SUBMILLIMETER ARRAY OUTFLOW/DISK STUDIES IN THE MASSIVE STAR-FORMING REGION IRAS 18089-1732

H. BEUTHER,¹ T. R. HUNTER,¹ Q. ZHANG,¹ T. K. SRIDHARAN,¹ J.-H. ZHAO,¹ P. SOLLINS,¹ P. T. P. HO,^{1,2}

N. Ohashi,² Y. N. Su,² J. Lim, and S.-Y. Liu²

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ABSTRACT

Submillimeter Array observations of the massive star-forming region IRAS 18089–1732 in the 1 mm and 850 μ m band reveal outflow and disk signatures in different molecular lines. The SiO (5–4) data show a collimated outflow in the northern direction. In contrast, the HCOOCH₃ (20–19) line, which traces high-density gas, is confined to the very center of the region and shows a velocity gradient across the core. The HCOOCH₃ velocity gradient is not exactly perpendicular to the outflow axis but between an assumed disk plane and the outflow axis. We interpret these HCOOCH₃ features as originating from a rotating disk that is influenced by the outflow and infall. On the basis of the (sub)millimeter continuum emission, the mass of the central core is estimated to be around 38 M_{\odot} . The dynamical mass derived from the HCOOCH₃ data is 22 M_{\odot} , of about the same order as the core mass. Thus, the mass of the core indicate a low dust opacity index $\beta \sim 1.2$ in the outer part, decreasing to $\beta \sim 0.5$ on shorter spatial scales.

Subject headings: accretion, accretion disks — ISM: individual (IRAS 18089-1732) — ISM: jets and outflows — stars: formation — submillimeter — techniques: interferometric

1. INTRODUCTION

Unambiguous proof for disks in massive star formation is still missing. Millimeter continuum observations suggest flattened structures without providing velocity information (e.g., Shepherd et al. 2001), and molecular line studies suggest rotational motions but are often confused by outflows and/or ambient gas (e.g., Zhang et al. 1998; Beuther et al. 2004). Maser studies show disk signatures in some cases but are mostly not unambiguous as well (e.g., Churchwell 2002). The best evidence yet for genuine disk emission comes from CH₃CN observations in IRAS 20126+4104 (Cesaroni et al. 1999). In this case, the velocity gradient defining the presence of the disk is aligned perpendicular to the bipolar outflow, consistent with the common disk/jet paradigm. To further investigate possible disk emission and its association with molecular jets, we used the Submillimeter Array (SMA) to observe the jet tracer SiO (5-4) and the hot-core tracer HCOOCH₃ (20-19) in a massive star-forming region.

The source IRAS 18089–1732 is a young high-mass protostellar object (HMPO) that has been studied in detail over recent years. The source is part of a sample of 69 HMPOs selected mainly via infrared color-color criteria and the absence of strong centimeter emission (Sridharan et al. 2002). IRAS 18089–1732 is approximately at a distance of 3.6 kpc,³ and its bolometric luminosity is about $10^{4.5} L_{\odot}$ (Sridharan et al. 2002). Millimeter continuum observations reveal a massive core greater than 2000 M_{\odot} with H₂O and CH₃OH maser emission, and a weak 1 mJy source is detected at 3.6 cm (Beuther et al. 2002a, 2002c). As part of a single-dish CO outflow study, wing emission indicative of molecular outflows was detected, but the CO map was too confused to define a bipolar outflow (Beuther et al. 2002b). During these observations, Beuther et al. (2002b) also observed SiO (2–1) at 3 mm, and bipolar structure was detected in the north-south direction. Furthermore, Sridharan et al. (2002) reported the detection of the hot-core–tracing molecules CH_3CN and CH_3OH . This Letter focuses on the jet/disk observations and the (sub)millimeter continuum data. A description of the line forest observed simultaneously is presented in an accompanying Letter (Beuther et al. 2004).

