TWO BIPOLAR OUTFLOWS AND MAGNETIC FIELDS IN THE MULTIPLE PROTOSTAR SYSTEM L1448 IRS 3

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ABSTRACT

We present spectral line observations of CO J = 2 → 1, 13CO J = 1 → 0, and C18O J = 1 → 0 and polarimetric observations in the λ = 1.3 mm continuum and in CO J = 2 → 1 toward the multiple protostar system L1448 IRS 3, using the BIMA array. In the λ = 1.3 mm continuum, two sources (IRS 3A and 3B) were clearly detected with estimated envelope masses of 0.21 and 1.15 M⊙, and one source (IRS 3C) was marginally detected with an upper mass limit of 0.03 M⊙. In CO J = 2 → 1, we revealed two outflows originating from IRS 3A and 3B. The masses, mean number densities, momentums, and kinetic energies of outflow lobes were estimated. Based on those estimates and outflow features, we conclude that the two outflows are interacting and that the IRS 3A outflow is nearly perpendicular to the line of sight. In addition, we estimate the velocity, inclination, and opening of the IRS 3B outflow using Bayesian statistics. Linear polarization was detected in both the λ = 1.3 mm continuum and CO J = 2 → 1. The linear polarization in the continuum shows a magnetic field at the central source (IRS 3B) perpendicular to the outflow direction, and the linear polarization in the CO J = 2 → 1 was detected in the outflow regions either parallel or perpendicular to the outflow direction. Moreover, we comprehensively discuss whether the binary system of IRS 3A and 3B is gravitationally bound, based on the velocity differences detected in 13CO J = 1 → 0 and C18O J = 1 → 0 observations and on the outflow features. The specific angular momentum of the system is estimated as ~3 × 1026 cm2 s−1, comparable to the values obtained from previous studies of binary stars and molecular cloud cores.

Subject headings: ISM: individual (L1448 IRS 3) — magnetic fields — polarization — stars: winds, outflows

1 INTRODUCTION

L1448 is a dark cloud located approximately 1° southwest from NGC 1333 in the Perseus cloud complex at a distance of ~250 pc (e.g., Enoch et al. 2006). Three infrared sources were observed by the Infrared Astronomical Satellite (IRAS) and denoted as IRS 1, IRS 2, and IRS 3 by Bachiller & Cernicharo (1986). Due to its brightness in the IRAS bands, IRS 3 has been focused on more than the others. Meanwhile, Bachiller et al. (1990, 1995) revealed a well-collimated, large outflow originating from L1448-mm, located 70° southeast of L1448 IRS 3. In fact, IRS 3 is overlapped by the blueshifted lobe of the outflow. Curiel et al. (1990) detected the L1448-mm continuum source and two sources separated by 7″ in the L1448 IRS 3 region using the Very Large Array (VLA) at λ = 6 and 2 cm wavelengths. They named the sources L1448 C (for Center) and L1448 N(A) and N(B) (for North), for L1448-mm and the two sources in IRS 3, respectively. Terebéy & Padgett (1997) detected another source 20″ northwest of the two IRS 3 sources at λ = 2.7 mm continuum, using the Owens Valley Radio Observatory (OVRO) millimeter interferometer. Looney et al. (2000) resolved all three sources in IRS 3 with high-resolution Berkeley-Illinois-Maryland Association (BIMA) observations at λ = 2.7 mm continuum. In this paper, we call these sources L1448-mm and L1448 IRS 3A, 3B, and 3C, using IAU nomenclature.

In addition to the multiplicity of young sources in L1448 IRS 3, multiple outflows in the region have been suggested in previous studies. Bachiller et al. (1990, 1995) suggested an outflow originating from IRS 3B, since they detected a redshifted component in the blueshifted lobe of the L1448-mm outflow and since IRS 3B is the brightest source at millimeter wavelengths. In contrast, Curiel et al. (1990) suggested that the outflow was driven by IRS 3A, based on a spectral index of 0.2, similar to thermal jet models (e.g., Reynolds 1986), and coincident H2O maser observations. Davis & Smith (1995) and Eisloeffel (2000) presented H2 emission images showing shocked regions. They suggested up to three outflows in the IRS 3 region from collimated features in the images. Several Herbig-Haro objects were also detected and explained as outflows driven by the three IRS 3 sources (Bally et al. 1997). Wolf-Chase et al. (2000) suggested two outflows from IRS 3A and 3B, based on previous studies and their large-scale maps of CO J = 1 → 0 emission. Moreover, Girart & Acord (2001) reported a well-collimated redshifted component detected along a line of position angle 110° from IRS 3B in the SiO J = 2 → 1 emission. These previous studies, however, could not clearly show the outflow features relative to the sources due to a lack of angular resolution and the inherent complexity of the region.

Theoretical studies have suggested that magnetic fields play key roles in the outflows of protostars, as well as star formation itself. Observations of magnetic field morphology and strength are possible using the Zeeman effect (e.g., Crutcher 1999) and linear polarization of dust emission and spectral lines (e.g., Girart et al. 1999). Crutcher et al. (2004) recently estimated the magnetic field strength, as well as morphology, from linear polarization of dust emission in three prestellar cores (starless cores) using the Chandrasekhar-Fermi method (Chandrasekhar & Fermi 1953). In the case of magnetic fields related to protostars (Class 0 sources) with outflows, Girart et al. (1999) detected linear polarization in the λ = 1.3 mm dust emission and in the CO J = 2 → 1 spectral line. Their study was unique for low-mass protostars with outflows.

In this paper, we present polarimetric observations in the λ = 1.3 mm continuum and in CO J = 2 → 1 showing two outflows and magnetic fields in the L1448 IRS 3 region, using the BIMA array...
array. The $^{13}$CO $J = 1 \rightarrow 0$ and $^{18}$O $J = 1 \rightarrow 0$ observation results are also presented. Using these $^{13}$CO and $^{18}$O observations, we argue that the binary system of L1448 IRS 3A and 3B is gravitationally bound.

