Depletion and the Evolution of Massive Cores

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ABSTRACT

Despite the increased attention the formation of massive stars has received in recent years, a reliable, observable evolutionary sequence for the earliest stages of the process is still lacking. A promising indicator for the evolutionary status of these high-mass star forming cores is the degree of depletion of molecules onto the surface of the dust grains. Depletion occurs rapidly and persists until radiation from the forming star or shock waves generated by outflows increase the temperature sufficiently to allow desorption back into the gas phase. We have observed $C^{17}O$ towards a large sample of embedded high-mass protostellar objects (HMPOs) and observe a substantial scatter in abundances which we attribute to varying degrees of depletion from source to source. Analysing the sample on the basis of linewidth, we find three distinct groups: Sources with broad linewidths with high depletion (group MC1), sources with narrow linewidths with high depletion (group MC2) and sources with narrow linewidths with no depletion (group MC3). The group MC1 sources also possess high detection rates of both hot core molecules and masers, and have more centrally peaked density profiles; these appear to be the most dynamically active group. The narrow linewidth sources meanwhile show very low detection rates of either hot core molecules or masers and also have flatter density profiles. We propose that the different properties we observe are the result of evolutionary differences between these groups of sources and subsequently develop a sequence for the evolutionary status of these groups.

SAMPLE OF HMPOs

The sources we are observing have been selected from the IRAS point source catalogue by Sridharan et al. (2002). They are selected to match the IRAS colours of Wood & Churchwell (1989) but not be associated with any radio emission indicating the presence of a UCHII region. These sources have been subsequently studied in depth by Beuther et al. (2002a,b), Williams, Fuller & Sridharan (2004, 2005) and Fuller, Williams & Sridharan (2005). Continuum emission surveys have revealed one or more submm peaks associated with each IRAS source which are believed to the locations of massive star formation. We observed these sources in the J=2-1transition of the $C^{17}O$ (224.714 GHz). Typically the line has $T_A^* < 3$ K, linewidths of 1.5 – 3.5 km/s and $\tau < 0.1$. Direct comparison of the $C^{17}O$ and dust column densities (as derived from the 850μm mass given in Williams et al. 2004) reveal a scatter in the abundances of $C^{17}O$ of ~15.

MODELLING

We test our assumption of a single excitation temperature and dust temperature with modeling of the sources. We use the 1D radiative transfer code RATRAN developed by Hogerheijde & van der Tak (2000) to model a subset of the sample whose envelope parameters have been previously constrained by dust continuum models performed by Williams et al. (2005).

SOURCE ID	$[C^{17}O]/[H_2]$ ($\times 10^{-8}$)	χ^2	R ($C^{17}O$)
WFS14	5.2	1.7	1.35
WFS16	10.1	1.5	2.16
WFS29	10.0	1.8	1.00
WFS30	5.0	1.1	1.49
WFS36	15.0	1.6	1.88
WFS79	1.8	2.4	0.98
WFS90	4.5	0.9	1.69
WFS107	4.0	1.1	0.94

Table 1: Col. 2 is the best fit fractional abundances of $C^{17}O$. Col. 4 represents the ratio of the best fit abundance from the modelling and the abundance derived from observations.

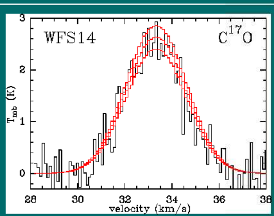


Figure 1. Model sensitivity: Modelled abundances of 5×10^{-8}, 5.5×10^{-8} & 6×10^{-8}

For simplicity we assumed a constant $C^{17}O$ abundance with respect to hydrogen, varying the abundance to match the observed line intensity. Comparison of the $C^{17}O$ abundance inferred by the modeling and that derived directly from the observations agree within a factor of ~2 supporting our temperature assumptions for the rest of the sample (Thomas & Fuller 2006a).

