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CO, CS, AND HCN IN A CLUSTERING OF REFLECTION NEBULAE IN MONOCEROS

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ABSTRACT

Carbon monoxide line emission at $\lambda = 2.6$ mm has been observed over an area of $\sim 3\frac{1}{2}° \times 3\frac{1}{2}°$ in L1646, a diffuse dust cloud containing a grouping of reflection nebulae. The H_2 mass is estimated from the CO observations to be $> 3.2 \times 10^4\ M_{\odot}$. Five CO emission peaks are observed, each apparently associated with at least one reflection nebula, with the strongest peak at $\alpha(1950) = 6^h05^m20^s$, $\delta(1950) = -6°22'30''$. Around this position, extended ($10' \times 10'$) emission is observed from HCN and CS, suggesting a core with H_2 density $\lesssim 8 \times 10^4$ cm^{-3}. This core appears to be rotating with $\Omega \geq 7.4 \times 10^{-14}$ s^{-1}. There is also evidence for self-absorption in the CO line in this direction, suggestive of a collapsing cloud.

Subject headings: molecules, interstellar — nebulae

I. INTRODUCTION

Since the discovery of interstellar carbon monoxide (Wilson *et al.* 1970), the 2.6-mm, $J = 1 \rightarrow 0$, lines of CO and its isotopic species have been widely observed in the Galaxy and have proven to be valuable tools for the study of dark diffuse nebulae and dense molecular clouds. Early CO observations were primarily directed toward detailed mapping of the strongest molecular sources found in the directions of H II regions (e.g., Liszt 1973), but these observations did not reveal the full extent of CO emission. Recent observations, on the other hand, have shown that sources of intense millimeter emission from CO and other molecules are often associated with extremely extended clouds of weaker CO emission whose linear dimensions are of the order of tens of parsecs (Tucker, Kutner, and Thaddeus 1973; Lada, Dickinson, and Penfield 1974*a*; Tucker and Kutner 1975), and that there exist strong sources of molecular emission which are not associated with prominent H II regions (e.g., Encrenaz 1974).

We present in this paper our observations of the 2.6-mm line of CO from an extended region in the constellation Monoceros in which we have found a source of relatively strong millimeter emission from CS and HCN. This region, which is sketched in Figure 1, contains a complex of dust clouds, the largest cloud being designated L1646 (Lynds 1962), and a number of B1–B6 stars embedded in the dust. The brightest stars are surrounded by nebulosity, presumably reflected starlight. Such groupings of reflection nebulae have been studied extensively by van den Bergh (1966) and Racine (1968), who have designated this grouping, or R association, as Mon R2. As indicated in Figure 1, four of the reflection nebulae correspond to NGC objects; two of these, NGC 2183 and 2185, mark the location of a group of three Orion population stars (Herbig and Rao 1972). In general, the presence of R associations signifies "active young regions of star formation" (van den Bergh 1966) and thus should be considered a likely indicator of possible millimeter molecular emission.

II. OBSERVATIONS

Observations were made in November 1973 and April and June 1974 with the 16-foot (5 m) antenna of the Millimeter Wave Observatory, Ft. Davis, Texas.[1] At 2.6 mm the half-power beamwidth is 2'.6. Spectral resolution of 250 kHz (0.65 km s^{-1} at 115 GHz) was provided by a 40-channel filter bank. Baseline stability was achieved by frequency switching at 5 Hz. Calibration was done using an absorbing chopper wheel in front of the feed. The scale of radiation temperatures ($T_R = I_\nu \lambda^2/2k$), corrected for atmospheric attenuation and beam efficiency, was established in the manner of Davis and Vanden Bout (1973). The carbon monoxide observations were mostly of the common isotopic species $^{12}C^{16}O$ at 115.3 GHz, but at a number of positions spectra of the $^{13}C^{16}O$ line at 110.2 GHz were also obtained.