2. OBSERVATION AND DATA REDUCTION

We performed $\lambda = 1.3$ mm continuum and CO $J = 2 \rightarrow 1$ polarimetric observations toward L1448 IRS 3, using 9 of the 10 antennas in the BIMA array$^3$ (Welch et al. 1996). The data were obtained on 2003 October 17, 25, 26, and November 13 in C configuration and integrated for 9 hr, except October 17, which was integrated for 3 hr due to weather. To get $\lambda = 1.3$ mm continuum data, as well as the CO $J = 2 \rightarrow 1$ spectral line, a correlator mode with 8 windows of 100 MHz bandwidth each in both sidebands was used. This mode gives $\sim 4$ km s$^{-1}$ channel width for the CO $J = 2 \rightarrow 1$ spectral line. The first window of the upper sideband was centered at the rest frequency of CO $J = 2 \rightarrow 1$, 230.538 GHz. The synthesized beam, obtained through natural weighting, is around $2.5' \times 4.5'$.

0237+288 was used as a secondary flux calibrator as well as a phase calibrator; Uranus was the primary flux calibrator. We set the 0237+288 flux of all data sets to the value determined from Uranus, observed on October 25, the best data set. As the 0237+288 flux is not variable in such a short period (40 days), it is the most consistent combination of the data. The flux of 0237+288 estimated by the primary flux calibrator is 1.33 Jy; our flux calibration is estimated at a 20% absolute uncertainty.

Each antenna of the BIMA array has a quarter-wave plate in the front of the linearly polarized feed for polarimetric observations. The quarter-wave plate gives left (L) or right (R) circular polarizations, and the cross correlations (LL, RR, LR, RL) enable the calculation of the Stokes parameters. To obtain quasi-simultaneous measurements of dual polarizations, antennas switch to measure L or R circular polarization following a fast Walsh function. The data are averaged over the Walsh cycle. The details of the BIMA polarimetric instrument can be found in Rao (1999). In the polarimetry observations, instrumental leakage must be compensated. The leakage terms are $\sim 5\%$ at $\lambda \sim 1$ mm and constant until quarter-wave plates are reinstalled (Rao 1999; Rao et al. 1998). In addition, they are strongly dependent on frequency. We used SC279 data observed on 2003 March 4 at the same frequency (230.538 GHz) to get the leakage terms.

MIRIAD (Sault et al. 1995) was used to reduce our data. First, we applied gains obtained from calibrators and constructed models for each observation date. Data of each observation date were self-calibrated with the model constructed from their own data. After combining the individually self-calibrated data, we constructed a combined model. Finally, all data were individually self-calibrated again with this model and combined to the final result. $^{13}$CO $J = 1 \rightarrow 0$ ($\nu_{\text{rest}} = 110.201$ GHz) and $^{18}$O $J = 1 \rightarrow 0$ ($\nu_{\text{rest}} = 109.782$ GHz) data were obtained on 2004 April in C configuration of the BIMA array. These two spectral lines were observed simultaneously with a channel width of $\sim 1$ km s$^{-1}$ and synthesized beam size of $\sim 8'' \times 7''$. Uranus was used as a primary flux calibrator and 0336+323 as a phase calibrator and a secondary flux calibrator. The estimated 0336+323 flux was 1.65 Jy. Again, this flux calibration is estimated at a 20% absolute uncertainty.

Submillimeter continuum observations of L1448 IRS 3 at 850 $\mu$m were accessed from the James Clerk Maxwell Telescope (JCMT) data archive. They had originally been observed with SCUBA (Holland et al. 1999) on the JCMT on Mauna Kea, during the evenings of 1999 August 28 (6 pointings), 2000 January 3 (7 pointings), and 2000 February 24 (2 pointings). SCUBA was used with the SCUBAPOL (Greaves et al. 2003) polarimeter, which uses a rotating half-wave plate and fixed analyzer. The wave plate is stepped through sixteen positions (each offset from the last by 22.5') and a Nyquist-sampled image (using a 16 point jiggle pattern) is taken at each wave plate position (Greaves et al. 2003). The observations were carried out while chopping the secondary mirror $120''$ in azimuth at 7 Hz and synchronously detecting the signal, thus rejecting sky emission. The integration time per point in the jiggle cycle was $1$ s in each of the left and right telescope beams of the dual-beam chop. The total on-source integration time per complete cycle was 512 s. The instrumental polarization (IP) of each bolometer was measured on the planets Mars and Uranus. This was subtracted from the data before calculating the true source polarization. The mean IP was found to be $0.93\% \pm 0.27\%$. The submillimeter zenith opacity for atmospheric extinction removal was determined by comparison with the 1.3 mm sky opacity (Archibald et al. 2002).

3. DUST CONTINUUM EMISSION

Looney et al. (2000) revealed three Class 0 sources in this region in the $\lambda = 2.7$ mm continuum with high-resolution BIMA observation and denominated as L1448 IRS 3A, 3B, and 3C (hereafter IRS 3A, 3B, and 3C). Note that some authors used L1448 N(A), N(B), and NW, respectively (Terebey & Padgett 1997; Barsony et al. 1998). Ciardi et al. (2003) reported a mid-infrared ($\sim 10$–25 $\mu$m) observation of IRS 3A and 3B. They suggested that IRS 3A and 3B are Class I and Class 0 sources, respectively, based on a comparison of the envelope and central source masses. On one hand, IRS 3A and 3B could be a “coeval” binary system with different central masses and so be evolving at different rates. On the other hand, they may be evolving at a same rate under different environments due to interaction, a mass flow from one to the other. Although we do not focus on distinguishing the two cases, we discuss the binarity (i.e., if the two sources are gravitationally bound) later, which is a basis for the two ideas.

Figure 1 shows the observed $\lambda = 1.3$ mm continuum image. IRS 3A and 3B are distinct, but IRS 3C is marginally detected. The vectors in Figure 1 indicate the linear polarization direction, which will be discussed in § 7. The locations of IRS 3A, 3B, and 3C in Figure 1 are from Looney et al. (2000). Table 1 summarizes locations, fluxes, and estimated masses of the three sources. To estimate the mass of the circumstellar material (envelopes and disks), we assume optically thin dust emission and a uniform envelope dust temperature of 35 K,

$$F_{\nu} = B_{\nu}(T_{\text{dust}})\kappa_{\nu}M_{\text{tot}}D^{-2},$$

where $B_{\nu}$ is a blackbody intensity of a temperature $T_{\text{dust}}$, $\kappa_{\nu}$ is a mass absorption coefficient, $M_{\text{tot}}$ is the total mass of gas and dust, and $D$ is the source distance. We assume a mass absorption coefficient, $\kappa_{\nu} = 0.005$ cm$^2$ g$^{-1}$ at $\lambda = 1.3$ mm. The mass absorption coefficient was acquired following a dust emissivity model of a power law ($\kappa_{\nu} \sim \lambda^{-\beta}$) with $\beta = 1$. Dust emissivity studies of submillimeter wavelengths suggested $\lambda^{-1}$ dependence in circumstellar disks and dense cores rather than $\lambda^{-2}$.

