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CO Observations of Compact H II Regions Associated with OH Masers

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Summary. CO observations are presented of two isolated regions of star formation. Both regions consist of compact H II regions, embedded in a molecular cloud, several parsecs in size. Densities are derived from the ratio of ^{12}CO and ^{13}CO intensities.

Key words: star formation — interstellar matter — compact H II regions

1. Introduction

Star formation is intimately associated with the presence of dense molecular clouds. Millimeterwave observations of several large and complex H II regions have shown a wealth of molecular line emission, of which CO is the most widespread. Usually, the CO cloud is much more extended than the optical or the radio continuum structure, but there is often a strong positional correlation in strength between the line and the continuum emission (Wilson et al., 1974). Moreover, molecular line hot spots have often been found near young objects—Ae and Be type stars (Loren et al., 1973) and small Hα regions (Blair et al., 1975). The fact that CO emission is associated with these young objects indicates the presence of dense clouds.

In this paper I present CO observations of several compact H II regions associated with OH masers. In a search for 6 cm continuum radiation in the direction of Type I OH masers (Turner, 1970), Habing et al., (1974) found several isolated compact H II regions coincident with these masers. I have selected the regions around G75.7 and G45.5, associated with the masers ON2 and OH 45.5+0.0 and OH 45.5+0.1, respectively. A region around G69.9+0.0, associated with ON1, was also observed, but incomplete mapping does not justify a full discussion. The isolated nature of these compact H II regions appears from the lack of more extended thermal emission in the field. All regions studied in this paper are obscured by foreground material. Identification of the sources as small regions of active star formation is therefore solely based on the association with a Type I OH maser. In order to derive physical parameters, the G75.7 and G45.5 regions were observed in the ^{13}CO line at some selected positions.

* A substantial part of this work was done while the author was a visitor to the Center of Astrophysics, Cambridge, Mass., from March to July 1974

II. Observations

The search for emission of the $J=1\rightarrow0$ transition of ^{12}CO and ^{13}CO was made with the 16 ft (5 m) millimeterwave telescope at MacDonald Observatory near Fort Davis, Texas[1]. This instrument has a half power beamwidth of 2.′6 at a wavelength of 2.6 mm. The observations were made with a bandwidth of 10 MHz in a frequency-switched mode, with a separation of 10 MHz between the signal and the reference bands. The receiver backend was a 40-channel IF filterbank, resulting in a velocity resolution of 0.65 km/s. The antenna temperature scale was determined by synchroneously detecting a chopper wheel with an absorber at ambient temperature. Corrections for atmospheric and instrumental effects were made in the usual way (Davis and Vanden Bout, 1973) using a correction factor of 1.2. The single-sideband system temperature was about 2000 K and 2400 K at the frequency of ^{12}CO and ^{13}CO respectively. Mapping was generally done in intervals of 3′ but wherever a sharp gradient was found, an interval of 1.5′ was used.

Table 1 lists the observed ^{12}CO and ^{13}CO line parameters at or near the positions of the compact H II regions, which have been detected by Habing et al. (1974) at or nearby the OH masers.

1 The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory, University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation and McDonald Observatory. The instrumentation used for spectral-line observations with this antenna was developed jointly by the University of Texas, Bell Telephone Laboratories and the Radio Astronomy Group of the Center for Astrophysics

Table 1.

Name	Position		^{12}CO			^{13}CO		
	α(1950)	δ(1950)	T_A^*(K)	V_{LSR}(km s^{-1})	ΔV(km s^{-1})	T_A^*(K)	V_{LSR}(km s^{-1})	ΔV(km s^{-1})
ON2	20^{h}19^{m}52^s	+37°17′06″	8.0	+ 1.2	5.9	3.5	+ 0.1	5.4
G75.7+0.3	20 19 52	+37 15 36	8.1	+ 0.0	6.5	–	–	–
G75.8+0.4	20 19 46	+37 21 36	9.7	− 0.5	4.5	–	–	–
G45.5+0.0	19 12 04	+11 04 18	11.2	+57.2	7.2	5.0	+57.6	6.1
G45.5+0.1	19 11 46	+11 07 18	8.6	+56.6	10.4	3.8	+61.0	8.2
ON1	20 08 10	+31 22 41	10.9	+11.0	6.0	–	–	–

