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DETECTION OF SUBMILLIMETER (870 μm) CO EMISSION FROM THE ORION MOLECULAR CLOUD

T. G. PHILLIPS AND P. J. HUGGINS*
Bell Laboratories, Murray Hill

AND

G. NEUGEBAUER AND M. W. WERNER
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
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ABSTRACT

We report the first measurements of the interstellar $J = 3$ to $J = 2$ carbon monoxide line at a wavelength of 870 μm (346 GHz). Observations of the Orion molecular cloud were made with a heterodyne bolometer receiver at the prime focus of the Hale 5 m telescope. A major feature of the observed spectra is the great strength of the high-velocity wings of the line. The position and spatial extent of the region of high-velocity emission are determined and compared with shock wave models for CO and H_2 emission. It is concluded that the high-velocity gas is probably at or near the front face of the molecular cloud and has a kinetic temperature $\gtrsim 100$ K, a mass $\gtrsim 10\ M_\odot$, and a density $n_{H_2} \gtrsim 5 \times 10^5$ cm^{-3}.

Subject headings: interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

In this *Letter* we report the detection of 870 μm CO($J = 3$–2) emission from the Orion molecular cloud, representing the first observation of a submillimeter line in an astronomical source. The precise frequency is 345.796 GHz (Lovas and Tiemann 1974).

II. OBSERVATIONAL TECHNIQUES

In 1976 November and 1977 February observations were carried out from the prime focus of the Hale 5 m telescope at Mount Palomar. The receiver feed horn provided a cosine illumination function, which together with the 2 m central aperture blockage gave a theoretical beamwidth of 36″. This was confirmed within an error of ±3″ by scanning of Jupiter. These observations of Jupiter were also used for comparison of the optical and submillimeter beam positions so that the telescope could be pointed by offsetting from visible stars.

The detection scheme employed a liquid-helium-cooled InSb hot electron bolometer element in a fundamental mode waveguide mount. Local oscillator power was provided by a millimeter wave klystron driving a Schottky barrier diode harmonic generator. Mixer action by the bolometer provided an intermediate-frequency response which, for these observations, was chosen to be a single channel of 1 MHz width, and spectra were obtained by stepping of the local oscillator under computer control. This type of scheme was earlier used for the detection of lower-frequency lines such as CO(2–1) (Phillips, Jefferts, and Wannier 1973) where the receiver noise temperature was about 300 K. For these higher-frequency observations the noise temperature was about 2000 K, the degradation being mainly due to extra front end losses. At a wavelength of 870 μm, atmospheric losses from the Mount Palomar site (1.8 km) varied between 1.5 dB per air mass and unmeasurably large values.

III. RESULTS

In Figure 1 we show a spectrum of the $^{12}C^{16}O$(3–2) line from a position close to the center of the Orion molecular cloud. While the 1 MHz channel width corresponds to a velocity of 0.9 km s^{-1}, the sampling interval is 1.9 km s^{-1} and dominates the velocity resolution. We retain the units of corrected antenna temperature (T_A*) which were introduced for the CO(2–1) line (Phillips, Jefferts, and Wannier 1973); this scale is linear in terms of received power. For hot, extended objects such as Orion ($T_A^* \approx 80$ K) the brightness temperature is only ~10% greater than T_A*.

The most striking feature of the spectrum of Figure 1 is the great enhancement of the high-velocity wings when compared with the CO(1–0) spectrum (Zuckerman, Kuiper, and Kuiper 1976; Kwan and Scoville 1976). Such behavior is anticipated from the CO(2–1) spectrum (Wannier and Phillips 1977) which shows an increase of about a factor of 2 in the high-velocity emission as compared with the CO(1–0) spectrum. Note, however, that the very weak CO(1–0) emission seen at very high velocities (Zuckerman, Kuiper, and Kuiper 1976) is not obvious in the CO(3–2) spectrum. As discussed by Zuckerman and Palmer (1975), the high-velocity, or "plateau," emission is thought to arise from a small source near the center of the cloud which is distinct from the gas which produces the low-velocity emission spike.

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* Postdoctoral research fellow.

