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## Observations of the $J=2\rightarrow 1$ Transitions of $^{12}\text{C}^{16}\text{O}$ and $^{12}\text{C}^{18}\text{O}$ Towards Galactic H II Regions

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**Summary.** Observations are reported of the  $J=2\rightarrow 1$  transitions of CO and  $^{12}\text{C}^{18}\text{O}$  at 230 and 219 GHz respectively from a number of galactic sources. A map of the central  $1/2^\circ \times 1/2^\circ$  of the Orion A molecular cloud is presented. The spectra are interpreted to derive molecular densities and abundance ratios in the molecular clouds observed.

**Key words:** interstellar molecules – H II regions – molecular clouds

### Introduction

Observations of Carbon Monoxide emission in the galactic plane have been made towards many sources in the  $J=1\rightarrow 0$ ,  $2\rightarrow 1$ , and  $3\rightarrow 2$  rotational transitions. As the lines of the most abundant isotopic species  $^{12}\text{C}^{16}\text{O}$  are usually highly saturated, it is necessary to observe the corresponding lines in  $^{12}\text{C}^{18}\text{O}$  and  $^{13}\text{C}^{16}\text{O}$ , which are optically thinner, in order to estimate quantities such as hydrogen densities, and abundance ratios. In this paper we present data on the  $^{12}\text{C}^{18}\text{O}$  isotope towards several sources, and we interpret the data using a simple radially collapsing cloud model.

### The Observations

The data were obtained during 1978 November, using the 1.5 m infrared flux collector at Izaña, Tenerife (altitude 2400 m). The receiver was an Indium Antimonide hot-electron bolometer heterodyne system, which was mounted at the  $F/13$  Cassegrain focus. Major system improvements have been made over an earlier version of the receiver (White et al., 1979), by using a quasi-optical directional coupler and polyethylene lens combination to mix the local oscillator power with the astronomical beam from the telescope. Typical system noise temperatures were close to 600 K. The halfpower beamwidth and main beam efficiency were measured, from observations of the moon, to be 4.5 arc min and 53% respectively. During the period of the observations, the zenith precipitable water vapour, measured using a calibrated near-infrared water vapour meter, had an average value of 2.2 mm, although under good conditions it reached a minimum value of 0.8 mm. The atmospheric attenuation at  $\lambda=1.3$  mm was measured using the standard skydipping procedure. Good cor-

relation was observed between these values, and those derived independently from the water vapour meter readings. Antenna temperatures were modified to yield corrected values,  $T_A^*$ , in the manner described by White et al. (1979).

### The Results

#### a) CO Distribution in Orion A (OMC-1)

The distribution of CO within OMC-1 has been measured by several groups (Liszt et al., 1974; Phillips et al., 1976; Kutner et al., 1977). The central core of the cloud has dimensions  $9 \times 4$  arc min, and is surrounded by a less intense, more diffuse cloud of molecular emission. Phillips et al. (1974) have interpreted the large scale distribution as evidence for a wave-like structure, possibly induced by gravitational instability.

In order to obtain as rapidly as possible a fully sampled map of the OMC-1 cloud in the  $J=2\rightarrow 1$  transition of  $^{12}\text{C}^{16}\text{O}$ , a series of drift scans, each 1 degree long and separated by between 1 and 4 arc min in declination, were obtained under conditions of excellent atmospheric transparency and stability. The area mapped was 0.6 square degrees, at a central frequency corresponding to an l.s.r. velocity of  $9.0 \text{ km s}^{-1}$  with a spectral channel width of  $2.6 \text{ km s}^{-1}$ . These data are shown in Fig. 1 as a contour map, and in Fig. 2 several of the individual scans are illustrated. The rms noise and atmospheric fluctuations are close to 0.5 K per beamwidth. Two 'hot spots' are visible to the south and southeast of the central core, as well as a diffuse extension some 15 arc min long in an easterly direction.

