THE ASTROPHYSICAL JOURNAL, 337: L45–L48, 1989 February 1

INTERFEROMETRIC $C^{18}O$ OBSERVATIONS OF DR 21(OH) AND L1551 IRS 5 AT $\lambda = 1.4$ MILLIMETERS

S. PADIN, A. I. SARGENT, L. G. MUNDY, N. Z. SCOVILLE, D. P. WOODY, R. B. LEIGHTON, C. R. MASSON, S. L. SCOTT, T. V. SELING, K. R. STAPELFELDT, AND S. TEREBEY
Division of Physics, Mathematics, and Astronomy, California Institute of Technology
Received 1988 August 31; accepted 1988 November 2

ABSTRACT

High-resolution (3″) aperture synthesis maps in the $J = 2 \rightarrow 1$ transition of $C^{18}O$ have been obtained for the star formation regions DR 21(OH) and L1551 IRS 5. Two compact sources, separated by 7″ (0.12 pc), have been discovered at the centers of H_2O maser activity associated with DR 21(OH). Mass estimates from the 1.4 mm continuum and $C^{18}O$ line emission are similar to the 110 $M_{\odot}$ required for a bound system with the observed 4 km s^{-1} radial velocity difference, suggesting that a massive multiple star system is forming. The $C^{18}O$ emission from L1551 IRS 5 is extended in an elongated structure of radius 700 AU and mass 0.1 $M_{\odot}$.

Subject headings: nebulae: H II regions — stars: circumstellar shells — stars: formation — stars: individual (L1551 IRS 5) — stars: pre–main-sequence

I. INTRODUCTION

The construction of sensitive receivers operating in the 1 mm range (see Woody *et al.* 1989) for the 10.4 m Leighton telescopes of the Owens Valley Radio Observatory (OVRO) Millimeter-Wave Interferometer provides the first opportunity for aperture synthesis mapping at 1.4 mm. The improvement in resolution (a factor of 2 over the 2.7 mm band) and significant gain in sensitivity (for given spatial and spectral resolution) allow detailed spatial and kinematic studies. Here, we present the first $C^{18}O$ ($J = 2 \rightarrow 1$) aperture synthesis maps of the star-formation regions DR 21(OH) and L1551 IRS 5.

DR 21(OH) is an area of active star formation located 3′ north of the H II region DR 21 (cf. Harvey *et al.* 1986). Maps at 50 and 100 μm show an extended north-south ridge of dust emission with distinct peaks at DR 21 and DR 21(OH) (Harvey *et al.* 1986). The total infrared luminosity associated with DR 21(OH) is 5×10^4 $L_{\odot}$, assuming a distance of 3 kpc. The high-resolution observations reported here were designed to resolve the spatial structure of the DR 21(OH) nebula and map the kinematics of the gas. L1551 IRS 5 is a heavily obscured, pre–main-sequence star of mass $\lesssim 2.5 M_{\odot}$ (Strom, Strom, and Vrba 1976) and luminosity ~ 35 $L_{\odot}$ (Emerson *et al.* 1984) at a distance of 160 pc. The detection of two oppositely directed streams of high-velocity molecular gas originating at the star has led to the suggestion that the circumstellar material may be distributed in a disk or toroid (Snell, Loren, and Plambeck 1980). High-resolution, 2.2 μm images (Strom *et al.* 1985; Moneti *et al.* 1988) and recent aperture synthesis mapping of the $C^{18}O$ $J = 1 \rightarrow 0$ emission around IRS 5 (Sargent *et al.* 1988) indeed show a flattened, elongated structure with radius $\sim$ 600 AU.

II. RESULTS

Observations in the $C^{18}O$ $J = 2 \rightarrow 1$ line were acquired with the OVRO three-element Millimeter-Wave Array in 1988 March and April. The overall characteristics of the instrument and calibration of the data are described in Woody *et al.* (1989). Two configurations of the 10.4 m telescopes were used, giving a FWHM synthesized beam of 6″.8 × 3″.4 at PA 6° for DR 21(OH); the inclusion of a third configuration produced a circular synthesized beam of diameter 3″.3 (FWHM) for L1551 IRS 5. The field of view of the primary beam is 34″ FWHM. The spectrometer consisted of two 32 channel filterbanks with resolutions of 1 MHz (1.3 km s^{-1}) and 50 kHz (0.65 km s^{-1}). The 1 MHz maps have noise levels of 0.7 Jy per beam (rms) for L1551 IRS 5 and 1 Jy per beam for DR 21(OH). Absolute values of the line fluxes are estimated to be uncertain by about 30%, and absolute positions are accurate to 0.2–0.3 of the synthesized beam size.

