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SMALL-SCALE STRUCTURE OF THE CIRCUMSTELLAR GAS AROUND L1551 IRS 5

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ABSTRACT

High-resolution (≈3″.5) maps centered on the embedded infrared source, L1551 IRS 5, have been made in the $J = 1$–0 transition of $C^{18}O$, using the Millimeter Wave Interferometer of the Owens Valley Radio Observatory. An elongated concentration of gas, with its long axis ~700 AU in radius, and of mass ~0.1 $M_{\odot}$, has been detected. The orientation is perpendicular to the direction of outflow of the high-velocity molecular gas, suggesting a causal relationship. The observations are consistent with this gas being bound to the star, and the overall properties are fairly similar to those of the HL Tau system. It is not yet possible to establish whether the rotation curve shows Keplerian motion for the gas.

Subject headings: infrared: sources — stars: circumstellar shells — stars: individual (L1551 IRS 5) — stars: pre–main-sequence

I. INTRODUCTION

The object IRS 5 in the L1551 dark cloud is a low-mass, ≲2.5 $M_{\odot}$, pre–main sequence star (Strom, Strom, and Vrba 1976; Emerson *et al.* 1984 and references therein; Cohen *et al.* 1984). Owing to the extremely high opacity of the surrounding material, direct observations of this star are possible only at infrared wavelengths, if at all (see Campbell *et al.* 1988). L1551 IRS 5 is the source of two well-collimated and oppositely directed streams of high-velocity molecular gas, implying an axisymmetric distribution for the circumstellar matter (Snell, Loren, and Plambeck 1980). Indeed, infrared imaging of the scattered light from the star suggests the presence of a flared disk extending at least several hundred AU from IRS 5 (Strom *et al.* 1985; Moneti *et al.* 1988). Such disks around low-mass stars in their early stages of evolution are especially interesting because of their possible connection to planet-forming episodes, similar to that which resulted in our solar system.

There have been several attempts to detect a disk around L1551 IRS 5 via molecular emission lines at millimeter wavelengths, and to establish whether the velocity field is compatible with material being bound to the star. The results to date have been controversial, largely because the spatial resolution has been inadequate to separate gas bound to the star from that in the surrounding cloud. Kaifu *et al.* (1984) interpreted their CS observations as a 2 $M_{\odot}$ "torus" of gas, 2′ in extent—0.1 pc at the 160 pc distance of L1551 (Snell 1981)—orbiting IRS 5. Subsequent observations with improved spatial and velocity resolution (Menten and Walmsley 1985; Batrla and Menten 1985; Moriarty-Schieven *et al.* 1987*a*) failed to confirm this rotation pattern. In addition, Moriarty-Schieven *et al.* (1987*a*) showed that any disk would have to be much smaller than ~30″ (0.02 pc), the resolution of their deconvolved single-dish observations.

VLA radio continuum, far-infrared, and optical observations suggest that collimation of the outflow takes place within 1″ of the star (Cohen, Bieging, and Schwartz 1982; Mundt and Fried 1983; Davidson and Jaffe 1984; Snell *et al.* 1985). Thus, any disk around IRS 5 must indeed be very small and dense. Rodríguez *et al.* (1986) have suggested that two compact sources, separated by only 0″.3 in their very high resolution VLA continuum maps, are the ionized inner part of a confining torus (see also Bieging and Cohen 1985). But these two compact sources are not aligned either parallel or perpendicular to the collimated outflow, further complicating the morphology of the region, and raising doubts as to whether the large-scale bipolar lobes really reflect axisymmetry in the matter distribution close to the star.

At millimeter wavelengths, the continuum emission from IRS 5 is quite compact, ≤3″, also indicating small-scale circumstellar structure (Keene and Masson 1986). Walmsley and Menten (1987) searched for a gaseous counterpart to this compact continuum source and detected $C^{18}O$ emission. However, there was no clear structure at the 22″ resolution of their measurements. If a gaseous disk indeed surrounds this object, it will probably be similar to the disk surrounding the nearby star HL Tauri (Sargent and Beckwith 1987, hereafter Paper I), and angular resolution ≤6″ (0.0047 pc) is necessary to discern its structure.

Here, we present $C^{18}O$ ($J = 1$–0) aperture synthesis maps of L1551 IRS 5. Aside from the obvious advantage to be accrued from higher resolution, interferometric observations make it possible to distinguish small-scale structure against strong, extended emission from a larger scale molecular cloud. Emission from the $C^{18}O$ isotope is more likely to be optically thin, and hence a better measure of the circumstellar gas column density distribution, than CO or ^{13}CO. Of primary interest are three questions raised by the previous work on this object: (1) Is there a clearly identifiable disk around IRS 5? (2) Is the disk axis aligned closely with the collimated outflow? and (3) Does the rotation curve indicate Keplerian orbits for the gas?