The position and size of the plateau source have been determined from these data with greater precision than previously possible. Figure 2 shows a plot of the peak (3–2) plateau antenna temperature as a function of position; the peak antenna temperature is found by fitting a Gaussian to the spectrum for velocities further than ± 6 km s^{-1} from the line center. We find the plateau source to be centered at $5^{\mathrm{h}}32^{\mathrm{m}}46\overset{\mathrm{s}}{.}7$ and $-5°24'19''$ (1950), about 5″ north of KL and 5″ south of BN. However, (1 σ) errors are $\pm 5''$ in both right ascension and declination due to differential refraction between visual and submillimeter images and to the limited signal-to-noise ratio of the data. In declination the data indicate that the observed source size is slightly larger than the beam, whereas in right ascension the points essentially fall on the beam profile. Taking into account the various

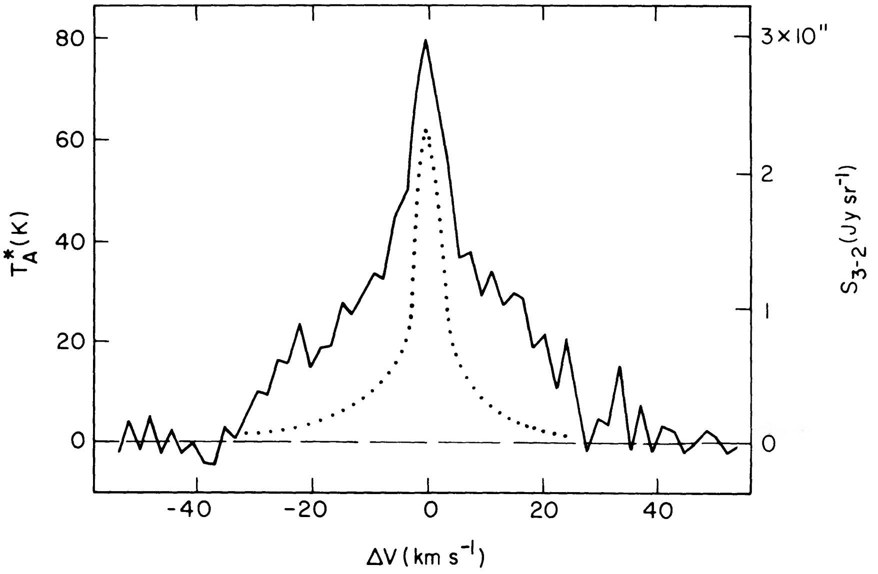

FIG. 1.—A spectrum of the CO(J = 3–2) emission line from the Orion molecular cloud (*solid curve*). Velocity resolution is 0.9 km s^{-1}, sampling interval is 1.9 km s^{-1}, and ΔV is with respect to V_{LSR} = 9.0 km s^{-1}. The left-hand ordinate gives corrected antenna temperature, T_A*, while the right-hand ordinate gives the specific intensity, S_{3-2}, of the (3–2) emission line. The spectrum is interpreted as a convolution of two lines, the narrow one due to the extended molecular cloud and the broad one (plateau) from a small region centered at α = $5^{\mathrm{h}}32^{\mathrm{m}}46\overset{\mathrm{s}}{.}7$ and δ = $-5°24'19''$ (1950), about 5″ N of KL, with positional errors of about $\pm 5''$ in right ascension and declination. For comparison, the spectrum of the CO(1–0) emission line (Kwan and Scoville 1976) is shown as the dotted curve.

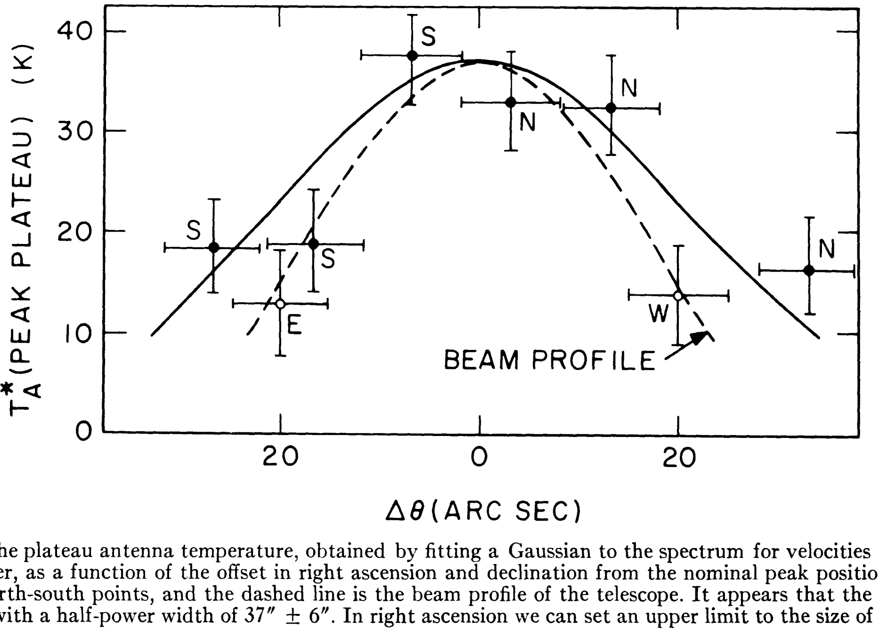

FIG. 2.—A plot of the plateau antenna temperature, obtained by fitting a Gaussian to the spectrum for velocities further than ± 6 km s^{-1} from the line center, as a function of the offset in right ascension and declination from the nominal peak position. The solid line is a Gaussian fit to the north-south points, and the dashed line is the beam profile of the telescope. It appears that the plateau source is extended in declination with a half-power width of 37″ ± 6″. In right ascension we can set an upper limit to the size of 22″.

