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A documentary of high-mass star formation: Probing the dynamical evolution of Orion Source I on 10–100 AU scales using SiO masers

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Abstract. A comprehensive picture of high-mass star formation has remained elusive, in part because examples of high-mass young stellar objects (YSOs) tend to be relatively distant, deeply embedded, and confused with other emission sources. These factors have impeded dynamical investigations within tens of AU of high-mass YSOs—scales that are critical for probing the interfaces where outflows from accretion disks are launched and collimated. Using observations of SiO masers obtained with the Very Large Array (VLA) and the Very Long Baseline Array (VLBA), the KaLYPSO project is overcoming these limitations by mapping the structure and dynamical/temporal evolution of the material 10-1000 AU from the nearest high-mass YSO: Radio Source I in the Orion BN/KL region. Our data include ∼40 epochs of VLBA observations over a several-year period, allowing us to track the proper motions of individual SiO maser spots and to monitor changes in the physical conditions of the emitting material with time. Ultimately these data will provide 3-D maps of the outflow structure over approximately 30% of the outflow crossing time. Here we summarize recent results from the KaLYPSO project, including evidence that high-mass star formation occurs via disk-mediated accretion.

Keywords. masers, stars: pre-main sequence, techniques: high angular resolution, circumstellar matter, stars: formation, stars: winds, outflows, stars: individual (Source I)

1. The KaLYPSO Project: Introduction and motivation

Increasing observational evidence supports a picture in which high-mass stars ($M \gtrsim 10M_{\odot}$) form through disk-mediated accretion, in a manner analogous to a scaled-up version of low-mass star formation (e.g., Zhang *et al.* 1998; Cesaroni 2002; Beuther *et al.* 2002; Patel *et al.* 2005; Beltrán *et al.* 2006). However, the details of this process remain poorly understood. For example, rapid formation timescales ($\ll 10^6$ years) seem to necessitate extremely high mass accretion rates. Meanwhile, strong radiation pressure from a high-mass YSO is expected to impede accretion, and the lack of a strong stellar dynamo in high-mass protostars necessitates an alternative mechanism for shedding large amounts of angular momentum. Although a number of theoretical studies have attempted to address these issues (e.g., McKee *et al.* 2002; Bonnell *et al.* 2005, Krumholtz *et al.* 2005), observations have been unable to readily distinguish between various models. Open questions include: What are the sizes and structures of accretion disks around high-mass YSOs? What is the driving mechanism of their outflows? What are the physical properties (density, temperature) of the disk-outflow interface? What is the role of magnetic fields in high mass star formation?

One of the chief obstacles for constraining models of high-mass star formation is that examples of high-mass YSOs tend to be relatively distant ($d \gtrsim 1$ kpc), deeply embedded, and confused with other emission sources. Moreover, since high-mass stars evolve rapidly, by the time an unobstructed view of the young star emerges, the disk and outflow structures may have been destroyed. Consequently, observations to date have been unable to probe the 10-100 AU spatial scales over which outflows from the accretion disks are expected to be launched and collimated. The KaLYPSO (Kleinmann-Low Young Proto-Stellar Object) project (http://www.cfa.harvard.edu/kalypso/) aims to overcome these limitations and provide the most detailed picture yet of a high-mass star in formation.

2. Our target: Radio Source I in the Orion BN/KL region

The nearest region of high-mass star formation is the Kleinmann-Low (KL) nebula in Orion, at a distance of ∼450 pc. Within this nebula is located the radio continuum-emitting "Source I", a luminous, highly embedded YSO with a disk-like morphology (Reid *et al.* 2007; Figure 1).

3. Goals of the KaLYPSO project

The KaLYPSO team has launched a multi-faceted study of Source I with unprecedented angular and temporal resolution. Our goals include:

- Chart the time-varying distribution of ∼1000 SiO maser spots within 10–100 AU of Source I
- Measure proper motions of ∼100 individual SiO masers with precision <1 km s^{-1}.
- Produce geometric and dynamical models of the molecular gas surrounding Source I
- Compare distributions of different maser transitions surrounding Source I to probe local density and temperature conditions
- Constrain the physical processes (e.g., shocks, collisions, fragmentation, magnetic fields) that contribute to the process of forming a high-mass star
- Produce a movie documenting the 3-D evolution of the outflows surrounding a massive protostar over ∼30% of the outflow crossing time

4. The Observations of SiO Masers toward Source I

Observations of masers using Very Long Baseline Interferometry offer a powerful means to study massive star formation. Masers are not affected by extinction, furnish information on the physical conditions of the emitting gas, and can supply kinematic information on the material surrounding YSOs at extremely high angular resolutions.