2. THE SUBMILLIMETER ARRAY

IRAS 18089-1732 was observed with the SMA⁴ between 2003 May and July in two different configurations with 3-5 antennas in the array. The phase reference center of the observations was $R.A. = 18^{h}11^{m}51.4$ (J2000.0) and decl. = $-17^{\circ}31'28''.5$ (J2000.0). The frequency was centered on the SiO (5–4) line at 217.105 GHz; the HCOOCH₃ (20–19) line at 216.967 GHz could be observed simultaneously in the same band. The HCOOCH₃ line consists of eight distinct components but is dominated by four of them that are separated by 2.5 MHz (corresponding to 3.5 km s^{-1}). The correlator bandwidth at that time was 1 GHz with a frequency resolution of 0.825 MHz. We smoothed the SiO (5-4) data to a spectral resolution of 3 km s⁻¹ and the HCOOCH₃ (20–19) data to 2 km s⁻¹ to increase the signal-to-noise ratio (S/N). The continuum was constructed via averaging the line-free channels in the upper sideband. The beam size at 217 GHz was $2^{"}_{...7}$ × 1".7 and at 354 GHz 1".4 \times 0".9. System temperatures in the 850 μ m band were between 300 and 900 K and in the 1 mm band around 200 K. The continuum rms at 217 GHz was ~8 mJy and at 354 GHz ~40 mJy. The flux calibration was estimated to be accurate to 25%. For more details on the SMA, the observations, and data reduction, see the accompanying Letters by Ho et al. (2004) and Beuther et al. (2004).

¹ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

² Academia Sinica Institute of Astronomy and Astrophysics, 1 Roosevelt Road, Section 4, Taipei 106, Taiwan.

³ The kinematic distance ambiguity is solved by associating the region via the near- and mid-infrared Two Micron All Sky Survey and *Midcourse Space Experiment* on larger scales with sources of known distance (S. Bontemps 2003, private communication).

⁴ The SMA is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.



FIG. 1.—Gray scale (with dotted contours) showing the SMA 1.3 mm continuum emission in both panels. *Left*: Heavy contours the SMA 850 μ m continuum emission and the 850 μ m synthesized beam. *Right*: Centimeter continuum emission and H₂O (*triangle*) and CH₃OH (*square*) maser position (taken from Beuther et al. 2002c) and the 1.3 mm synthesized beam.

3. RESULTS

3.1. Dust Continuum Emission

Figure 1 compares the (sub)millimeter continuum observations and shows additional centimeter continuum and H₂O and CH₃OH maser data (Beuther et al. 2002c). Even in the highest spatial resolution data at 850 μ m, the dust emission remains singly peaked; i.e., it does not split up into multiple sources as observed in other massive star-forming regions, e.g., IRAS 19410+2336 (Beuther & Schilke 2004). Nevertheless, in our 1 mm data we resolve elongated emission in the south and northwest, which demonstrates that IRAS 18089-1732 has a compact millimeter core with extended halo emission (Fig. 1). The halo emission is not seen in the 850 μ m observations because of the reduced sensitivity and u-v coverage. While the weak 3.6 cm peak and the H₂O maser position coincide exactly with the (sub)millimeter continuum peak, the CH₃OH maser position is about 1".4 to the south. The latter could indicate that there might be a second source at the position of the CH₃OH maser that we cannot distinguish. Table 1 shows the derived peak and integrated fluxes (\tilde{S}_{peak} and S_{int}) at 1 mm and 850 μ m. Comparing the SMA 1 mm data with single-dish observations of the region (Beuther et al. 2002a), we find that about 85% of the flux is filtered out in the interferometric data.

It is difficult to derive a spectral index from the continuum images because the different u-v coverages filter out different amounts of flux. However, we can measure fluxes S_{u-v} in the

 TABLE 1

 (Sub)Millimeter Continuum Data

Parameter	1.3 mm ^a	$850 \ \mu m^a$	$oldsymbol{eta}^{\mathrm{a}}$
S_{neak} (mJy)	690	1410	
$S_{\text{int}}^{\text{int}}$ (mJy)	1360	1900	
$S_{u-v}(20-40 \text{ k}\lambda) \text{ (mJy)} \dots$	600	2870	1.2
$S_{u-v}(60-80 \text{ k}\lambda) \text{ (mJy)} \dots$	360	1240	0.5
$M (M_{\odot}) \dots$	38		
$N (10^{23} \text{ cm}^{-2}) \dots$	8.2		

^a Uncertainties are discussed in the main text.

