Bispectrum speckle interferometry of the massive protostellar outflow source IRAS 23151+5912

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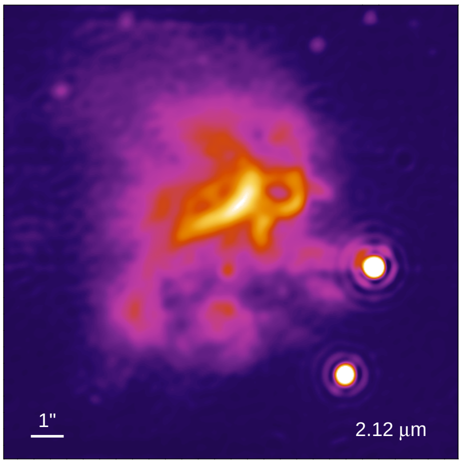
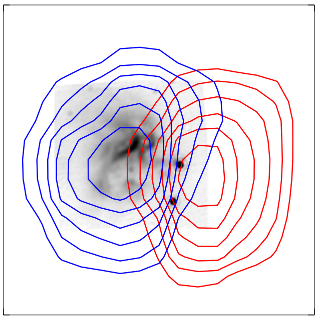


Pseudocolor representation of our K'-band bispectrum speckle image of IRAS 23151+5912

We have obtained near-infrared bispectrum speckle interferometry of the massive protostellar object IRAS 23151+5912. Our speckle image, which was recorded on 20 December 2004 with the 6.5 m MMT in Arizona, shows two point-like sources (IRS 1, the brighter, northern object, and IRS 2) and extended diffuse nebulosity. The nebulosity in the eastern part of our image shows a remarkable wealth of detail. Its structure is dominated by several curved features which look like bow shocks. In remarkable contrast to "usual" bow-shocks seen in many young jet and outflow sources, which are well aligned and point away from the jet source, the curved features in IRAS 23151+5912 appear to be oriented in random directions.
The nebulosity seems to be connected to IRS 1 but not to IRS 2. Considering the fainter parts of the nebula as seen in the deep seeing-limited K-band images (e.g. [1]), the shape of the nebula is clearly cone-like, with IRS 1 at its tip. The axis of the cone is along position angle PA $\sim 73°$, and the opening angle is about $90°$. IRS 2 appears to be outside the cone-like nebular structure.
Our image also reveals a narrow linear structure connecting the central point source to the extended diffuse nebulosity. This feature may represent the innermost parts of the jet that drives the strong molecular outflow from IRAS 23151+5912.

Comparison of infrared and radio emission



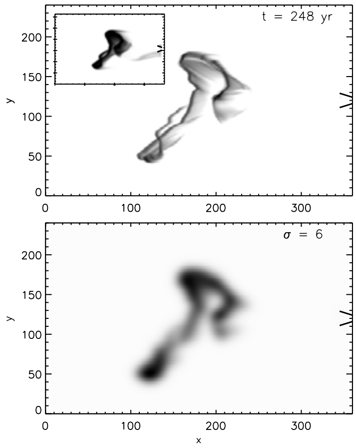
Comparison of our K-band speckle image of IRAS 23151+5912 (greyscale) to CO radio maps [2] shown as red and blue contours for the red- and blue-shifted CO emission. The field-of-view is $30'' \times 30''$.

By comparing our near-infrared image with mm and CO radio maps we find that the brighter of the two point sources lies in the center of the mm peak, indicating that it is the massive protostar. The nebulosity coincides very well with the blueshifted molecular outflow component. This strongly suggests the following interpretation of the observed structures: the bright point-like K-band source is the protostar in the center of the compact molecular cloud core. The protostar is embedded in a dense circumstellar envelope or perhaps a thick circumstellar disk. The outflow has cleared a cavity in the circumstellar material, and what we see as the diffuse nebulosity is light from the central protostar that is scattered by dust grains at the inner wall of this low-density outflow cavity or by material within the cavity in our direction.

The asymmetric general shape of our image, i.e. the fact that we do not see a counter lobe to the west of the bright point-like source, is easily explained as a geometrical effect. The red-shifted outflow component has probably cleared a similar cavity, which, however, is not visible in our near-infrared images, because it is pointing away from us, and the light predominantly escapes in a direction away from us.

Structure of the nebulosity and outflow simulations

The most prominent feature in the nebulosity east of IRS 1 is an arc with bow-shock-like shape, pointing towards the bright point source. We suspect that this feature indicates the action of a precessing jet which has created an inward-pointed cone in the swept up material. Below we present numerical jet simulations that reproduce this and several other features in our speckle image of the nebulosity.

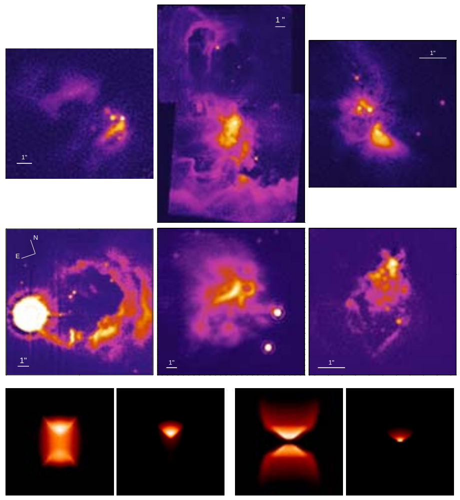


Simulated images of the outflow resulting from a precessing jet. Shown here are (upper panel) the 1-0 S(1) emission from H_2 at 2.12μm and (lower panel) the 1-0 S(1) emission convolved with a Gaussian with $\sigma = 6$ zones. The insert shows the appearance of a wispy jet feature on a 'deeply exposed' simulated image.