As Figure 1 shows, the $^{12}C^{16}O$ emission has north-south and east-west extents of $\sim 3\frac{1}{2}°$. Five local maxima in the CO emission have been found, each being near

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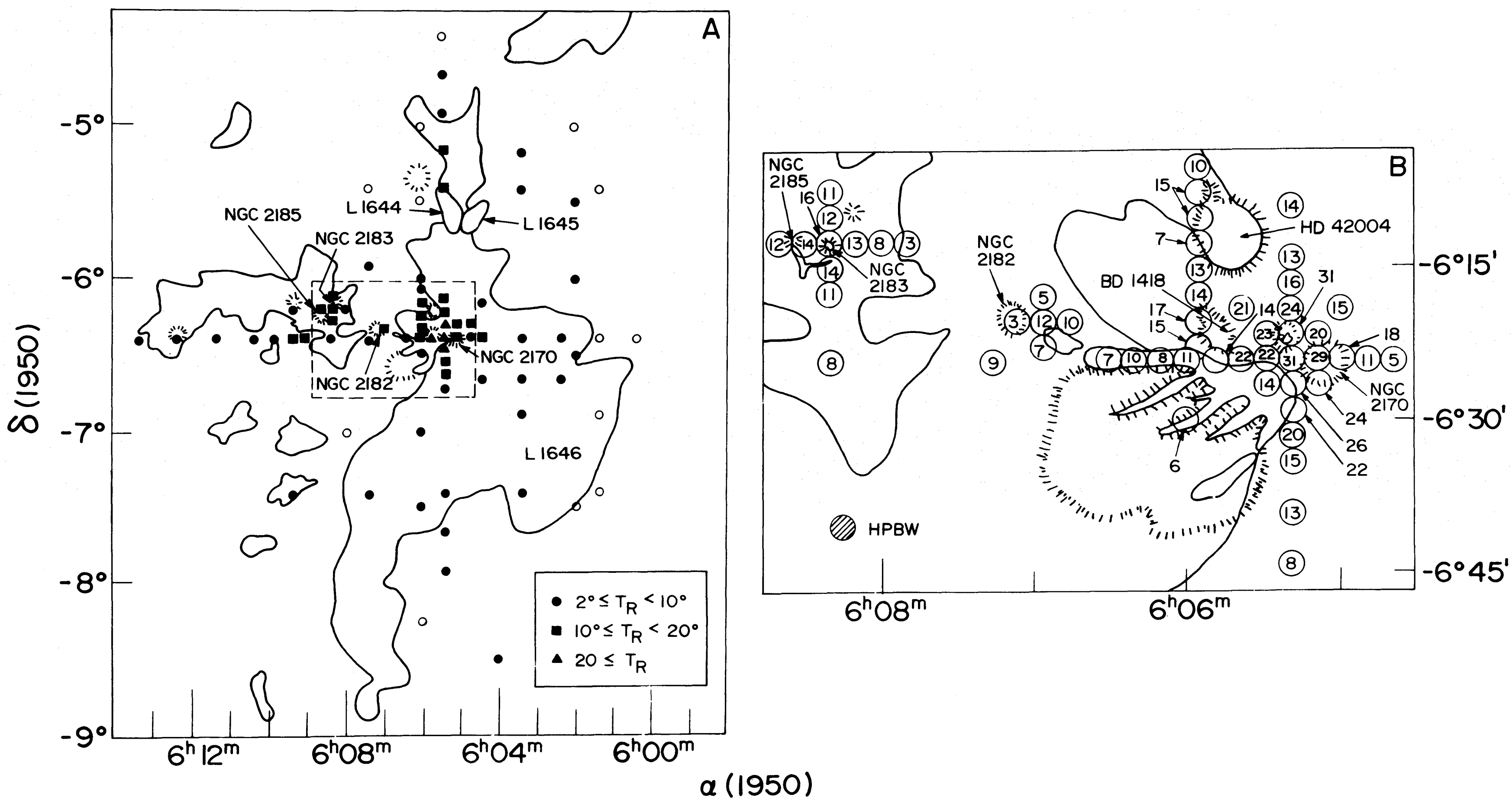

FIG. 1.—$^{12}C^{16}O$ emission in the Mon R2 region. (A) Filled circles, squares, and triangles are about twice the 2′.6 beamwidth (HPBW) and represent CO detections. Open circles are negative results, usually $T_R < 2$ K. The solid contours represent roughly the outlines of regions of strongest extinction ($\gtrsim 1$ mag) on the Palomar Sky Survey blueprint. The hatched boundaries represent reflection nebulae. (B) A closeup of the region indicated by the dashed rectangle in Fig. 1A. Circles indicate the HPBW, and the enclosed numbers give the line radiation temperature ($T_R = I_\nu \lambda^2/2k$).