No suggestion of any symmetrical or periodic large scale cloud structure is seen in this map. However, these measurements do not conclusively contradict the interpretation of Phillips et al. (1974, 1979) as the discrepancies could result from the different beam sizes used in the two experiments. Although there is a well known velocity gradient in the N-S direction across the cloud core, which has been ascribed either to cloud rotation (Liszt et al., 1974; Kutner et al., 1976), or several independently moving clouds (Ho and Barrett, 1979), this alone would not provide very large variations from the CO distribution measured in the present experiment. An  $\text{NH}_3$  source recently reported by Ho and Barrett (1979) at  $(\Delta\alpha, \Delta\delta) = (+3, +11)$  arc min relative to the OMC-1 core, lies on the edge of a narrow CO ridge in our map.

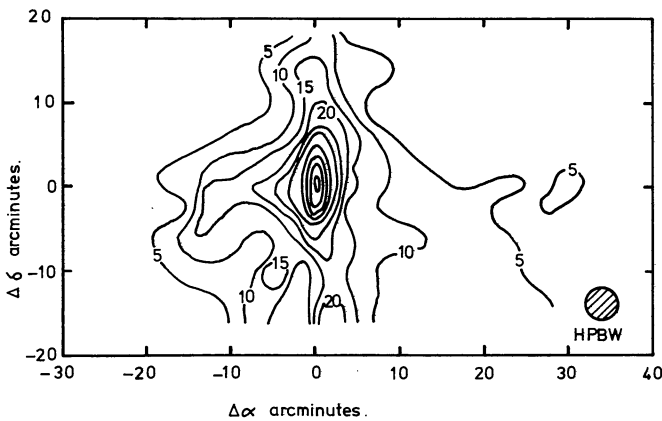
#### b) Observations of CO and $^{12}\text{C}^{18}\text{O}$ towards H II Regions

Although the  $^{12}\text{C}^{16}\text{O}$  transition is useful as a probe of the kinetic temperature of a molecular cloud, the high opacity makes it of

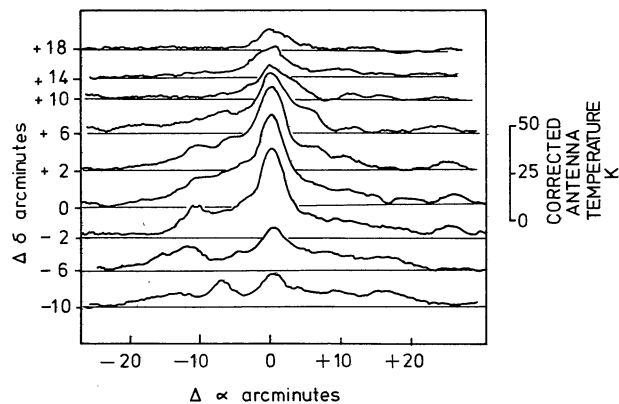
Send offprint requests to: G. J. White

**Table 1.** Observed physical parameters

Source	$\alpha$ (1950.0)		$^{12}\text{C}^{16}\text{O} (J=2\rightarrow 1)$			$^{12}\text{C}^{18}\text{O} (J=2\rightarrow 1)$		
	h	m s	$T_A^*$ (K)	$V$ (km s $^{-1}$ )	$V$ (FWHM) (km s $^{-1}$ )	$T_A^*$ (K)	$V$ (km s $^{-1}$ )	$V$ (FWHM) (km s $^{-1}$ )
W3	02 21 47	+61 52 54	20	-40.0	8.0	<1.0	—	—
OMC-1	05 32 47	-05 24 30	52	+ 9.5	6.0	3.5	+10.0	3.0
NGC 2023	05 39 10	-02 17 49	34	+10.0	4.0	—	—	—
NGC 2024	05 39 14	-01 56 57	23,5	+10.5, +5.0	6.5	3.4	+ 9.0	3.0
MON R2	06 05 20	-06 22 30	24	+10.0	5.0	<0.5	—	—
S 269	06 11 44	+13 50 12	12	17.0	4.0	—	—	—
DR 21	20 37 10	+42 09 00	18,4	- 2.6, +10.0	7.0	2.7	- 2.6	7.0



