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New detections of isotopic molecular absorption lines: a low [^{12}C:^{13}C] ratio in nearby gas

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Abstract. Molecular absorption line observations towards the background source Sgr B2 'M' are presented. Previous observations have shown that there are $\sim$ 9 foreground clouds of moderate density along this line of sight, which produce absorption lines that are well spaced in velocity. In two of these clouds, first detections have now been made of the rare isotopomers ^{13}CS, HN^{13}C, HC^{15}N and HC^{18}O$^+$. For a feature at lsr velocities of –4 to +18 km s^{-1}, the isotopic ratio [^{12}C:^{13}C] has been estimated, from the relative intensities of ^{12}CS and ^{13}CS J=1–0 lines, and also by comparing the strength of the ^{13}CS line with that of C^{34}S J=1–0 observed previously. A convergent solution for the two methods is found if ^{12}CS is optically thick but the isotopomer lines are optically thin. In this case [^{12}C:^{13}C] is 24 $\pm$ 11, which is surprisingly low if the gas lies near the Sun, as indicated by its velocity. However, it has been suggested that parts of this feature may in fact arise in hot gas close to the Sgr B2 cloud, where a low isotope ratio is expected. If this region of the line is excluded, the [^{12}C:^{13}C] ratio for the remaining lsr velocities of +11 to +18 km s^{-1} is only slightly changed, with a value of 22 $\pm$ 13. This is the true carbon isotope ratio in some nearby gas, if effects such as peculiar velocities and isotopic fractionation are unimportant. The value found here is well below the local average of $\sim$ 60–70 in the solar neighbourhood, which suggests that some of the nearby absorbing gas has been recently isotopically enriched by stellar ejecta. This moderate density absorbing gas is then more likely to be material left over after star-formation, rather than a pre-star-forming cloud.

Key words: ISM: abundances – ISM: molecules – Galaxy: solar neighbourhood – radio lines: ISM

1. Introduction

Although molecular clouds are generally observed via the rotational emission lines of trace species, it has been known for some time that these molecules can also be detected in absorption lines, along lines of sight to bright millimetre-wavelength background sources. Species including HCN, HCO$^+$, CS, etc. have been detected in absorption in several foreground clouds (e.g. by Encrenaz et al. 1980; Nyman 1983, 1984; Greaves et al. 1992), against background sources such as compact HII regions in the Sgr B2 and W49 A star-formation regions. These molecules in the absorbing clouds are found to have very low excitation temperatures, close to that of the cosmic microwave background radiation, hence strong absorption lines are seen, with a limit set by the strength of the continuum.

The nature of these clouds is not well understood, with only rough estimates available for their sizes and densities (e.g. Greaves & Williams 1994), and their place in the evolution of interstellar material is uncertain. It is therefore of interest to measure isotopic ratios in the absorbing gas, to determine if they differ from those found from emission lines in nearby dense clouds. In particular, this might clarify whether the intermediate density absorption clouds represent gas before or after star-formation has occurred.

We have therefore attempted to detect absorption towards Sgr B2 'M' in the transitions ^{13}CS, HN^{13}C, HC^{15}N and HC^{18}O$^+$ J=1–0, which combined with previous observations of CS, H^{13}CN and H^{13}CO$^+$ (Greaves et al. 1992) can potentially give the isotopic ratios [^{12}C:^{13}C], [^{14}N:^{15}N] and [^{16}O:^{18}O]. However, the optical depths of the isotopomeric lines were found to be very low, and not all the foreground clouds were detected. In this paper, we present the spectra obtained in the four target lines, and estimate the value of [^{12}C:^{13}C] in one cloud where high signal-to-noise data were obtained.

