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DETECTION OF BIPOLAR CO OUTFLOW IN ORION

Neal R. Erickson, Paul F. Goldsmith, Ronald L. Snell, Ronna L. Berson, and G. R. Huguenin
Five College Radio Astronomy Observatory, University of Massachusetts
B. L. Ulich
Multiple Mirror Telescope Observatory
and
C. J. Lada[1]
Steward Observatory, University of Arizona
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ABSTRACT

We have used the Multiple Mirror Telescope as a phase coherent array to map the CO $J = 3\text{–}2$ emission from the central 1′ region of the Orion molecular cloud. The angular resolution was 26″ and the absolute pointing accuracy was better than 5″. The peak radiation temperature of the high-velocity gas is approximately 75 K, and the characteristic size of the emission region is 30″–40″. The centroid of the high-velocity emission is located roughly 10″ northeast of IRc2. The peaks in the emission strength of the redshifted and blueshifted high-velocity CO are offset with the redshifted emission peaking east and the blueshifted emission peaking north of IRc2. The axis of the high-velocity CO emission is aligned with the two maxima of the 2 μm H_2 emission suggesting that the CO is participating in the same bipolar outflow.

Subject headings: interstellar: molecules — nebulae: Orion

I. INTRODUCTION

Numerous observations of the core of the Orion molecular cloud indicate that it is the site of dynamical activity probably associated with the formation of massive stars. Emission with high-velocity dispersion has been detected from many molecular species within this region. The high-velocity gas has been particularly well studied in CO emission, for which this component is spectrally resolved in five rotational transitions in the millimeter and submillimeter regions (Kwan and Scoville 1976; Zuckerman, Kuiper, and Rodriguez-Kuiper 1976; Wannier and Phillips 1977; Phillips *et al.* 1977; Goldsmith *et al.* 1981; Van Vliet *et al.* 1981), and its presence inferred in four additional far-infrared transitions (Storey *et al.* 1981; Stacey *et al.* 1982). These observations have shown that the velocity dispersion of this gas component is greater than 100 km s^{-1} and has a spatial extent of $\leq 40''$ centered approximately 10″ north of the KL Nebula (Solomon, Huguenin, and Scoville 1981; Knapp *et al.* 1981); thus in the immediate vicinity of the infrared sources IRc2, IRc4, and the BN object. The KL/BN region is a complex of infrared continuum sources which have a total luminosity of $\sim 10^5\ L_\odot$ (Rieke, Low, and Kleinman 1973).

The Orion molecular cloud core has also been found to be the source of strong, vibrationally excited H_2 emission (Gautier *et al.* 1976; Beckwith *et al.* 1978). This emission requires gas at a temperature of 2000 K which can be best explained by shock excitation (Kwan 1977; Hollenbach and Shull 1977) produced by outflowing material from a central source encountering the dense surrounding molecular cloud. Further indication of the presence of outflow is the large velocity dispersion observed for the H_2O maser components. The proper motion of these maser features has been measured by Genzel *et al.* (1981), and they were shown to be moving radially away from a common center near IRc2.

The outflow of material from newly formed stellar objects has been recently observed in a number of other sources (Snell, Loren, and Plambeck 1980; Rodriguez, Ho, and Moran 1980; Lada and Harvey 1981; Snell and Edwards 1981). Many of these sources share the common feature that the outflow is bipolar, with the redshifted and blueshifted high-velocity gas spatially resolved into two distinct emission peaks. Orion has thus far been one of the few high-velocity sources not observed to be bipolar.

We present a high spatial resolution map of the $J = 3\text{–}2$ CO emission from the central 1′ region of the Orion molecular cloud obtained using the Multiple Mirror Telescope. These observations resolve the high-velocity flow and clearly reveal the presence of a bipolar structure in the Orion high-velocity emission. The bipolar flow is aligned with the H_2 vibrational emission

[1]Alfred P. Sloan Foundation Fellow.

and may be related to the flows observed in other molecular species.

II. OBSERVATIONS

For these observations carried out in 1982 February, we used the Multiple Mirror Telescope (MMT) located on Mount Hopkins, Arizona. The beams of the six telescopes, each 1.82 m in diameter with their centers located on a circle 5.3 m in diameter, were combined in a coherent power splitter whose output was coupled to a cryogenic 0.9 mm receiver. A detailed description of the apparatus and its performance can be found elsewhere (Ulich *et al.* 1982). In use during a 5 day period, the phase stability was accurate to $\lambda/30$ (30 μm) and the beam pattern, measured to be 26″ (FWHM) by scans of Saturn, remained constant in shape. As expected for the beam pattern produced by an antenna array, there are significant sidelobes within the pattern produced by an individual element. The measured pattern of the array agrees very well with the theoretical calculations, and from the latter we deduce that 0.32 of the power in the forward beam is contained within the central lobe. The absolute pointing accuracy of the Optics Support Structure (OSS) of the MMT is approximately 1″ rms. Checks of the relative pointing between the submillimeter beam and the OSS using Saturn indicated that the pointing errors during the course of the observations did not exceed 5″.