but not always exactly in the same direction as one or more reflection nebulae. (In some cases incomplete mapping does not allow the precise location of the peak.) The strongest peak, with a radiation temperature of the ^{12}CO line, $T_R{}^{12} = 31$ K, occurs near NGC 2170 at

$$\alpha(1950) = 6^h05^m20^s\,,$$

$$\delta(1950) = -6°22'30''\,.$$

Some spectra of both CO isotopes around this location are shown in Figure 2. Secondary peaks appear in the direction of NGC 2183 ($T_R{}^{12} = 15$ K, $T_R{}^{13} = 9$ K), about 2′ W of NGC 2182 and near the reflection nebulae associated with the stars BD−6°1418 and HD 42004 (see Fig. 1).

To obtain more information about the region of the most intense CO emission, observations were made of the $J = 1 \rightarrow 0$ transition (88.6 GHz) of HCN, the $J = 2 \rightarrow 1$ and $3 \rightarrow 2$ transitions of CS (98.0, 147.0 GHz), and the $J = 2 \rightarrow 1$ transition of the isotopic species $C^{34}S$ (96.4 GHz). Figure 3 shows profiles of the three CS transitions in the direction of the CO peak. The results of mapping HCN and the normal isotope lines of CS are shown in Figure 4. Emission from all three transitions appears to come from a dense core which is extended over ~10′ × 10′. (In a study of this region, Loren, Peters, and Vanden Bout [1974] have detected 2-mm formaldehyde emission.) We have also detected a CS ($2 \rightarrow 1$) line with $T_R = 1.8$ K in the direction of the secondary peak at NGC 2183. No CS observations were made in the directions of the other three CO peaks.

III. DISCUSSION

These observations show that the Mon R2 region provides another example of an extended CO cloud which contains, or at least appears to be associated with, a small denser source of millimeter emission from a number of other molecules. Before discussing this new molecular source, we first consider the extended CO emission and its relationship to the reflection nebulae.

The CO column density, N_{CO}, is estimated by assuming that both the ^{12}CO and ^{13}CO have the same excitation temperature, which is constant along the line of sight and that the isotope ratio is terrestrial. This yields typical column densities of $\sim 10^{18}$ cm^{-2} over the extended cloud. If the H_2 densities are not sufficient to bring the excitation temperature T_x close to T_{kin}, the kinetic temperature, then trapping in the optically thick ^{12}CO line will cause $T_x{}^{12} > T_x{}^{13}$ (see, e.g., Goldreich and Kwan 1974), resulting in an underestimation of the ^{13}CO optical depth. In the determination of column densities this is usually only partially offset by the resulting overestimation of the partition function. Therefore, the value of N_{CO} obtained on the assumption of equal excitation temperatures, is taken as a lower limit.[2]

[2] In a few cases when $T_x{}^{12} \gtrsim 20$ K and $T_x{}^{13} \sim \frac{2}{3}T_x{}^{12}$, an overestimation in N_{CO} by ~10 percent may occur.

A lower limit to the hydrogen column density, N_{H_2}, is then obtained by assuming that the ratio of CO to hydrogen column densities is less than the terrestrial C/H abundance ratio. This yields typical H_2 column densities, $N_{H_2} \gtrsim 1.6 \times 10^{21}$ cm^{-2}, a factor of 2 below the value obtained by assuming an average extinction, $A_v = 3$ mag, and a "normal" gas-to-dust ratio, $N_{H_2}/A_v = 10^{21}$ cm^{-2} mag^{-1}. To find the size of the cloud, we use Racine's (1968) value of 830 ± 50 pc for the distance to the Mon R2 reflection nebulae. At this distance, the $3\frac{1}{2}°$ extent of the CO emission corresponds to a linear extent of 50 pc. We have not mapped the CO extent in all directions, but for a reasonable estimate of 10 square degrees the derived H_2 column density gives a total mass $M \gtrsim 3.2 \times 10^4\ M_\odot$.