DEPLETION

We would expect the coolest dust to display the highest levels of depletion. We test this by calculating the mass-weighted temperatures for each of our modelled sources.

$$\overline{T}_{MW} = \frac{\int T(r)\rho(r)r^3\,dr}{\int \rho(r)r^3\,dr}$$

Figure 2 shows the $C^{17}O$ abundance against the mass-weighted temperature for both our sources and those from van der Tak et al. (2002) for comparison, the distribution of both is consistent with depletion at low temperatures.

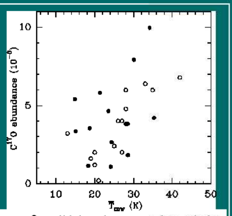


Figure 2: Solid dots denote our data. Circles represent the data of van der Tak et al. (2002)

KINEMATICS

Figure 3 compares the hyperfine linewidth of $C^{17}O$ (J=2-1) from Thomas & Fuller (2006a) with the linewidth of both N_2H^+ (J=1-0) from Fuller et al. (2005) and CS (J=3-2) from Beuther et al. (2002a). The $C^{17}O$ linewidths are well correlated those of N_2H^+ over the full range of linewidths, however the situation with CS is quite different. The CS and $C^{17}O$ have very similar linewidths when the lines are narrow, < 3 km/s, but at larger linewidths the CS line becomes increasingly broader. This large ratio at broad linewidths is also seen in the rare isotopologue $C^{34}S$ suggesting that this is not a result of the opacity of the line.

Together these comparisons suggests that the $C^{17}O$ and N_2H^+ are tracing similar, relatively quiescent material in these cores. For the more quiescent cores (those with CS linewidths Δv(CS) <3 km/s), the CS is also closely associated with this material. On the other hand for sources with linewidths Δv(CS) >3 km/s, while the $C^{17}O$ and N_2H^+ still trace a quiescent component of material in the core, there is a much less quiescent and kinematically distinct component of the core material traced by the CS.

DIVIDING THE SOURCES

A number of properties of the cores seem to be associated with the ratio of $C^{17}O$ to CS linewidth. To demonstrate this we divide the sample around Δv (CS) = 3 km/s. The broad linewidth sources have consistently low $C^{17}O$ abundances whilst the narrow linewidths sources show a full range of abundances. We identify 3 distinct groups:

Group *MC1*:	Δv(CS) > 3 km/s	low abundance
Group *MC2*:	Δv(CS) < 3 km/s	low abundance
Group *MC3*:	Δv(CS) < 3 km/s	high abundance

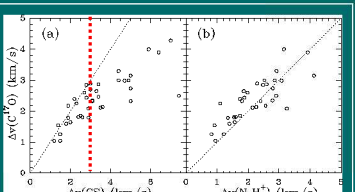


Figure 3. $C^{17}O$(J=2-1) linewidth against (a) CS(J=3-2) linewidth (b) N_2H^+ linewidth.

TRENDS

$C^{17}O$ ABUNDANCES: Gp MC1 have significantly lower abundances than Gp MC2/3. A Kolmogorov-Smirnov (K-S) two-sample test reveals they differ at a 99.7% confidence level (see Figure 4a).

HOT CORE SIGNATURES: 79% of the Gp MC1 sources are detected in CH_3OH with 57% detected in CH_3CN. For group Gp MC2/3 the detection rates are only 23% and 15% respectively.

MASERS: Gp MC1 sources have detection rates of 55% and 72% for water and methanol masers respectively, for Gp MC2/3 they are 16% and 5%.

DENSITY PROFILES: We have compared the radial density profiles derived by Williams et al. (2005) (see Figure 4b). Gp MC1 sources have a mean of 1.54 against 1.07 for Gp MC2/3 sources. A KS-test reveals a 99% difference between the samples. This result is echoed by Gp MC1 sources showing much higher masses within a 20" beam.

