Abstract. We report measurements of the $^{12}$C/$^{13}$C abundance ratio in the three galactic regions G 333.0-0.4, NGC 6334 A and G 351.6-1.3 from observations of the $^{13}$C $^3P_2 \rightarrow ^3P_1$ transition and the hyperfine components of the corresponding $^{13}$C transition near 809 GHz. These transitions were observed simultaneously with the CO $7$–$6$ line emission at 806 GHz with the AST/RO telescope located at the South Pole. From a simultaneous fit to the $^{13}$C $^3P_2 \rightarrow ^3P_1$ transition and the HF components of the corresponding $^{13}$C transition and an independent estimate of an upper limit to the optical depth of the $^{13}$C emission we determine intrinsic $^{12}$C/$^{13}$C column density ratios of $23 \pm 1$ for G 333.0-0.4, $56 \pm 14$ for NGC 6334 A and $69 \pm 12$ for G 351.6-1.3. As the regions observed are photon dominated, we argue that the apparent enhancement in the abundance of $^{13}$C towards G 333.0-0.4 may be due to strong isotope-selective photodissociation of $^{13}$CO, outweighing the effects of chemical isotopic fractionation as suggested by models of PDRs. Towards NGC 6334 A and G 351.6-1.3 these effects appear to be balanced, similar to the situation for the Orion Bar region observed by Keene et al. (1998).

Key words. ISM: abundances, atoms, clouds, H II regions; Submillimeter

1. Introduction

The study of CNO isotope abundance ratios in the interstellar medium is crucial to understanding galactic chemical evolution. In particular, the ubiquity of C-based molecules in interstellar clouds has made the $^{12}$C/$^{13}$C abundance ratio an important chemical diagnostic. From measurements of $^{12}$C$^{18}$O and $^{13}$C$^{18}$O in 13 interstellar clouds, Langer & Penzias (1990, 1993) found a galactic gradient in the local carbon isotope abundance ratio (hereafter: n(C)-ratio) ranging from 23 towards the galactic center to about 60–70 in the local ISM and out to a galactic radius of about 10 kpc. They also found an increase in the n(C)-ratio derived from CO towards clouds exposed to higher UV radiation fields (namely Orion KL and W33), supporting the suggestion made by models of photon dominated regions (PDRs) that depletion in $^{13}$CO can be ascribed to inefficient self-shielding resulting in isotope-selective photodissociation (van Dishoeck & Black 1988).

As discussed by Keene et al. (1998), who report the first detection of the strongest of the $^{13}$C$^1$ hyperfine (HF) structure components at 809 GHz from the Orion Bar region, the abundance of atomic carbon is sensitive to the effects of chemical isotopic fractionation and isotope-selective photodissociation, allowing the study of the significance of these competing effects in PDRs and to verify model predictions (e.g. Le Bourlot et al. 1993, K"oster et al. 1994). The charge exchange fractionation reaction, $^{13}$C$^+$ + $^{12}$CO $\rightleftharpoons ^{12}$C$^+ + ^{13}$CO + 36 K, being exothermic, preferentially incorporates $^{13}$C$^+$ into $^{13}$CO, thus leading to a local $^{13}$C$^+$ and $^{13}$C$^1$ depletion and a corresponding $^{13}$CO enhancement. This may be balanced by isotope-selective photodissociation, which in contrast reduces the gas-phase abundance of the less efficiently self-shielded $^{13}$CO isotopomer (van Dishoeck & Black 1988). Models show that the proportion of these effects strongly depends on the temperature derived for the C$^+$/CI/CO transition zone (due to the low energy barrier of the exchange reaction) and the comparison between different models gives non-conclusive results (K"oster et al. 1994, Le Bourlot et al. 1993).