**Fig. 1.** CO distribution around the OMC-1 cloud. The contour levels are expressed as values of  $T_A^*$ , the maximum antenna temperature corresponding to  $T_A^* = 52$  K. The map is relative to the position  $\alpha_{1950} = 5^{\text{h}}32^{\text{m}}47^{\text{s}}$ ;  $\delta_{1950} = -05^{\circ}24'30''$



**Fig. 2.** A sequence of drift scans across the OMC-1 cloud at an l.s.r. velocity of  $9.0$  km s $^{-1}$  and channel width of  $2.6$  km s $^{-1}$

very limited value as a tracer of molecular density. However, a combination of  $^{12}\text{C}^{16}\text{O}$  data with  $^{13}\text{C}^{16}\text{O}$  and  $^{12}\text{C}^{18}\text{O}$  observations enables a wider range of opacities to be studied. Previous measurements of  $^{13}\text{C}^{16}\text{O}$  have shown it to have a moderate optical depth so that, taking predicted abundance ratios into account, mea-

surements of the optically thin  $^{12}\text{C}^{18}\text{O}$  should supply an important link in the chain of deductions leading to estimates of density and of cloud mass (White et al., 1979; Watt et al., 1979; Phillips et al., 1979). We therefore looked for  $^{12}\text{C}^{18}\text{O}$  in a number of sources. In Fig. 3 are shown spectra of the  $^{12}\text{C}^{18}\text{O} J=2\rightarrow 1$ , transitions towards Orion A, DR21 and NGC 2024 together with their CO counterparts. Upper limits on  $^{12}\text{C}^{18}\text{O}$  were obtained towards several other sources shown in Fig. 4. The measured values of  $T_A^*$ , the velocities and halfwidths are summarised in Table 1.

We note some differences between the present CO spectra and those presented in Phillips et al. (1979) obtained with a 1 arc min beamwidth. In W3, no evidence for a self absorption dip is seen at the centre of the spectrum in the present data. This could indicate either that the region responsible for the self-absorption has angular diameter small compared with our beamwidth, or that a strong velocity gradient is present over a small angular structure. In DR21, our spectrum resembles the  $J=1\rightarrow 0$  spectrum with two separate components at velocities of  $-2.6$  and  $+10$  km s $^{-1}$ . This latter component is not present in the  $J=2\rightarrow 1$  spectrum of Phillips et al. (1979), an effect which could be due to poor baseline subtraction, if their off source beam was not far enough from DR21.

## Discussion

The present observations may be used to predict a range for hydrogen densities,  $n_{\text{H}_2}$ , in the sources using a collapsing cloud model based on that of Goldreich and Kwan (1974). The model used for the present analysis has the following parameters, expressed as functions of cloud radius,  $r$ :

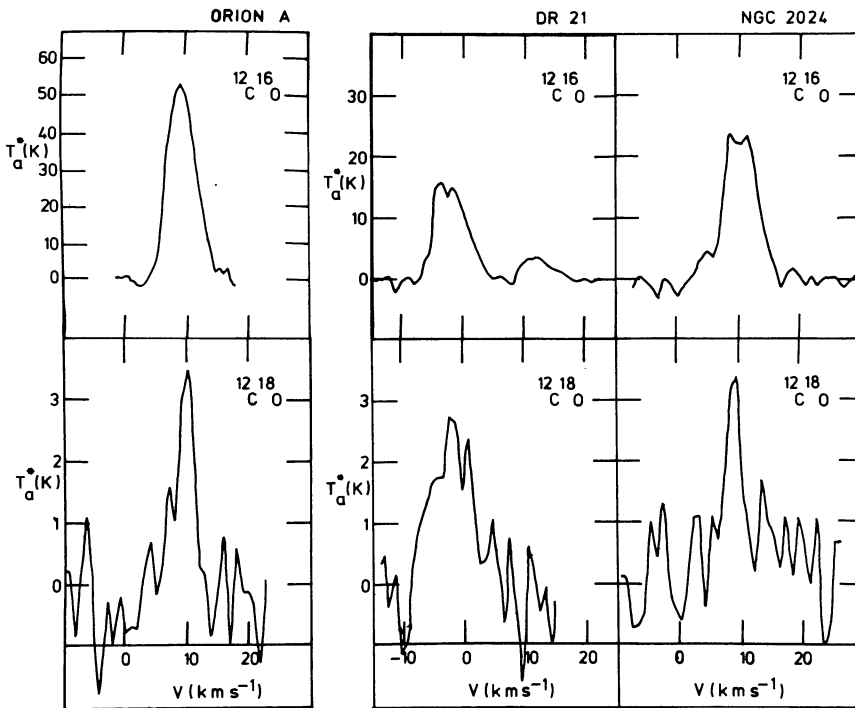
$$\text{Radial density dependence} \quad n_{\text{H}_2}(r) \propto r^{-2}$$