CENTRAL HEATING: Williams et al (2004) presented the ratio of the peak to average spectral index of the 850μm to 450μm emission. Gp MC1 sources possess higher ratios along with higher values for the spectral index of the dust opacity (β). These trends point to Gp MC1 sources having smaller dust grains and/or warmer dust towards the centre, consistent with significant heating by the central source.

NIR NEBULOSITY: Most sources have been surveyed at 2.2um and 3.8um (Thomas & Fuller 2006b). Of those surveyed only 9 sources showed significant nebulosity, all of which fall into Gp MC2.

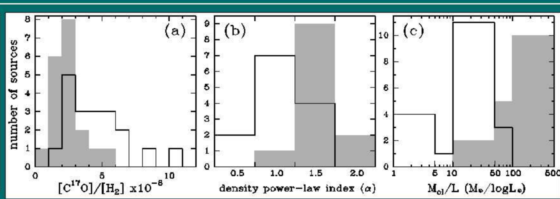
OUTFLOWS: Beuther et al. (2002b) mapped 26 of these sources in ^{12}CO (J=2-1) searching for outflows. The sources identified as driving outflows fall into both Gp MC1 & Gp MC2.

MASS/LUMINOSITY: Gp MC1 sources display much higher M/L ratios (see Figure 4c). This can be interpreted as Gp MC2/3 sources having evacuated a substantial proportion of their initial mass away from the core.

Figure 4:

Gp MC1 = solid bars
Gp MC2/3 = hollow bars

(a) $C^{17}O$ abundances
(b) power-law density index
(c) mass/luminosity ratio for the cores



SOURCE EVOLUTION?

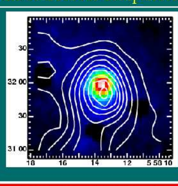
GROUP MC1: These sources show evidence of significant interaction between the forming stars and their environment. They possess broad CS linewidths, hot core and maser signatures and show evidence for strong heating towards their centre along with steeper density profiles. However they also show the lowest $C^{17}O$ abundances. There is clearly a component of the material which while aware of the presence of the central source as shown through the steep density profile, has not (yet) been significantly disturbed by it.

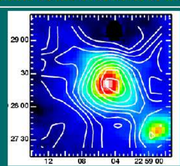
GROUP MC2: These sources appear to show less evidence of heating and interaction. Unlike Group MC1 sources they show a range of abundances. The presence of nebulosity and outflows is suggestive of these being more evolved sources than the Group MC1 sources with outflows having cleared a cavity in the circumstellar material allowing the NIR radiation to escape. An outflow at this stage will also have transported a substantial amount of matter away from the center of the core, as reflected by the flatter density profiles and low M/L ratios. This also explains the narrow linewidths as the disturbed inner region supplying the broad component has been cleared away from the centre of the cores.

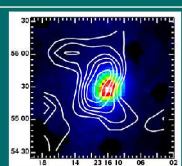
GROUP MC3: It is unclear whether these sources are the youngest where depletion does not yet dominate, or the most evolved objects where all ice has been desorbed from the grains restoring approximately canonical abundances.

RECENT MAPPING RESULTS

The images below compare our recent maps of $C^{17}O$ (J=2-1) integrated intensity (contours) with the SCUBA 850μm emisssion. These maps will be used to investigate the spatial distribution of depletion in the sources for comparison with models of the evolution of the cores.







CONCLUSIONS

- Having observed $C^{17}O$ (J=2-1) towards 84 HMPOs we find a factor of ~15 scatter in the abundances which we conclude is due to depletion.
- Group MC1 sources with broad linewidths, hot core signatures and steep density profiles represent the most dynamic and most likely the youngest of our sample.
- Group MC2 sources with their narrower linewidths and lack of hot core signatures and flatter density profiles represent a more evolved state and are the older sources of our sample.
- The high depletion levels towards Group MC1 sources point to the bulk of the envelope remaining undisturbed by the star formation process within until a relatively advanced stage.
- High resolution mapping of these cores is needed to identify the origin of depletion.

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