Molecular gas freeze-out in the pre-stellar core L1689B

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ABSTRACT
C\(^{17}\)O \(J = 2 \rightarrow 1\) observations have been carried out towards the pre-stellar core L1689B. By comparing the relative strengths of the hyperfine components of this line, the emission is shown to be optically thin. This allows accurate CO column densities to be determined and, for reference, this calculation is described in detail. The hydrogen column densities that these measurements imply are substantially smaller than those calculated from SCUBA dust emission data. Furthermore, the C\(^{17}\)O \(J = 2 \rightarrow 1\) column densities are approximately constant across L1689B whereas the SCUBA column densities are peaked towards the centre. The most likely explanation is that CO is depleted from the central regions of L1689B. Simple models of pre-stellar cores with an inner depleted region are compared with the results. This enables the magnitude of the CO depletion to be quantified and also allows the spatial extent of the freeze-out to be firmly established. We estimate that within about 5000 AU of the centre of L1689B, over 90% of the CO has frozen onto grains. This level of depletion can only be achieved after a duration that is at least comparable to the free-fall timescale.

Key words: radiative transfer - ISM: globules - ISM: individual: L1689B - stars: formation - stars:pre-main-sequence - submillimetre

1 INTRODUCTION
Molecular line profiles from pre-stellar and protostellar objects potentially offer the best opportunity to extract dynamical information about the collapse process that leads to the formation of stars. However, it is becoming clear that the interpretation of these line profiles can be fraught with difficulty. Rawlings & Yates (2001) used a self-consistent chemical and dynamical model of collapsing star-forming cores to explore the effects of abundance variations. They showed that the line profiles can be very sensitive to the assumed abundances due to freeze-out can have a profound influence on the line profiles. Accurate abundances are required deep within these cores in order that any freeze-out is characterised properly.

The widely used tracer of molecular hydrogen, CO, is so abundant that, in the cold dark clouds in which stars are forming, it has a large optical depth and thus cannot trace the densest material. Very rare CO isotopomers are therefore used and in order of decreasing abundance these are \(^{13}\)CO, \(^{18}\)O, \(^{17}\)O, \(^{13}\)C\(^{18}\)O and \(^{13}\)C\(^{17}\)O, recently discovered by Bensch et al. (2001) toward the \(\rho\) Ophiuchi molecular cloud. Measuring abundances is not straightforward however because even some of the rare isotopes are mildly optically thick and the very rare isotopes can require impractically large integration times. \(^{18}\)O is often selected as a result of these conflicting demands but the analysis can be complicated by the lack of an optical depth estimate. In contrast, \(^{17}\)O is slightly less abundant than \(^{18}\)O and has a complex hyperfine structure revealed in several distinct line components. For a well detected line the hyperfine structure can be used to identify whether optical depth effects are present and hence abundances can confidently be calculated.

Of course, in order to calculate hydrogen column densities, abundance ratios between the different isotopomers are required. Bensch et al. (2001) demonstrated how by using several different isotopes of CO, the optical depths could be cross-checked and the abundance ratios measured. Effects such as isotope-selective photo-dissociation and chemical fractionation can be important in translucent clouds but are not thought to be significant in the cold dense environments considered here (Bensch et al. 2001). Dust emission measurements can be used to calculate dust column densities and using a dust to gas ratio, a second estimate for the column density of hydrogen can be made. If this exceeds the hydrogen column density as traced by CO then it is possible that the CO is depleted from the gas-phase. The most probable reason for this is that the CO has frozen onto the surfaces of grains. Gibb & Little (1998) find CO abundances reduced by a factor of at least 10 towards the HH24-26 molecular cloud core by this method. They also carefully consider alternative explanations that do not require abundance differences such as optical depth
and beam filling effects and show them to be unlikely. Recently, Bergin et al. (2002) have found that not only CO but \(N_2H^+\) is depleted in the Bok globule B68. This raises the possibility that in some cores there will be very few available infall tracers. Two very recent papers have investigated CO depletion. Bacmann et al. (2002) have investigated seven pre-stellar cores and find CO to be underabundant by factors of 4-15 amongst the cores. Jørgensen et al. (2002) modelled 18 pre-stellar cores and found that the class 0 sources in their sample are depleted in CO by an order of magnitude.

