MILLIMETER INTERFEROMETRY OF CLASS 0 SOURCES: ROTATION AND INFALL TOWARDS L1448N

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Abstract. In order to study the kinematics of protostellar collapse we present high-spatial resolution millimeter interferometer data of the class 0 source L1448 N. The L1448 N cloud core has fragmented into two rapidly rotating subcores containing three protostars. One subcore is a protobinary system with 2000 AU separation. Strong evidence for infall is seen towards the N(B) component.

1. Introduction

Since their introduction Class 0 sources have been an interesting but controversial category of protostellar sources (André *et al.*, 1993). By definition class 0 sources have narrow "cold" spectral energy distributions, exhibit large circumstellar masses through their strong millimeter continuum fluxes, and show no visible or near-infrared emission at the position of the embedded star. Advocates propose them to be an earlier evolutionary phase than class I sources, having typical ages on order 2 $\times 10^4$ yr. In a general way their properties match the predictions of theoretical models for young protostars (Shu *et al.*, 1987). It is encouraging that recent observations of collapse motions (Zhao *et al.*, 1993; Zhao, 1995) involve targets which are primarily class 0 sources. However some authors argue the definition is flawed, and that many or all of the class 0 sources may instead be class I

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sources which have large inclination angles, i.e. are seen principally along the bulk of their flattened circumstellar structures.

By happenstance a high fraction of class 0 sources are also molecular jet sources, although the reason for this association is unclear. Will class 0 sources become typical class I sources as they age, or is there a more direct connection to Herbig-Haro jets? Are there other physical parameters of the collapsing cloud, such as rapid rotation (Goodman *et al.*, 1993) or high mass, which are important factors in the molecular jet phenomenon?

To gain a better understanding of the kinematics and density of the collapse phase we are studying class 0 sources using the high-spatial resolution provided by millimeter interferometry. Class 0 sources are excellent candidates for study: they are likely to be young, and by definition their large circumstellar masses ensure that they are strong millimeter targets. In this paper we present a case study of the class 0 source L1448 N, sometimes called L1448 IRS3.

2. Observations

The data presented are millimeter spectral line and continuum observations from the Owens Valley Millimeter Interferometer. The spatial resolution is 8″ for the long wavelength $C^{18}O$(1-0) and 2.7 mm continuum data. A higher spatial resolution of 2.5″ was achieved for the shorter wavelength $C^{18}O$(2-1), ^{13}CO(2-1), and 1.3 mm continuum observations. Previous continuum results and system performance are reported elsewhere (Terebey *et al.*, 1993).

3. Results

3.1. OVERVIEW OF L1448 CLOUD CORE

The L1448 cloud shows fragmentation and star formation activity in several regions. The cloud, as defined by NH_3 data is $10' = 1$ pc across and contains 50 $M_\odot$ of gas (Bachiller and Cernicharo, 1986). L1448 is located in the Perseus molecular cloud at a distance of 300 pc.

Figure 1 shows the distribution of the dense gas in integrated $C^{18}O$(1-0) emission towards the central 1′ of L1448 N. The well known outflow source L1448 C lies outside the field about 1′ to the southeast (Bachiller *et al.*, 1990). It is apparent in Figure 1 that there are two cores, one centered on L1448 N, and a second located 20″ northwest, which we call L1448 NW.

