High Mass Star Formation in Close Up: Accretion & Outflow within 10 – 1000 AU of Orion Source I

L. J. Greenhill[1], C. J. Chandler[2], M. J. Reid[1], E. M. L. Humphreys[1] & L. D. Matthews[1]
[1]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138;
[2]NRAO, 1003 Lopezville Road, Socorro, NM 87801.

Introduction

Unlike for low mass stars, no robust theory for high-mass star formation currently exists. Observations and theory appear to favor formation of young stellar objects (YSO) by disk-mediated accretion [e.g., 1,2,3,4,5], although coalescence is also a viable mechanism for high mass stars [e.g. 6,7]. Fundamental questions that remain open include:

- ***What is the structure of accretion disks for massive YSOs?***
- ***What is the outflow structure close to the YSOs (inside 1000 AU)?***
- ***What mechanisms shape and drive outflows – are magnetic fields important?***

In order to answer these questions, we need to study high mass star formation where outflows are launched and collimated i.e., at radii of 10 to 1000 AU. This can be challenging. High-mass YSOs are deeply embedded, lie in crowded fields, and they are distant. In even the closest one, Orion KL, 10 AU subtends only ~0.02 arcseconds.

Source I, Orion KL

About 20 near and mid infrared peaks have been identified in Orion KL [8,9,10], but there are only two compact radio continuum sources marking YSOs. One of these, source I (aka IRC 2), exhibits a compact disk morphology (~20 AU in radius; **Figures 1 and 2**) and powers a broad angular distribution of maser emission from different species and transitions at radii of 10 - 1000 AU (**Figures 2, 3 & 4**). Source I is unique in powering so many masers, tracing physical conditions over an especially wide range of radii from the YSO (**Table 1**). The presence of high brightness temperature masers enables high angular resolution imaging, making Source I a very attractive source for study (**Figure 5**).

Table 1. Molecular gas tracers 10 to 1000 AU from source I.

Maser	Probes[11]	Radius
SiO v=1 J=1-0	**Very dense, hot gas** T=1000-2000 K $n_{H2}=10^{10\pm1}$ cm^{-3}	**10 – 100 AU**
SiO v=2 J=1-0	**Very dense, hot gas** T=1000-2000 K $n_{H2}=10^{10\pm1}$ cm^{-3}	**10 – 100 AU**
SiO v=0 J=1-0	**Moderately dense, warm gas** T=800-1600 K $n_{H2}=10^{5-6}$ cm^{-3}	**100 - 1000 AU**
H_2O 6_{16}-5_{23}	**Very dense, warm gas** T~300-1000 K $n_{H2}=10^{9\pm1}$ cm^{-3}	**100 –1000 AU**

Disk-like Structure

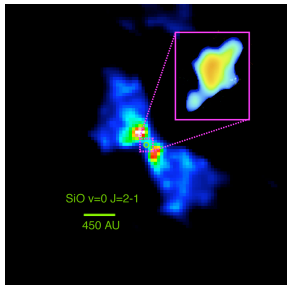

Figure 1: Bipolar outflow from radio source I (open circle), traced by thermal and maser emission from the λ3mm ground state (v=0) of SiO [12; resolution ~0.5″]. The spectra of the two lobes cover the same range of velocity all along the major axis, indicating outflow close to the plane of the sky, rather than rotation. *Inlay*: λ7mm continuum (probably HII [14]) associated with a putative disk [15].

Rotation and Outflow: 10 – 100 AU

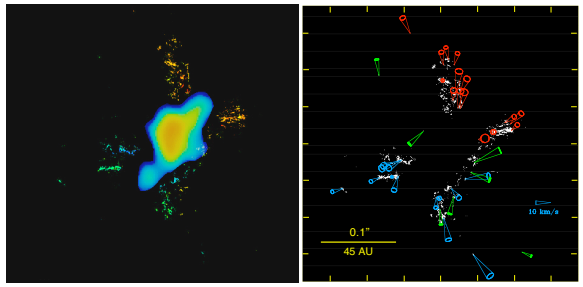

Figure 2: 10 – 100 AU - Distribution and proper motion of v=1 and v=2 SiO emission associated with source I and observed with the Very Long Baseline Array (VLBA‡). The linear resolution is ~0.3 AU. *Left:* Flux weighted mean velocity (small spots). Colors code Doppler shift. VLA λ7mm continuum from Figure 1 is superposed (color contours) [15]. Registration is accurate to ~50 AU or 0.″01. *Right:* Proper motions over four months. Cone length reflects 3-D velocity. Cone aspect indicates inclination with respect to the line of sight. Green cones indicate Doppler velocities within 5 km s^{-1} of the systemic velocity.

