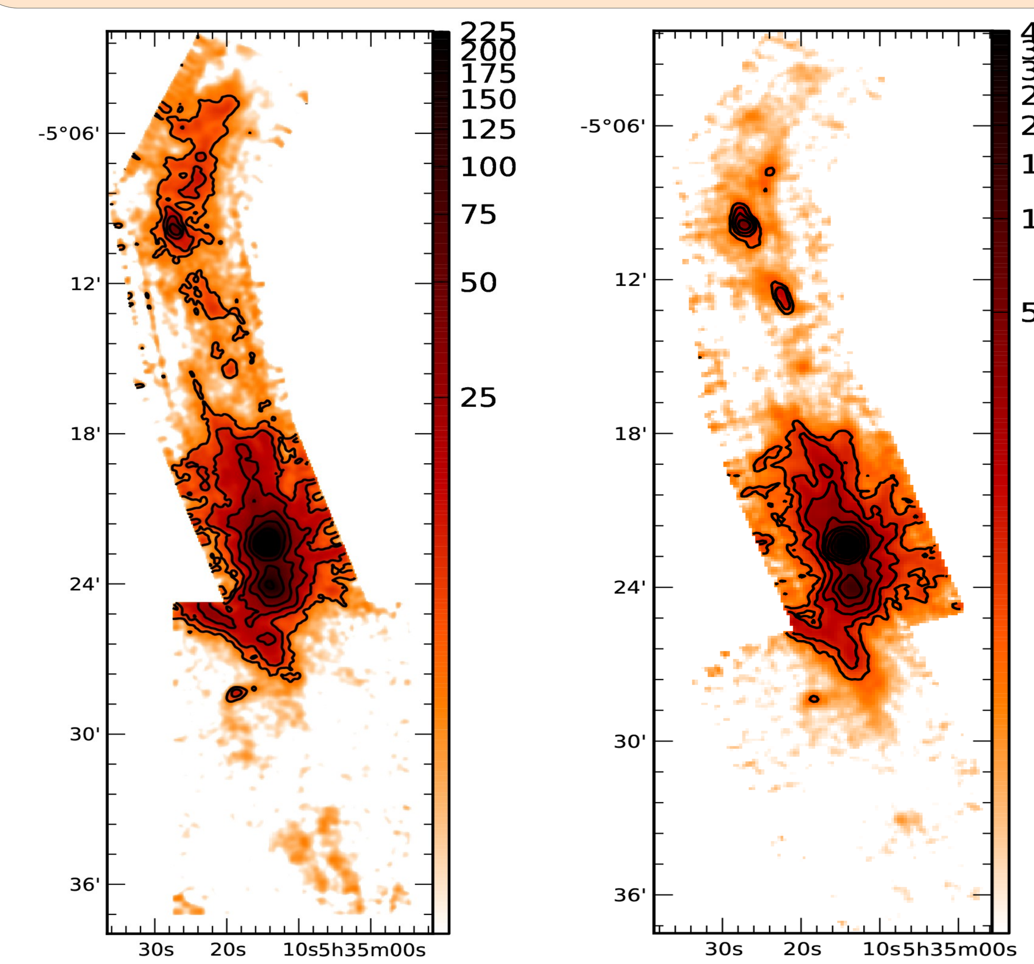


Figure 2: Comparison of the integrated intensity of HCO^+ (left) and HCN (right) for Orion A (OMC 1-4). The units for the colour scale are in K kms^{-1}.

