Carbon monoxide depletion in Orion B molecular cloud cores

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ABSTRACT
We have observed several cloud cores in the Orion B (L1630) molecular cloud in the 2 → 1 transitions of C18O, C17O and 13C18O. We use these data to show that a model where the cores consist of very optically thick C18O clumps cannot explain their relative intensities. There is strong evidence that the C18O is not very optically thick. The CO emission is compared with previous observations of dust continuum emission to deduce apparent molecular abundances. The abundance values depend somewhat on the temperature but, relative to ‘normal abundance’ values, the CO appears to be depleted by about a factor of 10 at the core positions. CO condensation on dust grains provides a natural explanation for the apparent depletion both through gas-phase depletion of CO, and through a possible increase in dust emissivity in the cores. The high brightness of HCO+ relative to CO is then naturally accounted for by time-dependent interstellar chemistry starting from ‘evolved’ initial conditions. Theoretical work has shown that condensation of H2O, which destroys HCO+, would allow the HCO+ abundance to increase while that of CO is falling.

Key words: ISM: abundances – ISM: clouds – ISM: individual: Orion B – ISM: molecules – radio continuum: ISM – radio lines: ISM.

1 INTRODUCTION
There is considerable evidence that protostellar collapse occurs from an interstellar envelope (scale ~10^4 au) on to, most likely, a circumstellar disc (scale ~100 au). For a long time, the collapse is likely to be isothermal and at a low temperature (about 10 K). This temperature is lower than the freeze-out temperatures of common interstellar molecules (CO 15–17 K, NH3 50–60 K, H2O 90 K; see Nakagawa 1980), and, as collapse proceeds, the freeze-out timescale becomes shorter than the collapse time-scale. The expectation is for a long isothermal phase at ~10 K, when the molecules freeze out on to grains, followed by re-heating when they come off again. These processes have been modelled by, inter alia, Nejad, Williams & Charnley (1990), Rawlings et al. (1992), Bergin & Langer (1997) and Charnley (1997).

There is observational evidence for depletion in cores (by about an order of magnitude) in molecules such as CO and CS (e.g. Bergin et al. 2001; Tafalla et al. 2002). Most of these results have come from observations of nearby molecular cloud cores in which low-mass stars are forming in small groups (e.g. Jorgensen, Schöier & van Dishoeck 2002). In the more distant Orion region where our targets lie, NGC 2024 (in L1630) contains several compact cores which show evidence for depletion of CO and other molecules (Mauersberger et al. 1992).

The interpretation as depletion has been criticized, however, by Chandler & Carlstrom (1996), who have provided evidence that some of the molecular gas is hot. Their criticisms include: (i) the dust opacity law in the cores will be non-standard; (ii) dust emission may become optically thick at the short submillimetre wavelengths, giving an ‘artificially low’ flux which is interpreted as a low temperature in an ‘optically thin’ interpretation; and (iii) the cores may contain unresolved components which are highly optically thick in molecular lines, but thin in submillimetre dust emission. Thus the true molecular abundance may be much higher. Mangum, Wootten & Bars ony (1999) also provide evidence that the gas in the cores of NGC 2024 is hot (>40 K), which would accommodate a normal abundance for CO.

One problem with NGC 2024, however, is that it is near strong external heat sources and H II emission, and hence it is not clear that the line emission from the molecular gas arises from within the cores from which the dust emission emanates.

In this paper, we report new observations of carbon monoxide isotopomers C18O, C17O and 13C18O from selected positions near and around cold cores in the same molecular cloud, L1630. These positions have been chosen with reference to previously published maps of HCO+, C18O and dust continuum emission from the condensations LBS 23 (also known as HH 24–26), LBS 17 and LBS 18 [e.g. Gibb et al. 1995; Gibb & Little 1998, 2000; Phillips,
Gibb & Little 2001 (GLHL, GL98, GL00, and PGL respectively)]. GL98 and GL00 deduced that there was depletion in several cores. The aim of this work is to confirm its significance and to evaluate its extent. We seek to determine optical depths from the CO isotopomers and use the previously published dust emission data, together with a range of possible emission laws, to examine the relative abundance.

In Sections 2 and 3, we justify our need to observe isotopomers as rare as $^{13}\text{C}^{18}\text{O}$. In Section 4, we describe the observations, which we analyse in Section 5 to deduce the depletion in and around the cores. The chemical significance of the results is outlined in Section 6.

2 PROVING DEPLETION?

Maps of two of the largest cores in the Orion B molecular cloud, LBS 17 and LBS 23, made in high-excitation HCO$^+$ and $^{13}\text{C}^{18}\text{O}$ ($J = 2 \rightarrow 1$) lines, show striking differences between the structures traced by the two molecules. Particularly apparent is the enhanced brightness of $J = 3 \rightarrow 2$ HCO$^+$ relative to $J = 2 \rightarrow 1$ $^{13}\text{C}^{18}\text{O}$ in the protostellar core LBS 17-H (fig. 2 of GL00), and of $J = 4 \rightarrow 3$ HCO$^+$ to $J = 2 \rightarrow 1$ $^{13}\text{C}^{18}\text{O}$ in HH25MMS (fig. 1 of GL98). Figs 1, 2 and 3 show the relation between the $^{13}\text{C}^{18}\text{O}$ and dust emission. $^{13}\text{C}^{18}\text{O}$ emission is surprisingly weak in some of the clumps, which stand out prominently in the other species. An interpretation, which assumes a simple source structure, optically thin $^{13}\text{C}^{18}\text{O}$ and the dust emissivity law proposed by Hildebrand (1983), implies widespread reductions of the $^{13}\text{C}^{18}\text{O}$ abundance in these clumps by factors of 13 to 57 compared with what we take to be its canonical value of $2 \times 10^{-7}$ (GL98; Frerking, Langer & Wilson 1982). Most of the clumps appear to be bound objects of several solar masses (for LBS 23, at least).