The receiver noise temperature was 1100 K (single-sideband); the system temperature referred to outside the atmosphere was 3000–7000 K. A spectrometer with 256 × 1 MHz channels (each corresponding to 0.87 km s^{-1}) was used, and the data were taken in a position-switched mode with a −90′ offset in R.A. between the signal and reference beams. The data were calibrated using an ambient temperature vane; this calibration should work well since the dominant attenuation at $\lambda = 0.9$ mm is due to water vapor having a physical temperature quite close to that at mountaintop level. The zenith optical depth varied from 0.3 to 0.8 on the 4 days when observations were made; a model of atmospheric opacity implies that the corresponding precipitable water vapor varied from 1.4 to 4.1 mm. Application of a correction factor of 1.2 to account for power in far out sidelobes due to diffraction from the secondary and spillover results in a temperature scale for sources moderately extended relative to the 2′ diameter pattern of a single element. An additional correction of $(0.32)^{-1}$ applies to emission from a region comparable to or larger than the 26″ synthesized beam but significantly smaller than 2′, such as the region of high-velocity CO emission.

III. RESULTS

We have obtained a 33 position map of CO $J = 3$–2 emission centered on IRc2; the spacing between map

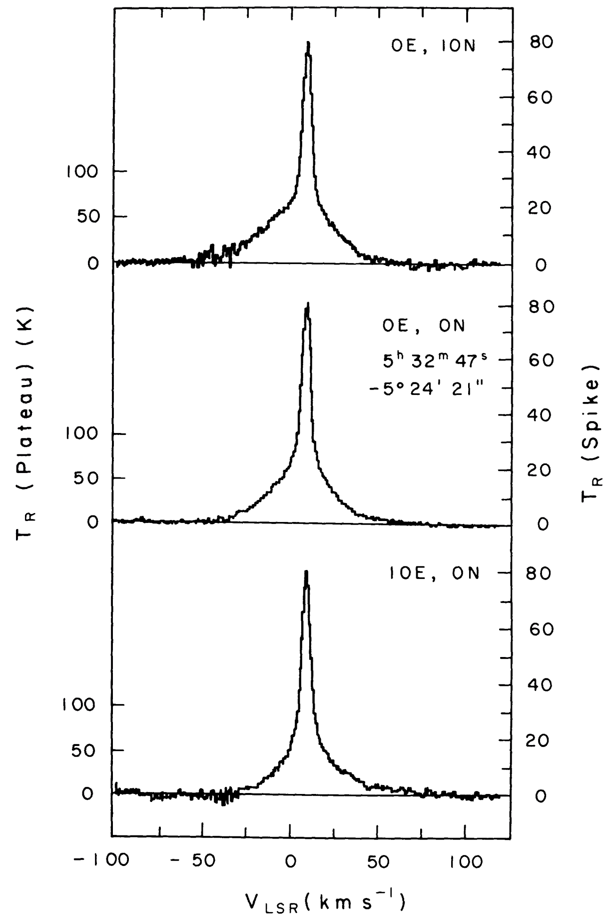

FIG. 1.—Three spectra of CO $J = 3$–2 emission from Orion. The middle panel is taken at the position of IRc2, and the upper and lower panels at the positions of maximum blueshifted and redshifted emission, respectively. The right-hand temperature scale refers to extended emission such as the narrow "spike" feature, while the left-hand scale is applicable to a source of dimensions comparable to the synthesized beam, such as the plateau emission feature.

positions is 10″. The total integration time per spectra was between 2 and 6 minutes, except for the central spectrum toward IRc2 for which the integration time was 16 minutes. In Figure 1 we present three of the spectra from the map; the middle panel shows the spectra obtained toward IRc2, and the upper and lower panels show spectra at the position of the peak redshifted and blueshifted emission, respectively. The calibration and corrections discussed in § II gave a peak radiation temperature for the narrow component (spike) equal to 80 K at the central position of the map. There did not appear to be any significant changes in the intensity of the spike component over the 80″ extent of the region mapped, and we have thus normalized the peak spike radiation temperature to this value at all positions. The radiation temperature scale for the high-velocity dispersion (plateau) emission includes the additional correction appropriate for a source not much larger than the 26″ main beam. The noise level in some of the spectra was increased in the -30 km s^{-1} to -60 km s^{-1} interval due to a problem in the spectrometer-computer interface system.