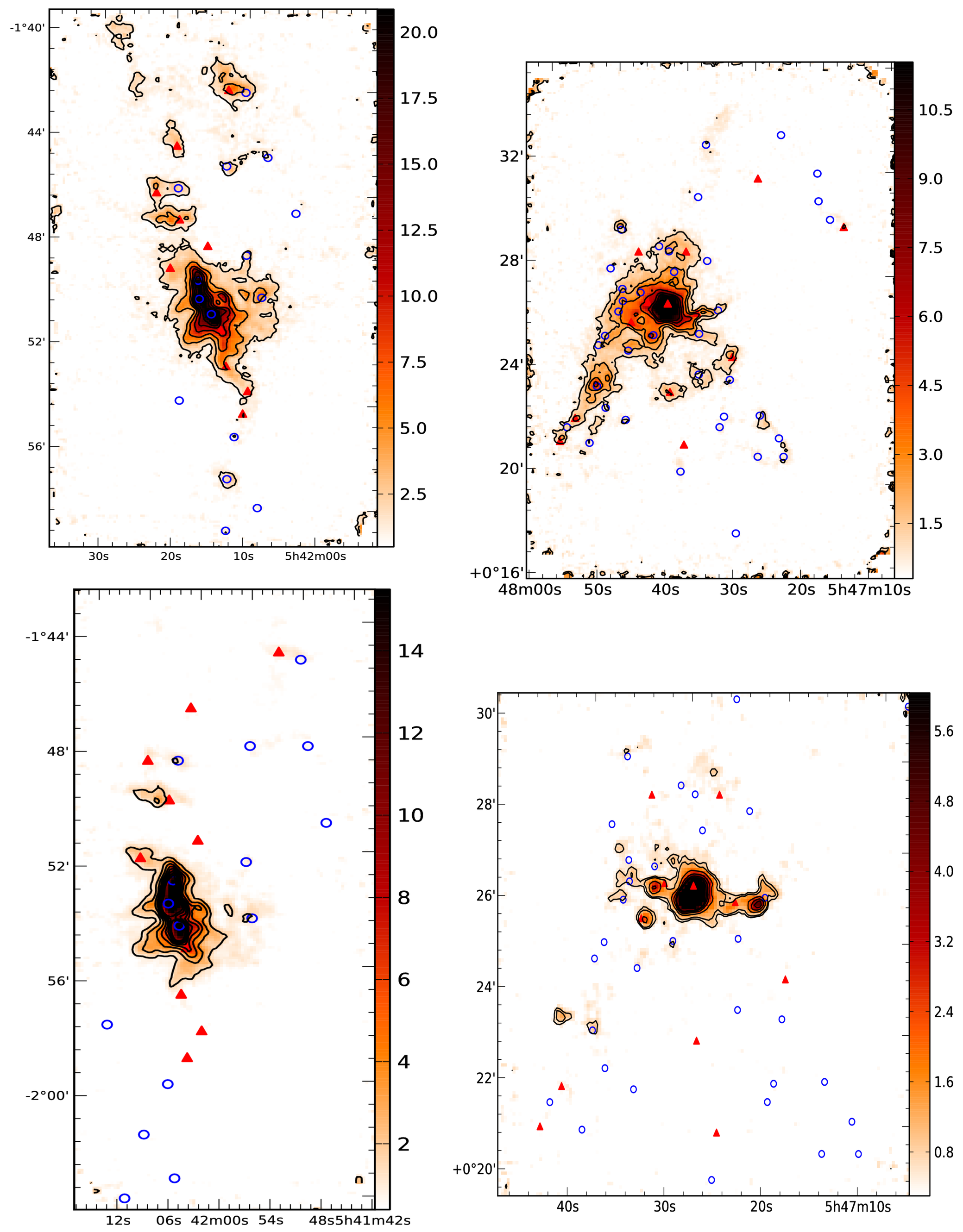


Figure 3: Comparison of the integrated intensity of HCO^+ (above) and HCN (below) for NGC2024 (left) and NGC2071 (right). SCUBA-identified cores (Nutter & Ward-Thompson 2007) are overlaid on the maps as red triangles (YSOs) and blue circles (starless cores). The units for the colour scale are in K kms^{-1}.

2. Data reduction

- Final data were sampled on a 6" grid using a Gaussian gridding kernel with a FWHM of 9", giving an effective spatial resolution of 16.8".
- The final noise on the data is between 0.15 – 0.23 K, at a velocity resolution of 0.2 kms^{-1}.