GL98 consider other ideas to explain the apparent reduction in abundance for the clumps in LBS 23. Abnormal dust properties do not appear to be required because dust emission derived masses for the clumps are in good agreement with their virial masses.

Another possibility is the absorption of $^{13}\text{C}^{18}\text{O}$ emission from intervening low excitation temperature gas. If this were the case, then the effect would be seen as strong self-absorption in the optically thicker CO lines. However, there is no evidence for such self-absorption in the CO spectra (GH93). Since the observed antenna temperatures measure the excitation temperature where the optical depth becomes equal to unity, a comparison of the CO and $^{13}\text{C}^{18}\text{O}$ antenna temperatures would then suggest that the cloud cores are externally heated (see e.g. GL98).

If the $^{13}\text{C}^{18}\text{O}$ emission arises in optically thick, unresolved sub-clumps, the need for depletion might be avoided as all the $^{13}\text{C}^{18}\text{O}$ might not be detected. Accordingly, we have made careful observations of weak isotopomers, including $^{13}\text{C}^{18}\text{O}$, $^{17}\text{C}^{18}\text{O}$ and $^{13}\text{C}^{13}\text{O}$, to seek to eliminate a subclump model. To illustrate how this can be

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Figure 1. LBS 17 (22-arcsec beam). Contours are $^{13}\text{C}^{18}\text{O} J = 2 \rightarrow 1$ emission integrated from LSR = 7 to 13 km s$^{-1}$. Contours are at 3, 4, 5, 6 and 7 K km s$^{-1}$, and at the peak intensity of 7.60 K km s$^{-1}$. Grey-scale is 850-$\mu$m emission with a peak flux of 1.76 Jy beam$^{-1}$.

Figure 2. HH25MMS (22-arcsec beam). Contours are $^{13}\text{C}^{18}\text{O} J = 2 \rightarrow 1$ emission integrated from LSR = 7 to 13 km s$^{-1}$. Contours are at 1.65, 3.3 and 4.95 K km s$^{-1}$, and at the peak intensity of 5.51 K km s$^{-1}$. Grey-scale is 850-$\mu$m emission with a peak flux of 1.10 Jy beam$^{-1}$.

Figure 3. HH24MMS (22-arcsec beam). Contours are $^{13}\text{C}^{18}\text{O} J = 2 \rightarrow 1$ emission integrated from LSR = 7 to 13 km s$^{-1}$. Contours are at 4.4, 3.2, 4.0, 4.8, 5.6 and 6.4 K km s$^{-1}$, and at the peak intensity of 7.66 K km s$^{-1}$. Grey-scale is 850-$\mu$m emission with a peak flux of 2.21 Jy beam$^{-1}$. 

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achieved, we consider a simple two-component model in the next section.

3 OPTICALLY THICK CLUMPING MODEL

In section 5 of GL98, the authors describe a two-component model (‘envelope’ and ‘subclump’), where the envelope (component 1) is optically thin (depth $\tau_1$, linewidth $\Delta v_1$) in the less abundant CO isotopomers, such as C$^{18}$O, and the subclump material (component 2) is optically thick (depth $\tau_2$, linewidth $\Delta v_2$) in these same lines. Extending their analysis, it is also possible to define an apparent depletion factor, which describes how the presence of the optically thick clump mimics depletion within the beam in the simplistic interpretation as a single component. The CO abundance for such a source would be proportional to $(T_{A1}'\Delta v_1 + T_{A2}'\Delta v_2\tau_2)$. However, in the standard optically thin analysis, not knowing $\tau_2$, we would assume the CO abundance is proportional to $(T_{A1}'\Delta v_1 + T_{A2}'\Delta v_2)$. We will therefore deduce CO abundances that are too low by a ratio

$$A = \frac{T_{A1}'\Delta v_1 + T_{A2}'\Delta v_2}{T_{A1}'\Delta v_1 + T_{A2}'\Delta v_2\tau_2} = \frac{R_{12} + 1}{R_{12} + \tau_2},$$

(1)

where $R_{12}$ is defined in GL98 as the ratio of the integrated intensities of components 1 and 2. The optical depth of the subclump component $\tau_2$ in the denominator causes $A$ to be less than unity, and demonstrates how an optically thick clump can mimic depletion. If we assume that the abundance is in fact normal, then we can use our model – along with estimates of $R_{12}$ and $A$ – to deduce information concerning the nature of the subclumps.

For example, the clump HH25MMS (GLHL; GL98; PGL) stands out very prominently in dust continuum and $4 \rightarrow 3$ HCO$^+$ emission, but it is barely detectable as an independent source on the north–south ridge of $2 \rightarrow 1$ C$^{18}$O emission. The integrated intensity on the ridge is typically 2.5 K km s$^{-1}$ while HH25MMS adds about 0.8 K km s$^{-1}$ to it. Thus $R_{12} = 2.5/0.8 = 3.1$. Also, the apparent depletion factor, $A$, is about 1/30 (according to GL98). Hence, from equation (1), $\tau_2 = 120$.