From their measurement of the $^{13}$C $^3P_2 \rightarrow ^3P_1$ and the strongest HF component of the $^{13}$C equivalent transition, Keene et al. (1998) find a N($^{12}$C)/N($^{13}$C) column density ratio (hereafter: N(C)-ratio) of 58 ± 12 towards a position near the western end of the Orion bar. They derive a somewhat higher ratio of 75 ± 9 towards the same position from
observations of C$^{18}$O and C$^{13}$C$^{18}$O. In comparison, direct observations of the $^{12}$C$^+$/C$^{13}$ abundance ratio (Stacey et al. 1993; Boreiko & Betz 1996), which should not be significantly influenced by chemical isotopic fractionation or isotope-selective photodissociation, yield a n(C)-ratio of 58±6. Keene et al. (1998) conclude that, in contrast to the model results by Le Bourlot et al. (1993), the importance of chemical isotopic fractionation is (almost) compensated for by the isotope-selective photodissociation. Whether this compensation is peculiar to the special conditions of the Orion Bar, or whether it also holds for other massive star-forming cores is a significant question when addressing galactic chemical evolution, since our current understanding is almost entirely based on the observed carbon monoxide isotopomer abundance ratios. It is therefore important to extend the study of C$^{13}$C to other regions.

In this Letter, we report measurements of the $^3P_2 \rightarrow ^3P_0$ transition of C$^{13}$C at 809341.97 MHz and the $F=5/2 - 3/2$, $F=3/2 - 1/2$, and $F=3/2 - 3/2$ components of the equivalent transition of C$^{13}$C at 809493.7 MHz, 809125.5 MHz, and 809121.3 MHz, respectively, towards three galactic star-forming regions associated with strong IRAS sources and CO emission: G 333.0-0.4, part of the large H II complex RCW 106 and associated with a molecular cloud with bright CO lines (Gillespie et al. 1977; Brand et al. 1984), located within a giant molecular cloud at a distance of 4.2 kpc [Slipher & Goss 1976]; NGC 6334 A, a bright FIR continuum region (McBreen et al. 1973) associated with a bright PDR [Burton et al. 2000; Kraemer et al. 2000], located within a giant molecular cloud at a distance of 1.7 kpc (Neckel 1978); and G 351.6-1.3, a luminous (L$_{bol} \approx 10^6$L$_{⊙}$) compact H II region excited by an embedded O B cluster [McBreen et al. 1988] at a distance of 5 kpc (Radhakrishnan et al. 1973). These regions were selected because of strong emission in the $^3P_1 \rightarrow ^3P_0$ transition of C$^{12}$C at 492 GHz (Huang et al. 1999) from a list of 30 candidates of galactic H II regions having strong CO (Brand et al. 1984; Henning & Launhardt 1998) and CS (Bronfman, Nyman, & May 1996; Launhardt et al. 1998) emission lines.

2. Observations

The observation were made in the Austral winter of 2000 with the 800 GHz receiver at at the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO, cf. Stark et al. 2001). At these frequencies the FWHM beam size is \approx 80″. As back-end we used an AOS with a velocity resolution of 0.25 km s$^{-1}$ at the observed frequencies. The zenith opacities at 809 GHz at the times of observation were \approx 1.0 ± 0.2 System temperatures on average were between 11,000 K for G 333.0-0.4, 18,000 K for NGC 6334 A, and 25,000 K for G 351.6-1.4. The C$^{12}$C and C$^{13}$C lines were observed in the lower sideband simultaneously with the CO 7–6 line in the upper sideband. The spectra were calibrated to the effective radiation temperature $T_{R}^∗$ scale. The frequencies reported by Klein et al. (1998) (cf. Cologne Database for Molecular Spectroscopy – www.cdms.de) were used to determine the line centroids.

