# Molecular jet simulation with a large precession angle and its application to emission from NGC 7538 IRS1

A. Rosen[(1)], S. Kraus[(1)], G. Weigelt[(1)], M.D. Smith[(2)]

(1) Max-Planck-Institut für Radioastronomie, Bonn, Germany (2) Centre for Astrophysics and Planetary Science, University of Kent, Cantebury, UK

## Abstract

Recent high resolution bispectrum speckle interferometric observations in the near-infrared have revealed that the area surrounding NGC 7538 IRS1 is associated with a fan-like region that contains several stars and regions of diffuse emission. An interpretation of the speckle, CO, radio continuum, and methanol maser data, which shows the current position angle of the protostar's accretion disk on the sky, is of a jet with a large precession angle. Here, we present a molecular jet simulation with a similarly wide precession angle. We analyze the simulation for properties associated with the flow and the calculated emission. We can reproduce the "older" average position angle for the CO emission, compared with a more recent value from molecular hydrogen (i.e., shocked gas) emission (which we use as a proxy for the $K'$-band emission). Thus, the model is consistent with the interpretation that a precessing jet is responsible for much of the molecular emission (covering different emission lines) in the IRS1 region.

## The Source and A Model

IRS1 is a massive (30 $M_\odot$) protostar which is associated with an ultracompact (UC) H II region and a CO outflow. Remarkably, at the position of IRS1, a group of linear-aligned methanol masers has been detected, which most likely trace a Keplerian-rotating circumstellar disk (Pestalozzi et al. 2004). Examination of the data reveals a misalignment between the outflow direction expected from the orientation of the methanol maser disk and the other outflow tracers, which can be interpreted in the context of a disk precession model. A simple analytic precessional model for the S-shaped morphology in the $K'$-band images yields a best fit with precession period of 280 years and a precession half-angle of 40° (see Fig. 2). These values put strict constraints on possible precession mechanisms. After considering several mechanisms, we identify tidal interaction with a companion as most plausible. The short precession period implies a non-coplanar orbit which is causing the circumbinary disk to precess and maybe to warp (Larwood et al. 1997). A more complete analysis, including additional observational data, will appear in a manuscript (Kraus et al., in preparation).

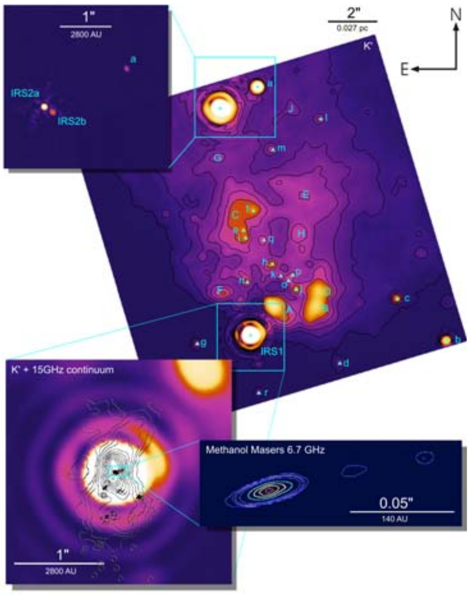


**Figure 1:** Speckle image reconstructed from MMT data with a resolution of 334 mas. The inset in the upper left corner shows a diffraction-limited image (73 mas, SAO-data) of IRS2, around which we discovered a companion (separation 195 mas). In the lower left, IRS1 is shown, emphasizing the elongation of the IRS1 Airy disk overplotted with the 15-GHz radio continuum and the position of the OH (circles) and methanol (crosses) masers (from Hutawarakorn & Cohen 2003). In the lower right, we show the integrated brightness of the methanol masers in order to stress the misalignment of the suspected maser disk with the outflow direction.

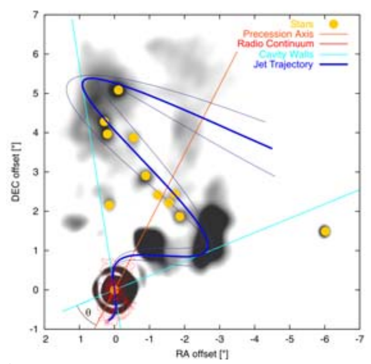


**Figure 2:** MMT-Speckle image overplotted with the trajectory of ejecta from a precessing outflow projected onto the plane of the sky (thick blue line) in a simple analytic model. The precession period is 280 years and the half-opening precession angle is 40°. The thin blue lines show the full extent of the projected trajectory when both the average position angle and the viewing angle (in the plane of the sky) for the precession axis is modified by ±5°. The red contours show the 15-GHz radio continuum map by Hutawarakorn & Cohen (2003).