GL98 showed that the beam-filling factor of the subclumps was given by

$$f_c = \frac{\tau_1\Delta v_1}{R_{12}\Delta v_2 + \tau_1\Delta v_1},$$

(2)

Table 1. Line optical depth and brightness (K) predictions for the ‘subclump’ and ‘depletion’ models, and observed values, for HH25MMS.

| Molecule | Subclump optical depth | Subclump model $T_{A1}'$ (K) | Subclump model $T_{A2}'$ (K) Envelope | Total (K) | Depletion Model (K) | Observed (K) |
|----------|------------------------|-----------------------------|---------------------------------|-----------|---------------------|-------------|
| C$^{18}$O | 120                    | 0.34                        | 1.1                             | 1.4       | 1.4                 | 1.3         |
| C$^{17}$O | 22                     | 0.34                        | 0.2                             | 0.55      | 0.25                | 0.28        |
| 1$^{3}$C$^{18}$O | 2                     | 0.34                        | 0.02                            | 0.35      | 0.025               | <0.08       |

The $4 \rightarrow 3$ HCO$^+$ emission is closely correlated with the continuum dust emission, rather than the C$^{18}$O, but has a linewidth similar to the C$^{18}$O, so $\Delta v_1 = \Delta v_2$. Also, $\tau_1 \sim 0.2$ for HH25MMS, so that the subclump filling factor is $f_c = 0.06$. These would be subclumps with a very high C$^{18}$O optical depth and a very small beam-filling factor in the 22-arcsec James Clerk Maxwell Telescope (JCMT) beam.

We shall assume that the JCMT beam, of radius $R$, contains $n$ identical subclumps of radius $r$. Then $f_c = n(r/R)^2$. We know that $n \geq 1$, because HH25MMS is resolved. It follows that $r \leq 2.4$ arcsec or 1000 au at the distance of L1630 (400 pc). Since the apparent depletion is high, most of the mass within the beam at HH25MMS is in the subclumps. GLHL quote a mass of 8 M$_\odot$ in the core of HH25MMS. The subclump mass is then $\sim (8/n)$ M$_\odot$ and its density is greater than $2.5 \times 10^4$ cm$^{-3}$. The density of the envelope material is much lower. Its mass is 1/30th of that of the clumps, and taking the mass to be within a beamwidth gives a density of $5 \times 10^3$ cm$^{-3}$.

As described by GL98, the most obvious problem with the ‘subclump’ interpretation seems to lie in the fact that the HCO$^+$ intensity follows the submillimetre dust continuum emission well (rather than the envelope observable in C$^{18}$O), yet its brightness temperature is so high that it must have a beam filling factor near unity, which is much greater than that deduced for the subclumps from C$^{18}$O. None the less, it is important to test the structure within the clumps, either via interferometric observations or via beam-matched observations of weaker CO isotopomers.

We may predict C$^{17}$O line intensities, assuming $\tau_2 = 120$. The component 1 intensity should decrease by a factor of 5.4 compared with C$^{18}$O, since it is optically thin, but that from component 2 will be unaltered because its optical depth will still be extremely high ($=120/5.4$). Referring to Table 1, the intensity will be

$$T_k' = T_k'' + 0.34 + 0.2 = 0.54 K,$$

(3)

so the ratio of the C$^{18}$O to C$^{17}$O intensities will be 2.6. This might easily be misinterpreted as indicating that the C$^{18}$O was just slightly optically thick. Observations of even rarer isotopomers – so that the optically thin ‘envelope’ contribution becomes negligible, while the optically thick core component still remains – are required. Table 1 gives predicted line intensities for the ‘depletion’ and ‘subclump’ models. It can be seen that observations of $^{13}$C$^{18}$O are clearly capable of distinguishing between them.

4 OBSERVATIONS

4.1 CO observations

Observations of the $J = 2 \rightarrow 1$ transitions of C$^{18}$O, C$^{17}$O and $^{13}$C$^{18}$O were carried out over the period of 1998 February 16–28 at the JCMT, using the common-user SIS receiver (A2) (Davies et al. 1992) and the digital autocorrelation spectrometer (DAS). The original mixer in A2 had been replaced by one from the National Radio Astronomy Observatories. The C$^{17}$O Observations were made assuming a rest frequency of 224.714 GHz, the C$^{18}$O observations at 219.560 GHz and the $^{13}$C$^{18}$O observations at 209.419 GHz. Key positions were selected from our previous maps of the cores, and, in addition, a new map of C$^{18}$O in LBS 18 was made. The positions
Table 2. Positions studied in this investigation (B1950).

| Source   | RA     | DEC     | Core? |
|----------|--------|---------|-------|
|          | h      | m       | s     |        |        |
| HH24MMS  | 05     | 43      | 34.7  | −00    | 11 49.0 Yes |
| HH25MMS  | 05     | 43      | 33.8  | −00    | 14 45.0 Yes |
| LBS 17H  | 05     | 43      | 57.1  | −00    | 03 44.3 Yes |
| LBS 18S  | 05     | 43      | 54.2  | +00    | 18 23.0 Yes |
| LBS 23E1 | 05     | 43      | 33.8  | −00    | 14 36.0 No  |
| LBS 17F  | 05     | 43      | 54.2  | −00    | 02 48.0 No  |
| LBS 18A  | 05     | 43      | 55.2  | +00    | 18 57.0 No  |
| LBS 18B  | 05     | 43      | 54.7  | +00    | 18 48.0 No  |
| LBS 23A  | 05     | 43      | 35.0  | −00    | 11 00.0 No  |

chosen are listed in Table 2. The positions of cores were observed, as well as a selection of references off-core, where there was sign of continuum emission.

The pointing and antenna temperature were measured with reference to the nearby source OMC1. The pointing was consistent typically to within about 3 arcsec. On February 16 and 17, the apparent antenna temperatures of lines from the frequently observed calibrating source OMC1 varied with time when observing the C$^{18}$O and 13C$^{18}$O lines. The intensity of the C$^{18}$O line varied systematically with time between 0.51 and 0.80 of that of the observatory reference spectrum for OMC1 C$^{18}$O, $T_A^*$ = 7.5 K. The C$^{18}$O intensities we quote have been systematically corrected for this variation, which brought three of the observations into agreement with similar ones described by GL98.