$^3$ The BIMA Array was operated by the Berkeley-Illinois-Maryland Association under funding from the National Science Foundation. BIMA has since combined with the Owens Valley Radio Observatory millimeter interferometer, moved to a new higher site, and was recommissioned as the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in 2006.
Isotopic observations such as $^{13}$CO and C$^{18}$O are used to trace denser regions and to verify their optical depth. However, we do not follow the standard procedure because the masses of envelopes are better estimated using our dust emission data, especially in the case of complicated regions like IRS 3. Also, these isotopes may not trace outflows. Instead, we use the optical depth results of Bachiller et al. (1990) deduced from CO $J = 1 \rightarrow 0$ and CO $J = 2 \rightarrow 1$, and follow their procedures to estimate the outflow masses in § 5.2.

5. CO $J = 2 \rightarrow 1$ OBSERVATION

5.1. Bipolar Outflows

As introduced in § 1, one, two, or up to three outflows have been suggested for this region. Bachiller et al. (1990) proposed that an outflow in the east-west direction originates from IRS 3, based on a redshifted component that was detected in the region of the blueshifted lobe of the L1448-mm outflow. Recently Wolf-Chase et al. (2000) suggested outflows of position angle 150$^\circ$ and 129$^\circ$ from IRS 3A and 3B, respectively, using their large-scale CO $J = 1 \rightarrow 0$ observation as well as previous studies of H$_2$ observations and Herbig-Haro objects. In addition, Girart & Acord (2001) presented a redshifted SiO component along a line of position angle 110$^\circ$ from IRS 3B. However, to date there were no observations with enough angular resolution to clearly identify outflows with sources. Here we present high angular resolution BIMA observations to illustrate outflows in IRS 3. We reveal two outflows from IRS 3A and 3B, but no outflow from IRS 3C, based on channel maps and integrated intensity maps.

Figure 4 shows the CO $J = 2 \rightarrow 1$ channel maps with a velocity range from +29 to −36 km s$^{-1}$. The values in the upper left of each panel indicate the channel central velocities in units of km s$^{-1}$ and the two lines in each panel show our determined directions of the two outflows originating from IRS 3A and 3B. As introduced in § 4, the $V_{\text{LSR}}$ of these sources is around 5 km s$^{-1}$, which is located at the boundary between the +7 and +3 km s$^{-1}$ channels.

The outflow of IRS 3A is mainly shown in two channels around $V_{\text{LSR}}$, +7 and +3 km s$^{-1}$ channels, with symmetric features across the central source. Some redshifted components of the IRS 3A outflow also appear in the +15 and +11 km s$^{-1}$ channels. The feature might be just an elongated cloud. However, the $^{13}$CO and C$^{18}$O maps indicating ambient clouds do not show such features. In addition, the facts that two channels of +7 and +3 km s$^{-1}$ show a shape very similar to each other, that two redshifted channels of +15 and +11 km s$^{-1}$ have blobs on both sides of IRS 3A, and that H$_2$ emission observations reveal a string of H$_2$ knots in a consistent direction (Davis & Smith 1995; Eisloffel 2000) strongly suggest that it is an outflow nearly perpendicular to the line of sight.

### TABLE 1

| Source           | $\alpha$ (J2000.0)$^a$ | $\delta$ (J2000.0)$^a$ | Flux (Jy) | Mass ($M_\odot$) | $n(H_2)$ (cm$^{-3}$) |
|------------------|------------------------|------------------------|-----------|-----------------|---------------------|
| L1448 IRS 3A     | 03 25 36.532           | +30 45 21.35           | 0.196 ± 0.019 | 0.21 ± 0.02              | 3.7 x 10$^7$        |
| L1448 IRS 3B     | 03 25 36.339           | +30 45 14.94           | 1.094 ± 0.027 | 1.15 ± 0.03              | 4.8 x 10$^7$        |
| L1448 IRS 3C     | 03 25 35.653           | +30 45 34.20           | <0.031     | <0.03            | <8.1 x 10$^7$        |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ The positions are from Looney et al. (2000).

$^b$ Mean number density represented by hydrogen molecules. The volumes are estimated as spheres with diameters of 5", 8", and 2" for 3A, 3B, and 3C, respectively.
originating from IRS 3A. The position angle of the IRS 3A outflow is 155°.

As shown in Figure 4, the outflow from IRS 3B appears from the +23 km s⁻¹ channel, an end channel of a redshifted lobe, along the position angle of 105°. This position angle is consistent with the Girart & Acord (2001) estimate of 110°. The redshifted lobe is clearly seen from the +23 to +11 km s⁻¹ channels and overlaps the southern lobe originating from IRS 3A in the +7 and +3 km s⁻¹ channels. Note that the blueshifted channels after +3 km s⁻¹ look complicated, with many blobs. This can be
explained by the overlap with the blueshifted outflow lobe of L1448-mm, located 70" southeast. Indeed, its velocity range is consistent with these channels (see Fig. 10 in Bachiller et al. 1990). Due to the complexity in blueshifted channels, the outflow direction is deduced from the redshifted channels first. However, we can still see the blueshifted components of the IRS 3B outflow up to +30 km s\(^{-1}\) along the 105° position angle. In addition, a string of three blobs along the outflow direction is shown in the -5.2 km s\(^{-1}\) channel. The blobs in the +15 and +11 km s\(^{-1}\) channels can be the opposite components of these three blobs.

Figure 5 is an integrated intensity map of CO \(J = 2 \rightarrow 1\) that more clearly shows the outflows. The red contours represent a velocity range from +25 to +9 km s\(^{-1}\), black contours from +9 to +1 km s\(^{-1}\), and blue contours from +1 to -32 km s\(^{-1}\). Again, the blue contours appear with several blobs due to the effect of the overlapped blueshifted lobe of the L1448-mm outflow. This integrated intensity map confirms two outflows originating from IRS 3A and 3B as suggested from channel maps. Black contours in Figure 5 show an outflow from IRS 3A and especially the redshifted and blueshifted lobes around IRS 3B are clearly seen.