Using the VLBA of the National Radio Astronomy Observatory, we have obtained ∼40 epochs of observations of the SiO $v = 1$ and v=2 masers toward Source I at one-month intervals over a multi-year period. The two transitions were observed simultaneously with a spectral resolution of 0.2 km s^{-1}. Our resulting images have an angular resolution of ∼0.2 mas—corresponding to ∼0.1 AU at the distance of Orion.

5. Preliminary results

5.1. *The large-scale picture*

Figure 1 shows a large-scale (∼1000 AU) bipolar structure surrounding Radio Source I, as previously observed in thermal and maser emission from the SiO ground state ($v = 0$) with $\sim 0.5''$ resolution (Wright *et al.* 1995). Spectroscopy has confirmed similar velocity

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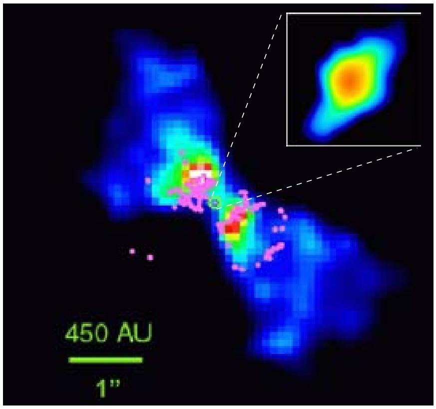

Figure 1. The large-scale (~1000 AU) bipolar structure surrounding Radio Source I, as observed in thermal and maser emission from the SiO ground state ($v = 0$) with $\sim 0.5''$ resolution by Wright *et al.* 1995. Locations of H_2O masers mapped with the VLA by Greenhill *et al.* 1998 are overplotted as pink spots (for color see the electronic version). The inset shows a λ7mm continuum map of Radio Source I from Reid *et al.* 2007.

spreads in both the north and south lobes, consistent with an outflow along the plane of the sky. H_2O masers also lie along the apparent outflow.

The Figure 1 inset shows a λ7mm continuum map of Radio Source I from Reid *et al.* (2007). The 7-mm emission appears to trace an edge-on, ionized disk with a diameter of ~100 AU, centered on the larger-scale outflow. The SiO $v = 1$ and $v = 2$ observations described here are providing key new information linking the observations shown in Figure 1, and further solidify the picture of Source I as a high-mass star in the process of formation via disk-mediated accretion and outflow.

5.2. *The Distribution and Kinematics of the SiO Masers around Source I*

Figure 2 shows a velocity field derived from one epoch of our combined VLBA SiO $v = 1$ and $v = 2$ observations toward Source I. The maser emission lies within an "X"-shaped distribution centered on Source I (whose position is indicated by an asterisk symbol). The SiO $v = 2$ emission tends to lie closer to Source I than the $v = 1$ emission, although there is considerable overlap. Emission is observed over the velocity range $-15 \lesssim V_{\rm LSR} \lesssim 30$ km s^{-1} (and is color-coded by Doppler shift in the electronic version of this article). Emission to the north/west is predominantly redshifted, while that to the east/south is predominantly blue-shifted, suggesting rotational motion. Consistent with this, material in the "bridge" between the south and west lobes lies near the systemic velocity. A similar but fainter bridge between the north and southeast lobes is also seen in some epochs. Proper motions of individual maser features (~10 km s^{-1}) are observed between consecutive epochs; their bulk directions are indicated by arrows. A more detailed analysis of these proper motions is forthcoming.