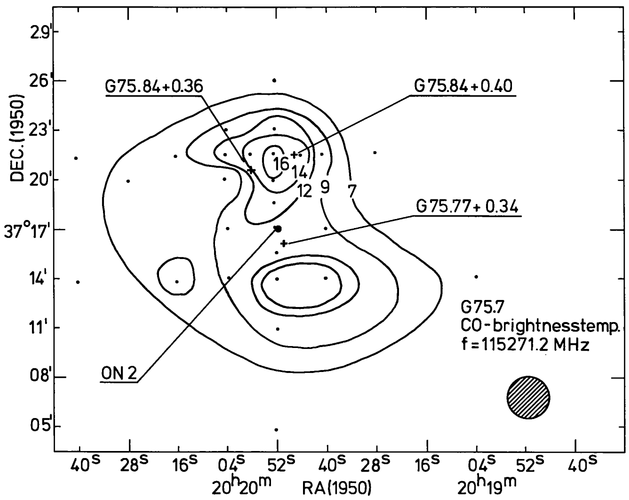

Fig. 1. Countermap of ^{12}CO peak brightness temperature of the region around G75.7. Positions of the compact H II regions and the OH maser are shown. Small dots indicate observed positions

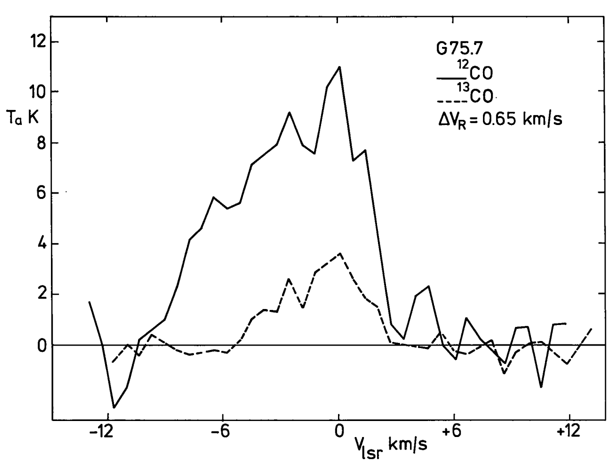

Fig. 2. ^{12}CO and ^{13}CO profiles of G75.7 taken at the position 3′ south of the maser ON2. Intensities are in observed antenna-temperature

Contour maps of the regions around G75.7 and G45.5, which are converted to a Rayleigh-Jeans brightness temperature scale, adopting a beam efficiency of 0.8, are shown in Figures 1 and 4. At some selected positions in both regions, we searched for ^{13}CO emission. The ratio of brightness temperature of ^{12}CO and ^{13}CO (∼4) is similar to what is found in other molecular clouds (Lada et al., 1974), suggesting that the CO is optically thick. We will now discuss the regions individually.

III. Results

a) G75.7

In this region an OH maser source, ON 2, was first discovered by Elldér et al. (1969). Subsequent observations (Winnberg, 1970) showed it to be of Type I. An H_2O maser, coinciding with the OH maser, was discovered by Johnston et al. (1973). Reifenstein et al. (1970) detected an H II region associated with the maser, but a deeper understanding of the nature of the area came from a study by Matthews et al. (1973) who mapped the area at 6 cm with high resolution. They discovered that the continuum source consists of three components, the smallest of which coincides with the maser source to within the positional errors. Observations at several frequencies show the spectra to be thermal, leading to the conclusion that the sources are compact H II regions. No Hα emission has been found in this region (Dickel et al., 1969).

Figure 1 shows contours of equal ^{12}CO brightness temperatures. The cloud consists of an extended, somewhat elongated plateau, with two, not very dominent emission peaks, 4′ north and south of the maser. The intensity of the peaks is less than a factor of two greater than that of the plateau. Outside the plateau the line emission disappears within a distance of 3′.

At positions three beamwidth's away from the lowest contour no emission was detected, confirming the isolated nature of this region of star-formation.

The position of ON 2 which coincides with a very small compact H II region and the maxima of continuum emission of the three nearby compact H II regions are indicated. The southern source G 75.77+0.34 and ON 2 are situated in between the two CO emission peaks. As the ^{12}CO line is certainly optically thick, the line emission originates from the frontside of the cloud. The absence of a CO hot spot around ON 2 and G75.7+0.34 suggests that these sources are deeply embedded in the cloud. The northern region G75.84+0.40 is projected well within the northern CO peak and may be physically associated with it, the positional difference being less than 1′. Another very small, thermal continuum source, G75.84+0.36, has recently been detected by Matthews et al. (1977) at $\alpha(1950)=20^h19^m58^s$, $\delta(1950)=37°20'37''$. This position is about 1′.5 east and less than 1′ south of the northern CO peak.