3. HCO^+/HCN structure and kinematics

Emission structure

- HCO^+ shows some extended structure (although much less filamentary structure than the dust emission) and is emitted over a wider area than HCN.
- Allows density of filamentary structure to be constrained between critical densities of HCO^+ and HCN (in line with #1S019).
- HCN is generally confined to compact clumps and is almost exclusively associated with protostellar objects.
- HCO^+ has a higher integrated intensity than HCN (ratio of 0.1 – 0.6) over many of the areas covered, because of its lower critical density.
- In regions with powerful outflows, however, there is much greater HCN integrated intensity than HCO^+.

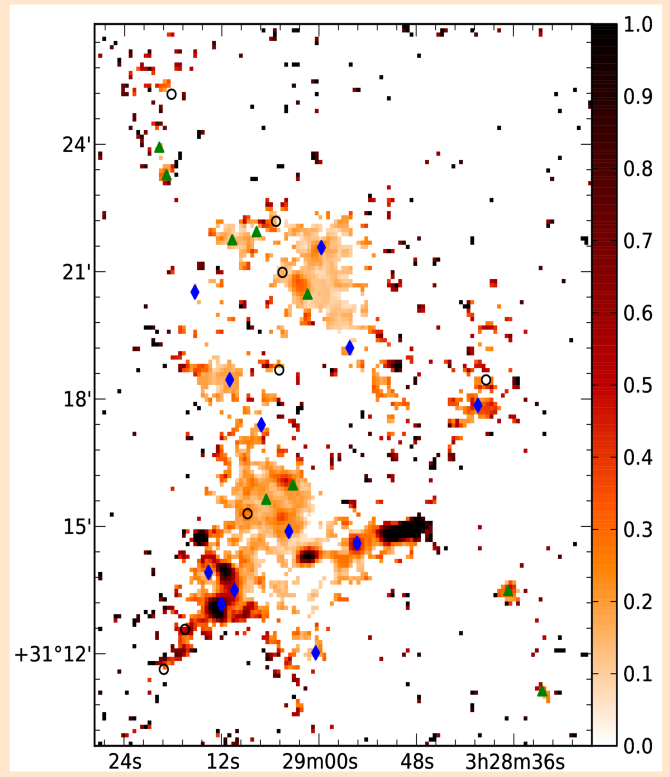


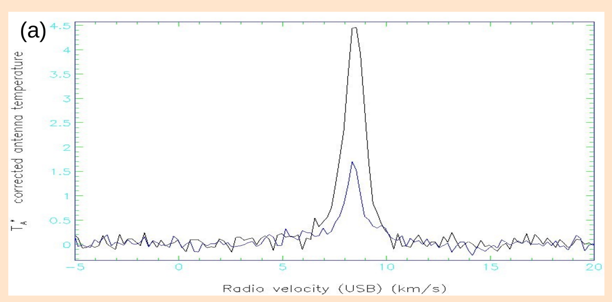
Figure 4: Ratio map of the integrated intensities of HCN/HCO^+ for NGC 1333. The darker the colour, the greater the integrated intensity of HCN compared to HCO^+.

Table 1: The transition frequencies ν, critical densities n_{crit} and abundances X_{mol} of the HCO^+ and HCN (as obtained from the LAMBDA database).

Molecule	ν/GHz	n_{crit}/cm^{-3}	X_{mol}
HCO^+	356.73	1.8×10^6	2.0×10^{-9}
HCN	354.51	8.5×10^6	1.0×10^{-11}

Velocity Structure

- The ambient HCN linewidths are typically narrower than the HCO^+ linewidths: ~ 0.4 kms^{-1} for HCN compared to ~ 0.6 kms^{-1} for HCO+ (see Figure 5a).
- This indicates that the HCN generally traces denser, more quiescent gas than the HCO^+.
- HCO^+ (being optically thick) also demonstrates infall in collapsing protostars (see Figure 5b).



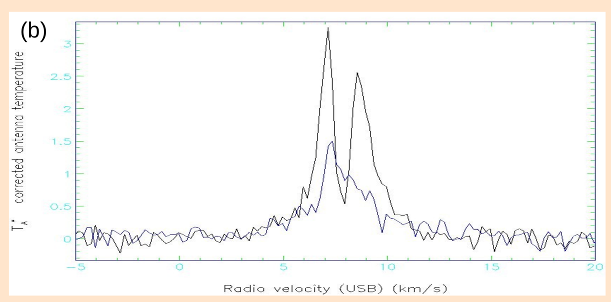


Figure 5: Comparison spectra of HCO^+ (black) with HCN (blue) for a starless core (left) and for IRAS 2, a Class 0 protostar (right). The HCO^+ in IRAS 2 is an example of a classic infall profile.