2. Observations

The observations were made at the Nobeyama Radio Observatory 45m telescope, in March 1991 and May 1992. The transitions observed are listed in Table 1 (omitting the superscripts for the most common isotopes, ^{12}C, ^{14}N and ^{16}O). The position of the background source, Sgr B2 'M', was R.A.(1950) = 17h 44m 10.6s, Dec.(1950) = –28° 22' 03"; the telescope beam at

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Table 1. Rest frequencies of transitions observed

Transition	ν_0 (GHz)
^{13}CS J=1–0	46.2476
CS J=1–0	48.9910
HC^{18}O$^+$ J=1–0	85.1622
HC^{15}N J=1–0	86.0550
HN^{13}C J=1–0	87.0909
HNC J=1–0	90.6636

this position includes several compact HII regions (Carlstrom & Vogel 1989). At the lowest frequencies the beam size (FWHM) was ≈ 37", decreasing to ≈ 19" at the highest frequency, with pointing errors (measured on nearby SiO masers) of ~ 5". The observations were made by position-switching to δR.A. = –30'.

SIS receivers were used (with the exception of HC^{15}N J=1–0, for which a Schottky-diode receiver was used), and the backends were two AOS which were split into sections to observe several lines simultaneously within the receiver passbands. On-source integration times ranged from 20 to 70 minutes, and single-sideband system temperatures were ~ 1000 – 2000 K. These high values of T_{sys} were due to a combination of low source elevations and poor observing conditions (high humidity), and fewer lines were detected in the weaker transitions than had been hoped. Also, atmospheric variations resulted in changing baseline levels, and it was not possible to measure the continuum strengths by inspecting the spectra before baseline subtraction. The calculations in the rest of the paper depend on a continuum measurement made previously at the 45m (Greaves et al. 1992).

The spectra are presented on a main-beam antenna temperature scale (T_{mb}), since the background sources are smaller than the beam. The main-beam efficiency had the values η_{mb} = 0.83 (CS, ^{13}CS), 0.58 (HC^{15}N), 0.55 (HN^{13}C, HC^{18}O$^+$) and 0.54 (HNC). The measurement errors in these values are ~ 0.05 – 0.07. The original spectral resolution was 0.04 MHz for CS, ^{13}CS and 0.25 MHz for the other lines, but some of the spectra presented here have been binned to improve the signal-to-noise.

3. Results

The spectra obtained are presented in Fig. 1. These data are all new results, with the exceptions of CS J=1–0, previously observed by Greaves et al. (1992), and the C^{34}S J=1–0 spectrum which is reproduced from that paper. A total of ≈ 9 separate absorption dips can be distinguished in the CS and HNC spectra, but the isotopomers are detected at fewer velocities. HC^{15}N, HC^{18}O$^+$, HN^{13}C and ^{13}CS are all seen around 0 km s^{-1}, a feature which corresponds to gas in the solar neighbourhood (within ~ 1–2 kpc). The HC^{18}O$^+$ profile extends to +20 km s^{-1}; this material is probably more distant. HN^{13}C is also clearly detected around –100 km s^{-1}, corresponding to gas in the '1 kpc disk' around the Galactic Centre. ^{13}CS shows some absorption at this velocity, but only at the level of a baseline defect also seen (near –60 km s^{-1}). Finally, there are marginal detections of ^{13}CS and HC^{15}N around –25 km s^{-1}, and C^{34}S is seen at five velocities in the range –50 to +40 km s^{-1} (discussed by Greaves et al. 1992).

To estimate [^{14}N:^{15}N] and [^{16}O:^{18}O] values, double isotope ratios with the H^{13}CN and H^{13}CO$^+$ lines observed previously must be used. The uncertainty in [^{12}C:^{13}C] found below, together with possible variations in observed continuum strengths between the different runs, result in very uncertain results for these two ratios. Thus the only isotopic ratio that can be reliably estimated is [^{12}C:^{13}C] at 0 km s^{-1}, where the signal-to-noise is high for all the spectra.

The very similar T_{mb} values of three of the HNC absorption dips (Fig. 1) suggest that the continuum is wholly absorbed at these velocities, and hence that HNC J=1–0 is highly optically thick. (This transition was originally chosen because the continuum is only partially absorbed towards W49 A (Nyman & Millar 1989), but the optical depths towards Sgr B2 appear to be larger.) The HNC, HN^{13}C data can therefore not be used to find [^{12}C:^{13}C], and instead, the J=1–0 transitions of CS and ^{13}CS were used. In addition, C^{34}S J=1–0 (ν = 48.2070 GHz) has been detected (Fig. 1), and by assuming a value for [^{32}S:^{34}S] the double ratio of C^{34}S to ^{13}CS can also be used to estimate [^{12}C:^{13}C]. The former method is simpler, but the latter has the advantage that the two isotopomers have similar optical depths, and thus the isotopic ratio is less affected by possible excitation differences.