The emission seen in Figure 1 extends from -55 km s^{-1} to $+70$ km s^{-1}. Thus the displacement of the velocity extremes of the emission is approximately symmetric about the 9 km s^{-1} velocity of the spike, although the shapes of the two wings are different. The center of the emission is located at R.A. (1950) = $5^h32^m47^s$ and decl. (1950) = $-5°24'10''$, approximately 10″ north of IRc2 and 5″ north of the BN object. The limited spatial coverage of our data prevents an accurate determination of the source size, but the apparent half-power size is 40″, which corresponds to a 30″ FWHM size if the source is Gaussian and to a diameter of 39″ if the source is a uniform disk.

In Figure 2 we show a contour map of the integrated redshifted and blueshifted emission treated separately; the map also includes contours of the 2 μm H_2 emission (Scoville 1981) and the location of three prominent infrared sources. Several features are quite striking about the CO emission and its relationship to the H_2 emission and infrared sources. First, there is a clear offset between the peaks of the emission in the two wings. The angular offset is close to 12″ which corresponds to a spatial separation of 0.03 pc. The relative displacement of the redshifted and blueshifted emission peaks strongly suggests that the plateau emission is produced by a bipolar outflow. Second, neither peak nor the centroid of the two peaks coincides with any of the IR sources; the bipolar flow is shifted by 10″ to the northeast relative to IRc2. We feel this difference is outside the limits of our pointing errors. Third, the axis of the bipolar flow coincides with a line connecting peak 1 (to the NW) and peak 2 (to the SE) of the H_2 emission. In addition, the sense of the velocity shift in the CO bipolar flow is the same as the velocity shift between peak 1 and peak 2 of the H_2 emission (Scoville *et al.* 1982) although the velocity pattern of the H_2 is complex. This alignment indicates that the high-velocity CO emission and the H_2 emission are probably closely related. A plausible model is one in which the same bipolar outflow that is responsible for the high-velocity CO emission also produces the H_2 emission by means of shock excitation at the boundary where the flow encounters the dense ambient molecular cloud.

IV. DISCUSSION

The observations reported here indicate that the basic mass motion in the core of Orion is a bipolar outflow. Certain important questions about the flow remain to be answered. The first question concerns how the $J = 3$–2 emission fits in with the emission observed in the numerous other CO transitions. Assuming local thermo-

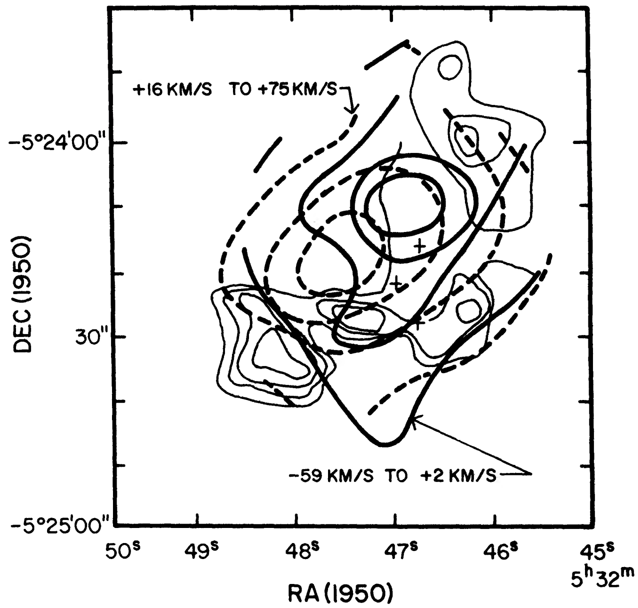

FIG. 2.—Contour maps of the redshifted (*heavy broken lines*) and blueshifted (*heavy continuous lines*) integrated CO $J = 3$–2 emission. The contours are at factors 0.9, 0.8, 0.6, and 0.4 times the peak values of the integrated emission which are 1160 K km s^{-1} for the redshifted gas and 1530 K km s^{-1} for the blueshifted gas. Contours of the 2 μm H_2 emission are indicated as light continuous lines, and the three crosses mark, from north to south, the positions of the BN object, IRc2, and the KL Nebula.

dynamic equilibrium, which is a good assumption for $J < 10$ and densities $\sim 10^6$ cm^{-3} (Goldsmith *et al.* 1980; McKee *et al.* 1982), the absorption coefficient increases approximately as J^2 for the lowest few CO transitions and is maximum for the $J = 6$–5 transition for a kinetic temperature of 100 K. Recent observations of the ^{13}CO $J = 1$–0 and $J = 2$–1 plateau emission (Snell, Scoville, and Sanders 1982) indicate that the ^{12}CO emission in both of these transitions has an optical depth greater than 1. Thus, the submillimeter transitions will have optical depths much greater than 1. These relatively large opacities are reasonable in view of chemical modeling of the shocked gas, which suggests that the fractional abundance of CO will be unchanged by the passage of the shock (Iglesias and Silk 1978; Mitchell and Deveau 1982). Taking $X(\mathrm{CO}) = 10^{-4}$, $n = 2 \times 10^6$ cm^{-3} (Goldsmith *et al.* 1980), and a source size of 0.1 pc, we obtain a CO column density of 6×10^{19} cm^{-2}. For the $J = 3$–2 transition, the absorption coefficient at a kinetic temperature of 100 K is 1.6×10^{-19} cm^2; therefore, the optical depth of this line is estimated to be ~ 10.