L1689B is a pre-stellar core located in Ophiuchus. Gregersen & Evans (2000) have observed L1689B in the lines of HCCO \(J = 3 \rightarrow 2\) and \(^1\)HCO \(J = 3 \rightarrow 2\). Their multi-point data seemed to indicate that the HCO \(J = 3 \rightarrow 2\) emission was double-peaked and blue-skewed, indicative of infall. This is supported by the single point CS \(J = 2 \rightarrow 1\) observations by Lee et al. (1999) which show a clear blue-peak asymmetry. Jessop & Ward-Thompson (2001) observed L1689B in \(^{17}\)O and although they did not have optical depth measurements and thus column densities for \(^{17}\)O they explored the dust density and temperature parameter space and argued that the CO has to be depleted in order to be compatible with the continuum data.

In this paper, observations of the rare \(^{17}\)O isotope are presented and column densities derived and analysed in an attempt to quantify any depletion that is taking place. These data are discussed in terms of current models for pre-stellar cores in general and L1689B in particular.

2 OBSERVATIONS

The observations were carried out at the James Clark Maxwell Telescope (JCMT), Mauna Kea, Hawaii on the night of 2001 August 19. The \(^{17}\)O \(J = 2 \rightarrow 1\) (224.714368 GHz) rotational transition was observed using the heterodyne receiver Ra3. The JCMT half-power beam width (HPBW) is 19 arcsec at these frequencies. Typical system temperatures were 325 K. Five pointings at 20 arcsecond offsets \((-40.0), (-20.0), (0.0), (20.0), (40.0)\) were obtained for \(^{17}\)O \(J = 2 \rightarrow 1\), centred at the epoch 1950 position (16:31:46.90, -24:31:55.98). Jessop & Ward-Thompson (2001) and Gregersen & Evans (2001) used a pointing position of (16:31:46.98, -24:31:48.00) while Lee et al. (1999) used a pointing position of (16:31:43.6, -24:31:40). The data were reduced in the standard manner using speex and the resulting spectra are displayed in Fig. 1.

3 RESULTS

Due to the spin of the \(^{17}\)O nucleus, \(^{17}\)O \(J = 2 \rightarrow 1\) is composed of nine hyperfine components. Figure 1 depicts these components and their relative strengths (from the tabulation of Ladd et al. 1998). The hyperfine components are shown with very narrow line widths and also with a broadening of 0.35 km s \(^{-1}\)  to illustrate the typical line shape that can be expected to be observed in cold quiescent cores. Since the stronger components will be affected relatively more by non-negligible optical depths, the shape of the blended line can be used to verify that the emission is optically thin in this line and transition. Figure 1 depicts an overlay of the data from the central position of L1689B with the expected optically thin line shape. We can conclude from the close fit that the line does not display any significant saturation effects and is thus of low optical depth. A detailed fit, using the HFS routine in the CLASS software package gives optical depths in the range 0.5 – 1.5. For such low optical depths, the actual value obtained from the software should be treated with some caution as the deviations from an optically thin line shape are very small (for example, the fit in Fig. 3 is for very low optical depth) and likely to be strongly affected by the noise. In our later analysis, we adopt an optical depth of \(\sim 0.7\) for all positions because this is consistent with other recent measurements (N.J. Evans et al., 2002 private communication). The results of the fit are given in Table 1 which also lists the line centre, line widths and optical depths obtained. The net broadening (due to turbulent and instrumental broadening), \(v_{\text{broad}} \approx 0.37\) km s \(^{-1}\). This is smaller than the \(^{13}\)C line width but measured by Jessop & Ward-Thompson (2001) who find \(v_{\text{WHM}} \approx 0.6–0.8\) km s \(^{-1}\) for their singly peaked and gaussian line profiles (though as discussed below, this line is actually optically thick).