II. OBSERVATIONS

The three-element, Millimeter Wave Interferometer of the Owens Valley Radio Observatory was used to observe L1551 IRS 5 in the $J = 1$–0 transition of $C^{18}O$ between 1986 November and 1987 March. The primary beam was 65″ FWHM. Six different configurations of the 10.4 m telescopes, with unprojected baselines ranging from 15 to 200 m, resulted in a FWHM synthesized beam of 2″.6(R.A.) × 2″.5(Decl). Four of these configurations, including unprojected baselines up to only 60 m, produced a circular synthesized beam of diameter

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6″.5 (FWHM). A 32 channel bank of 50 kHz filters, centered at 6.3 km s^{-1}, provided 0.13 km s^{-1} resolution over a 4.16 km s^{-1} band. The cryogenically cooled SIS receivers on each telescope (Woody, Miller, and Wengler 1985) yielded $C^{18}O$ maps with typical root-mean-square (RMS) noise level of 200 mJy $beam^{-1}$ in each 50 kHz channel. Simultaneous broad-band (350 MHz) measurements of the 2.7 mm continuous emission, with RMS noise $\approx$ 5 mJy, were also made and are discussed in a separate paper (Keene and Masson 1988).

For phase calibration, the unresolved continuum sources 0420−014 and 3C 120 were observed at 30 minute intervals. Corrections for atmospheric attenuation and for receiver gain were derived using an ambient temperature chopper wheel. Daily measurements of Mars, Uranus (see Ulich 1981), and 3C 84 established the flux density scale. Following calibration, CLEAN maps were produced from Fourier transforms of the visibilities for each of the channels, using the NRAO software package AIPS. As a result of uncertainties in the phases and in the baseline determinations, the positional uncertainty in an individual map is $\sim$1″. The overall uncertainty in the absolute fluxes is $\sim$20%.

III. RESULTS

Figure 1 shows a gray-scale map of the $C^{18}O$ emission from L1551 IRS 5, integrated over the velocity range 5.6–6.8 km s^{-1}. Very little emission above 200 mJy $beam^{-1}$ was observed outside these velocity limits. Some sacrifice in resolution was made to improve the signal to noise ratio, and Figure 1 results from convolving our 2″.5 resolution maps with a 3″.5 beam. The molecular gas is distributed fairly symmetrically about a cross which marks the position of the 2 cm compact continuum sources detected by Rodríguez *et al.* (1986; see also Bieging and Cohen 1985). The two $C^{18}O$ peaks are separated by 3″.5 $\approx$ 500 AU. Emission extends over $\sim$10″, corresponding to 1500 AU, along an axis joining these peaks. The overall morphology suggests the presence of an elongated, gaseous structure at P.A. $\approx$ 135°, perpendicular to the direction of flow of the high-velocity molecular gas (Snell, Loren, and Plambeck 1980).

More extended $C^{18}O$ emission, and some variation of peak intensity with velocity, are discernible in the maps of Figure 2, at degraded spatial resolution, 6″.5. Each map is an average of two filterbank channels, giving a velocity resolution of 0.26 km s^{-1}. A cross again indicates the position of the compact continuum sources (Rodríguez *et al.* 1986). In all maps, the emission is extended along P.A. $\approx$ 160° and unresolved along the orthogonal axis.

Figure 2*f* shows a map of the integrated $C^{18}O$ intensity at this lower resolution. This map reflects the structure observed in the individual channel maps; emission extends along P.A. $\approx$ 160° for $\sim$23″, 3600 AU, and is unresolved along the minor axis. The highest contour of Figure 2*f*, which encloses the structure seen in Figure 1, is elongated not along