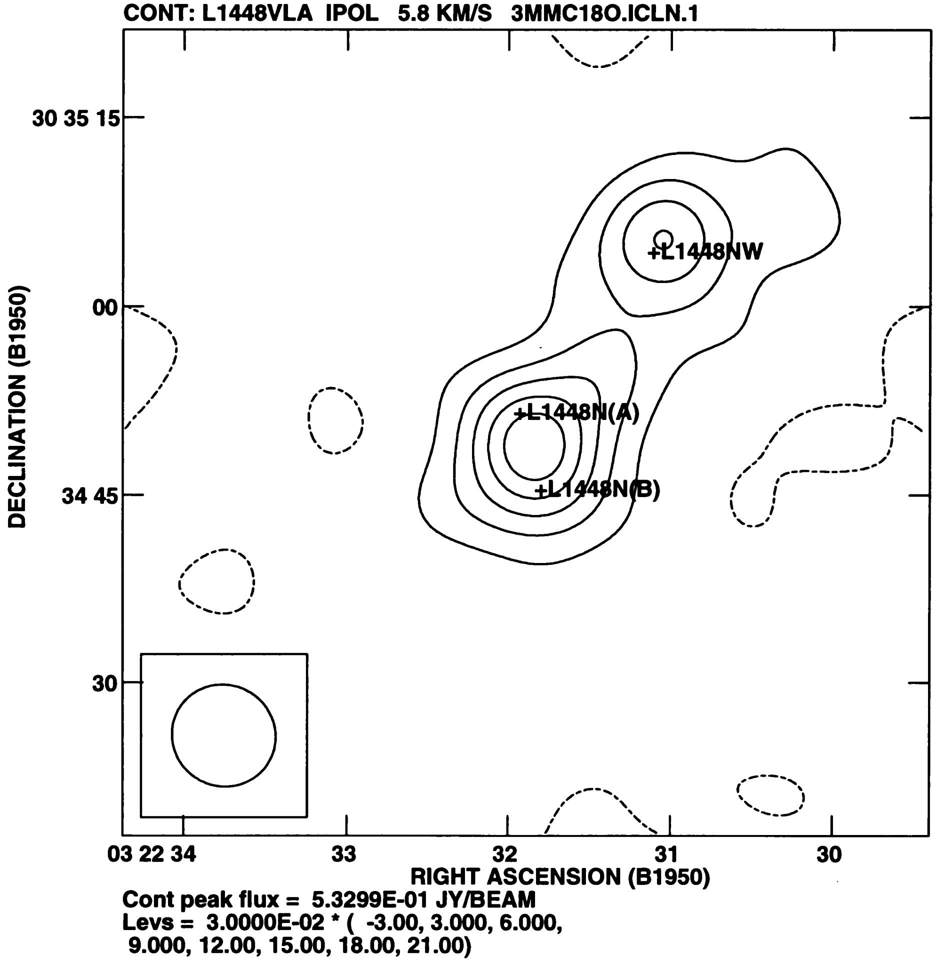

Figure 1. The integrated $C^{18}O$(1-0) map shows the dense gas in the L1448 N cloud core has fragmented into two subcores. Plus symbols show the positions of embedded protostellar sources.

3.2. EMBEDDED PROTOSTELLAR SOURCES

Millimeter continuum emission is sensitive to heated circumstellar dust and has proven to be a good indicator of protostars. The OVRO data show three sources of continuum emission whose positions are shown by plus symbols in Figure 1. Curiel *et al.* (1990) previously detected the VLA sources A and B in L1448 N. At millimeter wavelengths the continuum emission is dominated by the southernmost source (Terebey *et al.*, 1993), whose position coincides with the VLA source L1448 N(B). The separation of the components is about $6'' = 1800$ AU. The third embedded protostellar source is located in the center of the L1448 NW core, about $20''$ northwest.

The strong millimeter continuum emission from N(B) combined with the IRAS fluxes show L1448 N(B) has a cold spectral energy distribution which fits the definition of a class 0 source. What then is the status of the two other millimeter continuum sources? Unfortunately the sources are spatially unresolved by IRAS. However near-infrared images have the requisite spatial resolution and sensitivity to detect class I sources at the distance of Perseus. Although near-infrared images show H_2 emission and reflection nebulosity in the region there is no near-infrared emission detected from the protostellar positions above the detection threshold of 18th magnitude at K. The lack of near-infrared emission suggests all three protostars may be class 0 sources.

3.3. FRAGMENTATION AND ROTATION

Both the L1448 N and NW subcores show large velocity gradients which are consistent with rotation. The position angle of the rotational axis is approximately -45° for both subcores. The suggested geometry is that of a narrow rotating cylinder which has fragmented along its length. The magnitude of the gradient is about 100 km s^{-1} pc^{-1}, representing a rotational period of about 60,000 yr. The implied dynamical mass is about 1.5 $M_\odot$ which is consistent with the spectral line mass estimate. The projected distance between the two subcores is about $20''$, which suggests the fragmentation length scale is comparable at $20'' = 10^{17}$ cm.

The L1448 N subcore shows a flattened structure resembling a disk which extends over $30''$ in diameter. Figure 2 shows a position-velocity slice taken along the major axis in the optically thin $C^{18}O$(1-0) line. The P-V diagram shows a solid-body rotation curve in the inner $10''$. Outside this radius the velocity is flat or slightly declining. We constructed a simple thin disk model to explore the relative importance of density, inclination, and rotation law on the P-V diagram. Figure 3 shows the best fit model generated for a 60° inclined disk (approaching edge-on) with $16''$ radius and r^{-1} surface density profile. The rotation curve is solid body inside a $5''$ radius, switching to Keplerian outside that radius.