Our measurement of ~ 80 K for the radiation temperature in the plateau indicates that the gas temperature is at least 80 K but could be much larger if the beam filling factor is substantially less than unity. Observations of the $J = 6$–5 transition of CO with a 35″ beam size indicate gas temperatures in the plateau in excess of 150 K (Goldsmith *et al.* 1981). Thus, the

$J = 6\text{–}5$ emission must arise from a hotter gas than the $J = 3\text{–}2$ emission. In addition, the far-infrared transitions of CO observed by Storey *et al.* (1981) require a local excitation temperature of 750 K with $N(\mathrm{CO}) \sim 3 \times 10^{17}$ cm^{-2}, the latter being more than an order of magnitude less than that indicated by the millimeter transitions. These observations suggest that a model for the plateau with radial temperature gradients is necessary. Theoretical models of postshock cooling (cf. Kwan 1977) indicate that the temperature will drop to only a few hundred K at $\sim 10^{14}$ cm behind the shock. A consistent model for this source is one in which the far-infrared CO lines are formed in the thin, hot layers immediately behind the shock, where the vibrationally excited H_2 emission is also produced, while the submillimeter and millimeter lines are formed farther behind the shock in the cooler gas. Only in the lowest rotational transitions does the emission we see come from a substantial fraction of the high-velocity gas. The similar spatial extent of the emission in the far-infrared lines (Storey *et al.* 1981) to that of the H_2 emission also is consistent with such a model.

A second question raised by our observations is the relationship of the CO bipolar outflow to the high-density disk seen in interferometric observations of SO by Plambeck *et al.* (1982). Though the disk is offset slightly from the axis of the bipolar CO flow, the picture presented by Plambeck *et al.*, in which the disk is responsible for channeling the outflow into two bipolar lobes, seems reasonable. The two separate outflows observed in the H_2O masers (Genzel *et al.* 1981) may be identified with the expanding SO disk and the bipolar CO flow. Genzel *et al.* point out that the most prominent and stable high-velocity H_2O masers in this region are located northwest and southeast of IRc2 and are thus associated with the CO high-velocity flow, in contrast to the low-velocity masers which are confined to the disk; this distinction is in accord with the model of Elmegreen and Morris (1979). The source that is responsible for the CO bipolar outflow is uncertain. Although the center of the emission we observe does not coincide with any of the known IR sources, it is still possible that density inhomogeneities could allow IRc2 to be responsible for the expanding disk, the bipolar CO flow, and ultimately the H_2 emission.

Finally we can ask how the bipolar flow in Orion relates to bipolar flows seen in the cores of other molecular clouds. Numerous bipolar flows have been detected to date suggesting such events are a common evolutionary stage in the formation of stars. The Orion flow is unique in that it has the largest velocity dispersion and the smallest physical size of any of the known bipolar flows (Snell, Loren, and Plambeck 1980; Rodriguez, Ho, and Moran 1980; Lada and Harvey 1981; Snell and Edwards 1981; Lada and Gautier 1982; Bally 1982). These properties may be due in part to the orientation of the Orion bipolar flow relative to our line of sight, but they are extreme enough to suggest that Orion may be physically different than the other bipolar flows. Examining the known bipolar flows, it is evident that there is an inverse correlation between velocity dispersion and linear size. This correlation may be due to an age effect in which the smallest, hence youngest, flows have the largest velocity dispersion; as the source evolves, the outflow decelerates, and at a later time the bipolar flow is larger but has a smaller velocity dispersion. This comparison of Orion to the other bipolar flows implies that it may be the youngest example of a region in this evolutionary stage.

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Ronna L. Berson, Neal R. Erickson, Paul F. Goldsmith, G. R. Huguenin, and Ronald L. Snell: Five College Radio Astronomy Observatory, GRC Tower B, University of Massachusetts, Amherst, MA 01003

C. J. Lada: Steward Observatory, University of Arizona, Tucson, AZ 85721

B. L. Ulich: Multiple Mirror Telescope Observatory, University of Arizona, Tucson, AZ 85721