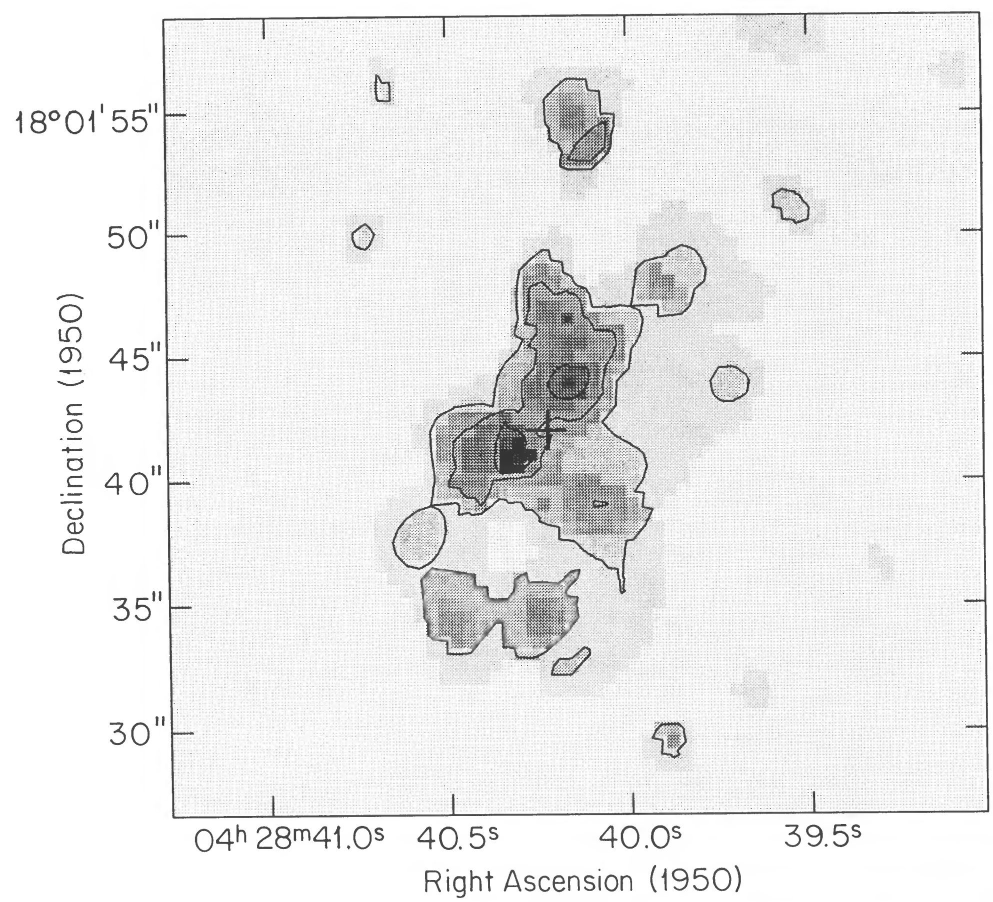

FIG. 1.—A gray-scale, aperture synthesis map of the integrated $C^{18}O$ emission from L1551 IRS 5 at 3″.5 resolution. A cross marks the position of the 2 cm compact continuum sources (Rodríguez *et al.* 1985).

