A SURVEY OF CIRCUMSTELLAR STRUCTURE AROUND YOUNG LOW MASS STARS

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Abstract. We present results from a near-infrared array, CO interferometer, and H_2O maser interferometer survey of the circumstellar environments of 26 young low-luminosity embedded stars located in nearby molecular clouds. About 75% of the sample show evidence for stellar winds/outflows in the near-infrared or CO data indicating that most of these sources are in the early wind clearing phase of their evolution. Close to 15% are multiple on the scale of 20″, suggesting that fragmentation of their surrounding dense cloud cores is important before or during gravitational collapse. Roughly 10% have H_2O maser emission and the kinematics imply the masers arise in gravitationally unbound gas (i.e., a stellar wind or outflow) rather than in a circumstellar disk.

Keywords : infrared sources, stars-accretion, circumstellar gas, star formation, pre-main-sequence stars, stellar winds, binaries

1. Introduction

We present high spatial resolution observations showing the circumstellar environments of young low mass stars on scales of roughly a 1000 AU. The sources are members of the class known as IRAS-Dense cores; highly obscured objects with steep IRAS spectra that are found near the peaks of dense gas emission (Myers and Benson 1983; Beichman et al. 1986; Myers et al. 1987; Benson and Myers 1989). These low-luminosity infrared sources embedded in dense cloud cores are suspected protostars, i.e. stars deriving part or all of their luminosity from accretion (Terebey, Shu, and Cassen 1984; Shu, Adams, and Lizano 1987; Adams, Lada, and Shu 1988).

Our current theoretical understanding of low mass star formation indicates that young stars form from the collapse a dense cloud core. During the wind clearing phase a vigorous young stellar wind erodes the infalling cloud core, eventually halts the infall and in the process reveals the young star. During the infall phase a

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protostellar disk–of uncertain size and mass– probably forms. Models of the collapse region (Terebey, Shu, and Cassen 1984) find it typically extends out to $10^{17}\,cm$, or 10,000 AU, roughly the region encompassed by our infrared and interferometer data. Matter inside the collapse zone will not be at rest; thus the gas observed inside this region should trace either the infall, outflow, or disk components.

Despite the successes of the theoretical picture, many important details of the process must be observationally confirmed. We use the morphology of the gas-rich circumstellar environment around young stars to investigate the importance of the different protostellar phenomena : winds, infall, disks, and stellar multiplicity.

2. Data

2. 1. SAMPLE

The sample consists of 26 sources which have an IRAS source close to the center of a dense molecular cloud core. These sources are all highly obscured–inferred visual extinctions are on the order of 30 magnitudes. Most sources have no optical counterpart and all have the steep IRAS spectra indicative of deeply embedded young stars. The dense cloud cores are typically 0.1 *pc* in size with kinetic temperatures of $10 - 20\ K$, and contain about $1 - 10\ M_\odot$ of gas. The sample is not a complete list of dense cores for every cloud but can be considered representative in that the sources satisfy well-defined criteria, span a range in luminosity from 0.5 to 100 $L_\odot$ with a typical value of 2 $L_\odot$, and come from a variety of nearby molecular clouds. The properties of the sample are described in more detail in Terebey, Vogel, and Myers (1989; hereafter TVM 1989). The source TMR-1 (IRAS 04361+2547), an embedded star in the Taurus molecular ring (TMC-1/Heiles Cloud 2 region) has been added to the original sample.

2. 2. OBSERVATIONS

We have surveyed the sources for compact CO outflows using visibility data from the Owens Valley Millimeter Interferometer. Follow-up synthesis maps for one-third of the sources confirm the initial survey results reported in TVM (1989). The sample was also searched for H_2O maser emission in a 2′ field of view using the VLA in the C/D array configuration, with follow-up high spatial resolution observations in the A or B arrays for the detected maser sources (Terebey, Vogel, and Myers 1990).