3.4. THE 2000 AU PROTOBINARY

The $30''$ flattened rotating structure contains two protostellar sources, N(A) and N(B), which are separated by $6'' = 1800$ AU. The dense gas forms a bridge which varies slowly in velocity between the two sources. We interpret the system to be a rotating and collapsing cloud which is in the process of

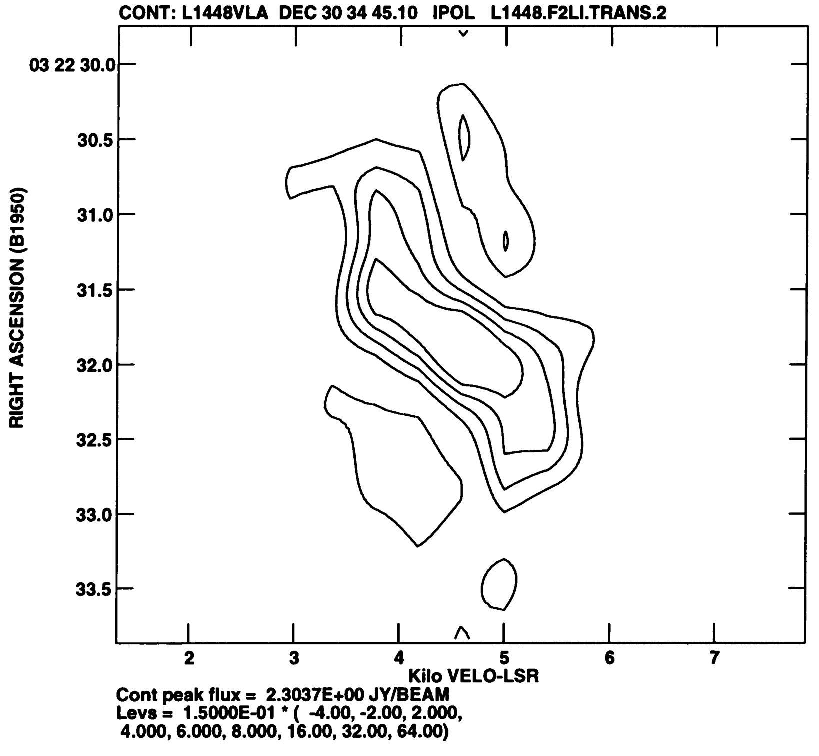

Figure 2. A position-velocity diagram shows evidence for rotation in L1448 N.

forming a protobinary. Corroborating dynamical evidence is the fact that the rotation curve looks like a solid-body in the inner 5″, suggesting that the dynamical mass is distributed, i.e. non-pointlike, and this occurs over the same scale as the binary separation.

The two sources are presumably coeval but differ markedly in their circumstellar mass. The continuum flux differs by a factor of ten between the two components. In addition evidence for an outflow is only seen toward N(B), the source with the high circumstellar mass. At centimeter wavelengths the N(A) component dominates (Curiel *et al.*, 1990). This suggests that N(A) has already accumulated most of its mass, while N(B) is in the midst of a rapid accretion phase.

3.5. INFALL

Infall motions exhibit a systematic pattern which can be searched for and in a few cases detected (Zhao *et al.*, 1993; Zhao, 1995). Spectral line profiles

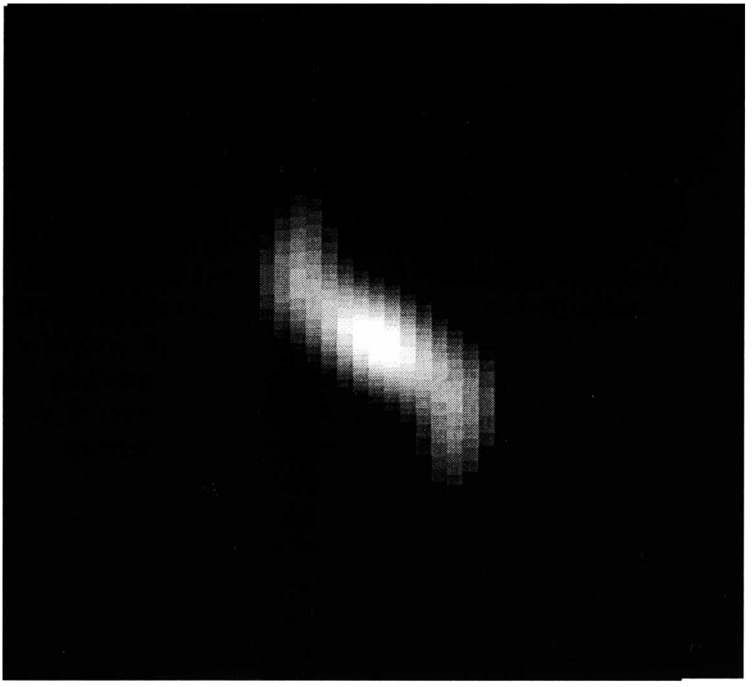

Figure 3. A simple model with solid body rotation in the interior, and Keplerian rotation exterior provides a good fit to the position-velocity data.