3.1. [^{12}C:^{13}C] *in the local gas*

The isotope ratios can be estimated from the ratios of integrated optical depth, since $\tau \propto X$, where X is the abundance of the molecule with respect to H$_2$. Other factors, such as the absorption coefficient and the fraction of the population in the J=0 level, differ only through the line frequencies, and since these are very similar (46 – 49 GHz), neglecting these factors introduces errors of only a few percent. Assuming local thermodynamic equilibrium, optical depths are given by

$$\tau = -ln\left[1 - \frac{T_{mb}(l)}{J(T_{ex}) - J(T_{cmb}) - T_{mb}(c)}\right] \qquad (1)$$

where l and c denote line and continuum, T_{ex} and T_{cmb} are the excitation temperature and the cosmic microwave background radiation temperature (2.73 K) respectively, and $J(T)$ is the blackbody function $(h\nu/k)(\exp(h\nu/kT) - 1)^{-1}$. It is assumed that the clouds are extended uniformly over scales larger than the beam, which is reasonable as similar profiles are seen towards Sgr B2 'N' (Greaves & Williams 1994). The beam-filling factors of the compact background source and the region of the foreground cloud in which absorption occurs must be the same, and thus do not enter into Eq. (1).

$T_{mb}(c)$ was not measured during the 1991 observations, but a value of 4.5 ± 1.2 K (rms error) at 43 GHz was obtained in 1987 (Greaves et al. 1992). This value could differ somewhat

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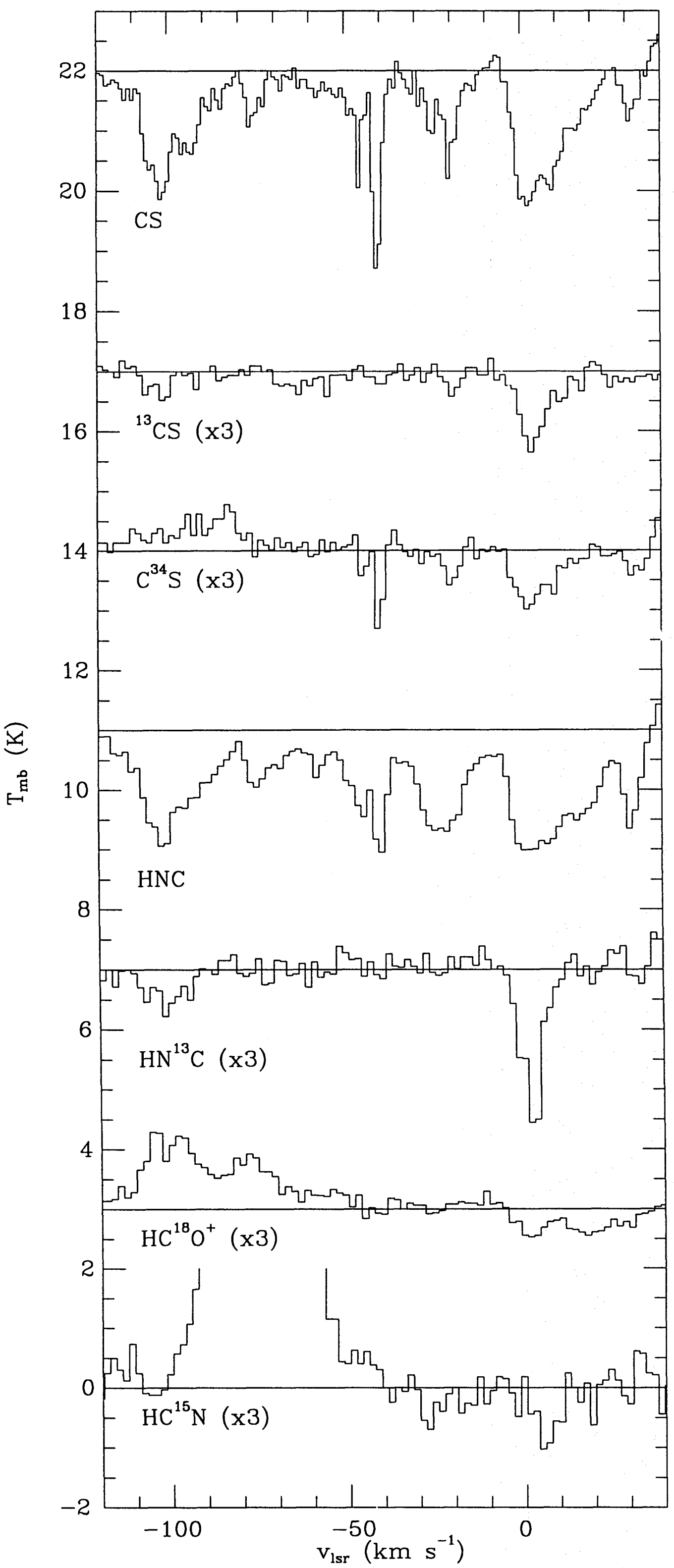