3.1 CO column densities

If it is assumed that the optical depth is small, local thermodynamic equilibrium holds, and the excitation temperature \(T_{\text{ex}} \gg T_{\text{mb}}\) then the total column density of a species is given by

\[
N_{\text{tot}} = \frac{3k}{8\pi^2\nu} \frac{Q(T_{\text{ex}})}{\mu m} \exp \left( \frac{E_u}{kT_{\text{ex}}} \right) \int T_{\text{mb}} \, dV. \tag{1}
\]

where \(\int T_{\text{mb}} \, dV \approx T_{\text{mb}}^3 \Delta V / \eta_B\), the integrated line intensity. If the integrated line strength is measured in km s \(^{-1}\), frequency in GHz, \(\mu\) in debye \(1\) debye \(= (1/3) \times 10^{-29}\) C m \(^{-1}\) and if an SI to CGS conversion factor of 4\(\pi\)\(\epsilon_0\) is used then the column density is

\[
N_{\text{tot}} = 1.67 \times 10^{14} \frac{Q(T_{\text{ex}})}{\nu^2 m} \times \exp \left( \frac{E_u}{kT_{\text{ex}}} \right) \int T_{\text{mb}} \, dV. \tag{2}
\]
Figure 1. C$^{17}$O J = 2 → 1 line profiles from offset positions of (from left to right) -40", -20", 0", 20", 40"

| Offset | Line centre (km s$^{-1}$) | Line width (km s$^{-1}$) | $\tau_{C^{17}O}$ | $\int T_a^2 dV$ K km s$^{-1}$ | $N_{C^{17}O}$ cm$^{-2}$ | $N_{tot}$ cm$^{-2}$ |
|--------|--------------------------|--------------------------|------------------|-----------------------------|-----------------|-----------------|
| -40"   | 3.577 ± 0.004            | 0.393 ± 0.012            | 0.673 ± 0.240    | 1.45                        | 1.0 x 10$^{15}$ | 1.3 x 10$^{22}$ |
| -20"   | 3.592 ± 0.004            | 0.378 ± 0.013            | 1.028 ± 0.242    | 1.43                        | 9.9 x 10$^{14}$ | 1.3 x 10$^{22}$ |
| 0"     | 3.526 ± 0.004            | 0.370 ± 0.012            | 1.346 ± 0.262    | 1.35                        | 9.3 x 10$^{14}$ | 1.2 x 10$^{22}$ |
| 20"    | 3.608 ± 0.004            | 0.346 ± 0.013            | 0.526 ± 0.278    | 1.34                        | 9.3 x 10$^{14}$ | 1.2 x 10$^{22}$ |
| 40"    | 3.537 ± 0.004            | 0.356 ± 0.011            | 1.462 ± 0.273    | 1.09                        | 7.5 x 10$^{14}$ | 9.9 x 10$^{21}$ |

Table 1. Optical depths, C$^{17}$O column densities and estimated total column densities for each offset position.

Figure 3. C$^{17}$O J = 2 → 1 data and expected line shape if the emission is optically thin with a turbulent velocity dispersion of 0.15 km s$^{-1}$ as in Figure 2, offset to 3.64 km s$^{-1}$. Both the data and the expected line shape are normalised to their peak intensities.

Table 2. Molecular data for C$^{17}$O and C$^{18}$O.

| Parameter | C$^{17}$O J = 2 → 1 | C$^{18}$O J = 2 → 1 |
|-----------|-----------------|-----------------|
| $\nu$ (GHz) | 224.714 | 219.560 |
| $E_u$ (K) | 16.177 | 15.8058 |
| $\mu$ (Debye) | 0.11034 | 0.11079 |
| $S$ | 2 | 2 |
| $Q$(120 K) | 4.80 | 4.93 |

This is possible since the C$^{17}$O J = 2 → 1 line is optically thin and so the optical depth of the C$^{18}$O J = 2 → 1 line can be calculated. Ladd et al. (1998) show that simply using the ratio of the peaks in these lines to calculate the optical depth is unsuitable. This is because the closely spaced fine structure of the C$^{17}$O J = 2 → 1 line means that the peak in this transition is very sensitive to the turbulent velocity. The integrated intensities are much more robust and the ratio of these are compared with figure 1 of Ladd et al. (1998) to infer that the optical depth in the C$^{18}$O J = 2 → 1 line is $\tau_{C^{18}O} \gtrsim 2$. When the optical depth is moderate as in this case, Eqn (1) multiplied by a correction factor of $\tau/(1 - \exp(-\tau))$ can be used to calculate column density.

The column densities derived from the two lines are plotted as a function of offset in Figure 4. The agreement is excellent and both datasets show that the column density is remarkably flat across the face of the core.