There was no appropriate Observatory reference for that part of the passband containing 13C$^{18}$O or C$^{17}$O. Although 13C$^{18}$O was not clearly discernible for OMC1 on February 16, the intensities of several bright lines in the passband containing it varied systematically with time between 0.42 and 0.64 of their value on February 18 and 19. It has been assumed that the values for February 18 and 19 are correct, and our 13C$^{18}$O intensities were scaled on this basis. The C$^{17}$O line observed in OMC1 showed no significant variation over February 17, 18 and 20, yielding $T_A^*$ = 1.9 ± 0.1 K. This value has been assumed correct, and no scaling applied to our observed C$^{17}$O intensities.

An observation of CO in OMC1 on February 17 yielded a line of brightness 0.9 of the observatory reference value. The reason for the time variation of C$^{18}$O and 13C$^{18}$O line intensities on February 16 and 17 has not been established. Based on the authors’ experience, possibilities might include incorrect adjustment of one of the telescope mirrors, problems in SIS receiver calibration (see e.g. Davies et al. 1992) or uncertainty in receiver sideband calibration, though this last one might not be expected to vary with time. The receiver was tuned for double-sideband performance and it is expected that the sideband ratio should be no worse than 1.2. Changing the local oscillator frequency to observe the same C$^{18}$O line in both sidebands on February 17, when the observed strength was low (though not a measurement of the sideband ratio), produced very similar line intensities, tending to suggest that the sideband ratio was not responsible.

Fig. 4 shows the new map of the LBS 18 region along with the 850-µm map from PGL; Figs 5 to 8 show the new spectra obtained for HH24MMS, HH25MMS, LBS 17H and LBS 18S, respectively.

4.2 Continuum observations

The continuum observations used in this paper were made using the Submillimetre Common-User Bolometer Array receiver (SCUBA) and are described in PGL. For the purposes of this paper, we have smoothed their 850-µm maps to the same resolution as that of our CO data, i.e. 22 arcsec.

5 RESULTS AND ANALYSIS

Table 3 contains the data taken from the new observations. The antenna temperatures, $T_A^*$, derived from the CO observations for all three species at each of the positions, are shown. The observations were made with a channel spacing and noise bandwidth of 0.45 km s$^{-1}$. Four channels were averaged to give the temperatures quoted in Table 3. (Note that the spectra are shown in the original spectral
Figure 5. HH24MMS: C$^{18}$O, C$^{17}$O and $^{13}$C$^{18}$O spectra at the core position (RA = $05^\circ43^\prime34^\prime.7$, Dec. = $-00^\circ11^\prime49^\prime.0$).

Figure 6. HH25MMS: C$^{18}$O, C$^{17}$O and $^{13}$C$^{18}$O spectra at the core position (RA = $05^\circ43^\prime33^\prime.8$, Dec. = $-00^\circ14^\prime45^\prime.0$).

Figure 7. LBS 17H: C$^{18}$O, C$^{17}$O and $^{13}$C$^{18}$O spectra at the core position (RA = $05^\circ43^\prime57^\prime.1$, Dec. = $-00^\circ03^\prime44^\prime.3$).

Figure 8. LBS 18S: C$^{18}$O, C$^{17}$O and $^{13}$C$^{18}$O spectra at the core position (RA = $05^\circ43^\prime54^\prime.2$, Dec. = $+00^\circ18^\prime23^\prime.0$).

5.1 Temperatures and masses

From the fluxes at 850 and 450 µm, we seek to derive the temperatures and masses. The results depend on the opacity law, which is uncertain. Rather than seeking to justify a law, we chose to investigate the effect of varying it by comparing the different results obtained, assuming two typical but reasonably extreme examples: the laws proposed by Hildebrand (1983) ($\beta = 2$) and by Testi & Sargent (1998) ($\beta = 1.1$). These predict very similar opacities at 850 µm, but different temperatures from 850/450 flux ratios. We accordingly derive temperatures from both these laws, and compare them with already published temperatures from greybody spectral fits and ammonia inversion line observations to deduce plausible temperature limits. These are then used with the 850-µm opacities to deduce masses.

If the absorption coefficient $\kappa(\nu)$ is written in terms of the dust and molecular hydrogen density ($n_{H_2}$) as

$$\kappa(\nu) = \kappa_d \rho_d = \kappa_{H_2} n_{H_2},$$

the total number of hydrogen molecules $N(H_2)$ implied by observation of a flux $F_\nu$, from dust assumed to be optically...
of the submillimetre continuum equation (5). Flux-ratio maps were produced by using the COMB comparing it with that predicted for different temperatures using D

where \( \beta \) can be found in Table 4 for both values of temperature. The measured at each point from these maps and used to the contours representing the higher values of (22-arcsec) continuum map in Fig. 9, where it can be seen that to a resolution of 22 arcsec, has been plotted over the 850-\(\mu m \) (15-arcsec resolution) maps. The ratio, the 450-\(\mu m \) emission being optically thick.

The resulting value of the dust temperature (\( T_d \)) for each position can be found in Table 4 for both values of \( \beta \). As expected, the temperatures are higher for the lower value of \( \beta \). The errors are derived using the calibration uncertainties and random-noise errors quoted in PGL.

The assumption that the dust is optically thin can produce misleadingly low temperatures and high derived masses if the dust is, in fact, optically thick at 450-\(\mu m \). However, PGL used a radiative transfer program to model the cores that was not limited by this assumption, but derived very similar temperatures to those found here. In reality, the results we find represent an average over the beam. It is also quite likely that there are temperature gradients within the beam, either decreasing towards the centre of the core (e.g. an externally heated protostellar cloud) or increasing (e.g. an interstellar cloud heated by a central young star). If there are, then the derived beam-averaged temperature will be weighted towards the hotter dust which radiates more strongly. This means that the derived dust masses will be too low (colder dust being underweighted). CO column densities are less sensitive to temperature, so the overall effect is to derive CO abundances that are higher than the true ones, i.e. to make the depletion appear less marked than it really is.