Fig. 1. Absorption spectra towards Sgr B2. The baselines are all continuum-subtracted (i.e. 0 K), and are offset for clarity. Emission lines are from other species in the background star-formation region, at $v_{lsr} \approx +65$ km s^{-1}. The $C^{34}S$ J=1–0 spectrum is reproduced from Greaves et al. (1992), but with an improved baseline; the nominal (0,0) position was offset by 2", less than the pointing errors

between the two runs, because of pointing offsets and calibration changes, but it is possible to scale the continuum strengths using CS J=1–0 spectra obtained on both occasions. The CS features were stronger in 1991, because for the 1987 run, Sgr B2 was close to the Sun, which affected the absolute pointing. The resulting positional errors resulted in a reduced $T_{mb}(c)$ and hence weaker CS absorption. Note that for the 1987 data, the CS and $C^{34}S$ spectra were observed simultaneously, thus the same $T_{mb}(c)$ applies to each (any frequency dependence will be less than the error in the measurement). In 1991, CS and ^{13}CS were not observed simultaneously, but pointing errors were small and the relative calibration uncertainty is believed to be < 20 %.

We consider two cases: $T_{ex} = T_{cmb}$ and $T_{ex} > T_{cmb}$. In the first case, Eq. (1) shows that the continuum temperatures are proportional to $T_{mb}(l)$ of the CS J=1–0 spectra, as τ and T_{ex} will be approximately constant over the small scale of the pointing shifts. Over the velocity range of interest in the 0 km s^{-1} absorption line, the scaling factor from 1987 T_{mb} to 1991 T_{mb} is estimated at 1.7 ± 0.3, thus the scaled (1991) $T_{mb}(c)$ is $\approx 7.7 \pm 2.4$ K. In this case, both CS and ^{13}CS J=1–0 have $\tau \ll 1$ in the 0 km s^{-1} feature, and the isotopic ratio can be estimated directly from the ratio of their integrated optical depths. However, this gives [^{12}C:^{13}C] ~ 10, a very low value, approaching the canonical minimum of 4 obtainable in stars during CNO processing (Wannier 1989). This value is therefore considered to be unlikely, and the second case ($T_{ex} > T_{cmb}$) is adopted.