As we have noted, apart from the main CO peak there are four secondary peaks, each at least approximately coincident with reflection nebulae. Since the ^{12}CO line is optically thick, these peaks reflect an increase in the excitation temperature. In view of recent studies of CO line formation (Goldreich and Kwan 1974; Scoville and Solomon 1974), one might ask whether it is possible that the cloud has a roughly constant $T_{kin} \sim 20$ K with the variations in $T_x{}^{12}$ resulting from changes in N_{CO} and in the H_2 density, n_{H_2}. Consider, for example, the case of NGC 2183, where the observation of CS suggests a rise in n_{H_2} to $\sim 10^4$ cm^{-3}. From the ^{13}CO observations we find that N_{CO} rises to 6×10^{18} cm^{-2}. For $n_{H_2} \sim 10^4$, $T_x{}^{12} \approx T_x{}^{13}$ (Scoville and Solomon 1974, Fig. 1*a*), so it is not necessary to treat the derived column densities as lower limits. Such increases in N_{CO} and n_{H_2} will have an effect on the excitation, but based on the results of Scoville and Solomon it is doubtful that at constant T_{kin} these changes alone will account for the observed variations in CO intensity. Though further observations are necessary for a firm generalization, it would appear that the CO peaks in the vicinity of reflection nebulae result from the combined effects of increases in N_{CO}, n_{H_2}, and T_{kin}.

Two possible situations are suggested regarding the relationship between the reflection nebulae and the CO peaks: (1) The stronger CO emission may be coming from the remnants of the material out of which the visible star formed. This material would still be denser than the extended cloud, and may also be heated by the embedded star. The fact that the molecular peak does not always coincide with the position of the reflection nebula may mean that the star has had time to move away from or disturb the material from which it formed. Presumably molecular peaks associated with younger objects would not show such separations, as indicated by the results of Lada *et al.* (1974*b*) for molecular peaks associated with Herbig-Haro objects. (2) It is also possible that the reflection nebulae just mark regions of multiple condensations, the molecular peaks occurring in regions of collapse where stars have not yet formed. It would be interesting to see if infrared observations indicate any such multiple condensations.

We now turn our attention to the 10′ × 10′ source of CS and HCN emission, which we shall refer to as