5.2. Mass, Momentum, and Energy

Bachiller et al. (1990) showed that the outflow regions in IRS 3 are optically thin in CO, using CO \(J = 2 \rightarrow 1\) and \(J = 1 \rightarrow 0\) lines instead of the CO isotopes \(^{13}\)CO or \(^{18}\)O, since the outflow regions are not dense enough to be traced by these isotopic observations. In addition, they estimated the excitation temperature of CO. As described in Bachiller et al. (1990), the CO column density can be estimated from the integrated intensity, assuming optically thin emission and level populations in local thermal equilibrium at the excitation temperature \(T_{21}\),

\[
\frac{N(\text{CO})}{\text{cm}^{-2}} = 1.06 \times 10^{13} T_{21} \exp (16.5/T_{21}) \times \int T_R(2 - 1) d\left(\frac{v}{\text{km s}^{-1}}\right).
\]

To estimate the masses of the lobes, we assume a typical abundance of CO, \(\text{CO}/\text{H}_2 = X(\text{CO}) \sim 10^{-4}\), optically thin CO emission in outflow regions, and a CO excitation temperature of 11 K,
Fig. 5.—Integrated intensity map of L1448 IRS 3. Red, black, and blue contours represent velocity ranges from +25 to +9 km s$^{-1}$ (4 channels), from +9 to +1 km s$^{-1}$ (2 channels), and from +1 to –32 km s$^{-1}$ (6 channels), respectively. The three subimages on the right have the same velocity ranges as the main panel with the same contour levels, size scale, etc., but they are separated for easier comparison. The synthesized beam is 4.75 $\times$ 2.5 and P.A. = –24.4. Black contours mainly show the IRS 3A outflow and red and blue contours mainly represent redshifted and blueshifted lobes of the IRS 3B outflow. Blue contours look complicated due to redshifted components of the L1448-mm outflow. Contour levels are 3, 5, 7, 9, 11, 13, 17, 21, 25, 29, 35, 41, and 49 times 2.3 Jy beam$^{-1}$ km s$^{-1}$.

as reported by Bachiller et al. (1990). These assumptions give the mass estimate equation,

$$M_{\text{lobe}} = 2m_{\text{H}}A_{\text{lobe}}10^4 N(\text{CO})$$

$$= 2m_{\text{H}}5.23 \times 10^{-5} \frac{D^2}{2k} \int \frac{F_{\text{lobe}}[\text{CO}(2 - 1)]}{\text{Jy}} \, d(v_{\text{km s}^{-1}})$$

$$= 3.22 \times 10^{-6} M_{\odot} \left( \frac{D}{250 \text{ pc}} \right) \int \frac{F_{\text{lobe}}[\text{CO}(2 - 1)]}{\text{Jy}} \, d(v_{\text{km s}^{-1}}),$$

(3)

where $A_{\text{lobe}} = \Omega D^2$ is the lobe area and $F_{\text{lobe}}$ is the total lobe flux density. The mass estimates are summarized in Table 2, with momentum and kinetic energy. Note that the errors tabulated are only statistical errors. Moreover, important uncertainties like CO opacities and unknown three-dimensional geometry of outflows affect these outflow mass estimates (Lada 1985; Bachiller et al. 1990). In the case of the blueshifted lobes, there is also the uncertainty from the contribution of the L1448-mm outflow.

We also need to consider that interferometric observations resolve out flux from extended structures. The missing flux makes mass estimates of extended structures difficult and underestimated. On the other hand, interferometry is a powerful technique that can reveal small structures overlapped with large-scale emission. In this case, L1448 IRS 3 is overlapped with the large blueshifted lobe of the L1448-mm outflow. Therefore, we have the advantage of minimizing the L1448-mm outflow contamination, as well as the disadvantage of losing the flux of extended features. The $u$-$v$ coverage of our observations allows us to recover flux up to $15''$ structures. The missing flux is less significant in elongated structures because it also depends on the size scales of the minor axis.

Compared to the single dish observations (beam size $\sim 12''$) of Bachiller et al. (1990) there is no significant missing flux in the redshifted wing ($\gtrsim 10$ km s$^{-1}$); the flux is consistent within the uncertainties. The low-velocity components (0 to 10 km s$^{-1}$) are dominated by the ambient cloud (Bachiller et al. 1990). Since our two channels in that velocity range still show outflow features consistent with the redshifted channels (see Fig. 4), we argue that the majority of missing flux comes from the ambient cloud emission. From this point of view, the missing flux is a large advantage, as it avoids contamination with the ambient cloud emission, rather than a disadvantage. On the other hand, the channel with $-1.1$ km s$^{-1}$ central velocity may experience relatively large flux loss, as the IRS 3B outflow feature disappears or is indistinct from the extended, and mostly resolved out, blueshifted lobe of the L1448-mm source. The missing flux in this channel would cause an underestimation of the IRS 3B outflow mass but does not significantly affect our interpretations. We discuss the effects caused by the missing flux in this channel later. Overall, although the true size of the emission is unknown, we conclude that the missing flux probably does not significantly affect our results.

We estimate the masses of the northern and the southern lobes of the IRS 3A outflow as $0.70 \times 10^{-3}$ and $1.12 \times 10^{-3} M_{\odot}$, respectively. Considering that the southern lobe overlaps with a

| Parameter | Red-North | Red-East | Black-North | Black-South | Blue-West |
|-----------|-----------|----------|-------------|-------------|----------|
| Outflow flux (Jy km s$^{-1}$) | 47.47 ± 1.43 | 101.6 ± 1.55 | 168.7 ± 1.75 | 347.3 ± 2.01 | 304.2 ± 4.36 |
| Mass ($10^{-3} M_{\odot}$) | 0.153 ± 0.005 | 0.327 ± 0.005 | 0.543 ± 0.006 | 1.12 ± 0.006 | 0.980 ± 0.014 |
| Mean no. density ($10^5$ cm$^{-3}$) | 6.6 | 6.9 | 7.0 | 5.9 | 9.2 |
| Momentum ($10^{-3} M_{\odot}$ km s$^{-1}$) | 1.2 | 3.5 | 0.43, –0.64$^a$ | 1.1, –1.1 | –18 |
| Kinetic energy ($10^{41}$ ergs) | 1.0 | 4.4 | 0.22 | 0.44 | 38 |

$^a$ Components in Fig. 5 as contour colors and positions.