Further information is available which can be used to constrain the temperatures. Greybody fits to the spectra of dust continuum emission give \( T_d = 17-35 \) K for HH25MMS (Gibb & Davis 1998), \( T_d = 20 \pm 5 \) K for HH24MMS (Ward-Thompson et al. 1995) and

\[
N(H_2) = \frac{D^2 c^2 [\exp(\nu/kT) - 1]}{2h^3 \kappa_{HI} v} F_v \tag{5}
\]

where \( D \) is the distance from Earth.

The temperature of the gas can be derived by forming the ratio of the submillimetre continuum fluxes at the two wavelengths and comparing it with that predicted for different temperatures using equation (5). Flux-ratio maps were produced by using the COMB task in AIPS to divide the 850-\(\mu m \) (15-arcsec resolution) maps by the 450-\(\mu m \) (15-arcsec resolution) maps. The ratio, \( r(850/450) \), was measured at each point from these maps and used to find the temperature. The flux-ratio map of LBS 18, which has been smoothed to a resolution of 22 arcsec, has been plotted over the 850-\(\mu m \) (22-arcsec) continuum map in Fig. 9, where it can be seen that the contours representing the higher values of \( r(850/450) \) are coincident with the dust peaks. This may be a result of: (i) a lower temperature; (ii) a flatter emissivity law; or (iii) the 450-\(\mu m \) emission being optically thick.

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\[ T_d < 20 \) K for LBS 17H (GL00). It is also of interest to compare the derived temperatures with those obtained from NH\(_3\) inversion lines. Harju, Walmsley & Wouterloot (1993) used NH\(_3\) (1, 1) and (2, 2) observations of 40-arcsec resolution to derive the kinetic temperature of 43 star-forming cores, 16 of which are associated with

### Table 3. \(^{13}\)C\(_2\)O, \(^{13}\)C\(_2\)O and \(^{13}\)C\(_2\)O line temperatures and integrated intensities, and 850-\(\mu m \) flux measurements at each position. Note that the noise levels quoted are derived from spectra binned by four channels, and are therefore a factor of 2 lower than might be expected from a direct comparison with Figs 5 to 8.

| Source       | \(^{13}\)C\(_2\)O \( T_d \) | \(^{13}\)C\(_2\)O \( I_{int} \) | \(^{13}\)C\(_2\)O \( T_d \) | \(^{13}\)C\(_2\)O \( I_{int} \) | \(^{13}\)C\(_2\)O \( T_d \) | \(^{13}\)C\(_2\)O \( I_{int} \) | 850 \(\mu m \) |
|--------------|----------------|----------------|----------------|----------------|----------------|----------------|--------------|
| HH24MMS      | 2.8 ± 0.03 | 5.8 ± 0.07 | 1.75 ± 0.03 | 0.057 ± 0.020 | 0.09 ± 0.03 | 4.76          |
| HH25MMS      | 1.3 ± 0.03 | 2.5 ± 0.09 | 0.80 ± 0.02 | <0.080 ± 0.045 | <0.02 ± 0.05 | 2.36          |
| LBS 17H      | 2.6 ± 0.03 | 6.0 ± 0.07 | 1.80 ± 0.03 | 0.088 ± 0.048 | 0.16 ± 0.06 | 3.79          |
| LBS 18S      | 1.5 ± 0.03 | 3.0 ± 0.16 | 0.80 ± 0.03 | <0.072 ± 0.048 | <0.02 ± 0.06 | 1.34          |
| LBS 23E1     | 1.8 ± 0.06 | 3.4 ± 0.15 | 0.80 ± 0.05 | –             | –             | 1.97          |
| LBS 17F      | 3.9 ± 0.06 | 7.3 ± 0.15 | 0.90 ± 0.02 | 2.20 ± 0.05   | –             | 1.85          |
| LBS 18A      | 2.6 ± 0.06 | 3.0 ± 0.15 | 0.75 ± 0.05 | –             | –             | 0.82          |
| LBS 18B      | 3.0 ± 0.06 | 3.4 ± 0.13 | 0.90 ± 0.05 | –             | –             | 0.85          |
| LBS 23A      | 2.6 ± 0.10 | 6.0 ± 0.23 | –             | <0.05 ± 0.015 | <0.12 ± 0.02 | 1.08          |

**Figure 9.** Flux-ratio map (22 arcsec) of the LBS 18 region, plotted over the 850-\(\mu m \) (22 arcsec) continuum map. Contour levels are at 0.3, 0.4, 0.5, 0.6 and 0.7 ratio, with a peak of 0.9 ratio at the dust peak.
the Orion L1630 and L1641 clouds. They mapped LBS 23, finding temperatures of about 15 K at the positions of HH24MMS and HH25MMS. These results and those from the greybody fits are included in Table 4. In general, the kinetic temperature shows little variation over their maps. Their results show that the average kinetic temperature is ∼15.7 K for the Orion cores. Only two of their cores showed temperatures greater than 20 K. Matthews & Little (1983) also mapped LBS 23 with 130-arcsec resolution; at HH 25 they found a temperature of 14 K which is similar to that of Harju et al. As the cloud is extended and their beam contained a substantial region surrounding the core, it is likely that a temperature of 14 K is representative of the envelope surrounding the core.

On the basis of Table 4 and the general considerations above, we regard conservative limits for the dust temperatures to be 20 ± 5 K for HH24MMS and HH25MMS and 15 ± 5 K for LBS 17H and LBS 18S, while for the off-core envelope positions we take $T = 15 \pm 5$ K. We then use these temperatures and the 850-μm fluxes together with the 850-μm opacity of Testi & Sargent to deduce gas temperatures of about 15 K at the positions of HH24MMS and HH25MMS and 15 K for LBS 17H and LBS 18S.