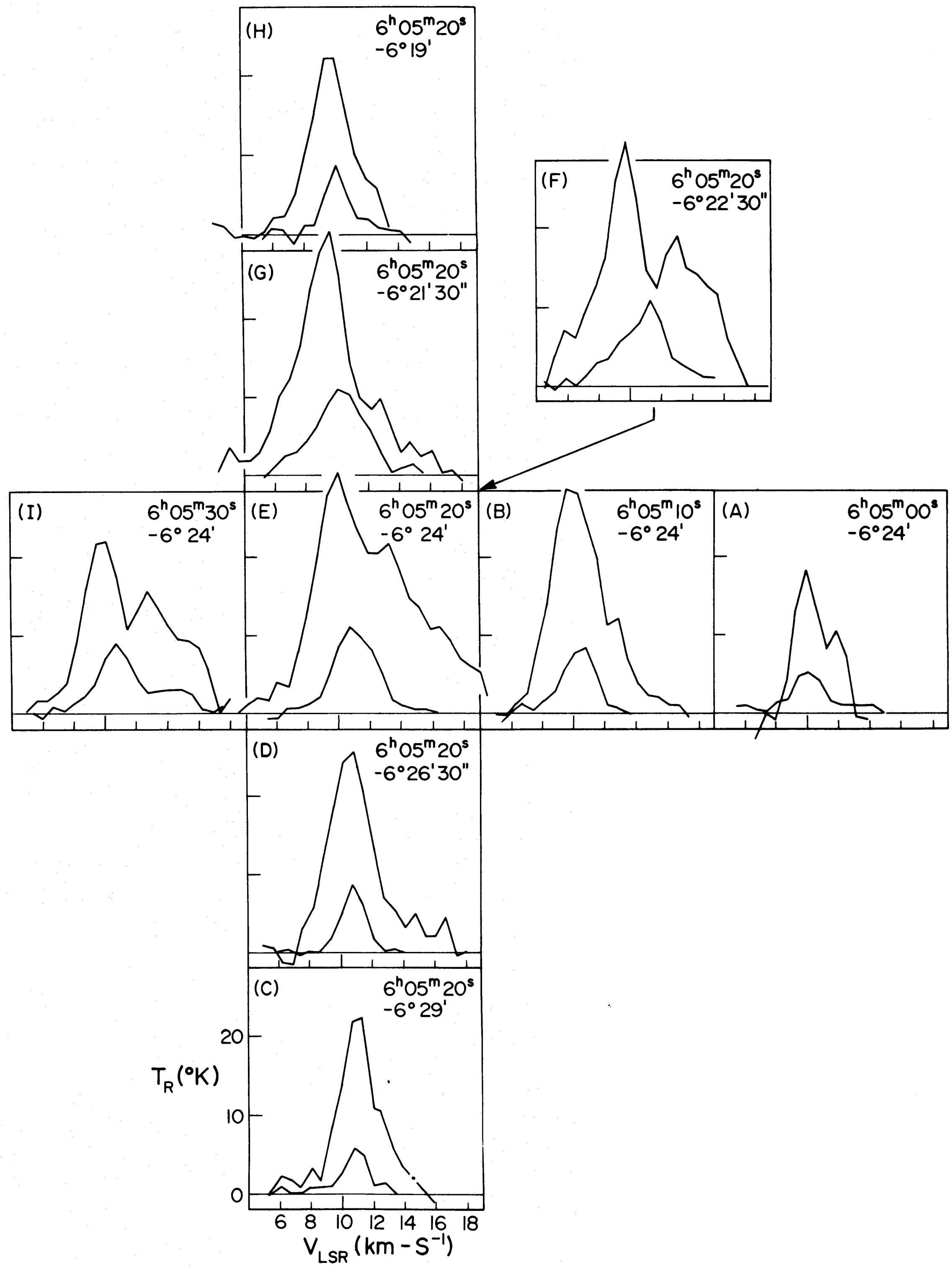

FIG. 2.—$^{12}C^{16}O$ and $^{13}C^{16}O$ profiles in the vicinity of the most intense molecular emission. Box size represents approximately 1 beamwidth. Profile F was taken in a half-beamwidth step between G and H. Velocity resolution is 0.65 km s^{-1}.

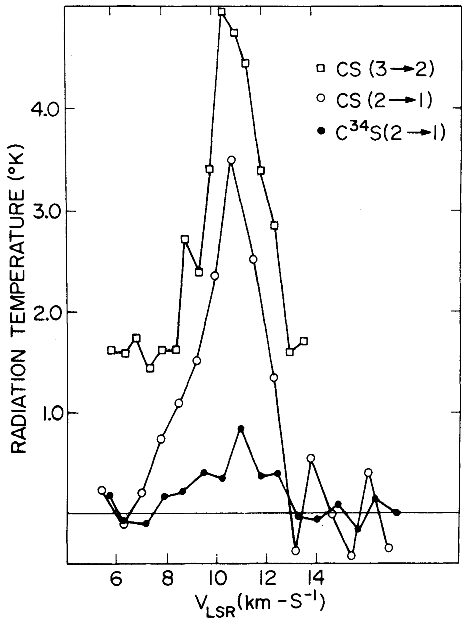

FIG. 3.—Contours of CS and HCN emission around the molecular peak (marked by cross). Contours represent 25, 50, and 75% of the peak T_R indicated for each line. Shaded circle represents half-power beamwidth.

the core. At a distance of 830 pc, the 10′ extent corresponds to a diameter of 2.2 pc. The peak is in the direction of a small H II region, PKS 0605−06 (Shimmins, Clarke, and Ekers 1966). Following the initial report of a molecular source at this location (Kutner and Tucker 1974), Beckwith and Evans (1975) found a grouping of three infrared (10 μ) sources within 1′ of the molecular peak. The weakest source appears to be the H II region. The extent of the infrared emission is about one-tenth that of the HCN and CS emission.

We can estimate the density of the core by using the CS observations along with the calculations of Goldreich and Kwan (1974) who consider molecular line formation in a homogeneous, collapsing sphere with collapse velocity proportional to the radius. For a given molecule and $T_{\rm kin}$, their results for optically thick lines depend on the parameter $\epsilon\tau$, which for CS is given by

$$\epsilon\tau = 3.5 \times 10^{-14} \frac{N_{\rm CS} n_{\rm H_2}}{V T_{\rm kin}^{1/2}} \qquad (1)$$

where V is the collapse velocity at the surface. We take V to be 2 km s^{-1}, or about half the observed line width for ^{13}CO. For $T_{\rm kin} = 25$ K, our observed intensities, $T_R \approx 3$ K, for both the 3–2 and 2–1 transitions correspond to $\epsilon\tau \cong 1$ or