^b S_{int} is measured within the 2 σ contour levels.

u-v plane. Ideally, one would select the same regions in the *u-v* plane, but as this would reduce the amount of available data even more, it is reasonable to compare the values for matching baseline ranges (in units of $k\lambda$). We selected one range of short baselines (20–40 k λ , corresponding to spatial scales between 10".7 and 5".4) and one range of longer baselines (60–80 k λ , corresponding to spatial scales between 3".6 and 2".7) where there were sufficient data in both frequency bands: the flux values are shown in Table 1. The 3.6 cm flux is only 0.9 mJy (Sridharan et al. 2002), and assuming free-free emission its contribution to the sub(millimeter) observations is negligible. Assuming a power-law relation $S \propto v^{2+\beta}$ in the Rayleigh-Jeans limit with the dust opacity index β , we find $\beta \sim 1.2$ for short baselines corresponding to large spatial scales and $\beta \sim 0.5$ for large baselines corresponding to small spatial scales. These values are lower than the canonical value of 2 (Hildebrand 1983) and decrease to small spatial scales. The exact values should be taken with caution because of the large calibration uncertainty (estimated to be within 25%), but the trend of a low β decreasing with decreasing spatial scales appears real. Without mapping the selected sets of u-v data in the image plane, we cannot determine whether the smaller spatial scales correspond to the central core or to another unresolved structure. However, the 850 μ m continuum image, which is based on larger baselines, is more compact than the 1.3 mm emission (Fig. 1), indicating that the largest baselines do trace the emission from the core center. A low value of β has also recently been found in another high-mass star-forming region (Kumar et al. 2003), and Hogerheijde & Sandell (2000) report that β decreases in L1489 from 1.5 to 2 in the envelope down to $\beta = 1$ at the inner peak. This trend may be due to grain growth within the central core/disk or high optical depth.

Assuming optically thin dust emission at millimeter wavelength, we calculate the mass and peak column density using the 1.3 mm data following the procedure outlined for the single-dish dust continuum data by Beuther et al. (2002a). We use a grain emissivity index $\beta = 1$ and a temperature typical for hot-core–like sources of 100 K. The central core mass then is ~38 M_{\odot} and the peak column density ~8 × 10²³ cm⁻², corresponding to a visual ex-

tinction A_v (mag) = $N_{\rm H_2}/(10^{21} \text{ cm}^{-2}) \sim 800$. As discussed by Beuther et al. (2002a), the errors are dominated by systematics, e.g., exact knowledge of β or the temperature. We estimate the masses and column densities to be correct within a factor of 5.

3.2. The Outflow in SiO

Figure 2 presents a channel map of SiO (5–4), and we find blue and red emission (systemic velocity 34.9 km s⁻¹; § 3.3) north of the continuum core. The SiO emission by itself allows an interpretation of a bipolar outflow centered 2"–3" north of the core. However, we do not detect any submillimeter continuum source there (850 μ m 1 σ mass sensitivity ~1 M_{\odot}), and a massive outflow without a submillimeter continuum source at the driving center is very unlikely. Therefore, we favor the interpretation of an outflow emanating from the core toward the north with a position angle (P.A.) of ~20°. The fact that we see blue and red SiO emission toward the northern lobe indicates that the outflow axis is near the plane of the sky. For the red lobe, we find an increase in velocity with distance from the center of the core resembling the Hubble law within molecular outflows (e.g., Downes & Ray 1999).

Previous unpublished single-dish SiO (2-1) observations with 29" resolution also show a bipolar outflow in the northsouth direction. The main difference is that the southern part of the SiO (2-1) outflow is not observed at the higher frequency and higher spatial resolution with the SMA. We can attribute this difference to several possible reasons. First, interferometers filter out the large-scale emission, and without additional short spacing information, only the more compact jetlike emission is detected with the SMA. Second, the excitation of the 5-4transition is higher with respect to the 2-1 transition. While the SiO (2–1) line traces the lower temperature gas, the SiO (5-4) line is sensitive to the more excited gas being associated with the more collimated component of the outflow. Furthermore, an asymmetry in the small-scale distribution of the dense gas can also contribute to the differences of the large-scale SiO (2–1) and small-scale SiO (5–4) observations.

3.3. HCOOCH₃ Tracing the Disk?

The high-density gas tracing molecular $HCOOCH_3$ (20–19) emission is confined to the central core traced by the (sub)millimeter continuum (Fig. 2). A Gaussian fit to the central spectrum results in a systemic velocity of \sim 34.9 km s⁻¹, and we observe a velocity gradient across the core. It is possible to fit the peak position of each spectral channel shown in Figure 2 to a higher accuracy than the nominal spatial resolution, down to 0.5 HPBW/(S/N) (Reid et al. 1988). We performed these fits in the *u*-*v* plane to avoid artifacts due to inverting and cleaning the data; the resulting positions are shown in Figure 3. The derived velocity gradient follows a P.A. of ~55°($\pm 10^{\circ}$) from blue to red velocities. The separation of the most blue and most red positions is ~ 0 ".6, corresponding to ~2200 AU. Figure 3 also presents a position-velocity diagram for the fitted channels at the P.A. of 55° confirming the spacevelocity shift. This velocity gradient is neither in the direction of the SiO outflow nor directly perpendicular to it.