errors, we conclude that if the plateau object is assumed to be Gaussian in shape, the half-power width is 37″ ± 6″ in declination and less than 22″ in right ascension. If, however, the source is assumed to be uniform, the sizes become 52″ and less than 31″, respectively.

IV. DISCUSSION

The typical ratio of $T_A{}^*(3\text{–}2)$ outside the central spike to the corresponding $T_A{}^*(1\text{–}0)$ is about 7:1, though there is some change of shape in the spectrum. For a hot, dense, optically thin source the ratio should be (1–0):(2–1):(3–2) = 1:4:9. The observed ratios of 1:2:7 tend to confirm the view taken by Wannier and Phillips (1977) that the plateau source is optically thin in CO(1–0).

For the Gaussian model, the CO(3–2) plateau $T_A{}^*$, when corrected for beam dilution, is $\gtrsim 100$ K, the lower limit arising from the upper limit in right ascension size. A similar beam dilution argument applied to the (1–0) observations from the Kitt Peak 11 m telescope gives a peak plateau $T_A{}^*(1\text{–}0) \gtrsim 30$ K, assuming the source is the same size at both frequencies. If the source were optically thin and in LTE, this limit and the theoretical predictions quoted above indicate that $T_A{}^*(3\text{–}2)$ should be greater than 270 K. The fact that a value of $T_A(3\text{–}2)$ as low as 100 K is consistent with the (3–2) observations suggests that the CO(3–2) plateau is partially saturated.

The size determination permits a new estimate of the parameters of the plateau source. For the Gaussian model, in the optically thin limit and assuming an excitation temperature $\gtrsim 100$ K, we find from the (1–0) line intensity that the CO column density $N_{\text{CO}} \gtrsim 6 \times 10^{18}$ cm^{-2}. Assuming $N_{\text{CO}}/N_{\text{H}_2} = 5 \times 10^{-5}$, the column density of H_2 is $N_{\text{H}_2} \gtrsim 1 \times 10^{23}$ cm^{-2}, and the mass $\gtrsim 10 M_{\odot}$. If it is further assumed that the line-of-sight extent is no greater than the observed lateral extent of the source, the density $n_{\text{H}_2} \gtrsim 5 \times 10^5$ cm^{-3}. Therefore, the lower limit of 100 K found for $T_A{}^*(3\text{–}2)$ suggests that the kinetic temperature of the gas is greater than 100 K since the CO will be excited collisionally in this range of densities.

The spectrum of Figure 1 permits an investigation of the relative positions of plateau and spike sources along the line of sight by means of self-absorption arguments. It is known from CO(1–0) and (2–1) observations (Liszt *et al.* 1974; Phillips, Jefferts, and Wannier 1973) that the central emission spike originates from the bulk of the cloud, is optically thick, and shows little variation in amplitude ($T_A{}^* \approx 75$ K) or width (FWHP ≈ 6 km s^{-1}) for 2′ or 3′ about the center of the source. We therefore assume that the observed (3–2) spectrum is a convolution of a spatially extended source spectrum with a peak $T_A{}^* \approx 75$ K and Δv (FWHP) ≈ 6 km s^{-1}, and a beam-diluted plateau source spectrum of unknown opacity and velocity width $\Delta v \approx 40$ km s^{-1}. For the extended source the values of the excitation temperature and opacity as a function of velocity are estimated from the $^{12}C^{16}O(1\text{–}0)$ and $^{13}C^{16}O(1\text{–}0)$ profiles. Figure 3 shows $^{12}C^{16}O(3\text{–}2)$ spectra computed for the following assumptions: (*a*) Plateau source is behind the extended source; self-absorption occurs on both red and blue sides of the line for both turbulent models and uniform velocity gradient models for the bulk motion of the gas producing the spike feature (Leung and Liszt 1976; Goldreich and Kwan 1974; Scoville and Solomon 1974). (*b*) Plateau source is at the center of a spherical, extended, contracting velocity gradient source (Goldreich and Kwan 1974); case (i) is for an optically thick plateau source, case (ii) for a thin source. Self-absorption is present, but only on the red side. For the plateau source at the center of a turbulent extended source, (*a*) results again. (*c*) Plateau source is in front of extended source; case (i) is for an optically thick plateau source, (ii) for a thin source. In Figure 3 the velocity resolution is 2 km s^{-1}, matching the experimental resolution of Figure 1.