The shape of the CO profiles is typical of that of other molecular clouds. Figure 2 shows examples for both ^{12}CO and ^{13}CO, at the position of the southern CO peak. Both profiles are asymmetric, with a sharp edge at the high- and a more gradual decrease at the low velocity side. At the position of the CO hot spots, the full width at half-maximum line intensity, ΔV, is typically about 6 km s^{-1} for ^{12}CO and somewhat less for ^{13}CO. An analysis of CO profiles over the surface of the cloud shows a rather strong correlation between antenna temperature and line width. The weaker lines tend to be narrower, as is shown in Figure 3. A similar trend, though less pronounced, is present in the ^{13}CO profiles. The radial velocities do not suggest rotation of the cloud.

b) G45.5

This region of star formation was first detected by Downes (1970). Synthesis observations at 2.7 and 5 GHz by Wynn-Williams et al. (1971) show two compact H II regions, G45.5+0.0 and G45.5+0.1. Both are associated with Type I OH masers. Continuum observations at 6 cm with the Westerbork Synthesis Radio Telescope (Matthews et al., 1977) have shown that OH 45.5+0.0 is to within the positional errors coincident with an ultracompact H II region, 1′ east of G45.5+0.0. Zeilik et al. (1975) detected extended 10.6 μm emission from G45.5+0.0. No IR emission was discovered at the position of OH 45.5+0.0. As OH 45.5+0.1 does not coincide exactly with the corresponding H II region, Habing et al. (1974) suggest that the coincidence is merely a projection effect.

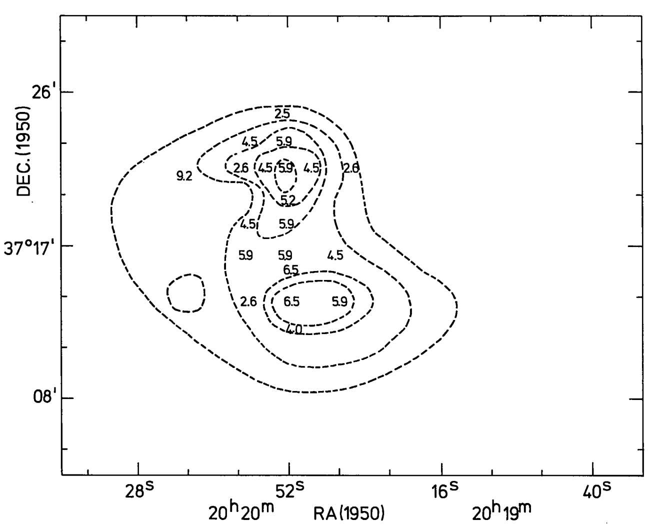

Fig. 3. Line broadening ΔV in the cloud around G75.7. Observed ΔV's in km s^{-1} are projected onto the countermap of Figure 1

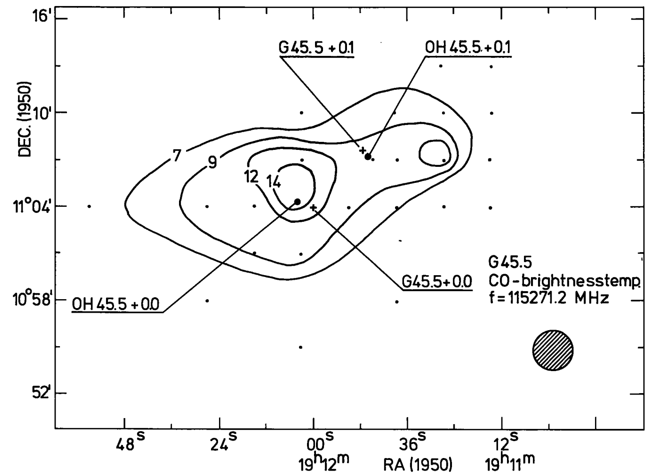

Fig. 4. Contourmap of ^{12}CO peak brightness temperature of the region around G45.5. Position of the compact H II regions and the OH masers are shown. Small dots indicate observed positions