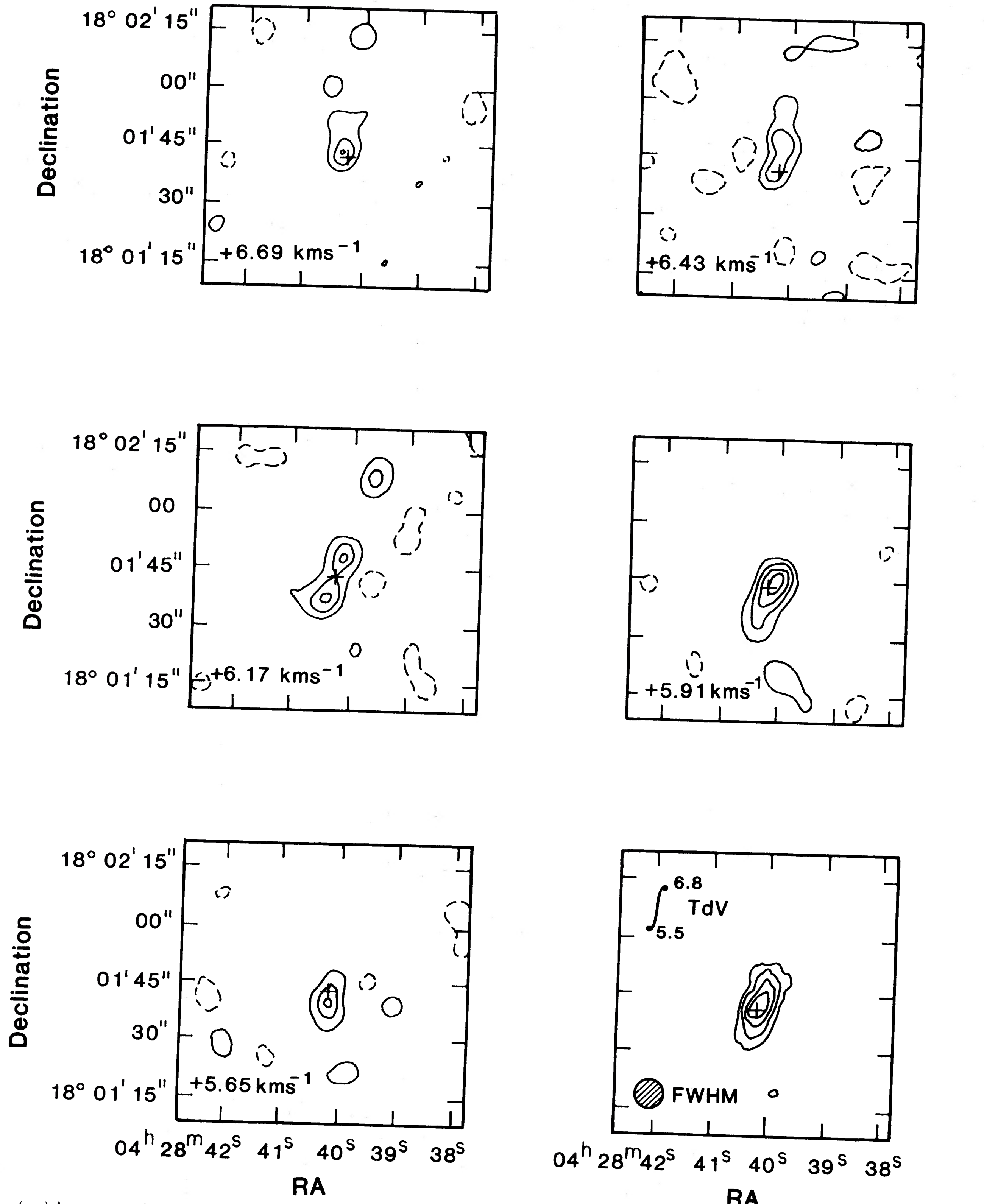

FIG. 2.—(*a–e*) Aperture synthesis maps of the $C^{18}O$ emission from L1551 IRS 5 at different velocities and at 6".5 spatial resolution. The velocity resolution is smoothed to 0.26 km s^{-1}. Contours are spaced by 0.50 Jy $beam^{-1}$, the lowest being 0.50 Jy $beam^{-1}$. (*f*) The integrated emission, similar to Fig. 1, but at 6".5 resolution. In each map, a cross marks the position of the VLA compact continuum sources.

P.A. $\approx 160°$ but along 140°, very similar to the orientation in the first figure.

The positions of maximum intensity in the lower resolution maps of Figures 2*a*, 2*b*, 2*d*, and 2*e* all lie within the boundaries of the compact structure shown in Figure 1. The very small velocity extent of the $C^{18}O$ line, ± 0.6 km s^{-1}, makes it unlikely that the emission reflects mass loss by IRS 5 (see Beckwith *et al.* 1986). Rather, the structure seen in Figure 1 is probably produced by gas bound to the star. Two aspects of Figure 2 suggest the gas is, in fact, in orbit. First, there is a gradual shift of position with velocity from northwest (at velocities ≥ 6.17 km s^{-1}) to southwest (at velocities ≤ 6.17 km s^{-1}) indicative of overall rotation. Second, close to 6.17 km s^{-1} the emission extends further from IRS 5 than at the extreme velocities, where the emission is more confined to the stellar vicinity. Thus, the velocity of the surrounding material does appear to decrease with distance from the star. There is little other evidence, however, of a Keplerian velocity pattern (see, e.g., Paper I), which would establish that the matter is moving in a centrally condensed potential; we shall return to this point in § IV.

We can estimate the mass in the IRS 5 circumstellar disk from the $C^{18}O$ brightness temperature and from judicious choices of the optical depth and excitation temperature, both of which are uncertain. The mean column density of $C^{18}O$ averaged over the beam, N_{18}, is given by

$$N_{18} \approx 4.76 \times 10^{13} \int T_B \frac{(T_{ex} + 0.88)}{e^{-5.27/T_{ex}}} \frac{\tau_{18}}{1 - e^{-\tau_{18}}} dv , \quad \mathrm{cm}^{-2} , \tag{1}$$

where T_B is the observed Rayleigh-Jeans brightness temperature, T_{ex} is the excitation temperature, τ_{18} is the $C^{18}O$ optical depth, and dv is the velocity range expressed in km s^{-1} (see Scoville *et al.* 1986, using molecular constants from Chakerian and Tipping 1983). L1551 is part of the larger Taurus cloud where the visual extinction, A_V, is related to N_{18} through the relation

$$A_V = 1.9 + 5.9 \times 10^{-15} N_{18} \quad \mathrm{mag} \tag{2}$$

(Frerking, Langer, and Wilson 1982), where the first term represents line-of-sight extinction far removed from IRS 5 and is not relevant to our discussion of the circumstellar material. Since N_{H_2}, the column density of molecular hydrogen, is given by $0.94 \times 10^{21} A_V$ (Bohlin, Savage, and Drake 1978), the total mass of molecular hydrogen, M_{H_2}, is therefore:

$$M_{H_2} = 1.20 \times 10^{-7} N_{18} \Omega D^2 \, M_\odot , \tag{3}$$

where Ω is the solid angle (FWHM) subtended by a uniform source and D is the distance in kpc. For L1551, equation (3) becomes

$$M_{H_2} = 3.95 \times 10^{-4} \frac{(T_{ex} + 0.88)}{e^{-5.27/T_{ex}}} \frac{\tau_{18}}{1 - e^{-\tau_{18}}} \int S_\nu dv \, M_\odot , \tag{4}$$

with the integrated line flux density, $\int S_\nu dv$, expressed in Jy km s^{-1}. Neither the optical depth nor the excitation temperature can be determined exactly from the present observations, but a plausible range of masses can be derived using reasonable estimates for these quantities.