## Observations

Initial observations were performed on 2002-09-24 using the 6m *Special Astrophysical Observatory* (SAO) telescope located on Mt. Pastukhov in Russia. Additional data was gathered on 2004-12-20 with the 6.5m *Multiple Mirror Telescope* (MMT) on Mt. Hopkins, Arizona. Images were reconstructed from the obtained speckle interferograms using the bispectrum speckle interferometry method (Weigelt 1977; Lohman et al. 1983).

## Detected NIR IRS1 Outflow Structure

Extending from IRS1, we detect a diffuse fan-shaped structure with an ~90° opening angle, which we interpret as scattered light from an outflow cavity excavated by strong outflow activity from IRS1. Contributions from the $H_2$ 1-0 S(1) (2.112 $\mu$m) line are also likely. Eighteen fainter stars and several blobs are embedded within this fan-shaped structure. The arrangement of the diffuse blobs suggests an S-shaped morphology.

## NGC 7538 IRS1 Maser Feature A

The massive protostar IRS1, located at a distance of $\sim$ 2.8 kpc, is associated with an UC H II region and is also the suspected driving source of a bipolar CO outflow. In 1998, Minier et al. reported the discovery of linear-aligned methanol masers at the position of IRS1 and interpreted them as an edge-on circumstellar disk. The accuracy of the alignment and the stunning precision with which the position-velocity diagram of these masers could be modelled makes the maser feature NGC 7538 IRS1-A one of the most intriguing candidates for Keplerian-rotating protostellar disks (see Pestalozzi et al. 2004). Therefore, for the following interpretation we assume that maser feature A resembles a circumstellar disk, mentioning that an alternative scenario was presented by De Buizer and Minier (2005) which suggests that the methanol masers might trace an outflow cavity.

## Indications for Disk and Jet Precession

It is most remarkable that the maser disk is not perpendicular to the large-scale outflow tracers (CO, $H_2$, fan-shaped outflow cavity) but misaligned by $\sim$ 60°. On scales $\lesssim 1''$, a bending ($\sim$ 25°) of the UC H II region can be conceived (Campbell 1984), which seems to continue in the S-shaped morphology in our $K'$-band images. Based on these indications for a systematic change in the outflow direction, we suggest jet precession as one possible explanation.

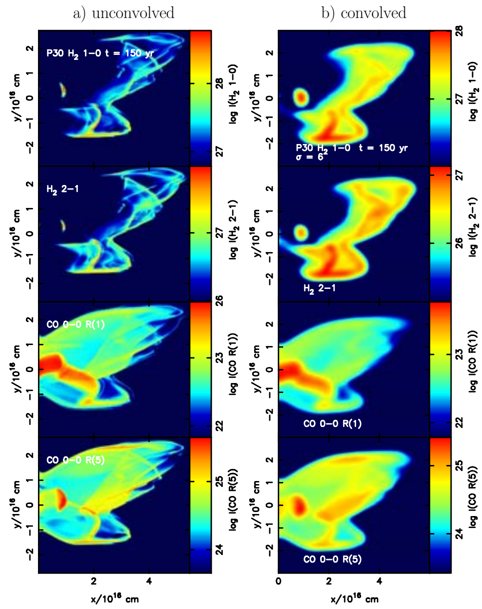


**Figure 3:** Integrated molecular emission line maps from the simulation for $\phi = 0°$. The images on the right are convolved with a Gaussian beam with $\sigma = 6$ zones.

## The Simulation

We use the version of the ZEUS-3D code as modified by Smith & Rosen (2003), which includes some molecular cooling and chemistry, as well as the ability to follow the molecular ($H_2$) fraction. For this simulation, we use a 3D Cartesian grid of 275 zones in each direction, where each zone spans $2 \times 10^{14}$ cm in each direction. This grid balances the desire for some spatial resolution of the flow with the ability to simulate a sufficiently large part of the observed flow associated with NGC 7538 IRS1.