$^b$ This lobe has two components, one from the IRS 3A outflow and the other from the IRS 3B outflow.

$^c$ Mean number density represented by hydrogen molecules. Cylinders along outflows are assumed to estimate the volumes. The assumed diameters and lengths of the cylinders are 575 and 1355, 600 and 1970, 800 and 1755, 1170 and 2370, and 1070 and 1575. Note that these are not mean number densities indicating the whole outflow lobes, but partial components of the lobes. For example, the mean number density of the northern lobe of the IRS 3A outflow would be 6.6 + 7.0 = 13.6 (10$^5$ cm$^{-3}$), assuming the two components occupy the same region.

$^d$ Inclination factor, $1/cos^2 \theta$, is not applied.

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TABLE 2

**MASS, MOMENTUM, AND KINETIC ENERGY ESTIMATES OF OUTFLOW LOBES**

| Lobes$^a$ | Red-North | Red-East | Black-North | Black-South | Blue-West |
|-----------|-----------|----------|-------------|-------------|----------|
| Outflow sources | IRS 3A | IRS 3B | IRS 3A | IRS 3A + 3B | IRS 3B |
| Integrated flux (Jy km s$^{-1}$) | 47.47 ± 1.43 | 101.6 ± 1.55 | 168.7 ± 1.75 | 347.3 ± 2.01 | 304.2 ± 4.36 |
| Mass ($10^{-3} M_{\odot}$) | 0.153 ± 0.005 | 0.327 ± 0.005 | 0.543 ± 0.006 | 1.12 ± 0.006 | 0.980 ± 0.014 |
| Mean no. density ($10^5$ cm$^{-3}$) | 6.6 | 6.9 | 7.0 | 5.9 | 9.2 |
| Momentum ($10^{-3} M_{\odot}$ km s$^{-1}$) | 1.2 | 3.5 | 0.43, –0.64$^a$ | 1.1, –1.1 | –18 |
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$^a$ Components in Fig. 5 as contour colors and positions.

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$^d$ Inclination factor, $1/cos^2 \theta$, is not applied.
portion of a redshifted lobe of an outflow from IRS 3B, we can regard $0.42 \times 10^{-3} M_\odot$ (the mass difference of the two lobes) as coming from IRS 3B. This assumes that the two lobes from an outflow have similar masses. As a result, the northern and the southern lobes of IRS 3A outflow have $\sim 0.70 \times 10^{-3} M_\odot$ each.

The redshifted and blueshifted lobes of the outflow originating from IRS 3B are well distinguished in the velocity range $+25$ to $-32$ km s$^{-1}$. The outflow spans the blue, black, and red contours in Figure 5. The blueshifted lobe of this outflow has $0.98 \times 10^{-3} M_\odot$, which is comparable to the $0.75 \times 10^{-3} M_\odot$ of the redshifted lobe as a combination of the red contours ($0.33 \times 10^{-3} M_\odot$) and a portion of the black contours ($0.42 \times 10^{-3} M_\odot$). The difference is reasonable, considering the blueshifted regions are contaminated by components of the L1448-mm outflow: probable flux loss in the $-1.1$ km s$^{-1}$ channel and flux gain in other blueshifted channels. In summary, the redshifted lobe of the IRS 3B outflow has $0.75 \times 10^{-3} M_\odot$ and the blueshifted lobe has $0.98 \times 10^{-3} M_\odot$, comparable within the uncertainties.

Estimates of momentum and kinetic energy of each component are also shown in Table 2. We use $v_{LSR} = 5$ km s$^{-1}$ and do not apply the inclination factors, which are $1/\cos \theta$ for momentum and $1/\cos^2 \theta$ for kinetic energy. Here $\theta$ is the inclination angle from the line of sight. When calculating the momentum and kinetic energy, we assume that components in each channel have the central channel velocity. Comparing momentum and energy of each lobe of the two outflows, the southern lobe of the IRS 3A outflow and the eastern lobe of the IRS 3B outflow have lower momentum and kinetic energy than their opposite lobes. Although the contamination of the L1448-mm outflow in the blueshifted lobe of the IRS 3B outflow and the nearly perpendicular aspect of the IRS 3A outflow to the line of sight make the interpretation difficult, it is probable that the outflows from IRS 3A and 3B interact in the overlapped region because the kinetic energy difference is distinct even when considering a portion of the blueshifted lobe of IRS 3B to be the same mass as the redshifted lobe. Due to the collision of two outflows, the kinetic energy would be reduced. The fact that there is no blueshifted opponent of the small redshifted blobs of the IRS 3A outflow in the $+15$ km s$^{-1}$ channel supports this idea as well. Besides, the heated clump, which Curiel et al. (1999) presented near IRS 3 in observations of the NH$_3$(J, K) = (1, 1) and (2, 2) inversion transitions, is located in the overlapped region of the two outflows from IRS 3A and 3B. Although they argued that the heated clump would be a part of a larger heated region because IRS 3 is at the edge of their field, it may present the interaction of the two outflows. In addition, the fact that the redshifted component of the IRS 3B outflow detected in SiO $J = 2 \rightarrow 1$ over the interaction region has relatively low velocity compared to the blueshifted component (Girart & Acor 2001) also supports interaction. Based on these considerations, we also suggest that IRS 3B is closer than IRS 3A because this deployment can reproduce the interaction. This is pointed out again later, in the CO $J = 2 \rightarrow 1$ linear polarization of § 7.

5.3. Velocity, Inclination, and Opening

Based on the mass of the outflow lobes and an assumed mass-loss rate, we can check whether or not the IRS 3A outflow is nearly perpendicular. If we assume a mass-loss rate of $6 \times 10^{-7} M_\odot$ yr$^{-1}$ from the two outflow lobes,$^4$ the age of the outflow would be $\sim 2300$ yr and the proper velocity of the outflow would be $\sim 10$ km s$^{-1}$ since the outflows extend to $20''$ (5000 AU at 250 pc). As the channel width is 4 km s$^{-1}$ and the $v_{LSR}$ is on the boundary of the two channels showing the main outflow feature, the inclination including opening angle must be less than $22^\circ$ from the plane of the sky; the IRS 3A outflow is nearly perpendicular to the line of sight.