Outflow: 100 – 1000 AU

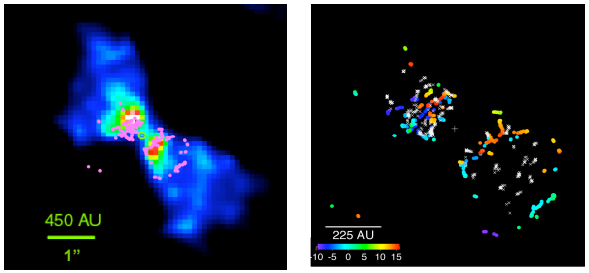

Figure 3: 100 – 1000 AU - Dense gas in the bipolar flow downstream. *Left:* Distribution of H_2O maser emission (pink spots) mapped with the Very Large Array (VLA) and linear resolution of ~20 AU (c. 2001) overlaid on a map of SiO v=0 emission, of linear resolution ~15 AU, from Figure 1. *Right:* H_2O masers alone. Spot color codes Doppler shift. The scale on the legend is in km s^{-1}. Also, shown in white, is the distribution of H_2O maser emission c.1983, demonstrating that the overall distribution is expanding at ~15 km s^{-1}.

Velocities

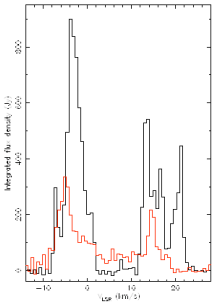

Figure 4: Velocity extent of SiO v=1 (black) and v=0 (red, multiplied up by 20) emission. Despite the very different size scales associated with each transition (see Table 1), the velocity extents are similar.

Working Model

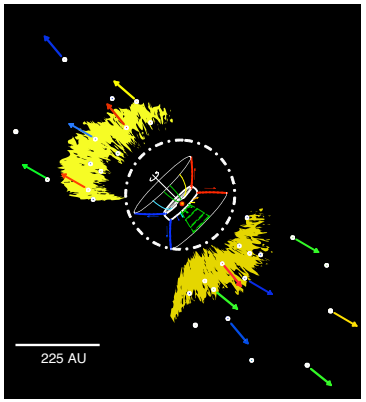

Figure 5: Schematic model for the accretion disk and outflow from radio source I. At radii < 100 AU *(inside dashed circle)*, material is driven into a wide-angle bipolar outflow. The funnel may be the interface between an initially spherical YSO wind and accreting material [16] or it may delineate some portion of a disk wind driven from the inclined accretion disk by photoevaporation or magnetic processes. The funnel walls close to the YSO appear to comprise the hottest, highest density molecular material and are traced by v=1 and v=2 SiO emission (heavy lines colored by Doppler shift). Lower density material lies downstream in the flow at radii > 100 AU *(outside dashed circle)*, traced by v=0 SiO (diffuse yellow) and H_2O emission (spots).

Summary

In total, we have accumulated ~40 monthly epochs of VLBA observations that will be used to follow the evolution of structure at radii < 100 AU, and supporting VLA epochs that will enable study for radii >100 AU. The VLA observations of ground state SiO include full Stokes information, and it should be possible to estimate the compact component of sky-plane magnetic field structure [cf. 17]. The program has been dubbed the KaLYPSO project (Kleinmann-Low Young-Proto-Stellar-Object.)§ Reduction and analysis are ongoing.

§http://www.cfa.harvard.edu/kalypso

‡ *The VLBA and VLA are operated by the National Radio Astronomy Observatory, that is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.*

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