5.2 Carbon monoxide optical depths

We can see immediately that the observed isotope line ratios listed in Table 1 for HH25MMS are in much better agreement with the predictions of the depletion model than with those for optically thick subclumps. It should be noted that – although optically thick non-depleted subclumps are unlikely to explain the apparent depletion – the existence of depleted clumps is not ruled out.

Table 5 shows the line temperatures and their ratios $X(18/17)$, denoting the ratio of $T_A^{18}$ and $T_A^{17}$ for the line temperatures of C$^{17}$O and C$^{17}$O, respectively. The mean value of $X(18/17)$ in the cores is 4.28; towards the other positions, it is 6.1. The latter value is in good agreement with the solar expectation of 5.4, suggesting that these positions are optically thin, and that the [C$^{17}$O]/[C$^{18}$O] ratio is normal. The former suggests that C$^{17}$O may be slightly optically thick in the cores, but certainly not sufficiently enough to discredit a former conclusion that CO is depleted in several of the cores of LBS 23 (GL98). The [C$^{17}$O]/[C$^{18}$O] ratios are consistent with the solar value.

The above constitutes good evidence that C$^{17}$O and C$^{18}$O are optically thin.

The optical depths of the three species in the individual positions have been calculated. First, the optical depth of C$^{17}$O can be calculated using equation (6):

$$ T_A^{17}/T_A^{18} = 1 - e^{-\tau^{17}}/1 - e^{-\tau^{18}}. $$

By assuming that solar values hold (i.e. $\tau^{18} = 5.4 \tau^{17}$), equation (6) was solved to obtain a value for $\tau^{17}$ at each position. The values of $\tau^{17}$ are displayed in Table 5, with the errors calculated for each value. Multiplying $\tau^{17}$ by 5.4 gives $\tau^{18}$ at each position. One can also calculate $\tau^{13,18}$, the optical depth of [13C$^{18}$O], by dividing $\tau^{17}$ by 16.6. It can be seen from these results that all three species of CO are optically thin in the regions where the abundances have been calculated and can therefore be used effectively in the calculations.

The negative optical depth values in Table 5 are likely to be due to noise errors, rather than weak maser emission.

5.3 Relative abundance of CO

For an optically thin transition, the total number of molecules within a beam $\theta$ (FWHM arcsec) from a source at $D$ (kpc) is given by

$$ N(MOL) = 2.5 \times 10^8 \left( \frac{D}{0.4} \right)^2 \left( \frac{\theta}{22} \right)^2 \left( \frac{2J + 1}{2FJ(1 - R)} \right) \left( \frac{0.1}{\mu} \right)^2 \int T_B^* d\nu, $$

where $B$ is the rotational constant (GHz), $\mu$ is the dipole moment (debye), $J$ is the upper level of the transition, $F_J$ is the fractional population of level $J$, $\int T_B^* d\nu$ is the integrated line intensity (K km s$^{-1}$), and $R$ is given by

$$ R = \frac{\exp(2hBJ/kT_B) - 1}{\exp(2hBJ/kT_B)} - 1. $$

Note that $T_B^*$ is the cosmic microwave background temperature (2.7 K).

The relative abundance of the CO isotopommer can be estimated by computing $N(MOL)$ from equation (7) and dividing by $N(H_2)$ from equation (5). To calculate the relative abundance, the integrated intensities in Table 3 were divided by $\eta_B(=0.8)$ to correct for beam efficiency.

The C$^{18}$O abundance, $X^{18}$O, was calculated in the same way as for C$^{17}$O and C$^{13}$C$^{18}$O, but the answers obtained for HH24MMS, HH25MMS, LBS 17H, LBS 18S and LBS 17F were multiplied by (5.4/$X$), where $X = X(18/17)$ (see Table 5), to allow for the finite optical depth of C$^{18}$O. The resulting relative abundances of C$^{17}$O, C$^{18}$O and C$^{13}$C$^{18}$O at each position can be found in Table 6.

Table 4. Temperatures (K) derived from published greybody fits, our observations assuming β = 1.1 and 2, and NH$_3$ observations of Harju et al.

| Source | $T_{gb}$ | $T_{d(1.1)}$ | $T_{d(2)}$ | $T_{NH_3}$ |
|--------|---------|-------------|------------|------------|
| HH24MMS | 20 ± 5 | $10^{+2}_{-1}$ | 7±1 | 15±3 |
| HH25MMS | 17−35 | $38^{+7}_{-20}$ | $13_{-3}^{+4}$ | 15±2 |
| LBS 17H | <20 | $14_{-5}^{+9}$ | 9±3 | – |
| LBS 18S | – | $14_{-5}^{+9}$ | 9±3 | – |
| LBS 23E | – | $37_{-22}^{+23}$ | $13_{-3}^{+4}$ | – |
| LBS 17F | – | $16_{-4}^{+6}$ | 9±5 | – |
| LBS 18A | – | $23_{-14}^{+5}$ | $11_{-4}^{+7}$ | – |
| LBS 18B | – | $24_{-14}^{+5}$ | $11_{-4}^{+6}$ | – |
| LBS 23A | – | $37_{-23}^{+5}$ | $13_{-3}^{+4}$ | – |

Table 5. Optical depth of C$^{17}$O at each position.