Walmsley and Menten (1987), using a 22″ beam, derive a value 0.55 for τ_{18} at L1551 IRS 5. In a 6″ × 4″ beam, Barsony (1987) finds a peak CO temperature of 13.7 K—a lower limit, owing to the unknown filling factor and absorption by the cloud. At similar resolution, the maximum $C^{18}O$ temperature we observe is 6.2 K, leading to $\tau_{18} = 0.6$. We will therefore assume, at least initially, that the $C^{18}O$ emission is optically thin, so $\tau_{18}/(1 - e^{-\tau_{18}})$ is very close to unity.

The excitation temperature of the circumstellar gas is even less certain than the optical depth, but can be constrained to within a factor of ~ 2. The far infrared spectrum indicates a dust temperature greater than 34 K, perhaps even as high as 75 K if most of the flux comes from a region 2″ across (Davidson and Jaffe 1984). Since the $C^{18}O$ is extended over a 10″ region, 75 K is probably an upper limit to the average excitation temperature of the gas. On the other hand, the stellar radiation field, possibly in conjunction with accretion energy, is likely to heat the gas in the disk to temperatures 20 K or greater. High densities in the disk, very much greater than 10^7 cm^{-3}, will couple the dust to the gas so that $T_{ex} \approx T_{dust}$. We have therefore adopted 50 K for the value of T_{ex} with the understanding that a range of temperatures almost certainly contributes to the emission. As shown below, M_{H_2} is not very sensitive to the choice of T_{ex}.

The total flux in the elongated structure seen in Figure 1 is 3.0 Jy km s^{-1}. For $T_{ex} = 50$ K, and optically thin emission, equation (4) implies a mass of 0.07 $M_\odot$. If T_{ex} is as low as 20 K, the mass could be as low as 0.03 $M_\odot$; if $\tau_{18} \gg 0.5$ and the source is compact, it could be considerably greater. The most likely range for the mass (see arguments in Beckwith *et al.* 1986; Paper I) is between 0.05 to 0.2 $M_\odot$, with the greatest uncertainty being in the upper limit.

In a companion paper, Keene and Masson (1988) present images of the 2.7 mm continuum emission from L1551 IRS 5. These allow an independent determination of the circumstellar mass based on the assumption that a large fraction of the continuum emission is thermal radiation from solid particles. The resulting value is ~ 0.5 $M_\odot$, not dissimilar to that derived from the gas emission alone. It seems likely that ~ 0.2 $M_\odot$ is the best estimate for the material contributing to the compact emission very close to the star.

IV. DISCUSSION

a) Circumstellar Gas

The shape and orientation of the $C^{18}O$ emission shown in Figure 1 suggest a gaseous disk, seen almost edge-on, whose axis is along the direction of molecular outflow from the star. The northern extension which is a prominent feature in both CO and ^{13}CO (Keene and Masson 1988; Barsony 1988) is of marginal significance in the $C^{18}O$ map. We believe this feature is not associated with the gas near IRS 5. Presumably in the rarer $C^{18}O$ isotope we can penetrate the intervening cloud and detect the denser circumstellar gas. While the data so far acquired cannot rule out the possibility of different orientations on subarcsecond scales, we argue below that they favor the existence of a circumstellar disk whose axis is aligned with the outflow direction.

The radius of the emission, ~ 700 AU, and position angle of the $C^{18}O$ peaks, $\sim 135°$, are similar to those of the dust disk proposed by Strom *et al.* (1985) to explain the distribution of scattered light in 2 μm images of IRS 5. These authors estimate a particle mass in this disk of between 2 and 5×10^{-5} $M_\odot$, leading to a gas mass $\lesssim 5 \times 10^{-3}$ $M_\odot$, if the gas/dust mass ratio is 100 as in the general interstellar medium. The millimeter observations of IRS 5, like those of HL Tau, sample a much greater mass than the infrared measurements; evidently, only a small fraction of the surrounding material scatters light from IRS 5.

Figure 2 shows weak evidence for rotation—the emission shifts from northwest to southeast with decreasing velocity, the most extreme velocities showing the most compact emission. There is, however, no compelling evidence for a decrease in gas velocity with increasing projected distance from the star, as was the case in HL Tau and as would be expected if these velocities reflect Keplerian rotation. It is possible that opacity variations along the line of sight to this edge-on disk confuse a clear signature. The IRS 5 structure is also generally more compact than that around HL Tau; gas actually orbiting the star may not extend beyond the limiting resolution, 6".5, making it difficult to observe a rotation curve.