Strong $C^{18}O$ emission was detected from the two 1.4 mm continuum sources near DR 21(OH) (Woody *et al.* 1989). A map of the integrated line emission is displayed in Figure 1. The total observed flux is 162 Jy km s^{-1}. Although the individual sources are completely resolved only in the east-west direction, they are clearly separated by 7″ (0.12 pc). The distributions of $C^{18}O$ and 1.4 mm continuum emission agree very well (see Woody *et al.* 1989). Maps at velocities between -6.9 and $+1.1$ km s^{-1} are shown in Figure 2. Blueshifted emission is clearly associated with the northeastern continuum source MM 1, while redshifted emission arises to the southwest near MM 2. Weaker emission at intermediate velocities bridges the intervening region. The peak flux density, 12 Jy per beam (13 K brightness temperature), occurs at -1.0 km s^{-1} and coincides with MM 2.

In L1551 the position of peak $C^{18}O$ intensity moves from south to north as velocity increases (Fig. 3), with the maximum 3.8 Jy per beam (brightness temperature 8.9 K) occurring at 7.0 km s^{-1}. In the map of integrated $C^{18}O$ intensity (Fig. 3*d*), the overall morphology is dominated by emission close to 7.0 km s^{-1} and centered on the unresolved, 1.4 mm continuum peak (Woody *et al.* 1989). The integrated emission is, for the most part, elongated along PA $\sim$ 140° and unresolved in the orthogonal direction. The radius of this elongated structure is about 700 AU, and the total observed flux is 29.1 Jy km s^{-1}. Within the uncertainties, the 1.4 mm line and continuum maxima are spatially coincident with two 2 cm compact continuum sources (Bieging and Cohen 1985; Rodríguez *et al.* 1986).

III. DISCUSSION

Figure 1 summarizes the phenomena observed in the DR 21(OH) region. The two 1.4 mm peaks and the H_2O maser

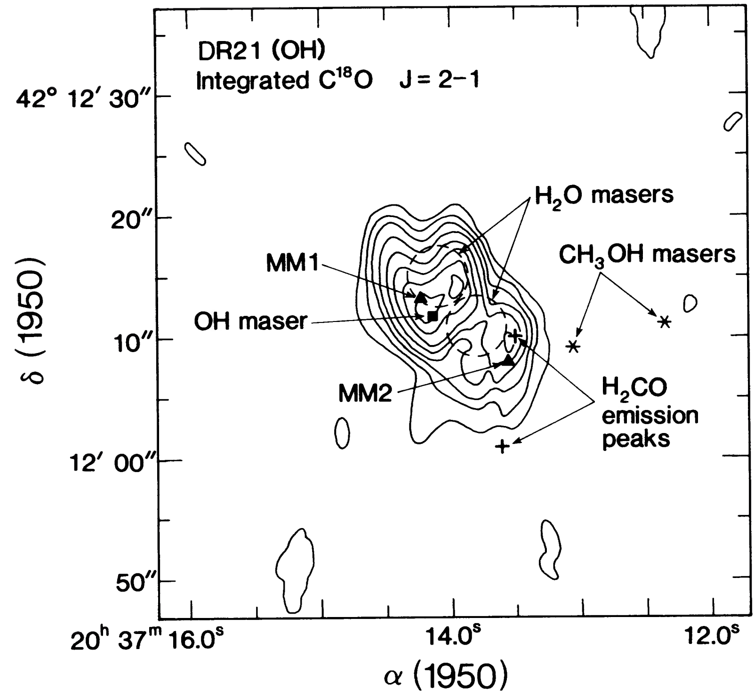

FIG. 1.—The $C^{18}O$ emission integrated over the velocity range of Fig. 2. Contours are in steps of 5 Jy beam km s^{-1}, with maximum 43 Jy per beam km s^{-1}. Positions of the OH (Norris *et al.* 1982), H_2O (Genzel and Downes 1977), and CH_3OH (Batrla and Menten 1988) masers and the H_2CO (Johnston, Henkel, and Wilson 1984) and 1.4 mm continuum peaks are indicated. Positional uncertainties are indicated by the sizes of dashed circles (H_2O masers) and crosses (H_2CO peaks).

emission centers (Genzel and Downes 1977) coincide; MM 1 also coincides with the OH maser (Norris *et al.* 1982). MM 2 corresponds to one of the high-density H_2CO regions (Johnston, Henkel, and Wilson 1984).