We report initial results for a near-infrared camera survey using the PFIRCAM on the Palomar Observatory Hale 5m telescope. The camera utilized a 128×128 array of HgCdTe detectors operating between 1 and 2.5 μm with 0.765″ pixels and covering a 98″ field of view. Each source was observed at K (2.2 μm); sources showing structure were also observed at J (1.25 μm) and H (1.65 μm). Three-quarters of the sample have been observed; the sources with IRAS upper limits at 12 microns were excluded.

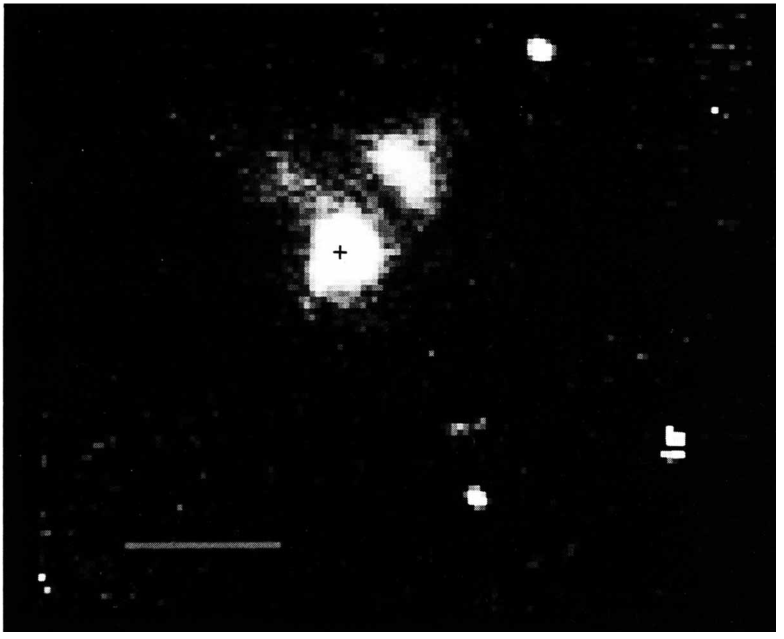

Fig. 1. A 2.2 μm image of the young embedded source TMR-1. The cross marks the infrared point source position. The reference line corresponds to 20″ (2800 AU). We interpret the spindle of emission extending to the NW to be a stellar wind cavity. Perpendicular to the direction of the spindle is a deep absorption feature. Two unrelated point sources lie to the NW and SW. *(See Color-plates section)*

2. 3. NEAR-INFRARED DATA

Figures 1 and 2 illustrate the phenomena present in the near-infrared images.

The 2.2 μm image (Fig. 1) of the Taurus cloud source TMR-1 reveals a bright point source and an elongated spindle approximately $20''$ ($2800AU$) in length that extends to the NW. We interpret the extended emission as scattered light that traces a stellar wind cavity. The CO interferometer data shows an outflow coincident with the near infrared spindle. Cutting across the spindle at a perpendicular angle lies a dust band in absorption. The dust band appears to be part of an incomplete ring or disk of circumstellar material, 1100 AU in radius, that is inclined to the line of sight. There is faint emission visible from the edge of the dust band to the NE, as if illuminated by the embedded source. Apparently we are seeing high density material that is detected because of its favorable placement with respect to the background continuum emission. This striking dust absorption feature is unique to TMR-1 of all the objects observed. Two other point sources are also located in the field, to the NW and to the SW. Further discussion of TMR-1 can be found in Terebey et al. (1990).

Figure 2 shows a near-infrared color composite image of the ρ Oph cloud source L1681B. L1681B is revealed to be a triple system; the three embedded sources are separated by about $25''$ and are nearly equal in brightness. Our VLA data detect water maser emission towards both the central star and the star to the NE. This indicates both stars (projected separation of $4000AU$) are very young. Probably all three stars have formed from the same dense molecular cloud core which has fragmented from its original size of roughly 0.1 pc.

The infrared nebulosity associated with the central star we interpret as scattered light that is tracing a stellar wind cavity. The molecular outflow detected in the CO interferometer data (Fig. 3) extends south of the infrared source, and apparently traces only one outflow lobe (TVM 1989).