In L1551 IRS 5, the small velocity range over which $C^{18}O$ has been observed does imply that the gas is bound to the star. In fact, for Keplerian orbits about a 2.5 $M_\odot$ star (see below), the peaks in Figure 1 are somewhat closer to the IRS 5 than would be expected from their velocities. The Keplerian velocity at 250 AU (half the separation of the $C^{18}O$ peaks) from a 2.5 $M_\odot$ object is 3 km s^{-1}, far larger than the ± 0.6 km s^{-1} shift from 6.17 km s^{-1} seen in Figure 2. In the appendix to Paper I, we showed that this effect can be understood as a distortion of the position of maximum emission caused by projection effects from gas at small radii moving obliquely to the line of sight. The positional distortion is strongest when the velocity resolution is not much greater than the velocity shifts observed, as is the case here, and it can easily create positional uncertainties of factors of 2 or more. In addition, because of strong velocity gradients, the distribution of the highest velocity material is smeared and probably too weak to map.

It is not clear whether this effect by itself is enough to account for the large discrepancy between the observed and anticipated velocities near IRS 5. The problem is exacerbated by assuming the disk mass itself is near the stellar mass, as suggested by the models of Adams, Lada, and Shu (1986); the small line width suggests a more modest disk than used in theoretical models. Coupled with the uncertainties in the stellar mass (discussed below), the present observations are probably just consistent with orbital motion.

From the position of IRS 5 relative to theoretical evolutionary tracks for quasi-static contraction toward the main sequence in the HR diagram (Stahler, Shu, and Taam 1980), Cohen *et al.* (1984) estimate an upper limit to the stellar mass of 2.5 $M_\odot$. This mass is very uncertain: its derivation depends almost entirely on the spectral type of the star, a very difficult quantity to estimate for an object which is virtually obscured and whose spectra are of the FU Orionis type (Carr, Harvey, and Lester 1987; Mundt *et al.* 1985). Moreover, the infrared spectrum indicates much of the 25–38 $L_\odot$ luminosity (Fridlund *et al.* 1980; Cohen *et al.* 1984; Emerson *et al.* 1984) may result from accretion of gas onto a circumstellar disk (Adams, Lada, and Shu 1987), rather than from quasi-static contraction of the star itself.

The attributes of L1551 IRS 5 are therefore reminiscent of the HL Tau system, where 0.1 $M_\odot$ of circumstellar gas appears to be distributed in a disk of radius $\approx$2000 AU and orbiting a 1.0 $M_\odot$ star (Paper I). The long axis of the HL Tau disk is perpendicular to the axis of the optical jet emanating from the star (see Mundt, Brugel, and Bührke 1987). The properties derived from observations in CO and its isotopes—gas masses, velocity ranges, and distributions—are very similar in the two systems, even though the optical and infrared opacity of the IRS 5 disk are vastly greater than those of HL Tau. This suggests that the axis of the disk around IRS 5 lies in the plane of the sky, whereas the HL Tau disk is slightly inclined (see also Beckwith *et al.* 1988). There could also be more material in the extended region around IRS 5, creating higher CO and ^{13}CO opacities, and probably reflecting a lesser age.

b) Extended Emission

More extended structure is evident in the lower resolution maps of Figure 2, but the total mass remains dominated by emission within 700 AU of IRS 5. This structure (see Fig. 2*f*) is oriented somewhat differently, P.A. 160°, from the more compact feature, P.A. 135° (Fig. 1). It is notable that the orientation of the minor axis of the compact $C^{18}O$ emission is the same as that of the ionized gas within 3" of IRS 5 (Snell *et al.* 1985).

The CS gas detected by Kaifu *et al.* (1984) is also extended along P.A. 160°, but over a much larger area. Moriarty-Schieven *et al.* (1987*a*) demonstrated that this elongated CS emission in fact reflects a ridge of enhanced emission in a very large feature, several arcminutes long, which delineates the northwest limb of the CO outflow (see also Moriarty-Schieven *et al.* 1987*b*). The extended emission visible in our low-resolution maps is considerably more diffuse than the central concentration defined in Figure 1 and is similarly oriented to the larger scale cloud structure. We therefore suggest that it is a small-scale component of the 2' ridge described above.