$$\text{Radial velocity dependence} \quad v(r) \propto r^{-0.5}$$

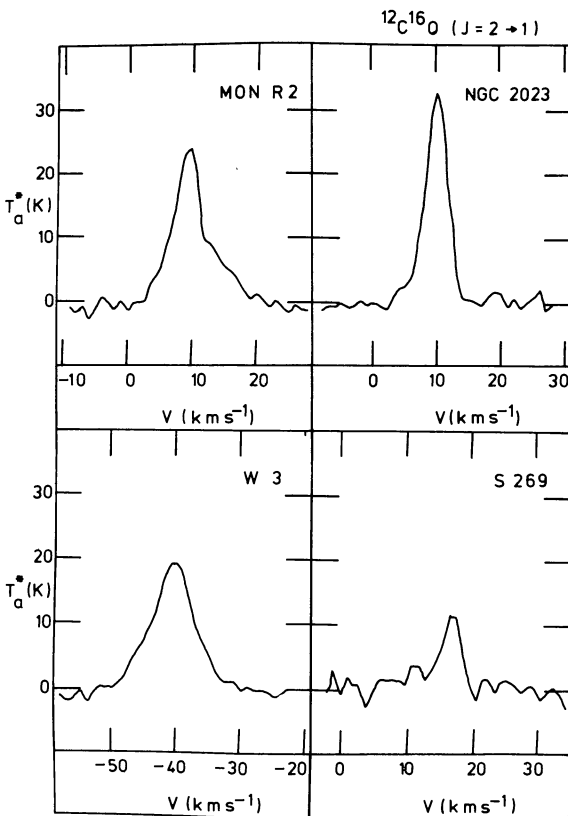
$$\text{Radial temperature dependence} \quad T_{\text{KIN}}(r) \propto r^{-0.1}$$

$$\text{CO abundance ratio} \quad [\text{CO}]/[\text{H}_2] = 3 \cdot 10^{-5} \text{ cm}^{-3}$$

The arguments leading to our choice of each appropriate radial power-law dependence, and of the numbers used, are as follows: the hydrogen density must fall off significantly with cloud radius in order to produce the observed line profiles. Previous authors have suggested values for the exponents between  $-1.5$  and  $-2.0$  (Kwok, 1978; Kwan, 1978). Several collapsing clouds appear to follow an  $n_{\text{H}_2}(r) \propto r^{-0.5}$  dependence (Loren, 1976, 1977, 1979)



**Fig. 3.** Spectra of CO and  $^{12}\text{C}^{18}\text{O}$  towards Orion A, DR 21 and NGC 2024. The data were taken with a velocity resolution of  $1.3 \text{ km s}^{-1}$ , and are unsmoothed



**Fig. 4.** CO spectra of Mon R2, NGC 2023, W3, and S269 with a velocity resolution of  $1.3 \text{ km s}^{-1}$

whilst most can also be modelled using a homogeneous collapse ( $v(r) \propto r$ ). The precise form chosen does not play a major role in our present analysis since we are only concerned with intensities observed at the cloud centre ( $v = 2.5 \text{ km s}^{-1}$ ). We have chosen the temperature dependence somewhat arbitrarily, but with a very slow  $r$  variation so that  $T$  remains roughly constant over the cloud. If we assume (see Leung, 1978) that molecular heating rates will vary as  $(n_{\text{H}})$ , and cooling rates as  $(n_{\text{H}})^2$ , then the overall variation in kinetic temperature throughout the cloud, except in localized regions near to embedded heat sources, is likely to be small. The CO/H<sub>2</sub> fraction is based on two assumptions: that the average cosmic abundance ratio  $\text{C}/\text{H}_2 \approx 3 \cdot 10^{-4}$  pertains in the clouds, and that only 10% of the C is bound in molecules.