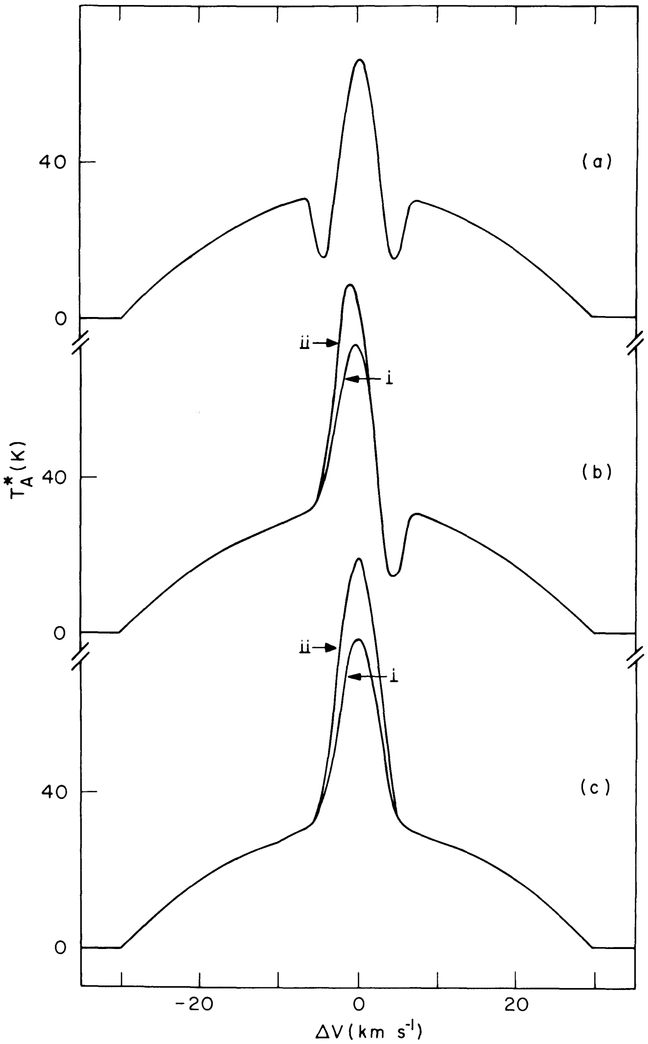

FIG. 3.—Computed CO(3–2) spectra. These spectra are computed using the radiative transfer models described in the text under the assumption that the plateau source is (*a*) behind, (*b*) at the center of, (*c*) in front of the low-velocity extended molecular cloud. The low-velocity cloud is assumed to be spatially continuous and spherically symmetric. Case (i) is for an optically thick plateau source and case (ii) for a thin source. The observed spectrum (Fig. 1) is consistent with (*c*) for moderate opacity.

Since no evidence for self-absorption is seen in the observed spectra, the observations support case (*c*), and the plateau source is presumably in front of, or at least near the front surface of, the extended molecular cloud. Further, from the amplitude of the observed signal we deduce that the plateau source is somewhat opaque in CO(3–2) emission, in agreement with the argument based on comparison of (1–0) and (3–2) line temperatures.

Recently, infrared H_2 emission has been observed from the vicinity of the plateau source (Gautier *et al.* 1976; Grasdalen and Joyce 1976; Beckwith *et al.* 1976), and it has been suggested that this H_2 emission is due to shock wave excitation (Kwan 1977; London and McCray 1976; Hollenbach and Shull 1976). We note that the extent of the high-velocity CO emission lies within that of the H_2 emission (45″ in right ascension and ∼1′ in declination; Beckwith *et al.* 1976). This can be taken as agreeing with the suggestion that the millimeter and submillimeter emission is due to gas behind the shock front which has cooled considerably from several thousand kelvins in the thin shell at the front (Kwan and Scoville 1976). Furthermore, it is clear from Figure 1 that the bulk of the plateau CO emission is at velocities within 25 km s^{-1} of the central velocity, again in agreement with the calculation of Kwan (1977) showing that if the H_2 emission is due to shock wave excitation, then the shock velocities are 10–24 km s^{-1}.

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G. NEUGEBAUER and M. W. WERNER: Physics Department 320-47, California Institute of Technology, Pasadena, CA 91125

T. G. PHILLIPS and P. J. HUGGINS: Bell Laboratories, 600 Mountain Avenue, Murray Hill, NJ 07974