That the ridge persists on fairly small scales is also indicated by 8" aperture, near-infrared polarization measurements (Nagata, Sato, and Kobayashi 1983). These can be explained by the presence of a flattened dust feature whose long axis is aligned with P.A. $\approx$ 160°. The considerable optical depth, which results in decreased $C^{18}O$ emission at 6.17 km s^{-1} in the direction of IRS 5, and the high visual extinction to IRS 5 (Snell *et al.* 1985) suggests that these 2 μm observations sample the polarization field of the ambient cloud rather than that of the central core.

c) Collimation of the Outflow

A conservative estimate for the axial ratio of the disk is 3:1 based on the appearance of $C^{18}O$ emission in Figure 1. Assuming 0.1 $M_\odot$ is distributed over a cylindrical volume, 700 AU in radius and 230 AU thick, the density of molecular hydrogen, n_{H_2}, is 5×10^7 cm^{-3}. If the distribution is more highly flattened—and on theoretical grounds thin disks are more likely (see Shu, Adams, and Lizano 1987)—the density could be considerably higher, especially at small radii where the disk thickness decreases owing to the greater influence of the stellar gravity. Arguments based solely on the relative extinctions northeast and southwest of IRS 5 also indicate that the density must be at least 10^6 cm^{-3}. Thus, even 700 AU from the star, the gas density is probably high enough to resist disruption by the stellar wind and, as suggested by various authors, to channel mass loss (e.g., Snell *et al.* 1985).

Rodríguez *et al.* (1986) argue that the two compact components in the ionized gas near IRS 5, which are separated by 0".3 along a line at P.A. 190°, define the inner edge of a torus of gas collimating material lost by the star. This model, requiring reorientation of the outflow, is less convincing in light of the new observations. The most compact $C^{18}O$ emission extends mainly along an axis at P.A. 135° and veers toward a more north-south distribution, P.A. 160°, at large distances from the star. These results are compatible only with a highly warped structure, rotating from P.A. 190°, to 135°, to 160° at increasing distance from the star. On the other hand, over tens of arcminutes, the molecular outflow is along P.A. $\sim 45°$ (Snell, Loren, and Plambeck 1980), and the diffuse ionized gas within a few tenths of arcseconds from the star—presumably associated with the outflow—is similarly aligned (Snell *et al.* 1985). As a consequence, it is natural to assume that the axis of any disk or torus must lie along the same direction, making the disk plane P.A. $\approx 135°$. Resolution of this issue must await observations of the velocity field at $\lesssim 1''$ from IRS 5.

Evidently, the interaction between the dense material bound to IRS 5 and the outflow is complex. The different orientations sensed through such varied components as the neutral and ionized gas emission and scattered light from small particles, have led to suggestions of precessing disks, reorientation of the outflow by material at different distances from the star, matter confined by toroids, or emission filling the bowls created by warped disks. The $C^{18}O$ observations presented here show that the dense gas bound to the star defines a direction perpendicular to the large-scale outflow, unambiguously suggesting a disk whose axis is parallel to this outflow, at least down to a scale of a few hundred AU from the star. Perhaps the complications introduced by observations of ionized gas and scattered light near the star arise because these observations sample only a small fraction of the material in the circumstellar region, whether that be in mass outflow or material orbiting the star.

Since gas distributions with similar morphologies and velocity patterns to those of L1551 IRS 5 and HL Tau are expected to precede the formation of planetary systems, a better understanding of the properties of these putative protoplanetary disks should shed considerable light on the development of the solar system. As a result, it is important to establish whether the behavior of the gas surrounding L1151 IRS 5 is similar to that anticipated for the primitive solar nebula.

V. CONCLUSIONS

Aperture synthesis maps in the $C^{18}O$ $J = 1\text{–}0$ line at $2''.5$ resolution show that L1551 IRS 5, the source of a well-documented, highly collimated, bipolar molecular outflow, is surrounded by a flattened, disk-like distribution of gas. The radius, ~ 700 AU, and mass, $\sim 0.1\ M_{\odot}$ are similar to those of the putative protoplanetary disk around HL Tau. Although the present observations are compatible with the gas being bound to IRS 5, it was impossible to establish whether the gas velocities clearly decrease with distance from the star, as would be the case for orbital motion.

Slightly lower resolution, $6''.5$, resolution maps of the source show that, even at projected distances of only 1500 AU ($10''$) from IRS 5, the velocity of the gas is typical of the larger scale cloud from which the star presumably collapsed. *IRAS* observations have been interpreted as implying that many nearby ($D \lesssim 30$ pc) stars are surrounded by protoplanetary material (Aumann 1985); our results suggest that this material can be detected only at high angular resolution, even in the most proximate pre–main-sequence stars.