3.2 Dust column densities

Evans et al. (2001) obtained SCUBA maps of L1689B and carried out a detailed radiative transfer analysis of the dust emission which enable them to place constraints on the temperature and density distribution in the envelope. The gas density distribution was well fitted by a Bonner-Ebert sphere with a central density of $n_c = 1 \times 10^6$ cm$^{-3}$ and outer
radius of $3 \times 10^4$ AU. The dust opacities used were from Os- 

Figure 4. Column densities across L1689B, measured using the 
$^{17}$O$J = 2 \rightarrow 1$ transition (crosses), $^{18}$O data of Jessop & 
Ward-Thompson (2001) (circles) and from SCUBA 850 $\mu$m radial 
profile fits of Evans et al. (2001) (pluses). The sizes of the symbols 
may be taken as a rough indication of the observational error.

3.3 Depletion of CO

It is clear from Figure 4 that the two independent tech-
niques for measuring the column density produce results 
that differ both in magnitude and distribution. As inferred 
by the above discussions, the exact normalisations of the 
curves in Figure 4 are subject to variation depending on the 
adopted values of dust opacity, isotopic ratios and molec-
ular abundances. The most important aspect of Figure 4 
is the flatness of the column density plot from CO com-
pared with the centrally peaked dust measurements. This 
strongly indicates that depletion is occurring because the 
column density should rise for positions that approach the 
strongly indicates that depletion is occurring because the 
colour profiles should reduce for positions that approach the 
present at a higher gas density and the lower dust temperature is the 
likely reason for a substantial freeze-out of CO in the cen-
tral regions of L1689B. An alternative explanation for these 
data is that the CO lies along the line of sight and is not 
actually part of the L1689B core. This can be ruled out since 
this would require the core to be completely depleted of CO 
in order that the column density remains roughly constant 
across the face of it.

Jessop & Ward-Thompson (2001) compared their 
$^{17}$O $J = 2 \rightarrow 1$ data with earlier mm continuum data of 
André et al. (1999). Using a model for L1689B with power 
law profiles for the density, temperature and CO abundance, 
they explored the parameter space that would be consistent 
with both datasets. They conclude that the CO could be de-
pleted by up to 95% but they did not have an optical depth 
measurement for their $^{18}$O data. In contrast, our results 
indicate that the ratio of the column densities towards the 
centre is only around a factor of 3 or so. Of course, the CO is 
unlikely to be uniformly depleted and this factor of 3 re-
prents the column depletion. The local depletion is likely 
be much higher. This can be investigated by plotting the 
column densities that result from models where the radial 
density profile, abundance and temperature are all varied. 
To illustrate this in a very simple case, we use a constant 
temperature model and vary the abundance such that in-
terior to a certain radius $\rho_{\text{freeze}}$ the CO is depleted by a 
factor 0.95 due to freeze-out. Instead of using the Bonner-
Ebert density distributions which are inconvenient to work 
with, we use the parameters of the fit of Evans et al. (2001) 
in an equivalent Plummer-like sphere which has a density 
profile of the form (see, e.g. Whitworth & Ward-Thompson 
2001; Whitworth & Batd 2001)

$$\rho(r) = \frac{\rho_0 R_0^2}{(R_0^2 + r^2)}$$

where $\rho_0 = 1.0 \times 10^6$ cm$^{-3}$ is the central density and 
$R_0 = 750$ AU is an inner radius within which the density 
is approximately $\rho_0$. For the purposes here, the difference 
between the Bonner-Ebert and Plummer density distribu-
tions are of little consequence - both approximate $\rho \sim r^{-2}$ 
in the envelope and are roughly constant close to the cen-
tre. Figure 4 shows the column density that results from 
this simple Plummer sphere model for a range of values of 
$\rho_{\text{freeze}}$, with the top curve showing the underlying density 
distribution. Comparison with Figure 4 shows clearly that 
values of $\rho_{\text{freeze}}$ of about 40'' $\equiv$ 5000 AU would be able to 
reproduce the approximately flat CO abundance with a col-
umn depletion factor of about the correct degree. One could 
of course investigate the parameter space fully and include 
realistic variations in the freeze-out and temperature but we 
defer that to a later paper.