$$n_{\rm H_2} \approx \frac{1}{3.5 \times 10^{-20} N_{\rm CS}} . \qquad (2)$$

On the assumption of a terrestrial isotope abundance ratio and equal excitation temperatures for the two isotopes, the $C^{34}S$ observations give $N_{\rm CS} = 3.5 \times 10^{14}$ cm^{-2}. Since the CS excitation temperature appears to be much less than $T_{\rm kin}$ (which in this case is essentially the CO excitation temperature, about 30 K), it is likely that trapping is significant, making this a lower limit to $N_{\rm CS}$. Putting this into equation (2), one obtains

$$n_{\rm H_2} \lesssim 8 \times 10^4 \ {\rm cm^{-3}} . \qquad (3)$$

This density corresponds to a mass of 5500 $M_\odot$.

The CS observations also show that the core is rotating. Figure 5 shows contours of intensity, as a function of radial velocity and declination for the CS (3 → 2) line, which affords the best spatial and velocity resolution of the lines we observed. There is clearly a shift to lower velocity as one moves north. A corresponding plot in right ascension shows no such shift, indicating an essentially east-west axis (close to the axis of Galactic rotation). At a distance of 830 pc the observed shift corresponds to an angular velocity $\Omega \geq 7.4 \times 10^{-14}$ s^{-1}, the inequality resulting from the unknown projection angle of the rotation axis. If this object collapsed from a sphere of initial density $n_{\rm H} = 10$ cm^{-3} with the Galactic angular velocity, then by conservation of angular momentum, the current rotation would be reached at $n_{\rm H_2} \geq 1 \times 10^4$ cm^{-3}. This rotation is particularly interesting, since comparable angular velocities are expected in such collapsed objects, but rotating molecular clouds are seldom observed.

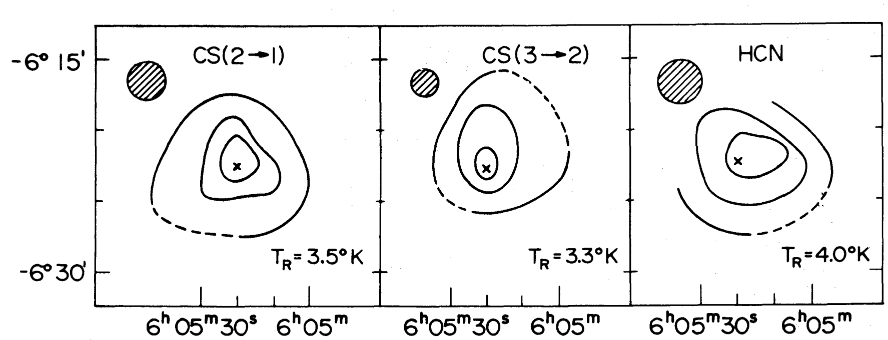

FIG. 4.—CS profiles in the direction of the molecular peak, $\alpha(1950) = 6^h05^m20^s$, $\delta(1950) = -6°22'30''$

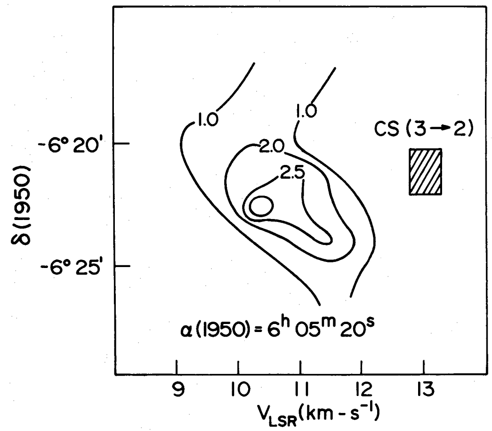

FIG. 5.—Contours of CS (3 → 2) intensity as a function of declination and LSR velocity. Shaded area represents resolution in each of these axes (2′ in declination, 0.5 km s^{-1} in velocity). Observations were made at half-beamwidth intervals.

We note that for a mass of 5500 $M_{\odot}$ in an object this size the surface collapse velocity $[V = (2GM/R)^{1/2}]$ should be about 7 km s^{-1}, rather than the 2 km s^{-1} derived from the ^{13}CO linewidth. This suggests that the free-fall collapse has been retarded. For the angular velocity derived above, the rotational energy is about one-tenth the gravitational energy. It is therefore unlikely that the retarded collapse can be completely explained by the rotation, suggesting another mechanism, possibly a magnetic field. For this cloud, the magnetic and gravitational energies would be comparable with a field of about 0.5 milligauss.