4. Outflow analysis in Perseus

Identification

- Outflows were identified by the presence of linewings in the emission with respect to a particular SCUBA core (see Figure 6).
- 24 protostellar cores were identified as driving sources using HCO^+, and 9 of these also showed HCN outflows.
- HCN is mainly associated with the younger, more powerful outflows (6/9 driving sources are Class 0).

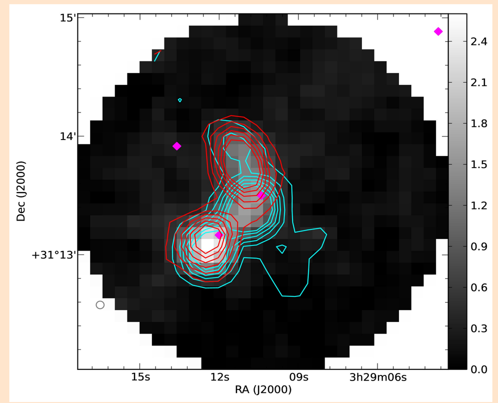


Figure 6: Plot of the integrated intensity of the HCO^+ emission for IRAS 4 (NGC 1333), integrated over the line FWHM. Linewing integrated intensities are overlaid as blue and red contours; positions of protostellar cores are marked with magenta diamonds.

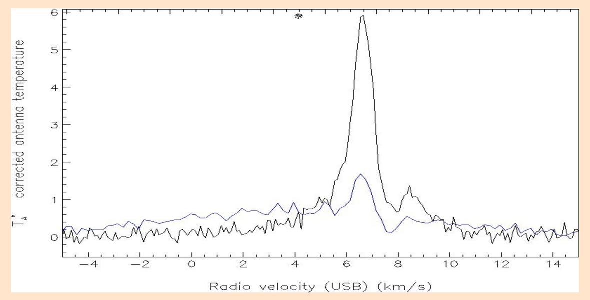


Figure 7: Plot of the HCN spectrum (blue) overlaid on the HCO^+ spectrum (black) from the central position of IRAS 4A. The excess wing emission in HCN compared to HCO^+ is very clear.

Driving force correlations with source properties

- Outflow masses M_{out} were calculated from the integrated intensity in the linewings for each source (using the nominal abundances in Table 1); then converted to the outflow driving force F_{out}
- Clear decrease in outflow driving force with mass of the source envelope that matches results found in Curtis et. al. (2010).
- Decrease in gradient of best-fit line between Class 0 and Class I (in Figure 8), indicating that the outflow driving force **decreases** with source age (Bontemps et. al., 1996).

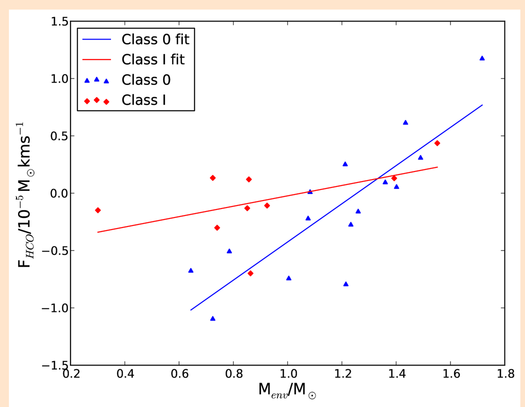


Figure 8: Correlation plot of driving force F_{out} against the source envelope mass M_{env} (Hatchell et. al., 2007) for the HCO^+-identified outflows. The sources are divided into Class 0 (blue) and Class I (red). Least-squares best-fit straight lines are plotted for each subset.