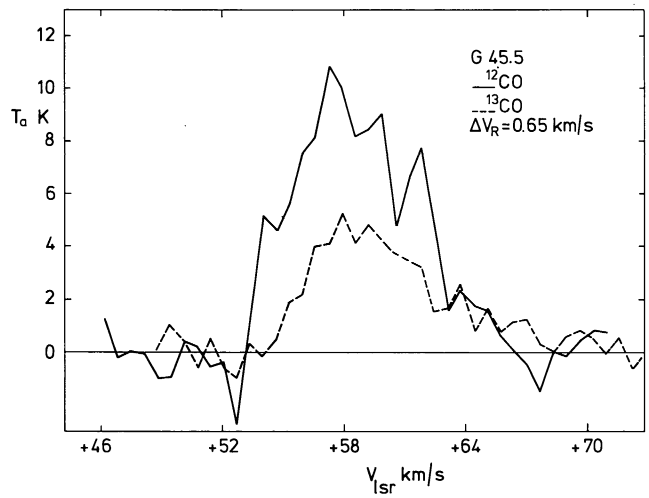

Fig. 5. Line-profiles of ^{12}CO and ^{13}CO of G45.5, taken at the position of the maser OH 45.5+0.0

Figure 4 shows the map of ^{12}CO brightness temperature. There is a similarity with the cloud near ON2. First, there is an extended plateau with two peaks, with intensities about a factor of 2 higher than in the plateau, and secondly, the lack of emission at several positions—north, south, east and west—three beamwidths away from the outer contour suggests that it is an isolated cloud.

Similar to the region around ON2, we see two compact H II regions in the direction of the cloud. G45.5+0.1 is projected at equal distances from the CO peaks, while G45.5+0.0 lies within 1′ of the eastern peak. A typical example of a ^{12}CO and ^{13}CO profile taken at the position of OH 45.5+0.0 is shown in Figure 5. It is ~8 km s^{-1} wide and somewhat asymmetric towards the high velocities. The radial velocity of the OH maser at 1665 MHz is +66 km s^{-1} while that of the H109α recombination line of G45.5+0.0 is +57 km s^{-1} (Matthews et al., 1977).

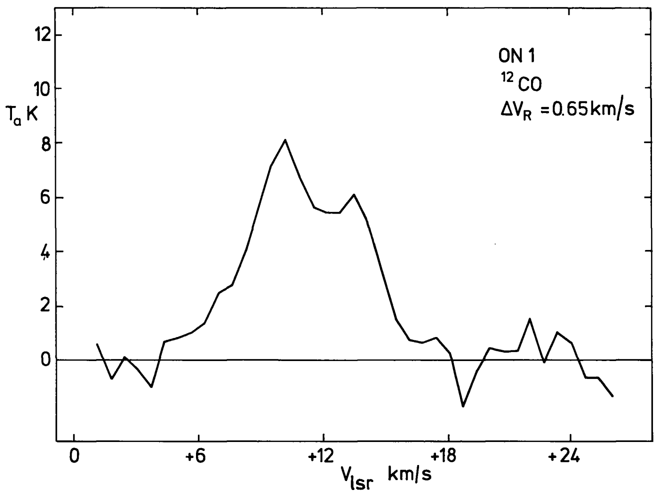

Fig. 6. Line-profile of ^{12}CO at the position of ON1

Table 2. Derived parameters for molecular clouds

Position with respect to maser			$\tau(13)$	T_{exc}	$N(\mathrm{cm}^{-2})$
ON2	0′	0′	0.43	13.8	$1.1\ 10^{+18}$
	0′	+4.′5	0.18	25.0	1.5
	0′	−3′	0.23	22.4	1.6
	+3′	+4.′5	0.25	19.6	0.6
	+3′	0′	0.43	17.0	1.7
OH 45.5+0.°0	0′	0′	0.33	21.6	2.5
	0′	+3′	0.23	20.8	1.6
	−4.′5	+3′	0.34	17.0	2.3
	+3′	0′	0.59	14.8	2.6
	0′	−3′	0.28	16.4	1.8