| Source | $T_A^{17}$ (K) | $T_A^{18}$ (K) | $X(18/17)$ | $\tau_{17}$ | $\delta\tau_{17}$ |
|--------|--------------|--------------|-------------|-------------|---------------|
| HH24MMS | 0.67 | 2.8 | 4.2 | 0.12 | 0.02 |
| HH25MMS | 0.28 | 1.3 | 4.6 | 0.08 | 0.04 |
| LBS 17H | 0.64 | 2.6 | 4.1 | 0.13 | 0.02 |
| LBS 18S | 0.37 | 1.5 | 4.1 | 0.13 | 0.04 |
| LBS 18E | 0.28 | 1.0 | 4.3 | 0.11 | 0.03 |
| LBS 18A | 0.45 | 2.6 | 5.8 | –0.03 | 0.05 |
| LBS 18B | 0.42 | 3.0 | 7.1 | –0.12 | 0.05 |
| LBS 23A | – | 2.6 | 7.3 | –0.13 | – |
6 DISCUSSION

6.1 Morphology

It appears, from comparing SCUBA and line results, that the cores tend to be found on the edges or ends of filaments. There are two kinds of core structure: ones where the HCO\(^+\) and dust are coincident but C\(^{18}\)O is very faint or absent (LBS 17H, HH24MMS); and others where HCO\(^+\), C\(^{18}\)O and dust peak successively towards the cloud edge [LBS 18S and the Luhmardt et al. (1996) core in LBS 17 (see GL100)]. The problem is to distinguish the effects of chemistry and excitation.

6.2 Depletion

The canonical values for the abundance of C\(^{18}\)O, C\(^{17}\)O and \(^{13}\)C\(^{18}\)O may be taken to be \(2 \times 10^{-7}\), \(4.7 \times 10^{-8}\) and (assuming simple proportion) \(2.7 \times 10^{-9}\) respectively, from Frerking et al. (1982). Dividing these values by the corresponding abundances in each position, one can estimate the depletion factor, \(d\), for each isotopomer. Table 7 displays these depletion factors and one can see that – in all cases – the CO is depleted significantly.

Relative to the canonical values, the isotopic species appear to be depleted by factors of about 10 in the cores, and approximately half that in the envelopes. The values are typically less than those quoted by GL98, the differences being a result of the assumption of slightly higher temperatures, careful matching of effective beam sizes and correction for the optical depths of C\(^{18}\)O.

A natural explanation for the depletion observed in these cores is the condensation of CO molecules on dust grains, because the density (~\(10^6\) cm\(^{-3}\): GLHL, GL98) is high enough to reduce the freeze-out time-scale to less than the dynamical time-scale. In addition, grain growth by coagulation is expected in such regions which gives rise to increased dust emissivity (Ossenkopf 1993). The consequence of these two processes is that dense collapsing cores become very well-defined in millimetre continuum emission while simultaneously becoming very poorly-defined in C\(^{18}\)O emission, such as we observe here.

A number of studies of other star-forming regions have also arrived at the conclusion that the CO abundance is lower than the canonical value. Studies by Kramer et al. (1999), Willacy, Langer & Velusamy (1998) and Caselli et al. (1999) have found that the C\(^{18}\)O abundance is reduced typically by factors ranging from a few to an order of magnitude towards the lines of sight with highest H\(_2\) column density. The study of Kramer et al. (1999) shows that the highest reduction in the C\(^{18}\)O abundance occurs in the coldest regions. In all cases, these authors also conclude that freeze-out of CO on to cold dust grains is responsible for the observed levels of depletion.

Although this investigation has shown that CO appears to be depleted in the cores, one cannot be sure that the factors are correct, as we are calculating the abundance using averages along the line of sight. If, for example, the cores are much colder than the envelopes, there will be a higher depletion factor in the cores and a lower one in the envelopes. This is one area which needs to be studied further in order to find a way of deriving the emission produced at the core positions, rather than averaged along the line of sight. One must also keep in mind that the canonical values of the abundance have been calculated using line-of-sight observations which may contain dust and gas that is a lot less dense than that found in protostellar cores, so comparing the core abundances with these values may not give a true depletion factor.

6.3 Implications for chemical models

Rawlings et al. (1992) show that as a protostar collapses, it is plausible that the chemistry occurring while molecules deplete out on to dust grains leads to an increasing HCO\(^+\)/CO ratio (by up to 50), although their absolute abundances finally fall. A requirement for this to happen is a high initial H\(_2\)O abundance, such as might result from initial conditions following a shock through already processed material, but not from initial conditions which are of simple atomic form.

Observations of water have been made towards the regions encompassing HH24MMS and HH25MMS with ISO, but these only trace a hot, dense component in shocked gas (Benedettini et al. 2000). Perhaps more reliable, but still less than ideal, are the observations of NGC 2024 with the Submillimeter-Wave Astronomy Satellite (SWAS) by Snell et al. (2000). Snell et al. estimate that the abundance of water (strictly only the ortho species) to be \(6 \times 10^{-10}\) – considerably lower than expected, but in agreement with the notion of ongoing and widespread depletion by freeze-out on to dust grains.

Other models have been developed which have different assumptions. Bergin & Langer (1997) followed chemistry during the collapse using a gas–grain chemical code, including desorption and depletion, but starting from an initial pristine state with elements only. The increase in HCO\(^+\)/CO suggested by observations was not produced by the model. Neither was it produced by the different type of model of Charnley (1997).