3. Discussion

3. 1. OUTFLOWS

From the CO data there is evidence for outflows in 69% (18/26) of the sources (TVM 1989 and references therein). About two-thirds of the outflow sources that have been observed in the near-infrared also show extended emission at 2.2 μm. In most cases the near-infrared colors of the extended emission are bluer than the colors of the embedded stars, consistent with the interpretation that the extended emission is due to scattered stellar light. Comparing the near-infrared images and CO interferometer maps shows that the near-infrared emission is less extended than the CO emission but is otherwise closely related to the CO outflow structure. In a few cases the near-infrared images show complementary structure as in L1681B (Fig. 2 and 3); the CO data show only one outflow lobe, while the near-infrared images detect another outflow lobe located on the opposite side of the embedded infrared source.

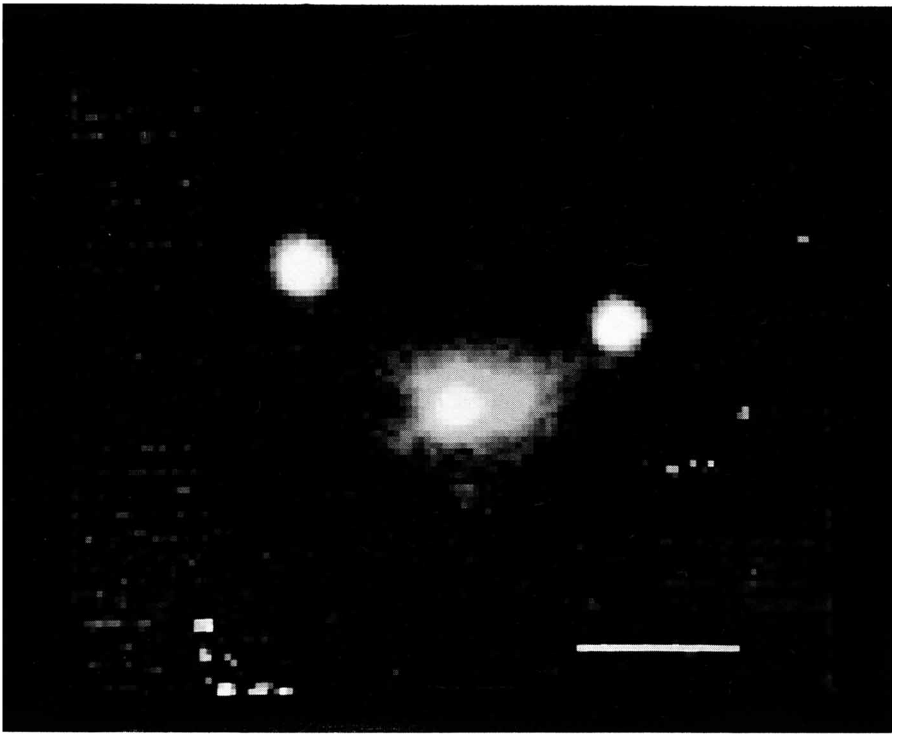

Fig. 2. A near infrared color composite image of the embedded source L1681B. Blue, green, and red correspond to 1.25, 1.65, and 2.2 μm, respectively. The reference line shows 20″ (3200 AU). There are three embedded sources separated by 3000 - 5000 AU. H_2O maser emission is detected coincident with the central and NE sources, thus demonstrating both sources are young. We interpret the nebulosity as scattered light that is tracing a poorly collimated stellar wind cavity. *(See Color-plates section)*

The higher resolution of the near-infrared images ($\sim 1.5''$) compared with the CO data allows us to trace the outflow closer to the embedded star. Generally there is only moderate collimation of the outflow to within several hundred AU of the star. Given the close correspondence between CO outflows and extended near-infrared emission we identify two new outflow sources on the basis of their extended near-infrared emission alone. This increases the outflow frequency to about 75% of the sample.