Table 3. Mass and density

	$n(H_2)$	$M(H_2)$
G75.7	120 cm^{-3}	$2.1\ 10^4\ M_\odot$
G45.5	195	$1.8\ 10^4$

The agreement of the radial velocities of the OH, CO and H109α lines support the close physical association between the molecular cloud and the continuum and maser sources. At the position of G45.5+0.1, the CO profile shows a double peak with a minimum at $+59\ \mathrm{km\ s^{-1}}$. Although this could be due to a blending of two velocity components, the single-peaked profiles all over the cloud suggest that this double feature is probably due to selfabsorption of cold gas on the front-side of the cloud. A similar shape has been seen in the Orion CO cloud (Tucker et al., 1973). This suggestion is supported by the fact, that the corresponding ^{13}CO profile does not show a double structure. At the radial velocity of the H 109α line of G45.5+0.1 ($71.3\ \mathrm{km\ s^{-1}}$) no ^{13}CO emission is seen. The difference between the recombination line velocity and the radial velocity of OH and CO for this source is about +12 km/s, the recombination-line velocity being the highest.

c) ON 1

ON 1 was first found by Winnberg (1970) to be a Type I OH maser. Subsequently, Winnberg et al. (1973) discovered a compact H II region at its position. It is unique in a sense that no other thermal continuum emission is seen in the 30′×30′ Westerbork field at 21 cm.

We detected CO emission at the velocity of the maser, confirming a physical association. An example of a ^{12}CO profile taken at the position of ON 1 is shown in Figure 6. Israel (in preparation) has observed this region more extensively and found a large CO cloud around ON 1. Since we did not search for ^{13}CO emission, we will not include ON 1 in the following discussion.

Discussion

The ratio of antenna temperatures of ^{12}CO and ^{13}CO in both CO clouds is about 4. In view of the observed $^{12}C/^{13}C$ interstellar isotopic abundance ratio of 40 (Wannier, 1975), this implies that the ^{12}CO line is optically thick. So we may put the excitation temperature equal to the observed brightness temperatures, after correction for the 2.7 K microwave background (Lada et al., 1974). Assuming that a) the excitation temperature T_{exc} is constant along the line of sight and equal for ^{12}CO and ^{13}CO, b) ^{13}CO is optically thin and c) the $^{12}C/^{13}C$ abundance ratio equals 40, we can calculate opacities and CO column densities using the well-known relations of Penzias et al. (1971). Table 2 lists the results for G75.7 and G45.5. With a distance of 5.5 kpc for G75.7 (Reifenstein et al., 1970) and 9.7 kpc for G45.5 (Wynn-Williams et al., 1971) we derive a density and a mass for the molecular clouds (Table 3), assuming all carbon is in the form of CO and that $C/H_2 = 1.5\ 10^{-4}$ (Allen, 1963). At molecular-hydrogen densities larger than about $300\ \mathrm{cm}^{-3}$ the analysis of Scoville and Solomon (1974) shows that the $J=1$ and $J=0$ levels are thermalized, consistent with the assumption that the excitation temperature equals the gas kinetic temperature. The densities we derived are of the order of $200\ \mathrm{cm}^{-3}$, thus it is possible that the excitation temperature may be somewhat less than the gas kinetic temperature. Scoville and Solomon (1974) have shown that radiative trapping can still increase the excitation temperature up to the kinetic temperature, if the line is optically thick. Because the large optical depth of the ^{12}CO emission, T_{exc} of ^{12}CO will then be relatively more enhanced, T_{exc} of ^{13}CO will be smaller than that of ^{12}CO and the derived densities are an upper limit. On the other hand, it is quite possible that some of the available carbon is tied up with dust-grains in the cloud. In the Ophiuchus cloud Encrenaz et al. (1975) found an upper limit of 5 to the depletion of carbon.

If a similar depletion is occurring in these molecular clouds, then the H_2 densities exceed $10^3\ \mathrm{cm}^{-3}$ and are certainly high enough to thermalize the $J=0$ and $J=1$ levels.

The correlation between profile width and brightness temperature could indicate that both clouds show overall collapse. In the inner parts the temperatures are probably higher due to heating by newly formed O stars. This effect could even be more enhanced, because at higher densities the excitation temperature, and as a result the observed brightness temperature, is more strongly coupled to the gas kinetic temperature.

In several dark clouds stars of lower mass (B type) have been detected in the near infrared (e.g. Vrba et al., 1975). The non-coincidence of at least one CO hot spot in each region with the compact H II regions could mean that recently formed stars of lower mass are heating these hot spots. A near infrared search for point sources within the clouds surrounding G75.7 and G45.5 could yield an upper limit to the age of these clouds.

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