The total mass of gas, M_{H_2+He}, in the two sources in DR 21(OH) can be estimated from both the continuum and $C^{18}O$ emission. Modifying the expressions given by Sargent *et al.* (1988) for the $J = 1 - 0$ transition, the mass can be determined from the $C^{18}O$ $J = 2 \rightarrow 1$ observations through

$$M_{H_2+He} = 1.0 \times 10^3 D^2 \frac{(T_{ex} + 0.22)}{e^{-(15.81/T_{ex})}} \frac{(2 \times 10^{-7})}{X_{18}} \frac{\tau_{18}}{1 - e^{-\tau_{18}}} \times \int S_\nu dv\, M_\odot ,$$

where X_{18} is the $C^{18}O$ abundance ratio and the integrated line flux density is in Jy km s^{-1}. For optically thin emission, with $X_{18} = 2 \times 10^{-7}$ and $T_{ex} = 50$ K, the mass for MM 1 and MM 2 is 100 $M_\odot$, consistent with the 125 $M_\odot$ derived from the continuum observations (Woody *et al.* 1989).

The spatial associations of MM 1 and MM 2 with masers and infrared continuum emission suggest that current star formation activity in DR 21(OH) is taking place at these two distinct centers. Their physical separation, 0.12 pc on the sky, is sufficiently small to indicate that they may be gravitationally bound to each other. The minimum mass required by the observed 4 km s^{-1} velocity difference is 110 $M_\odot$, comparable to our estimates. MM 1 and MM 2 could be viewed as a proto–binary star system involving sufficiently massive components, ≈ 15 $M_\odot$, to produce the observed IR luminosity. However, at a distance of DR 21(OH) our observations encompass an area comparable to that subtended by the Trapezium stars in Orion, and many stars may be present. For a normal Salpeter IMF with a 0.1 $M_\odot$ lower limit, the 1500 $M_\odot$ in stars necessary to produce the observed 5×10^4 $L_\odot$ vastly exceeds virial mass estimates for the region. To achieve the observed luminosity with ≤ 100 $M_\odot$ of stars, the IMF lower mass limit must be raised to ~ 6 $M_\odot$, where the stellar mass to luminosity ratio is approximately the same as that observed, $M_{Virial}/L_{IR} = 1/500$ $M_\odot/L_\odot$.

The integrated $C^{18}O$ $(2 \rightarrow 1)$ emission from L1551 IRS 5 (Fig. 3*d*) is similar to that observed in $C^{18}O$ $(1 \rightarrow 0)$ (Sargent *et al.* 1988). Both features are extended over 1400 AU along PA 140°, perpendicular to the CO outflow axis (Snell, Loren, and Plambeck 1979), and are unresolved in the orthogonal direction. Again assuming $T_{ex} = 50$ K and optically thin emission, the $C^{18}O$ $(2 \rightarrow 1)$ observations give a mass of 0.04 $M_\odot$, in good agreement with the 1.4 mm continuum and 2.7 mm line observations (Woody *et al.* 1989; Sargent *et al.* 1988). Observations in the optically thick CO $(1 \rightarrow 0)$ line (Moriarty-Schieven *et al.* 1987) show blueshifted molecular gas, at velocities of 3–5 km s^{-1}, south of IRS 5 and a redshifted component, at velocities of 8–9 km s^{-1}, to the north. Gas at these low velocities is presumably not part of the outflow but rather defines the walls of the cavity constraining the high-velocity gas motions. Thus, the outflow must be collimated within a few arcseconds of the star, as also suggested by radio continuum jets and optical observations (Mundt and Fried 1983; Snell *et al.* 1985).