The inclination angle of IRS 3B can be estimated from the velocity features detected. Figure 6 is a velocity-position diagram cut along the outflow direction of position angle $105^\circ$ from IRS 3B. Both redshifted (east) and blueshifted (west) lobes are divided into two components: one accelerating from the source and the other with a constant velocity. Using Figures 6 and 4, the accelerating portion up to $+23$ km s$^{-1}$ (channel central velocity) and the constant part at $+3$ km s$^{-1}$ are in the eastern (redshifted) region. Similarly, the accelerating portion up to $-30$ km s$^{-1}$ and the constant part at $-5$ km s$^{-1}$ are in the western (blueshifted) region. These velocities are $+18$, $-2$, $-10$, and $-35$ km s$^{-1}$ in the IRS 3B rest frame ($v_{LSR} = +5$ km s$^{-1}$). If the missing flux in the $-1.1$ km s$^{-1}$ channel is part of the constant component, then arguably $-6$ km s$^{-1}$ in the IRS 3B rest frame is a better extreme constant velocity. However, since the small difference in velocity will not significantly change the results derived below, and since it is strongly dependent on the assumed missing flux, we use $-10$ km s$^{-1}$ in the IRS 3B rest frame as the velocity of the constant velocity component in blueshifted region. The constant and accelerating features are best explained by two possible geometric outflow effects, although an outflow with various velocity components is also a possible explanation. One is the geometric effect caused by precession and the other by a trumpet-shaped outflow. The precession of the IRS 3B outflow could give the detected map features when the side of the redshifted lobe is precessing toward the observer and the side of the

$^4$ This is consistent with previous studies suggesting that massive young stars lose mass up to $10^{-3} M_\odot$ yr$^{-1}$ and low-mass stars down to $10^{-7} M_\odot$ yr$^{-1}$ (e.g., Kim & Kuznet 2006; Wu et al. 2004; Bontemps et al. 1996). In order to obtain a reasonable outflow velocity ($\sim 10$ km s$^{-1}$), we assume a mass-loss rate of $6 \times 10^{-7} M_\odot$ yr$^{-1}$. 
The velocity difference as before, the velocity difference between accelerating and nonaccelerating parameters such as velocity, inclination angle, and outflow inclination.

The nice aspect of the “trumpet” outflow is that we can estimate outflow parameters such as velocity, inclination angle, and opening angle based on the observed data. The opening angle is assumed as the angle on the end of the outflow “trumpet.” Therefore, the velocity difference between accelerating and nonaccelerating features of the redshifted or blueshifted lobe is coming from the opening angle. In addition to the velocity ($v$), the inclination angle ($\theta$), and the opening angle ($\Delta \theta$), we adopt the velocity difference ($\Delta v$) and the opening angle difference ($\Delta \theta_o$) between the redshifted and blueshifted lobes. Note that the inclination angle is measured from the line of sight and that the opening angle is half of the outflow opening. As mentioned in § 5.2, since the redshifted lobe of the IRS 3B outflow is likely to be interacting with the southern lobe of the IRS 3A outflow, a velocity difference needs to be included. The reason for applying the opening angle difference is that the side of the redshifted lobe has components in a blueshifted channel with a central velocity of $+3$ km s$^{-1}$ (Fig. 4), while the side of the blueshifted lobe does not. We define the velocity difference as $\Delta v = v_{\text{blue}} - v_{\text{red}} > 0$ ($v = v_{\text{bl}}$) and the opening angle difference as $\Delta \theta_o = \theta_{o, \text{red}} - \theta_{o, \text{blue}} > 0$ ($\theta = \theta_{o, \text{bl}}$). The blueshifted lobe is expected to have a higher velocity and a narrower opening angle than the redshifted lobe. Using Bayesian statistics, we determine the most likely parameter combinations to explain the observed velocity features,

$$P\{\text{parameters}||v'\} = \frac{P\{v'\}|\{\text{parameters}\}}{P\{v'\} | | v'\} \times P\{\text{parameters}||v'\},$$

where $\{\text{parameters} = \{v, \theta, \Delta v, \Delta \theta_o\}$. \hspace{1cm} (4)

The $\{v'\}$ is a set of four extreme values of the observed line-of-sight velocities in the outflow lobes with respect to the IRS 3B rest frame ($v'_1, v'_2, v'_3, \text{and} v'_4$), so the evidence term $P\{v'\} = 1$. In addition, since we do not have any preference to choose the five parameters, we assume that the prior probability densities, $P\{\text{parameters}\}$, are uniform. However, note that the opening angle should be less than 45°; otherwise, we would observe redshifted components on the side of the blueshifted lobe as well as the blueshifted components on the side of the redshifted lobe. For the likelihood, $P\{v'\}|\{\text{parameters}\}$, we choose a probability density having a constant value in the channel width (4 km s$^{-1}$) and exponentially decreasing outside of the channel width.

We found the parameters giving the maximum posterior probability after taking into account central velocities of four end channels showing outflow features in the IRS 3B rest frame, $\{v'\} = \{+18, -2, -10, -35\}$ km s$^{-1}$. The maximum posterior is obtained when the four velocities estimated from the five parameters are in the flat-top regions of each channel. Note that we adopted the likelihood (indicating channels) of functions having a constant value (flat-top) in the channel width (4 km s$^{-1}$) and exponentially decreasing outside. To explore the parameter space, the Metropolis-Hastings method (MacKay 2003) was used; we obtained a few hundred thousand samples with the maximum posterior probability through one million trials. Since we use flat-top shaped channel functions for the likelihood, the parameters are largely distributed. For example, the velocity distribution peaks at around 40 km s$^{-1}$ and quickly drops, but some cases have even a few hundred km s$^{-1}$. The inclination angle and the opening angle are distributed in $\sim 30°-80°$ and $\sim 5°-45°$, respectively.

However, as these parameters are not independent of each other, we can narrow the acceptable range of parameters. Figure 7 shows the velocity (filled circles), the inclination angle (filled squares), and the velocity and opening angle differences (open circles and open triangles, respectively) versus the opening angle. The opening angle is also plotted (filled triangles) to compare with the other parameters. For the plot, samples are divided by 5° bins of the opening angle and each bin has a few tens of thousand samples. The data points in Figure 7 are average values of the samples in each bin, and the error bars represent their standard deviation. The dotted line without data points indicates the opening angle plus the opening angle difference. The range of the derived opening angles that are consistent with the observations ($8° < \theta < 26°$) is indicated by the horizontal bars at the top and bottom of the plot.
uncertainties, and the velocity to \( \sim 45 \) km s\(^{-1}\). These parameters give a kinematic time scale of the IRS 3B outflow detected in our field-of-view as \( \sim 600 \) yr.