If T_{ex} is greater than 2.73 K for CS J=1–0, then this line can be optically thick. In the limit of $\tau \gg 1$, $T_{mb}(l) = J(T_{ex}) - J(T_{cmb}) - T_{mb}(c)$, and thus from the minimum of the 0 km s^{-1} feature observed in 1987, $T_{ex} = 5.8 \pm 1.2$ K. Applying this value to the 1991 data, a value of $T_{mb}(c) = 5.3 \pm 1.2$ K is found. Since the isotopomers are much less optically thick, their excitation temperatures may be lower, i.e. in the range 2.73 – 5.8 K. The integrated optical depths found are listed in Table 2. At any particular velocity, τ is < 0.3 for the ^{13}CS and $C^{34}S$ transitions, thus the effects of any excitation differences are negligible. Also included in Table 2 are the integrated optical depths of CS J=1–0 over regions of the 0 km s^{-1} line where $\tau \lesssim 1$, so that CS and ^{13}CS may be compared directly.

The isotopic ratio [^{12}C:^{13}C] has been estimated from the results in Table 2, with an assumed [^{32}S:^{34}S] value of 21 ± 6. (This is found from the data presented by Wannier (1980); there is no significant trend of this ratio with location in the Galaxy.) A consistent result is found from the two methods, [^{32}S:^{34}S] × [$C^{34}S$:^{13}CS] and [CS:^{13}CS], if $T_{ex} \approx 5.8$ K for CS but only ≈ 2.73 for ^{13}CS, $C^{34}S$. In this case, [^{12}C:^{13}C] is 22 ± 12 (first method) or 29 ± 18 (second method); the weighted average of these values is $\sim 24 \pm 11$. If T_{ex} is 5.8 K for all the transitions, the [^{12}C:^{13}C] ratios found diverge (values of ~ 30 and 13 respectively), thus this solution is rejected. The optical depth of the CS line minimum is ≈ 2, thus the initial assumption of $\tau \gg 1$ used to find T_{ex} is justified to a good approximation. Note also that for optically thick CS but optically thin isotopomer lines, T_{ex} is lower for the latter, as is expected from radiative transfer considerations.

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Table 2. Integrated optical depths (in km s^{-1}) of the 0 km s^{-1} feature, for the CS, ^{13}CS and C^{34}S J=1–0 transitions. The assumptions made are discussed in the text. The errors quoted include rms noise of the spectra (0.04 K for the isotopomers, 0.12 K for CS), the estimated uncertainty in the baseline levels, and the error in $T_{mb}(c)$, the effects of which have been added in quadrature

T_{ex} (K)	$\int \tau(\mathrm{CS})\, dv$	$\int \tau(^{13}\mathrm{CS})\, dv$	$\int \tau(\mathrm{C^{34}S})\, dv$
	v_{lsr} = –4 to +18 km s^{-1}		
5.8	—	1.28 ± 0.33	1.80 ± 0.58
2.73	—	0.54 ± 0.17	0.57 ± 0.21
	v_{lsr} = –4 to –2 and +11 to +18 km s^{-1}		
5.8	4.0 ± 1.6	0.31 ± 0.14	—
2.73	—	0.14 ± 0.06	—

Other sources of error not included above arise from neglecting the small frequency dependence of the proportionality of $\int \tau\, dv$ to X, and not treating separately the $\sim$ 10 % of the continuum emission in an 'extended component' of the HII region (Akabane et al. 1988). Since the fraction of absorption against the extended background is limited to $\lesssim$ 10 %, this latter effect is small. The assumptions made in estimating T_{ex} values have a much more significant effect on the [^{12}C:^{13}C] ratio, as discussed above. The convergence of the two methods suggests the true value is $\sim$ 25. Note that small changes to the T_{ex} values used in Table 2 produce [^{12}C:^{13}C] variations less than the quoted error ($\approx$ 11); for example, if the true τ of the CS minimum were $\sim$ 1, T_{ex} would be reduced by 0.9 K but the change in [^{12}C:^{13}C] would be only $\sim$ 1–2.

A limit on [^{12}C:^{13}C] at one other velocity has been estimated, using the ^{13}CS and C^{34}S spectra in Fig. 1, and calibrating the $T_{mb}(c)$ values as described above. For the double line at –45 km s^{-1}, which arises in the '3kpc arm', [^{12}C:^{13}C] is $\gtrsim$ 40. This value was estimated using the 2σ limit on $\int \tau\, dv$ of ^{13}CS, and the 1σ error in the other two factors.