should broaden in progressively smaller beams centered on the source. The magnitude of the velocity should be consistent with gravitationally bound motion. In the case of optically thick lines, the line will be self-absorbed, but with a stronger blue than red shoulder.

Figure 4 shows the ^{13}CO(2-1) profile toward L1448 N(B) with 2.5″ spatial resolution. The profile shows the characteristic infall signature for an optically thick spectral line. The magnitude of the velocity is consistent with gravitationally bound motion around a central mass of 0.75 $M_{\odot}$.

4. Conclusions

Millimeter interferometric observations of the class 0 source L1448 N were made in C^{18}O(1-0), C^{18}O(2-1) and ^{13}CO(2-1) in order to study the kinematics (rotation and infall) of a young protostellar source. L1448 N shows a variety of behaviors which are shared in part by other class 0 sources:

- The L1448 N cloud core has fragmented into two subcores containing three protostars. The lack of near-infrared emission suggests all three protostars may be class 0 sources.

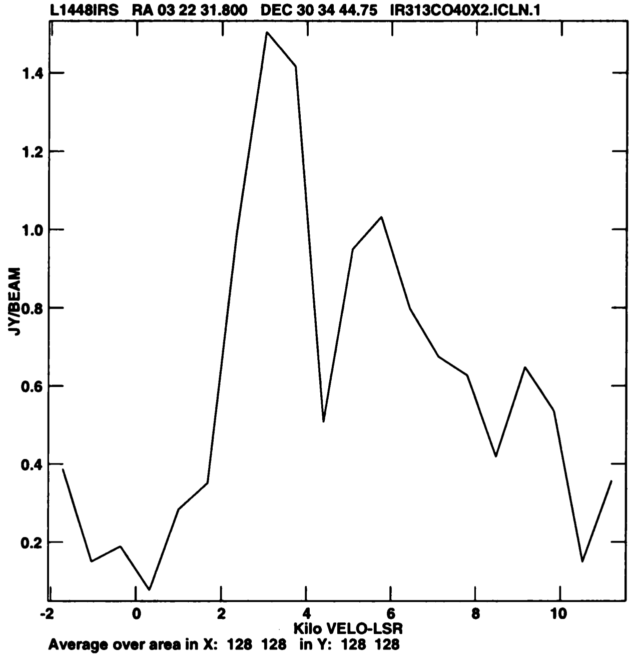

Figure 4. The $^{13}CO(2\text{-}1)$ spectrum directly towards the N(B) protostar shows the asymmetric profile characteristic of infall motions in an optically thick line tracer.

- The two subcores are rapidly rotating. In addition, the rotational axes are aligned. The suggested geometry is that of a narrow rotating cylinder which has fragmented along its length. The precollapse fragmentation scale in the Perseus cloud is about 6000 AU $= 10^{17}$ cm. The rotation rate is about 100 km s^{-1} pc^{-1}, for a rotational period of about 60,000 yr.

- The L1448 N subcore is a protobinary system, a dynamically rotating and collapsing core which is currently forming the two protostars N(A) and N(B). The two components are connected by a continuous gas bridge. The binary separation is 2000 AU, compatible with observed separations of stars in wide binary systems.

- The two sources are presumably coeval but differ markedly in their circumstellar mass and outflow properties. The continuum flux, which is proportional to the circumstellar mass, differs by a factor of ten between the two components. An outflow is seen only toward L1448 N(B), the source with the higher circumstellar mass. At centimeter wavelengths the N(A) component dominates.

- Toward the most massive/strongest continuum source L1448 N(B), the optical depth is sufficiently high to show the characteristic spectral signature of infall motions. The broadening of the spectral line due to infall is seen in the central 3″, whereas the velocity gradient due to rotation extends over 30″.

High sensitivities can be achieved by millimeter interferometers studying Class 0 objects, which are by definition strong millimeter continuum sources. A promising direction for future research is the detailed comparison of observations of protostellar density and kinematics with theoretical collapse models.

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