6. BINARY SYSTEM OF IRS 3A AND 3B

The velocity difference between IRS 3A and 3B detected in the \(^{13}\)CO \( J = 1 \rightarrow 0 \) and \(^{15}\)N\(^2\)O \( J = 1 \rightarrow 0 \) observations can be understood as an orbiting binary system. This also supports the interaction of the two outflows from IRS 3A and 3B. Here we introduce a kinematical constraint for a Class 0 binary system.

When denoting velocities of the two clouds with respect to the center of mass of the binary system as \( v_A \) (\( > 0 \)) and \( v_B \) (\( < 0 \)) and the components of the velocities in the line-of-sight plane of the IRS 3A and 3B as \( |v_A| \) and \( |v_B| \), the projected velocities on the line of sight are \( v_A' = v_A \sin \theta \) and \( v_B' = v_B \sin \theta \) (Fig. 8). Note that the vertical velocity components to the plane are \( v_A \perp \) and \( v_B \perp \), and so the proper motion velocities are indicated as \( (v_A \cos \theta + v_A \perp \cos \theta) \) and \( (v_B \cos \theta + v_B \perp \cos \theta) \). Similarly, the projected semimajor axis is \( a' = a \sin \theta = 7'' \times 250 \text{ pc} = 1750 \) AU.

The projected velocity difference (here assuming 0.8 km s\(^{-1}\)) and the projected semimajor axis (\( \sim 1750 \) AU) allow the estimation of the orbiting period \( (P) \) of the binary system,

\[
|v_A| = \sqrt{v_A^2 + v_A \perp^2} = \frac{2\pi a_A}{P} > |v_A|, \\
|v_B| = \sqrt{v_B^2 + v_B \perp^2} = \frac{2\pi a_B}{P} > |v_B|.
\]

Multiplying by \( \sin \theta \), they become

\[
|v_A| \sin \theta < \frac{2\pi a_A \sin \theta}{P}, \\
|v_B| \sin \theta < \frac{2\pi a_B \sin \theta}{P},
\]

and adding each side gives

\[
|v_A'| + |v_B'| < \frac{2\pi a'}{P}. \tag{5}
\]

In equation (5), since \( v_B' \) is negative, the left-hand side is the projected velocity difference, 0.8 km s\(^{-1}\). Using the projected semimajor axis (1750 AU), we obtain an upper limit of the orbiting period, \( \sim 6.54 \times 10^4 \) yr. Note that it is much longer than the age (~2300 yr) of the IRS 3A outflow, which is obtained assuming the mass-loss rate. Furthermore, since the masses of the two clouds were estimated as 0.21 and 1.15 \( M_\odot \), in § 3 and Table 1, we can also estimate an upper limit of the semimajor axis from the Kepler’s third law,

\[
a = \left( \frac{m_A + m_B}{2 \pi G} \right) \left( \frac{P}{2 \pi} \right)^2 \left( \frac{\sin \theta}{2} \right)^{1/3}. \tag{6}
\]

The estimated masses and the orbiting period give a semimajor axis of ~1800 AU, a slightly larger value than the projected semimajor axis. In this case, the \( \theta = \arcsin (a'/a) = 76^\circ \) (refer to Fig. 8), which means that the considered velocity difference (0.8 km s\(^{-1}\)) is acceptable for a gravitationally bound binary system. Note that the mass of the central luminous sources can increase the semimajor axis by 26% \((=2^{1/3})\) when they are assumed to have masses identical to the circumstellar material. This increases the probability of a gravitationally bound binary system. If the velocity difference were estimated as 0.5 km s\(^{-1}\) from higher spectral resolution observations, the upper limit of the orbiting period would be 1.05 \times 10^5 yr, the semimajor axis would be 2500 AU, and the \( \theta = \arcsin (a'/a) \) would be 44°. As described above, the total mass and the projected velocity difference and semimajor axis give a kinematical, gravitationally bound constraint on apparent binary systems. Since the projected velocity difference is within values for a binary system, we conclude that the IRS 3A and 3B sources are likely to be gravitationally bound. Observations with higher spectral resolution will give a better constraint.

The angular momentum of the binary system is also noteworthy. We estimate the specific angular momentum (angular momentum per unit mass) of this binary system using the projected velocity components, the projected distance, and the mass ratio from the mass estimates of the continuum emission at \( \lambda = 1.3 \) mm. This estimate has uncertainties caused by the ambiguities of velocities of the line of sight as well as proper motions. The ambiguity of the line of sight comes from the broad channel width of our observation. If we can remove the ambiguity using higher spectral resolution observation, the estimate would be a lower limit of the specific angular momentum. The value is \( \sim 3 \times 10^{-20} \) cm\(^2\) s\(^{-1}\), similar to the upper limit of the specific angular
momentum of binary stars in Taurus and to the lower limit of molecular cloud cores (Simon et al. 1995; Goodman et al. 1993).

7. MAGNETIC FIELDS

Linear polarization is marginally detected in both the $\lambda = 1.3$ mm continuum and CO $J = 2 \rightarrow 1$ spectral line. Vectors around IRS 3B in Figure 1 represent polarization detected in the $\lambda = 1.3$ mm continuum. Since polarization of dust emission is perpendicular to the magnetic field, the magnetic field is expected in the north-south direction around IRS 3B. This is consistent with the large-scale magnetic field observed by SCUBA at $\lambda = 850$ $\mu$m shown in Figure 9. Note that the vectors in Figure 9 also indicate linear polarization and the direction around IRS 3B is east-west like the $\lambda = 1.3$ mm continuum data in Figure 1. Toward the center of IRS 3B, weaker linear polarization is detected at both wavelengths. The polarization fractions are around 5% in our BIMA 1.3 mm continuum and around 2% in the SCUBA data. This smaller polarization fraction of the SCUBA data is from the larger beam size of SCUBA smearing out the linear polarization.