IV. CONCLUSIONS

Aperture synthesis mapping in the $C^{18}O$ $J = 2 \rightarrow 1$ line has revealed that the continuum sources, MM 1 and MM 2, in DR 21(OH) are separated in velocity by ~ 4 km s^{-1}. The mass required to bind such a system, 110 $M_\odot$, is compatible with masses derived from the 1.4 mm continuum and $C^{18}O$ observations. The MM 1/MM 2 system may represent a proto–

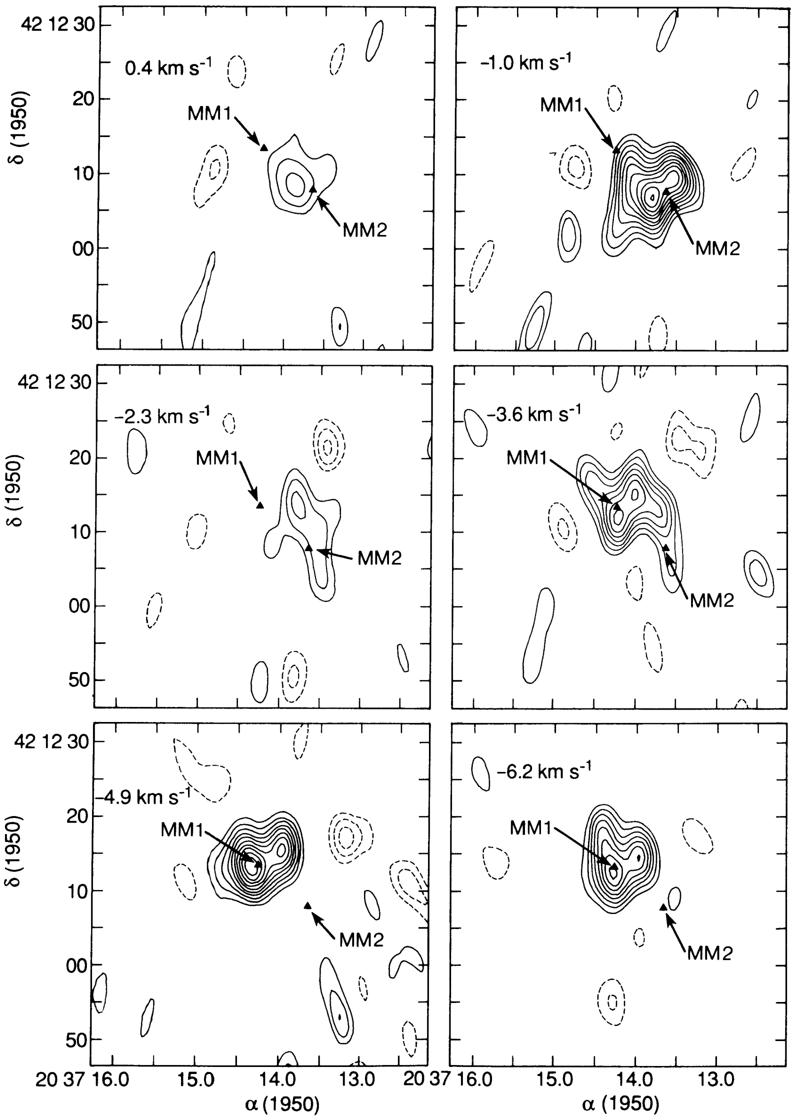

FIG. 2

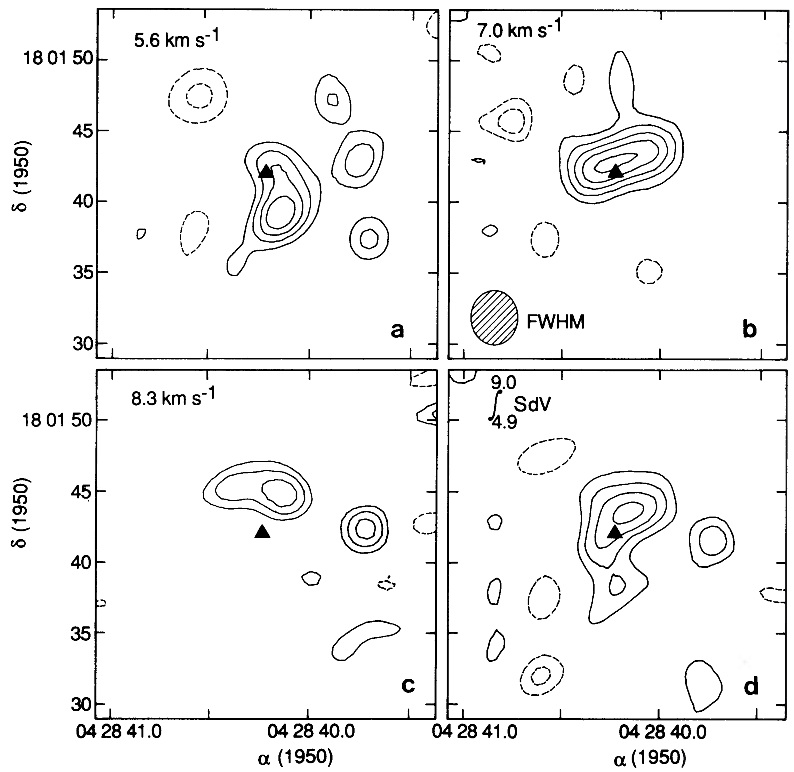

FIG. 3

FIG. 2.—Maps at 1.36 km s^{-1} resolution of the $C^{18}O$ $J = 2$–1 emission from DR 21(OH). Contours are in steps of 1 Jy per beam, starting at 2 Jy per beam. Triangles show the positions of the 1.4 mm dust continuum sources, MM 1 and MM 2 (Woody *et al.* 1989). Due to limited UV coverage, the northwest extension is highly uncertain.

FIG. 3.—Maps of the $C^{18}O$ $J = 2$–1 emission from L1551 IRS 5. Contour levels for the separate velocity maps (*a*)–(*c*) are 0.6 Jy/beam, beginning at 1.2 Jy/beam. For the integrated emission (*d*), contours are spaced by 0.5 Jy per beam km s^{-1} beginning at 1.0 Jy per beam km s^{-1}. A triangle marks the position of the 2 cm continuum sources.

binary or multiple star system. In L1551 IRS 5 an elongated structure of radius 700 AU oriented SE–NW, perpendicular to the outflow axis, is detected at the central velocity.

The junctions used in the SIS receivers were provided by R. E. Miller of AT&T Bell Labs. This work was supported by the NSF Foundation through grant AST 84-12473.

REFERENCES

Batrla, W., and Menten, K. M. 1988, *Ap. J. (Letters)*, **329**, L117.
Bieging, J., and Cohen, M. 1985, *Ap. J. (Letters)*, **289**, L5.
Emerson, J. P., Harris, S., Jennings, R. E., Beichman, C. A., Baud, B., Beintema, D. A., Marsden, P. L., and Wesselius, P. R. 1984, *Ap. J. (Letters)*, **278**, L49.