4. Discussion

The [^{12}C:^{13}C] ratio found here for the 0 km s^{-1} gas is confirmed by centimetre-wavelength observations of H_2CO and $H_2^{13}CO$ 1_{11}–1_{10} absorption lines towards Sgr B2 (Gardner & Whiteoak 1979). They found a value of 33 ± 3 from their data, in good agreement with our estimate of 24 ± 11. In addition, the H_2CO results give [^{12}C:^{13}C] = 54 ± 4 at –45 km s^{-1}, consistent with our limit of $\gtrsim$ 40. The good agreement of the two studies suggests that the millimetre wavelength absorption lines are a useful tracer of isotope ratios in these intermediate density clouds.

It is important to determine whether the carbon isotope ratio measured using CS might differ from the true [^{12}C:^{13}C] value. Isotopic fractionation can occur in both CS and CO, when a reaction with $^{13}C^+$ causes an isotope transfer, enhancing ^{13}CS or ^{13}CO abundance relative to the main isotopomer (Watson et al. 1976; Langer et al. 1984). There has been no study which includes both these processes, but the CS reaction will be somewhat less efficient, as the zero-point energy difference is only 26 K compared to 35 K with CO (Watson et al. 1976). Since CO is more abundant than CS, the net effect is likely to be an enhancement in ^{13}CO, with consequently less ^{13}C available to form other molecules, and the CS-based isotope ratio is therefore most likely to overestimate [^{12}C:^{13}C] (Langer et al. 1984).

The average value of [^{12}C:^{13}C] in the solar neighbourhood is $\sim$ 60 – 70 (Kaiser et al. 1991; Wilson & Matteucci 1992), with a gradient $\sim$ 5 kpc^{-1} of decreasing values towards the Galactic Centre (Langer & Penzias 1990). The value $\sim$ 25 found above for the local absorbing gas is therefore surprisingly low for the solar neighbourhood, and this cannot be a result of isotopic fractionation, as discussed above. One other line of sight in the local region has shown such a low value: optical observations of CH^+ and $^{13}CH^+$ towards the star HD183143 at $l \approx 53^{\circ}$ gave [^{12}C:^{13}C] = 28 ± 14 (Hawkins & Meyer 1989). This value is rather uncertain, but is lower than measurements towards other local stars, such as 63 ± 8 towards ζ Oph, 49 ± 15 towards ξ Per (Hawkins et al. 1993), which are much closer to the results from molecular line studies of the solar neighbourhood. With the exceptions of the HD183143 observation, and the data presented here, values $\sim$ 20 – 30 are found mainly in the vicinity of the Galactic Centre (Wannier 1989).

It could be argued that the 0 km s^{-1} gas is not located in the solar neighbourhood. The existence of Galactic non-circular motions would suggest that it cannot be very distant, and closer than the gas producing +30 km s^{-1} absorption, which is likely to be associated with the Scutum arm at a distance $\sim$ 4 kpc. However, Gardner et al. (1988) have argued that some of the 0 km s^{-1} material (detected by them in NH_3 absorption) is close to the Sgr B2 cloud, on the basis of high kinetic temperature. In this case, a low value of [^{12}C:^{13}C] would be unsurprising, as Sgr B2 lies close to the Galactic Centre. Gardner et al. identify two components of the 0 km s^{-1} gas, one of which has $T_{kin} > 100$ K and produces NH_3 absorption up to (J,K)=(6,6), and a much cooler foreground component, for which absorption is clearly identified only in the (1,1) transition. This latter component has a greater velocity extent than the hot gas (see the also more recent spectra obtained by Hüttemeister et al. 1993), and is presumably the material within $\sim$ 1–2 kpc of the Sun. If this local material has a 'normal' carbon isotope ratio, a trend towards higher [^{12}C:^{13}C] values further from the line minimum should be apparent in the data, but this is not the case. The isotope ratio has been estimated over the velocity range +11 to +18 km s^{-1}, which lies beyond the high-(J,K) NH_3 absorption region, and the combination of the two methods gives a value of [^{12}C:^{13}C] of 22 ± 13, assuming T_{ex} is 2.73 K. Thus even if there is CS absorption within the hot gas seen in NH_3, and this is at the Sgr B2 distance, the [^{12}C:^{13}C] values for the hot gas and the cool foreground material must be similar, and therefore the carbon isotope ratio is indeed anomalously low for part of the solar neighbourhood.