Table 6. Temperatures and CO abundances.

| Source     | T (K) | \(X_{\text{C}^{18}\text{O}}\) (10\(^{-9}\)) | \(X_{\text{C}^{17}\text{O}}\) (10\(^{-9}\)) | \(X_{\text{^{13}\text{C}^{18}\text{O}}}\) (10\(^{-10}\)) |
|------------|-------|----------------------------------------|----------------------------------------|----------------------------------------|
| HH24MMS    | 20 ± 5 | 2.4 ± 1.1                             | 0.6 ± 0.3                              | 2.8 ± 1.6                              |
| HH25MMS    | 20 ± 5 | 1.9 ± 0.9                             | 0.5 ± 0.2                              | <1.3 ± 0.2                             |
| LBS 17H    | 15 ± 5 | 2.0 ± 0.8                             | 0.5 ± 0.3                              | 4.1 ± 2.3                              |
| LBS 18S    | 15 ± 5 | 2.9 ± 1.0                             | 0.6 ± 0.3                              | <1.5 ± 0.3                             |
| LBS 23E1   | 15 ± 5 | 1.7 ± 0.9                             | 0.4 ± 0.2                              | –                                      |
| LBS 23E2   | 15 ± 5 | 4.8 ± 2.6                             | 1.2 ± 0.6                              | –                                      |
| LBS 23A    | 15 ± 5 | 3.6 ± 1.6                             | 0.9 ± 0.5                              | –                                      |
| LBS 23B    | 15 ± 5 | 3.9 ± 2.1                             | 1.0 ± 0.6                              | –                                      |
| LBS 23C    | 15 ± 5 | 5.4 ± 2.4                             | –                                      | <10.8 ± 6.9                            |

Table 7. Depletion factors.

| Source     | T (K) | \(d_{\text{C}^{18}\text{O}}\) | \(d_{\text{C}^{17}\text{O}}\) | \(d_{\text{^{13}\text{C}^{18}\text{O}}}\) |
|------------|-------|-----------------|-----------------|-----------------|
| HH24MMS    | 20 ± 5 | 8.5 ± 4.8       | 8.5 ± 4.6       | 9.5 ± 8.9       |
| HH25MMS    | 20 ± 5 | 10.7 ± 5.7      | 9.2 ± 5.0       | 21.3 ± 8.3      |
| LBS 17H    | 15 ± 5 | 9.8 ± 3.4       | 10.7 ± 3.6      | 6.6 ± 2.4       |
| LBS 18S    | 15 ± 5 | 7.0 ± 2.3       | 8.1 ± 2.8       | 18.6 ± 3.0      |
| LBS 23E1   | 15 ± 5 | 11.9 ± 9.8      | 11.8 ± 9.5      | –               |
| LBS 23E2   | 15 ± 5 | 4.1 ± 3.4       | 4.0 ± 3.5       | –               |
| LBS 23A    | 15 ± 5 | 5.6 ± 4.6       | 5.3 ± 4.5       | –               |
| LBS 23B    | 15 ± 5 | 5.1 ± 4.2       | 4.6 ± 4.3       | –               |
| LBS 23C    | 15 ± 5 | 3.7 ± 1.3       | –               | 2.5 ± 1.2       |
Bergin et al. (2000) have proposed an alternative method of reducing the CO abundance, prompted by results from SWAS. In their model, CO abundance can drop [even in warm clouds (say, 30 K)], as a result of destruction by He \(^+\) with the oxygen atoms freezing out and becoming locked in water ice. Unfortunately, their discussion excludes HCO\(^+\), and it should also be noted that the CO destruction occurs on extremely long time-scales (greater than a million years) – much longer than the collapse time-scales for these cloud cores.

The model of Rawlings et al. (1992) predicts an abundance for HCO\(^+\), in good agreement with a value we have derived for HH25MMS (\(5 \times 10^{-10}\), GLHL). In addition, the modelling of Caselli et al. (2002) shows that the HCO\(^+\) abundance may be used to estimate the maximum degree of depletion. Their model 3 (shown in their fig. 8) also predicts a value for the HCO\(^+\) abundance close to our large velocity gradient (LVG) estimate for HH25MMS. At this value (which is also at a radius close to the beam radius for our JCMT observations), the depletion factor is \(~20\), in good agreement with the levels of CO depletion we derived above.

However, it should also be noted that, from our LVG modelling (GLHL), we find that the HCO\(^+\) is optically thick, and thus any decrease in the HCO\(^+\) abundance in the centre of these cores (at radii less than \(~3000–4000\) au) is masked. Observations and modelling of rarer species will help to answer this question. We are currently analysing observations of HCO\(^+\) and DCO\(^+\) isotopomers on the cores to study this phenomenon more carefully.

Because star formation has already taken place in L1630 (e.g. Lada et al. 1991), the initial conditions for the chemistry will not be pristine. This supports our consideration of the model of Rawlings et al. (1992), which starts from ‘evolved’ conditions (including a high abundance of water). Only this model predicts an actual increase of HCO\(^+\) while CO is declining. It therefore provides a natural explanation for the brightness of high-excitation HCO\(^+\) emission relative to CO emission on cores. It therefore appears that the role of the initial conditions is very important in determining the later behaviour of the chemistry.

7 CONCLUSIONS

We have used new observations of C\(^{17}\)O, C\(^{18}\)O and \(^{13}\)C\(^{18}\)O along with existing 450- and 850-\(\mu\)m continuum observations to study four regions in the Orion B molecular cloud. This has allowed the determination of optical depths for the isotopic species, and the elimination of a model by which the cores contain many optically thick subclumps to explain the low isotopic CO emission.

If the dust emissivity falls within what are presently considered to be reasonable limits, CO is depleted in both the cores and the surrounding regions, but by a higher factor in the cores. Relative to the canonical abundances of Frerking et al. (1982), the CO appears to be depleted by about a factor of 10 at the core positions and a factor of 5 in the envelopes. Although the dust observations do not allow the temperatures to be constrained for \(\beta = 1.1\), we believe it is unlikely, from the NH\(_3\) observations of Harju et al. (1993) and Matthews & Little (1988), that temperatures will be greater than 15–20 K. It seems unlikely that the temperatures exceed the dust-derived values in the sources.

The low abundance of CO and the brightness of HCO\(^+\) emission in the cores tend to support the model of Rawlings et al. (1992), which suggests that the amount of HCO\(^+\) in the core increases as that of CO decreases. The HCO\(^+\) abundance and observed levels of CO depletion are also in good agreement with a recent model of molecular ion chemistry in collapsing cores by Caselli et al. (2002).

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