



Preliminary Modeling Results of Orion Source I from the KaLYPSO Project

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The KaLYPSO Project

<http://www.cfa.harvard.edu/kalypso>

The goal of the KaLYPSO (Kleinmann-Low Young Proto-Stellar Object) project is to answer key open questions of high-mass star formation through study of a YSO **within radii of 10 - 1000 AU**, i.e., the region where outflows from accretion disks are expected to be launched and collimated. In particular, (i) what is the accretion disk size and structure; (ii) what drives the outflow; and (iii) are magnetic fields important?

Radio Source I in Orion BN/KL, the nearest known high-mass YSO, powers a rich variety of SiO and H₂O masers within 10 - 1000 AU. VLBI observations of the masers have provided the most detailed picture yet of a forming high-mass star, with **strong evidence for a compact disk and bipolar flow**. The multiple observed maser transitions, and measurement of 3D velocities on small angular scales, make Source I a very valuable target for probing the physical conditions and kinematics close to a YSO using radiative transfer and geometric modeling. In this poster, we describe results of our ongoing observational and modeling work, and discuss the importance of ALMA for future studies of Source I.

Source I in Orion BN/KL

Two distinct regions are traced by different maser transitions:

Region A: R=10-100 AU

²⁸SiO v=1 and v=2 J=1-0 masers trace an "X"-shape that extends up to ~100 AU from Source I. We have studied this region using the VLBA, with a linear resolution of ~0.3 AU. Ground state ²⁹SiO and ³⁰SiO emission has also been detected from Region A using the VLA (Goddi Poster P.12).

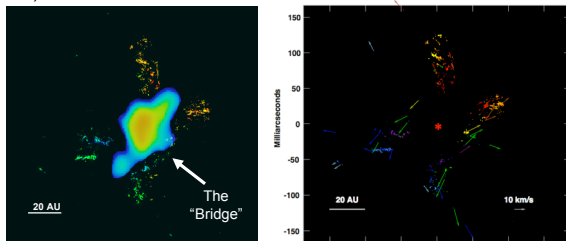


Figure 1: (left) Distribution of v=1 and v=2 SiO emission associated with Source I. Colors code Doppler shift. Probable ionized disk continuum emission at 7 mm, mapped with the VLA (Reid et al. 2007), is shown in filled contours. Note the "bridge" of maser emission (parallel to the disk elongation). **(right) Velocity field of the SiO masers** (Matthews et al. 2007). The kinematics of the bridge features provide strong evidence that the masers trace a rotating disk structure about Source I.

Region B: R=100 - 1000 AU

H₂O and v=0 SiO masers appear to trace extended regions of a bipolar outflow originating from Source I. We have observed these masers using the VLA, with linear resolutions of ~20 AU and ~15 AU for H₂O and SiO respectively.

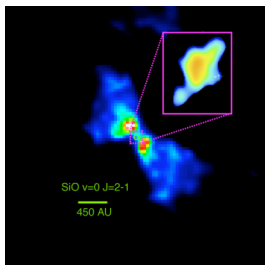


Figure 2: Source I on Large Scales. The "bowtie," bipolar outflow from radio source I traced by thermal and maser emission from ground state (v=0) SiO [Wright et al. (1995); resolution ~0.5"]. The spectra of the two lobes cover the same range of velocity, indicating the outflow lies close to the plane of the sky. Inlay: Disk continuum, as for Figure 1.

Working Model

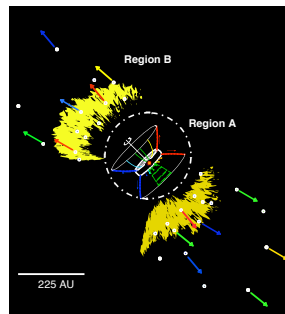


Figure 3: Schematic model for the accretion disk and outflow of radio Source I. In Region A, material is driven into a bipolar, rotating, funnel-like outflow from the inclined accretion disk of a massive YSO. The funnels walls comprise the hottest, highest density molecular material and are traced by v=1 and v=2 SiO emission (heavy lines colored by Doppler shift). Lower density material lies downstream in the flow in Region B, marked by v=0 SiO (diffuse yellow) and H₂O emission (spots). See also Cunningham et al. (2005).

Radiative Transfer Modeling: ^{28,29} & ³⁰SiO

OBSERVATIONS:

• Simultaneous VLA observations of ²⁸SiO v=0 J=1-0; v=1 J=1-0; v=2 J=1-0; and minor isotopes ²⁹SiO and ³⁰SiO v=0 J=1-0 have established the maser nature of emission (see Goddi Poster P.12). ²⁸SiO and ³⁰SiO v=0 emission is located with vibrationally excited ²⁸SiO maser emission in Region A (R=10-100 AU). ²⁸SiO v=0 emission is spatially separate, occurring from Region B (R=100-1000 AU)

MODELING:

- The observations have enabled constrained radiative transfer modeling.
- We have two RT codes developed by M. Gray (U. Manchester) with which to compare results. Both codes have 600 levels (v = 0 - 4; J = 0 - 39 for each isotopic species).
- (i) Large Velocity Gradient (LVG) pumping model: no overlap or maser saturation.
- (ii) Spherical Accelerated Lambda Iteration non-local RT, line overlap & saturation.
- We report results from 5000 runs of the LVG model here for an initial parameter sweep.