The outflow frequency has implications for the the relative durations of the the infall and stellar wind clearing phases. Assume that the ratio of time spent in each phase equals the ratio of the number of sources in each phase. Then the purely infall phase lasts no more than 30% the length of the outflow phase. Kinematic ages for the oldest outflows give ages on the order of $1-2\times 10^5$ yr (Myers et al. 1988), which imply an infall phase lasting less than 60,000 years. Given typical accretion rates ($\sim 5\times 10^{-6}$ $M_\odot yr^{-1}$) this time scale appears uncomfortably short to accrete a solar mass size star. The time scale problem has a simple resolution if the infall and outflow phases overlap for some moderate length of time.

3. 2. MULTIPLICITY AND FRAGMENTATION

Roughly 60% of the near-infrared images show more than one star on the object frame. To distinguish embedded stars from background stars requires additional photometry or spectroscopy. However our object frames and background sky frames are quantitatively similar (excluding the observed source) in terms of source brightness and star density, suggesting that many of these additional objects are background stars. One class of sources appear associated– they are separated by roughly 30″and are nearly equal in brightness. For this class the near-infrared images indicate about 15% of the sources are multiple on the scale of $20-30''$, or about $3000-5000$ AU. Since this is smaller than the typical 0.1 pc dense core size it implies that fragmentation of the dense cores is important and that more than one star can form per dense core.

Theoretical models of gravitational cloud collapse find that the velocity shear inhibits the growth of small density perturbations. This suggests that fragmentation occurs at an early stage before the dense cores become gravitationally unstable.

3. 3. H_2O MASERS

About 10% of the sources show water maser emission (Terebey, Vogel, and Myers 1990). The detected sources are preferentially those with the highest luminosity and steepest spectra (rising toward longer wavelengths). The maser emission is confined to within 100 AU of the star. Maser emission from circumstellar disks was searched for since the physical parameters expected in disks such as high density ($> 10^6$ cm^{-3}) and temperature (> 300 K at 1 AU) correspond to those in known masers and the protostar provides a nearby energy source. However the kinematics imply the masers originate in gravitationally unbound gas (i.e. a stellar wind or

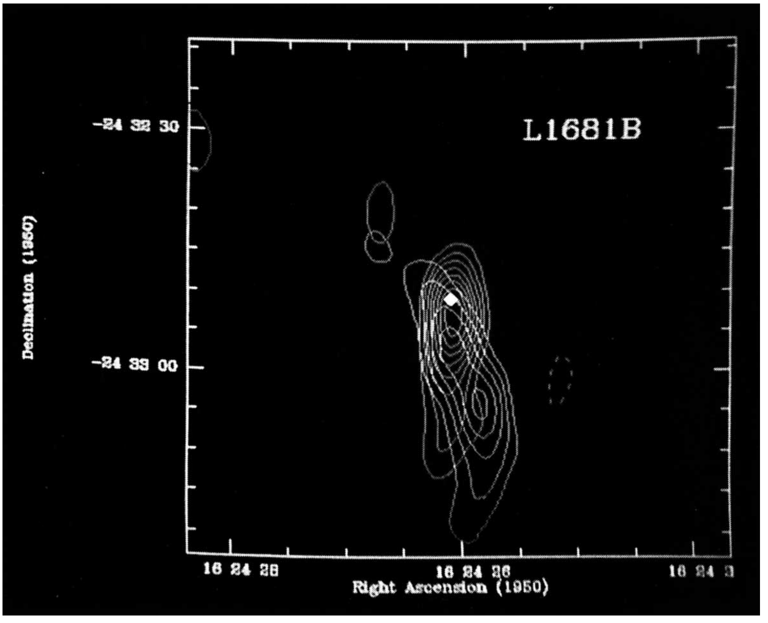

Fig. 3. An interferometer map of the CO outflow seen towards the embedded source L1681B. The diamond marks the position of the infrared point source. Red-shifted and blue-shifted gas defines a stellar wind cavity extending south of the infrared source.

(See Color-plates section)

outflow). The collimation of the outflow on small scales, as traced by the masers, matches the collimation seen in the CO data on a much larger scale.

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