The three-dimensional hydrodynamic simulations used to compute the above simulated image in the emission line of molecular hydrogen take a heavy molecular jet which cuts through a uniform external cloud, destroying some of the molecules in its path [3]. The simulations show that the reverse bow shock-like feature is a remnant of the initial ring of shocked gas around an inward pointed cone of ambient material trapped within the volume of material swept up by the precessing jet. The ring of shocked gas fragments into numerous bow-shocks and curved filaments, but the head of the inward pointed cone remains visible for some time and points towards the jet source. The reverse bow forms around the precession axis, along which the outflow is held back. This offers a good explanation of the brightest curved feature visible in our speckle image.

Comparison of the infrared morphologies of intermediate- and high-mass YSOs

Complex structures are generally detected in the immediate circumstellar environments of intermediate- and high-mass protostars, and IRAS 23151+5912 is no exception. However, as illustrated in the mosaic image to the right, different objects display intriguingly different near-infrared morphologies. This is, perhaps, not surprising given the following vital intrinsic sources of influence: the evolving properties of the central radiating source, the varying impact and disruption by the jet and/or wind, the clumpy small-scale distribution of surrounding material, and the configuration of large-scale geometric components. In addition, the viewing angle is an extrinsic factor which needs to be eliminat ed before we can relate the structure to the physical cause. With this purpose, we here compare bispectrum speckle images to each other and to radiative transfe r simulations.
A common feature in the menagerie of images is diffuse emission extending from the central point-like source with a fan-shaped morphology pronounced to varying degrees. In most cases, the diffuse emission is only seen in one direction, i.e. it is highly asymmetric. However, the detailed shape and structure of the diffuse emission varies strongly from object to object.



Comparison of K'-band images from our bispectrum speckle interferometry of several intermediate- and high-mass YSOs with radiation transfer simulations.
Upper two rows: Pseudocolor representations of our reconstructed images. The objects are arranged by increasing estimated luminosity or mass of the YSO. The first row displays S140 IRS3 [4], S140 IRS1 [5], and Mon R2 IRS 3 [6] (from left to right). The second row shows AFGL 2591 [7], IRAS 23151+5912, and K3-50 A [8].
Lower row: simulated K'-band images derived from 2D radiative transfer calculations [9]. The two left images correspond to a 'spherical torus' model with c one-like cavities, seen under inclination angles of $i = 85°$ and $i = 60°$. The two right images are from a model of a Keplerian disk embedded in a spherical halo with polar outflow cavities, again for inclination angles of $i = 85°$ and $i = 60°$.

A critical factor in the appearance of the structures is the viewing-angle i.e. the inclination between the outflow/cavity axis and the line-of-sight. In fact, the radiation transfer simulations demonstrate that the cone of the bipolar cavity oriented towards us appears very bright for moderate or low inclination angles ($i \lesssim 75°$). The opposite cone is considerably fainter or completely invisible because it is oriented away from us and hidden by circumstellar extinction. Objects which possess low inclination angles are thus suggested to be S140 IRS 1, K3-50A, and IRAS 23151+5912.
In systems with high inclination angles ($i \gtrsim 75°$), a more symmetric morphology is expected. A good example in our sample is Mon R2 IRS 3b where, in addition to the bright nebulosity toward the south, fainter nebulosity can be seen north of the point source, resembling a bipolar reflection nebulosit y.
The observations indicate that a second difference is related to the intrinsic asymmetry of the cavity structure itself. In some objects the shape of the cavity appears highly symmetric, often with very straight edges (e.g. S140 IRS1, AFGL 2591, K3-50A), while other objects show remarkable asymmetry (e.g. S140 IRS3).
A third major difference is the relative amount of reflected and shock emission. In S140 IRS1 and Mon R2 IRS 3b, the infrared morphology is strongly dominated by a bright cavity, i.e. by light reflected from the inner cavity walls. In other objects we observe emission from shocked material in the vicinity of the jets (e.g. the microjet from Mon R2 IRS 3a, or the extended jet from S140 IRS3A) or outflowing shock waves seen in reflected light, such as the loops in AFGL 2591.
Furthermore, a wide-angle wind is expected to clear a broader path in the surrounding circumstellar matter than a highly collimated jet. One would therefore expect broader cavities to be associated with the higher mass YSOs. In our sample of intermediate-to-high mass YSOs we see some indication that the cavity opening angle increases with increasing luminosity of the central YSO, tentatively supporting this suggestion. However, jet precession and multiple outflows also clearly act to broaden cavities in the two lower mass examples, making any relationship less obvious.
Comparing the observed images to the radiative transfer simulations, we find that the objects showing triangular shaped morphologies with rather straight walls (AFGL 2591, K 350 A, and IRAS 23151+5912) are quite well reproduced with Model E, the inclined torus or cavity model. The observed bipolar structure around Mon R2 IRS 3 a, on the other hand, appears very reminiscent of a disk model, seen under a rather high inclination angle. For S140 IRS3 and S140 IRS1 the very elongated observed nebulosities may indicate a very small cavity opening angle.
To summarize, the large-scale features observed in the speckle images can be understood in the frame of simple disk or envelope + cavity models, whereas the small scale structure depends on additional factors such as clumpiness of the circumstellar material and the presence of shock waves.

References:

[1] Hodapp 1994, ApJS 94,615; [2] Beuther et al. 2002, A&A 383,892; [3] Rosen & Smith 2004, MNRAS, 347,1097

[4] Preibisch et al. 2001, A&A 378,539; [5] Weigelt et al. 2002, A&A 381,905; [6] Preibisch et al. 2002, A&A 392,945

[7] Preibisch et al. 2003, A&A 412,735; [8] Hofmann et al. 2004, A&A 417,981; [9] Sonnhalter et al. 1995, A&A 299,545