3. Results

Fig. 1 shows the spectra obtained towards the three regions. The strongest HF component of C$^{13}$C at 809 GHz, F= 5/2 – 3/2, is clearly visible in the G 333.0-0.4 and NGC 6334 A spectra; it is marginally detected in G 351.6-1.3. The weaker HF structure satellites, F=3/2 – 1/2 and F=3/2 – 3/2, are still hidden in the noise in all cases. Following the first detection towards Orion by Keene et al. (1998), these regions are the only other C$^{13}$C detections to date. We derive the $^{12}$C$^{13}$/^{13}$C intensity ratio by a simultaneous Gaussian fit of the lines (including all C$^{13}$C HF components) with fixed spacing and a single line width, and with the ratio of the C$^{13}$C amplitudes fixed to their quantum mechanical values of 0.600:0.333:0.067; the free fit parameters are the common width and LSR-velocity, a common amplitude and the relative line intensity ratio.
Table 1. Line fit results

| emission | $T_R$ [K] | $\Delta v_{\text{em}}$ [kms$^{-1}$] | $\alpha$ |
|----------|--------|----------------|-------|
| $^{12}$C | 0.10 ± 0.02 | 4.9 ± 0.2 | 45 ± 11 | n |
| CO | 8.04 ± 0.06 | 5.3 ± 0.1 | n |
| CO | 0.14 ± 0.03 | 32 ± 7 | b |
| | G 333.0-0.4 | | |
| $^{12}$C | 0.12 ± 0.02 | 5.0 ± 0.1 | 18 ± 1 | narrow |
| $^{13}$C | 0.04 ± 0.01 | 18 ± 1 | 45 ± 4 | broad |
| CO | 3.57 ± 0.02 | 5.4 ± 0.1 | n |
| CO | 0.46 ± 0.02 | 12.6 ± 0.4 | b |
| | G 351.6-1.3 | | |
| $^{13}$C | 0.05 ± 0.01 | 4.4 ± 0.1 | 55 ± 10 | n |
| CO | 2.15 ± 0.02 | 3.3 ± 0.1 | n |
| CO | 1.11 ± 0.02 | 8.9 ± 0.2 | b |

The $^{13}$C amplitudes given are the sum over the three HF components (see text).

The intrinsic line ratios would be correspondingly lower. This temperature estimate is perfectly consistent with the scenario of extended PDR emission. In this regime of density and temperature, the observed $^{12}$C $^3P_2 \rightarrow ^3P_1/^3P_1 \rightarrow ^3P_0$ line ratio constrains the column density per unit velocity interval to values below $2 \times 10^{17}$ cm$^{-2}$/km s$^{-1}$ and corresponding optical depths of the $^{12}$C $^3P_2 \rightarrow ^3P_1$ line below $\tau = 0.4$.

At higher column densities trapping would push the line ratio to much higher values than observed.

The total column density in the $\approx 5$ km s$^{-1}$ wide $^{12}$C lines is then about $10^{19}$ cm$^{-2}$; this corresponds, with the standard gas phase abundance of carbon of about $10^{-4}$, to a hydrogen column density of $10^{22}$ cm$^{-2}$. Considering that each PDR surface has a C$^1$ column density corresponding to an $A_V$ of a few, we therefore conclude that we see a few PDR surfaces per beam, consistent with the usual scenario of a clumpy, UV-penetrated massive cloud core.

4. Discussion

For the range of density, temperature and column density derived above, our radiative transfer model predicts line brightnesses for the $^{12}$C $^3P_2 \rightarrow ^3P_1$ lines of around 5–10 K. Since the measured line brightnesses are a few degrees in the observed sources, we estimate a beam filling factor close to unity, consistent with extended, smooth emission within the AST/RO beam. This scenario suggests the $^{12}$C $^3P_2 \rightarrow ^3P_1$ line ratio, for instance, becomes almost unity, corresponding to a beam filling factor close to unity.
in the PDR models of \cite{leBoulot1993}, which produce a lower temperature in the transition zone due to reduced heating. Cloud surface temperatures therefore influence the balance of the two competing effects and, ultimately, determine the carbon isotope abundance ratio. The temperature structure in PDR surfaces, details of which are not consistently explained by present PDR models, might be responsible for the very different atomic carbon isotope abundance ratios observed to date.

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