Another interesting feature of these observations is that the CO profiles in the core (Fig. 2) show evidence of self-absorption. A few beamwidths away from the peak the ^{12}CO and ^{13}CO profiles are centered at the same velocity (e.g., positions A, C, D, H). Closer to the center (position G), there is an apparent shift in the ^{12}CO peak to lower velocity, and the high-velocity side of the line falls off sharply. The profiles at positions E, F, and I appear self-reversed, with the ^{13}CO peak falling between the two ^{12}CO peaks.

The interpretation of the spectra is complicated by the possible appearance of additional velocity components. (In view of the multiple infrared structure several velocity components might be expected.) The 15 km s^{-1} component is probably a separate velocity feature since it appears in the ^{13}CO line at position I and possibly at G, and would explain the additional "shoulders" at this velocity in the ^{12}CO spectra at positions E and F. The feature at ~12.5 km s^{-1} is more difficult to explain. If it is part of a self-reversed main peak, then the self-absorption is quite obvious. This interpretation is supported by noting that if one ignores the 15 km s^{-1} feature and "fills in" the self-absorbed part of the line, the ^{13}CO line appears centrally placed with respect to the ^{12}CO line. Even if the 12.5 km s^{-1} feature is shown to be an independent velocity component, self-absorption still appears on the high-velocity side of the main ^{12}CO component (best shown at position G).

In either case most of the absorption appears at velocities higher than the center of the ^{13}CO line, indicating cooler foreground material moving toward the core, with a relative velocity of 1–2 km s^{-1}. Though this foreground material may be anywhere in the line of sight, the confinement of the self-absorption to positions around the peak suggests a direct relationship, as in the case of a collapsing cloud. It should be pointed out that though this is a plausible explanation, it is not yet supported by any detailed model. Even the most recent discussions of CO line formation (Scoville and Solomon 1974; Goldreich and Kwan 1974) deal with isothermal, constant-density clouds, and are therefore inadequate for the discussion of self-absorption. We note that Loren *et al.* (1974) find line profile behavior suggestive of collapse or expansion, but their observations do not fit any proposed collapse models. The infrared observations offer an alternative possibility for the origin of the self-absorption. The two infrared peaks (excluding the H II region) are separated by only 35″, so the molecular emission associated with each may be sufficiently extended to cause overlapping in the line of sight, and "self-absorption" might occur if the cooler one were closer to us. Apart from theoretical considerations, observations with higher spatial and velocity resolution would be required to distinguish between the two possibilities.

IV. SUMMARY

The most important features of these observations can be summarized as follows:

1. CO emission has been detected over much of a 10 square-degree (~250 pc^2) cloud which apparently contains the grouping of reflection nebulae known as Mon R2. The estimated mass of this cloud is greater than 3×10^4 $M_{\odot}$.

2. Five CO peaks appear which are apparently associated with but not always exactly coincident with reflection nebulosity. The observations suggest that these peaks are characterized by higher temperature, H_2 density, and CO column density than the surrounding regions. These CO peaks may be either the remnants of the material out of which the visible stars formed, or may represent separate condensations, a question that might be resolved by searching for multiple infrared sources in these directions.

3. The strongest CO emission comes from the direction of H II region PKS 0605−06, an area which also contains three 10-μ sources (Beckwith and Evans 1975). Emission from the $J = 1 \rightarrow 0$ HCN and $J = 3 \rightarrow 2$, $2 \rightarrow 1$ CS transitions is observed with a radius of ~5′ (1.1 pc) about this direction. From the CS observations the average H_2 density deduced for this region is $\leq 8 \times 10^4$ cm^{-3}.

4. This peak region is rotating with an angular velocity, $\Omega \geq 7.4 \times 10^{-14}$ s^{-1}, consistent with its having collapsed to the above density from a region with $n_{\rm H} \approx 10$ cm^{-3} and the local Galactic angular velocity.

5. The CO profiles in the direction of the peak appear to show self-absorption. Though a collapsing

cloud is suggested, there is yet no model to support this, and other interpretations cannot be ruled out. It is hoped that with higher angular and velocity resolution observations this source will provide a useful example against which to test future radiative transfer models.

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