The close fit of the $^{17}$O $J = 2 \rightarrow 1$ lines by a model 
with only turbulent velocities (i.e. with no infall or outflow) 
indicates that the CO emitting material is static. In contrast, 
the HCO$^+$ $J = 3 \rightarrow 2$ and H$^{13}$CO$^+$ $J = 3 \rightarrow 2$ data of 
Gregersen & Evans (2000) show double peaked line profiles 
indicating both that the HCO$^+$ is self-absorbed and that 
the gas is undergoing bulk gas motions. These emissions 
are likely to originate from within the denser regions of the 
core. The flatness of the abundance points across the core 
measured using $^{17}$O $J = 2 \rightarrow 1$ (Figure 4) indicates that 
the CO is depleted from the central regions. Thus one can 
picture that L1689B is composed of a dynamical dense core 
which is depleted in CO but in which HCO$^+$ is present. This 
is surrounded by a quiescent surrounding region where both 
CO and HCO$^+$ are present.
4 CONCLUSIONS

Rare isotopes of CO have been observed towards the pre-stellar core L1689B. By using the hyperfine structure of C\(^{17}\)O \(^J = 2 \rightarrow 1\) the transition is confirmed to be optically thin and emitted by quiescent gas. This allows an estimate of the total column density as traced by this molecule to be made. A comparison of this value with that inferred from SCUBA dust emission measurements reveal the CO to be depleted in the central regions of this object. The magnitude and extent of the depletion is estimated by comparison with a simple model of a pre-stellar core with an inner depleted region. We estimate that within 5000 AU of the centre of L1689B, around 90% of the CO has frozen onto grains. The dust temperature at this radius is \(\sim 10 \, \text{K}\) (from figure 5 of Evans et al. 2001). The sublimation temperature of CO is \(\sim 20 \, \text{K}\) so potentially freeze-out could occur in the outer regions of the cloud. In practice of course, the timescale for freeze-out in the low density outer regions is long and freeze-out will occur only in those portions of the cloud with a high local density and low dust temperature.

For the physical parameters of L1689B, the rate of freeze-out of CO is given by (Rawlings et al. 1992)

\[
\dot{n}_{\text{CO}} = 4.57 \times 10^4 d^a g^{-1/2} C n_\text{H} S_{\text{CO}} m_{\text{CO}} \text{cm}^{-3} \text{s}^{-1}
\]

where \(n_\text{H}\) and \(n_{\text{CO}}\) are the hydrogen nucleus and CO densities respectively, \(m_{\text{CO}} = 28 \text{amu}\) is the molecular mass of CO, \(d_g\) is the ratio of the number density of grains to CO molecules, \(a\) is the grain radius, \(C\) is a factor which accounts for electrostatic effects, \(S_{\text{CO}} = 1\) is the assumed sticking coefficient for CO. Using \(<d_g a^2> \sim 2.2 \times 10^{-22} \text{cm}^{-2}\) and \(T \sim 10 \, \text{K}\) yields

\[
\dot{n}_{\text{CO}} = 6.0 \times 10^{-18} n_\text{H} n_{\text{CO}} \text{cm}^{-3} \text{s}^{-1}
\]

Using a value of \(n_\text{H} = 2.8 \times 10^6 \text{cm}^{-3}\) for L1689B (Bacmann et al. 2000) we find that in the absence of other CO formation and destruction mechanisms, 90% depletion of CO is achieved after \(\sim 43,400\) years. This is approximately half of the nominal free-fall timescale (97,400 years) for the value of \(n_\text{H}\) quoted above, but we should be aware that the freeze-out timescale is a lower limit and would be larger if the sticking coefficient were less than unity; or if (as would seem likely) the cores have condensed from a less dense state. We may therefore conclude that the level of CO depletion may provide a sensitive indicator of the age of cores relative to their free-fall times and that a C\(^{17}\)O survey of sources at various (early) stages of evolution could provide a powerful diagnostic of their dynamical status.

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Figure 5. Column densities from a Plummer-like sphere density distribution with a depletion ‘hole’ that extends from the centre to a radius \(R_{\text{freeze}}\). The local depletion within the hole is such that only 5% of the CO remains in the gas phase. The uppermost curve is with no depletion. The curves below it are for values of \(R_{\text{freeze}}\) of between 5 and 45 arcseconds. The curves have not been convolved with a telescope beam and hence are more centrally peaked than the observational data.