Since the physical size of the grid is rather small, we have chosen a nominal speed of 150 km $s^{-1}$, reduced from the inferred value of 250 km $s^{-1}$ for this source. The flow is precessed with a nearly 30° half-angle, with the amplitude of the radial components of the velocity 0.55 of that of the axial component. The precession has a period of 120 years, which leads to 1.25 cycles during a grid crossing time. The flow is also pulsed, with a 30% amplitude and a 30 year period. This short period assists in the reproduction of the multiple knots of K' emission near NGC 7538 IRS1. The jet flow also is sheared at the inlet, with the velocity at the jet radius 0.7 that of the jet center. We have chosen a jet number density of $10^5$ hydrogenic nuclei $cm^{-3}$, while the ambient density is $10^4$. The simulated jet radius is $4.0 \times 10^{15}$ cm (20 zones). Thus, the time-averaged mass flux is $2.6 \times 10^{-6}$ $M_\odot$ $yr^{-1}$, which is three orders of magnitude lower than the value as determined for the CO outflow (Davis et al. 1998). Similar calculations of the momentum flux and kinetic energy flux, or mechanical luminosity, yield values of $3.8 \times 10^{-4}$ km $s^{-1}$ $M_\odot$ $yr^{-1}$ and 4.7 $L_\odot$, respectively.

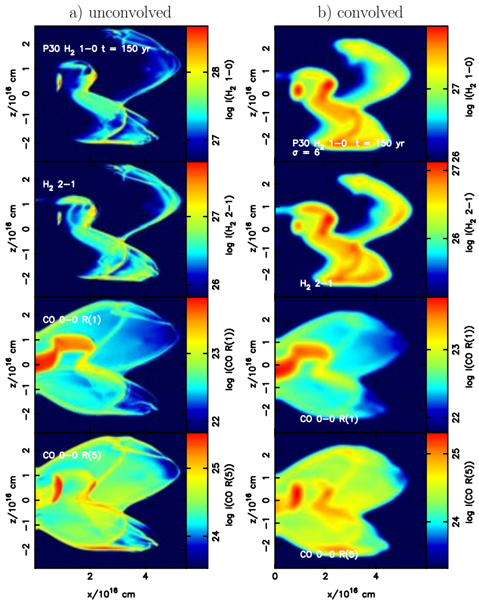


**Figure 4:** Integrated molecular emission line maps from the simulation for $\phi = 90°$. The images on the right are convolved with a Gaussian beam with $\sigma = 6$ zones.

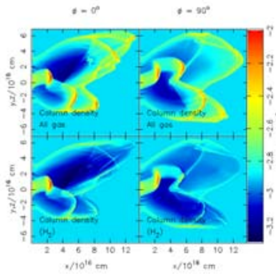


**Figure 5:** Integrated total and molecular hydrogen column density for the simulation. The reduction in column density, especially for $\phi = 0°$, may assist in seeing deeper into the molecular cloud and revealing the $K'$-band sources between blobs B/D and C in Fig. 1.

## Implications

Identifying the appropriate formation mechanism of massive stars, either accretion via a circumstellar disk or stellar coalescence, remains one of the major open questions in star formation. The detection of precessing outflows from massive stars might contribute a unique insight, as precessing outflows carry not only information about the accretion properties of the outflow driving source, but also about the kinematics (stellar multiplicity) within its closest vicinity.

Here, we see that the numerical simulation assists in the interpretation of the high resolution $K'$-emission from around NGC 7538 IRS1 as being associated with a precessing flow. Until now, clear indications for flow precession were reported for just two massive young stellar objects, namely IRAS 20126+4104 (Shepherd et al. 2000) and IRAS 23151+5912 (Weigelt et al. 2006).

### Acknowledgements

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### References

Campbell, B. 1984, ApJ 282, L27
Davis, C.J., Moriarty-Schieven, G., Eislöffel, J., et al. 1998, AJ 115, 1118
De Buizer, J.M., Minier, V. 2005, ApJ 628, L151
Hutawarakorn, B., Cohen, R.J. 2003, MNRAS 345, 175
Larwood, J.D., Papaloizou, J.C.B., 1997, MNRAS 285, 288
Lohmann, A.W., Weigelt, G., Wirnitzer, B. 1983, Appl. Opt. 22, 4028
Minier, V., Booth, R.S., Conway, J.E. 1998, A&A 336, L5
Pestalozzi, M.R., Elitzur, M., Conway, J.E. et al. 2004, ApJ 603, L113
Smith, M.D., Rosen, A. 2003, MNRAS 339, 133
Shepherd, D.S., Yu, K.C., Bally, J., et al. 2000, ApJ 535, 833
Weigelt, G. 1977, Opt. Commun. 21, 55
Weigelt, G., et al. 2006, A& A, in press (astro-ph/0511178)

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contact e-mail: arosen@mpifr-bonn.mpg.de