Genzel, R., and Downes, D. 1977, *Astr. Ap. Suppl.*, **30**, 145.
Harvey, P. M., Joy, M., Lester, D. F., and Wilking, B. A. 1986, *Ap. J.*, **300**, 737.
Johnston, K. J., Henkel, C., and Wilson, T. L. 1984, *Ap. J. (Letters)*, **285**, L85.
Moneti, A., Forrest, W. J., Pipher, J. L., and Woodward, C. E. 1988, *Ap. J.*, **327**, 870.
Moriarty-Schieven, G. H., Snell, R. L., Strom, S. E., Schloerb, F. P., Strom, K. M., and Grasdalen, G. L. 1987, *Ap. J.*, **319**, 742.
Mundt, R., and Fried, J. W. 1983, *Ap. J. (Letters)*, **274**, L83.
Norris, R. P., Booth, R. S., Diamond, P. J., and Porter, N. D. 1982, *M.N.R.A.S.*, **201**, 191.
Rodríguez, L. F., Cantó, J., Torrelles, J. M., and Ho, P. T. P. 1986, *Ap. J. (Letters)*, **301**, L25.
Sargent, A. I., Beckwith, S., Keene, J., and Masson, C. R. 1988, *Ap. J.*, **333**, 936.
Snell, R. L., Bally, J., Strom, S. E., and Strom, K. M. 1985, *Ap. J.*, **290**, 587.
Snell, R. L., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J. (Letters)*, **239**, L17.
Strom, S. E., Strom, K. M., Grasdalen, G. L., Capps, R. W., and Thompson, D. 1985, *A.J.*, **90**, 2575.
Strom, K. M., Strom, S. E., and Vrba, F. J. 1976, *A.J.*, **81**, 320.
Woody, D. P., Scott. S. L., Scoville, N. Z., Mundy, L. G., Sargent, A. I., Padin, S., Tinney, C. G., and Wilson, C. 1989, *Ap. J. (Letters)*, **337**, L41.

R. B. Leighton: Downs Laboratory of Physics 320-47, California Institute of Technology, Pasadena, CA 91125

C. R. Masson, L. G. Mundy, S. Padin, A. I. Sargent, S. L. Scott, N. Z. Scoville, T. V. Seling, K. R. Stapelfeldt, S. Terebey, and D. P. Woody: Owens Valley Radio Observatory 105-24, California Institute of Technology, Pasadena, CA 91125