An adequate determination of the density and velocity distribution of the circumstellar gas around L1551 IRS 5 will require the highest resolution achieved here, $\lesssim 2''.5$, and increased sensitivity. Interferometric observations at wavelengths 1 mm or less would greatly improve the spatial resolution and sensitivity to line emission from warm gas, albeit at the expense of increasing line optical depth. Observations at these short wavelengths might determine unambiguously if the L1551 IRS 5 system is a further example of a nascent planetary system,

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REFERENCES

Adams, F. C., Lada, C. J., and Shu, F. H. 1987, *Ap. J.*, **312**, 788.
Aumann, H. H. 1985, *Pub. A.S.P.*, **97**, 885.
Barsony, M. 1988, in preparation.
Batrla, W., and Menten, K. M. 1985, *Ap. J.* (*Letters*), **298**, L19.
Beckwith, S., Sargent, A. I., Koresko, C. D., and Weintraub, D. A. 1988, *Ap. J.*, submitted.
Beckwith, S., Sargent, A. I., Scoville, N. Z., Masson, C. R., Zuckerman, B., and Phillips, T. G. 1986, *Ap. J.*, **309**, 755.
Bieging, J., and Cohen, M. 1985, *Ap. J.* (*Letters*), **289**, L5.
Bohlin, R. C., Savage, B. D., and Drake, J. F. 1978, *Ap. J.*, **224**, 132.
Campbell, B., Persson, S. E., Strom, S. E., and Grasdalen, G. L. 1988, *A.J.*, **95**, 1173.
Carr, J. S., Harvey, P. M., and Lester, D. F. 1988, *Ap. J.*, in press.
Chakerian, Z. Z., and Tipping, X. Z. 1983, *J. Molec. Spectrosc.*, **99**, 431.
Cohen, M., Bieging, J. H., and Schwartz, P. R. 1982, *Ap. J.*, **253**, 707.
Cohen, M., Harvey, P. M., Schwartz, R. D., and Wilking, B. A. 1984, *Ap. J.*, **278**, 671.
Davidson, J. A., and Jaffe, D. T. 1984, *Ap. J.* (*Letters*), **277**, L13.
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.
Frerking, M., Langer, W. K., and Wilson, R. 1982, *Ap. J.*, **262**, 590.
Fridlund, C. V. M., Nordh, H. L., van Duinen, R. J., Aalders, J. W. G., and Sargent, A. I. 1980, *Astr. Ap.*, **91**, L1.
Kaifu, N., Suzuki, S., Hasegawa, T., Morimoto, M., Inatani, J., Nagane, K., Miyazawa, K., Chikada, Y., Kanzawa, T., and Akabane, K. 1984, *Astr. Ap.*, **134**, 7.
Keene, J., and Masson, C. R. 1988, in preparation.
Menten, K. M., and Walmsley, C. M. 1985, *Astr. Ap.*, **146**, 369.
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., and Grasdalen, G. L. 1987*a*, *Ap. J.* (*Letters*), **317**, L95.
Moriarty-Schieven, G. H., Snell, R. L., Strom, S. E., Schloerb, F. P., Strom, K. M., and Grasdalen, G. L. 1987*b*, *Ap. J.*, **319**, 742.
Mundt, R. Brugel, E. W., and Bührke, T. 1987, *Ap. J.*, **319**, 275.
Mundt, R., and Fried, J. W. 1983, *Ap. J.* (*Letters*), **274**, L83.
Mundt, R., Stocke, J., Strom, S. E., Strom, K. M., and Anderson, E. R. 1985, *Ap. J.* (*Letters*), **297**, L41.
Nagata, T., Sato, S., and Kobayashi, Y. 1983, *Astr. Ap.*, **119**, L1.
Rodríguez, L. F., Cantó, J., Torrelles, J. M., and Ho, P. T. P. 1986, *Ap. J.* (*Letters*), **301**, L25.
Sargent, A. I., and Beckwith, S. 1987, *Ap. J.*, **323**, 294 (Paper I).
Scoville, N. Z., Sargent, A. I., Sanders, D. B., Claussen, M. J., Masson, C. R., Lo, K. Y., and Phillips, T. G. 1986, *Ap. J.*, **303**, 416.
Shu, F. H., Adams, F. C., and Lizano, S. 1987, *Ann. Rev. Astr. Ap.*, **25**, 23.
Snell, R. L. 1981, *Ap. J. Suppl.*, **45**, 121.

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.
Stahler, S. W., Shu, F. H., and Taam, R. E. 1980, *Ap. J.*, **241**, 637.
Strom, S. E., Strom, K. M., Grasdalen, G. L., Capps, R. W., and Thompson, D. A. 1985, *A. J.*, **90**, 2575.
Strom, K. M., Strom, S. L., and Vrba, F. J. 1976, *A.J.*, **81**, 320.
Ulich, B. L. 1981, *A. J.*, **86**, 1618.
Walmsley, C. M., and Menten, K. M. 1987, *Astr. Ap.*, **179**, 231.
Woody, D. P., Miller, R. E., and Wengler, M. J. 1985, *IEEE Trans. MTT.*, **MTT 33**, 90.

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