Linear polarization of the CO $J = 2 \rightarrow 1$ emission, tracing the outflows, was detected in patches of the overlapped region of the southern lobe of the IRS 3A outflow and the redshifted lobe of the IRS 3B outflow. Figure 10 is an intensity map of two channels combined in velocity from $+1$ to $+9$ km s$^{-1}$. Vectors represent linear polarization directions and two lines on IRS 3A and 3B indicate outflow directions. According to the Goldreich-Kylafis effect (e.g., Kylafis 1983), linear polarization of spectral lines can be either parallel or perpendicular to magnetic field, depending on the relation between line of sight, magnetic field direction, and velocity gradient. Since the polarization was detected in only a few small patches located in the overlapped region of the IRS 3A and 3B outflows, it is hard to define the morphology of the magnetic fields. However, as the vectors are likely parallel or perpendicular to the IRS 3B outflow, we suggest that the polarization comes from the IRS 3B outflow. At the same time, this suggestion implies that the magnetic field may be perpendicular or parallel to the outflow. Although we cannot distinguish between the two, the parallel magnetic field could be from a large-scale magnetic field morphology (hourglass morphology) widely accepted to occur in forming protostars, and the perpendicular magnetic field could be from a helical structure extended from a toroidal magnetic field suggested by some theoretical studies (e.g., Ostriker 1997). The fraction of linear polarization is around 6%–15%.

Based on both dust polarization and CO $J = 2 \rightarrow 1$ polarization, we suggest a unified magnetic field morphology related to the disk and outflow structures in forming protostars. The magnetic field inferred from the dust emission, perpendicular to outflow, may show a toroidal magnetic field around a circumstellar disk and the magnetic field inferred from CO $J = 2 \rightarrow 1$ may present a large-scale morphology parallel to the outflow or helical structure perpendicular to the outflow. As discussed in §5, we can also suggest that the IRS 3B source is closer, because the polarization appears to be from IRS 3B. Polarization of the farther source (IRS 3A) is harder to detect due to the foreground cloud (IRS 3B).

8. SUMMARY AND DISCUSSION

We present CO $J = 2 \rightarrow 1$, $^{13}$CO $J = 1 \rightarrow 0$, and C$^{18}$O $J = 1 \rightarrow 0$ observations and $\lambda = 1.3$ mm continuum and CO $J = 2 \rightarrow 1$ polarimetric observations toward L1448 IRS 3. IRS 3A and 3B are distinctly detected with mass estimates of 0.21 and 1.15 $M_\odot$ respectively at $\lambda = 1.3$ mm, but IRS 3C is marginally detected with upper mass limit of 0.03 $M_\odot$. The ambient velocities of IRS 3A, 3B, and 3C are estimated as 5.5, 4.5, and 3.5 km s$^{-1}$, respectively, from $^{13}$CO $J = 1 \rightarrow 0$ and C$^{18}$O $J = 1 \rightarrow 0$ channel maps (§4). The two close sources, IRS 3A and 3B, have a velocity difference less than 1 km s$^{-1}$; the difference is a kinematical constraint on a gravitationally bound binary system. Moreover, we estimated the specific angular momentum of the binary system as $\sim 3 \times 10^{20}$ cm$^2$ s$^{-1}$, similar to the upper limit of binary stars in Taurus and to the lower limit of molecular cloud cores (§6).

We present CO $J = 2 \rightarrow 1$ observations showing two outflows, one each from IRS 3A and 3B (§5). The outflow driven by IRS 3A has P.A. = 155° and is nearly perpendicular to the line of sight, while the outflow by IRS 3B has P.A. = 105°. In addition, we posit that the two outflows are interacting in the southern lobe of the IRS 3A outflow and the redshifted lobe of the IRS 3B outflow, based on a comparison of the kinetic energies of lobes. Coupled with the fact that the linear polarization detected in CO $J = 2 \rightarrow 1$ is likely to come from the IRS 3B outflow, IRS 3B is closer than IRS 3A. We also detected that the IRS 3B outflow has accelerating and nonaccelerating features in the velocity-position diagram, which is interpreted as either a precessing outflow or a “trumpet” outflow. Assuming a “trumpet” outflow of IRS 3B rather than its precession, we estimate the velocity, inclination angle, and the opening angle, using Bayesian statistics. The velocity and the inclination angle are constrained to between 100 and 40 km s$^{-1}$ and between 75° and 50°, respectively, as the opening angle is between 8° and 26°. Furthermore,

Girart et al. (1999) detected CO $J = 2 \rightarrow 1$ polarization perpendicular to dust polarization in NGC 1333 IRS 4A and interpreted the spectral line polarization as parallel to the magnetic field. However, polarization in the dust continuum and CO $J = 2 \rightarrow 1$ may not indicate the same magnetic field because dust continuum and CO $J = 2 \rightarrow 1$ trace different density regions; the magnetic field direction at the central core may change radially from an hour glass morphology (e.g., Fiedler & Mousschovias 1993). In addition, detected polarization directions in our dust emission and CO $J = 2 \rightarrow 1$ data are likely to be parallel around the IRS 3B center. Therefore, we cannot define the magnetic field direction as either perpendicular or parallel to the CO $J = 2 \rightarrow 1$ polarization here.
using an opening angle of \(\sim 20^\circ\) from Spitzer observations, the velocity and the inclination angle of the IRS 3B outflow are \(\sim 45\) km s\(^{-1}\) and \(\sim 57^\circ\).

Linear polarization in both the \(\lambda = 1.3\) mm continuum and CO\(J = 2 \rightarrow 1\) spectral line is marginally detected around the center and outflow of IRS 3B, respectively (\(\S 7\)). The dust emission polarization gives a magnetic field perpendicular to the outflow, which may be a toroidal magnetic field parallel to the circumstellar disk. In contrast, the spectral line polarization suggests either a perpendicular or a parallel magnetic field to the IRS 3B outflow. To determine the relation between the magnetic field and the outflow direction, more sensitive polarimetric observations are required.

The L1448 IRS 3 is an excellent region for studying star formation. The IRS 3A outflow, nearly perpendicular to the line of sight, enables the study of the disk and outflow structures in protostar systems more easily, since it shows the profile projected in the plane of the sky. In addition, the binary system of IRS 3A and 3B having two outflows in quite different directions gives us an opportunity to study the interaction between two sources, in addition to constraining binary system formation itself. Finally, more sensitive polarimetric observations will provide clues on the connection between outflows and magnetic fields.

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