A velocity gradient due solely to a rotating disk would be perpendicular to the outflow. The SiO outflow is near the plane of the sky, complicating an accurate determination of its P.A., and the outflow might also be affected by precession (e.g., IRAS 20126+4104; Shepherd et al. 2000). Regarding the HCOOCH₃ emission, it is unlikely that this high-density tracer depicts a different outflow that would remain undetected by



RA offset (arcsec; J2000) RA offset (arcsec; J2000) RA offset (arcsec; J2000)



FIG. 2.—SiO (5–4) (*top*) and HCOOCH₃ (*bottom*) channel maps. The gray scale outlines the 850 μ m continuum emission. At the bottom left of each panel, the filled ellipses show the 850 μ m beam and the unfilled ellipses the 1.3 mm beam. LSR velocities (in units of kilometers per second) are given in the top left corner of each panel. The LSR velocities for HCOOCH₃ are calculated with respect to the line component at 216.9662 GHz; the systemic velocity is ~34.9 km s⁻¹.

the SiO. Therefore, we regard neither the partially uncertain outflow P.A. nor a second outflow as sufficient to explain the difference in P.A. between the SiO and the HCOOCH₃ emission. However, as shown in an accompanying Letter (Beuther et al. 2004), most molecular line data are influenced by the molecular outflow, and it is likely that HCOOCH₃ is also affected by the outflow. Furthermore, Ohashi et al. (1996) have shown that infall can influence the dense gas velocity signature as well. Assuming that the inner core contains a rotating disk, which has an orientation perpendicular to the outflow, and that the HCOOCH₃ velocity signature is influenced by the disk, the outflow, and infall, it is plausible that the observed axis of the HCOOCH₃ velocity gradient is offset from the expected disk orientation. We do not observe the inner region of the disk where the outflow/jet is accelerated, but we may have detected the outer parts of the accretion disk.

Assuming equilibrium between centrifugal and gravitational forces at the outer radius of the disk, we calculate the dynamical mass enclosed within the central 0% to be ~22 $M_{\odot}/\sin^2 i$ (with



FIG. 3.—Presented are the position-position (*P-P*) and position-velocity (*P-V*) diagrams of HCOOCH₃. The offsets in the *P-P* plot were fitted in the *u-v* plane for each velocity channel presented in Fig. 2. The positions delineate the P.A. of 55°, and the error bars represent statistical errors of the fits. The open pentagon marks the position of the 1.3 mm continuum peak. The offsets in the *P-V* diagram are offsets from the continuum center position along the assumed disk plane (P.A. = 55°).

i the unknown inclination angle between the disk plane and the line of sight, and an HCOOCH₃ velocity shift⁵ of 4.25 km s⁻¹), of the order of the core mass derived from the dust emission (Table 1). Thus, in contrast to T Tauri systems where the disk mass is negligible compared with the protostellar mass, in IRAS 18089–1732 a considerable fraction of the enclosed mass seems to be part of a large accretion disk and/or rotating envelope. This result fits the picture that IRAS 18089–1732 is in a very young evolutionary state, with the central (proto)star still accreting material from the surrounding core/disk.

4. DISCUSSION

The combined SiO (5-4) and HCOOCH₃ (20-19) observations toward IRAS 18089-1732 support a massive star formation scenario where high-mass stars form in a similar fashion as their low-mass counterparts, i.e., via disk accretion accom-

⁵ The full-width zero intensity is 12 km s⁻¹. Taking into account the four dominant HCOOCH₃ line components spanning 3.5 km s⁻¹ (§ 2), the HCOOCH₃ velocity shift is (12 - 3.5)/2 = 4.25.

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panied by collimated jets/outflows. The HCOOCH₃ observations still barely resolve the disk/envelope structure, and the interpretation is not entirely unambiguous, but the data indicate rotation that might stem at least partly from an accretion disk. Higher resolution observations in different disk tracers are needed to investigate the disk/envelope conditions in more detail. Furthermore, the continuum data indicate a lower β than the standard value of 2, and we observe a decreasing β with decreasing spatial scales. As nearly all the gas observed in dust emission takes part in the assumed dynamical rotation observed in HCOOCH₃ this low β might be due to grain growth or high opacity within a disklike structure (e.g., Beckwith et al. 2000).

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