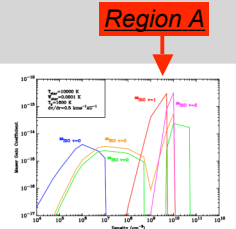
Table 1: The Standard Set of Physical Conditions

Parameter	Standard values for Region A	Standard values for Region B	Range of values
Stellar Temperature	10000 K	10000 K	
Radiation dilution W_{star}	10^{-4}	$\leq 10^{-5}$	$10^{-1} - 10^{-8}$
$n(\text{H}_2)$	10^9 cm^{-3}	10^6 cm^{-3}	$10^3 - 5 \times 10^{11} \text{ cm}^{-3}$
Kinetic Temperature	1600 K	800 K	600 - 2400 K
²⁸ SiO/H ₂ ratio	10^{-4}	10^{-4}	
Isotope abundance ratios ²⁸ SiO: ²⁹ SiO: ³⁰ SiO	1:0.0467:0.031	1:0.0467:0.031	
Velocity gradient	0.5 kms ⁻¹ AU ⁻¹	0.5 kms ⁻¹ AU ⁻¹	0.005 - 5 kms ⁻¹ AU ⁻¹
External and local dust T	1 K	1 K	n/a
Dilution external dust radiation	n/a	n/a	

Modeling Results

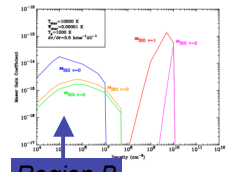
V=1 & v=2 J=1-0 ²⁸SiO

These transitions favor densities of $10^8 - 10^{10} \text{ cm}^{-3}$ (v=1) and $10^9 - 10^{11} \text{ cm}^{-3}$ (v=2). They are never inverted at $n(\text{H}_2) < 10^7 \text{ cm}^{-3}$. The v=2 maser is optimized at higher temperatures, $T_k > 2000 \text{ K}$, when it can be more strongly inverted than the v=1 maser transition. The v=2 maser survives a strong, hot radiation field more readily than the v=1 maser (never inverted for $W_{\text{star}} > 0.01$). These points may explain why the v=2 masers tend to lie closer to the star than the v=1.



V=0 J=1-0 ²⁸SiO

This SiO maser only occurs at $n(\text{H}_2) < 10^7 \text{ cm}^{-3}$ and $W_{\text{star}} < 0.01$, explaining why it occurs in Region B. It occurs at a wide range of kinetic temperatures $T_k > 600 \text{ K}$, however it is optimized at $T_k < 1200 \text{ K}$. Note that these are likely not the only conditions in Region B, as the H₂O masers require higher densities ($10^8 - 10^{10} \text{ cm}^{-3}$).



Minor Isotopes - ²⁹ and ³⁰SiO v=0 J=1-0 are inverted across a broad range of parameter space. However, they are optimized in the higher T_k and $n(\text{H}_2)$ of Region A. Relatively weak isotopic emission also occurs for Region B conditions. This may be resolved out by the VLA, potentially explaining the difference in the VLA and GBT spectra (Goddi Poster).

Summary: Our radiative transfer modeling reproduces observed line ratios for the five masers observed. It explains the spatial location of masers in Source I and establishes the physical conditions in a disk-outflow system within 10 - 1000 AU. In future work, we will use the non-local RT code with line overlap to investigate the maser excitation mechanisms.

ALMA Prospects

Source I is a uniquely good target for study using ALMA due to its proximity and wide range of molecular and maser emission species. In particular, our modeling predicts masers from chains of higher-J transitions of SiO that can be mapped at ~15 mas resolution for e.g., a J=7-6 maser at ~300 GHz to further probe disk/outflow dynamics and physical conditions. The prospect of measuring the maser proper motions using ALMA is very real, since yearly motion corresponds to ~1/3 of an ALMA beam at 1 mm. In addition, full polarization maser observations will enable estimation of B fields on small angular scales to test high-mass star formation theories.

REFERENCES: Cunningham, A. Frank, A., & Hartmann, L., 2005, ApJ, 631, 1010; Matthews, L. M., 2007, in: Proceedings of IAU 242, p.130; Reid, M. J., Menten, K. M., Greenhill, L. J., Chandler, C. J., 2007, ApJ, 664, 950; Wright, M. C. H. et al., 1995, ApJ, 455, L185

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