The most likely cause of this low value is recent enrichment by material ejected from stars. ^{12}C is formed directly from he-

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lium burning (3α process), and the amounts returned to the ISM are dominated by massive stars, whereas ^{13}C is formed from ^{12}C in intermediate-mass stars. Since ^{12}C is a 'primary' product and ^{13}C a 'secondary' one, the [^{12}C:^{13}C] ratio tends to increase with time, and in regions where there have been more generations of stars. (This explains the Galactic gradient, and also the fact that the local interstellar average is now lower than the solar value of 89.) For anomalously low values to be measured in some regions, there must be ^{13}C-rich stellar ejecta present, and the mixing time with other material needs to be long. The former condition can be met, as [^{12}C:^{13}C] ratios found in individual stars are very wide-ranging: Wannier (1980) gives a [^{12}C:^{13}C] range of $\approx$ 5–90 for red giants, and Bernatowicz et al. (1991) found [^{12}C:^{13}C] $\approx$ 7–1300 for interstellar grains preserved in a meteorite. Secondly, evidence of inefficient mixing in the ISM has recently been presented in two studies. Turner (1994) observed ^{12}CO and ^{13}CO emission lines from nearby low-A_V clouds in the Galactic Plane, and these data suggested [^{12}C:^{13}C] values ranging from $\sim$ 45 to 175 (although some of these values could be overestimated if the clouds are clumpy on small scales, allowing more dissociating radiation to penetrate, thus giving a smaller beam-filling factor for the less abundant isotopomer). Also, Vladilo et al. (1993) have observed optical CH^+ and $^{13}CH^+$ absorption towards two stars $\sim$ 2 kpc away in the general direction of the Galactic Centre, and these had [^{12}C:^{13}C] values $\approx$ 98 and 126, well above the local average, suggesting chemical inhomogeneities on scales of $\lesssim$ 1 kpc. Thus there is evidence that both conditions for an anomalous isotope ratio can be met.

If the observed [^{12}C:^{13}C] value $\sim$ 25 in the absorbing gas at 0 km s^{-1} is a result of recent contamination by stellar products, this would favour a model in which this absorption cloud represents an evolutionary stage *after* star-formation has occurred. (However, this may not apply to the –45 km s^{-1} feature, as the [^{12}C:^{13}C] value found by Gardner & Whiteoak 1979, is within the expected range for this region.) The 0 km s^{-1} absorbing gas is unlikely to be closely associated with stars, as then T_{ex} would be higher, producing emission lines. It is, however, possible that this material is gas left over after star-formation, perhaps being dispersed back into the ISM by stellar winds. Velocity shifts have been observed in these clouds (Greaves & Williams 1994), which might indicate disruption of the gas, and from recent estimates of typical diameters $\sim$ 5 pc and densities $\lesssim 10^4$ cm^{-3} (Greaves & Williams 1994), the estimated escape velocities are only $\lesssim$ 10 km s^{-1}, comparable to the FWHM of the 0 km s^{-1} lines.

5. Conclusions

First detections in absorption have been made of the molecules ^{13}CS, HN^{13}C, HC^{15}N and HC^{18}O$^+$, in foreground gas clouds located in the '1 kpc disk' around the Galactic Centre, and within $\sim$ 1–2 kpc of the Sun. In the latter region, [^{12}C:^{13}C] is found to be $\sim 24 \pm 11$, in good agreement with a previous estimate of 33 ± 3. This is much lower than the local average $\sim 60 - 70$, and cannot be explained by isotopic fractionation or an error in the distance estimate, instead indicating recent enrichment by ^{13}C-rich stellar ejecta. This absorbing cloud is most likely to be at an evolutionary stage after star-formation, rather than before the collapse to dense cores.

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