In using the model, the most abundant species  $^{12}\text{C}^{16}\text{O}$  is saturated at most points on our sources, and is used to set the cloud kinetic temperature. We then vary the H<sub>2</sub> density over a range  $2.0 \cdot 10^4 - 3.0 \cdot 10^5 \text{ cm}^{-3}$  to predict the intensities of our  $^{13}\text{C}^{16}\text{O}$  (from Watt et al., 1979) and  $^{12}\text{C}^{18}\text{O}$  transitions allowing for a 20% error in observed antenna temperature. For NGC 2024 the use of a  $^{12}\text{C}/^{13}\text{C}$  ratio of 40 yields  $1.0 \cdot 10^5 \leq n_{\text{H}_2} \leq 2.0 \cdot 10^5 \text{ cm}^{-3}$  and the observed  $^{12}\text{C}^{18}\text{O}$  emission intensity is then given by inserting  $^{16}\text{O}/^{18}\text{O} = 200$ . These ratios are consistent with the 'solar system' value of  $^{12}\text{C}^{18}\text{O}/^{13}\text{C}^{16}\text{O} \approx 0.2$ . A similar analysis on the data of Phillips et al. (1979) for OMC-1, NGC 2024 and NGC 2264 gives a similar result, viz: using  $^{12}\text{C}/^{13}\text{C} = 40$  and  $^{16}\text{O}/^{18}\text{O} = 150$ , a hydrogen density of  $1.0 \cdot 10^5 \text{ cm}^{-3}$  reproduces the observed line intensities. Alternative models with  $^{12}\text{C}/^{13}\text{C} = 89$ , and  $^{16}\text{O}/^{18}\text{O} = 300$ , i.e., a combined ratio of 0.13, can also predict correct line intensities, but require high molecular densities, well above  $2 \cdot 10^5 \text{ cm}^{-3}$ .

If we also invoke the recent data of Henkel et al. (1979), based on H<sub>2</sub>CO isotopes in SgrA, SgrB2, W33, and W51 obtaining a  $^{16}\text{O}/^{18}\text{O}$  ratio of  $< 250$  towards the galactic centre, it appears that our CO data is best satisfied using  $^{12}\text{C}/^{13}\text{C} = 40$ ,  $^{12}\text{C}^{18}\text{O}/^{13}\text{C}^{16}\text{O} = 0.2$ , and hence  $^{16}\text{O}/^{18}\text{O} \approx 200$ , i.e.,  $^{18}\text{O}$

appears to be overabundant in our sources by a factor 2 compared with solar system values. It is clear, however, that improved estimates of the molecular densities must be obtained before this conclusion can be considered definitive.

### Conclusions

1. CO emission  $\geq 5$  K extends over an area  $\sim 0.4$  square degrees around OMC-1. No evidence is seen for any wavelike cloud structure on a large scale similar to that reported by Phillips et al. (1974). Several new hot-spots are present in the map. Further observations of these regions with greater angular velocity and resolution are highly desirable.

2.  $^{12}\text{C}^{18}\text{O}$  has been detected towards three sources, and upper limits placed on its line intensity for several others.

3. In NGC 2024,  $n_{\text{H}_2}$  lies between 1 and  $2 \cdot 10^5 \text{ cm}^{-3}$ , and the double ratio  $\text{C}^{18}\text{O}/^{13}\text{CO}$  is close to 0.2. Although Wannier et al. (1976) give an estimate for  $^{12}\text{C}/^{13}\text{C}$  assuming a solar value for the  $^{16}\text{O}/^{18}\text{O}$  ratio, there are also other data, using  $\text{H}_2\text{CO}$ , CS, and HCN isotopes which agree with a ratio  $^{12}\text{C}/^{13}\text{C} \sim 40$  (Wilson and Bieging, 1977). Thus in this source  $^{18}\text{O}$  appears overabundant by a factor of two relative to solar system values.

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