6. An emerging model for source I

The morphology and kinematics of the emission surrounding Source I provide strong evidence of both accretion and outflow. Figure 3 shows a schematic model for the source, based on a synthesis of the observations in the previous two figures (see the electronic version for a full-color rendition). At $r < 150$ AU (dashed circle) material is being driven into a wide-angle bipolar outflow. The edges of the "funnel" (representing the

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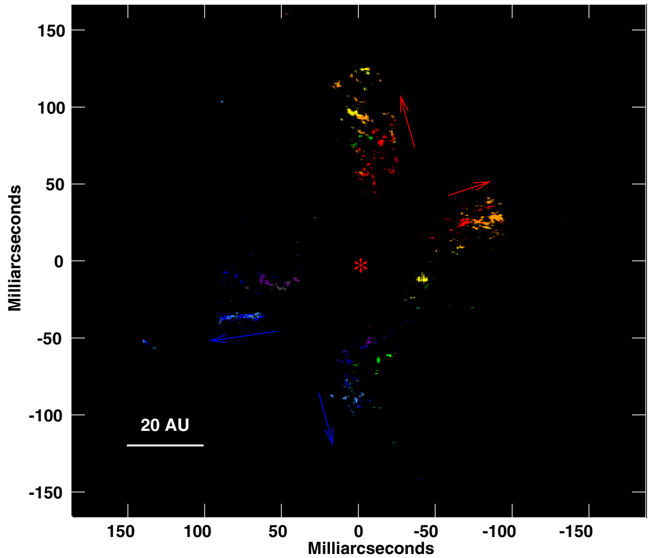

Figure 2. A velocity field derived from the combined SiO $v = 1$ and $v = 2$ emission toward Source I during one observational epoch. Emission is color-coded by Doppler shift (electronic version only) and spans the velocity range $-15 \lesssim V_{\rm LSR} \lesssim 30$ km s^{-1}. An asterisk indicates the position of Source I as determined from radio continuum observations. Directions of the bulk proper motions of individual maser spots observed over the course of multiple observing epochs are indicated by arrows.

loci of the Doppler-shifted SiO $v = 1$ & $v = 2$ emission; see Figure 2) may be infalling, rotating molecular material swept up by a wind/outflow (Cunningham *et al.* 2005), or may demarcate the edge-brightened portion of the wind from a highly inclined ($i \sim 80°$), flared, rotating accretion disk (traced at smaller radii by 7-mm continuum emission; see Figure 1). The canting of the individual SiO emission arms (see Figure 2) and the existence of a "bridge" of gas between the two sides of the funnel with a velocity gradient across it (see Figure 2) now seem to exclude a model of the masers as a biconical outflow along the northwest/southeast direction (cf. Greenhill *et al.* 1998; Doeleman *et al.* 1999).

At $r > 150$ AU (outside the dashed circle), cooler gas traced by SiO $v = 0$ maser+ thermal emission (represented by the shaded areas; cf. Figure 1) and H_2O maser emission (depicted as white spots) delineate a more extended bipolar outflow along a direction close to the plane of the sky.

7. Summary

Using the VLBA, our KaLYPSO team has obtained ~40 epochs of monthly observations of the SiO $v = 1$ and $v = 2$ masers toward Radio Source I in the Orion BN/KL region. Source I is believed to be the nearest example of a high-mass YSO. These observations are the first to probe the kinematics of the molecular gas within 10–100 AU of such an object. Our analysis of these data, together with complementary observations of the adjacent 7-mm radio continuum, H_2O masers, and SiO $v = 0$ masers/thermal emission, provide compelling evidence that disk-mediated accretion and outflow are fundamental to the process of high-mass star formation. Further data reduction and analysis are ongoing. Updates will be posted at http://www.cfa.harvard.edu/kalypso.

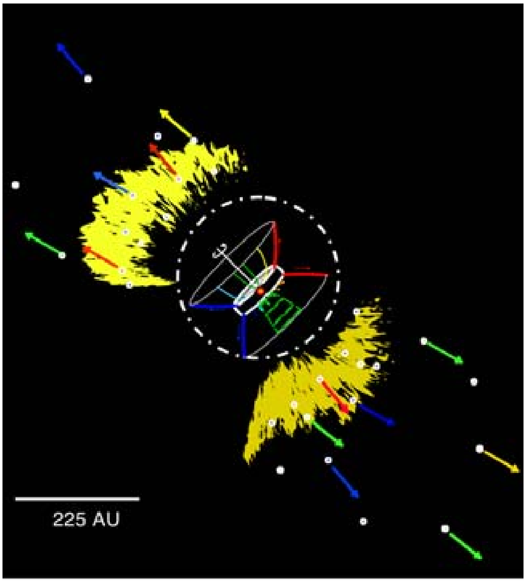

Figure 3. Schematic showing a working model for Source I. Details are described in the Text.

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