References
1. Bontemps S., Andre P., Terebey S., Cabrit S., 1996, A&A, 311,858
2. Curtis E. I., Richer J. S., Swift J. J., Williams J. P., 2010, MNRAS, 408, 1516
3. Hatchell J., Fuller G. A., Richer J. S., Harries T. J., Ladd E. F., 2007, A&A, 468, 1009
4. Tafalla M., Santiago-Garcia J., Hacar A., Bachiller R., 2010, A&A, 522, A91

5. HCO+/HCN abundances in IRAS 2

IRAS 2 outflows

- A young Class 0 protostar in NGC 1333 (Perseus), driving 2 perpendicular outflows: a jet-like E-W outflow (A) and a shell-like N-S outflow (B).
- Both outflows are traced and well-separated by the ^{12}CO (Figure 9a).
- HCO^+ traces the N-S outflow over a very small spatial range, closely associated with the central source (Figure 9b).
- HCN traces the E-W outflow and the lobes are well separated spatially from the central source (Figure 9c).

➤**Different chemistry within the two outflows**

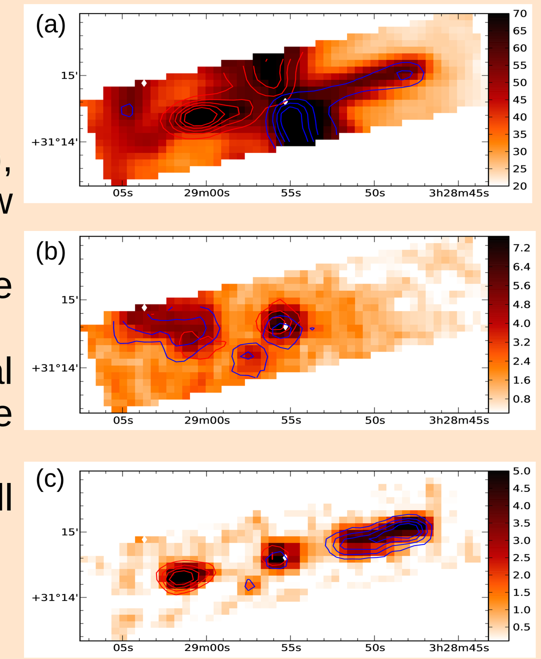


Figure 9: Plots of integrated intensity of 12CO (top), HCO^+ (middle) and HCN (bottom), with the red and blue linewing contours of the respective molecules overlaid. The position of the central IRAS 2 core is indicated by a white diamond.

Abundance enhancements in outflow A

- ^{12}CO-normalised abundances were calculated for each molecule; and enhancement factors F_{enh} were derived from these:

$$F_{enh} = (N_{mol}/N_{12CO}) * (X_{12CO}/X_{mol})$$

- The high enhancements for all molecules on the central source are indicative of high optical depth.
- HCO^+ is the least enhanced of all 4 molecules; HCN is the most enhanced, implying **shock-related chemistry effects** (similar to that found by Tafalla et. al, (2010)).

Red lobe		Central source		Blue lobe	
Molecule	F_{enh}	Molecule	F_{enh}	Molecule	F_{enh}
^{13}CO	7	^{13}CO	60	^{13}CO	3
$C^{18}O$	0.6	$C^{18}O$	110	$C^{18}O$	7
HCO^+	0.7	HCO^+	15	HCO^+	0.1
HCN	**940**	HCN	1300	**HCN**	**1100**

Table 2: ^{12}CO-normalised enhancement factor F_{enh} of each of the 4 molecules investigated for IRAS 2, for the red and blue lobes of outflow A, as well as over the line centre at the central driving source position for comparison.

Conclusions

- HCO^+ shows more extended structure than HCN, which is found in dense clumps; this allows the density of the filaments to be constrained by the critical densities of the 2 molecules.
- HCO^+ traces more protostellar objects than HCN, but HCN exhibits greater linewing emission than HCO^+ in some of the most powerful outflows.
- HCN is greatly enhanced (by several orders of magnitude compared to typical abundances) in certain outflows, while HCO^+ shows no such enhancement: due to shock chemistry in outflows.
- Both molecules show similar correlations in F_{out} with M_{env} to previous studies with ^{12}CO.