Multiple outflows from the massive protostar S140 IRS1

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Introduction

Some - perhaps all - newly formed stars go through a turbulent adolescence in which they eject streams of gas that collide with the surrounding molecular cloud material. These primary outflows power shock waves and entrain surrounding gas to produce molecular outflows. The mechanisms by which these flows are generated, accelerated, and collimated are largely unknown. The molecular outflows are probably of fundamental importance for the formation process and the earliest evolution stages of stars. For example, the outflows are thought to play a crucial role in removing angular momentum from the disk and thereby enabling the protostar to accrete disk material. Conventional observations have provided many interesting pieces of information about the properties of these outflows. However, if we want to learn about the origin of the outflows and how they are accelerated and collimated, we have to look at their origin, i.e. as close as possible to the disk/star boundary. In other words, high-spatial resolution observations are of crucial importance for further progress in this field.

Here we report high-resolution near-infrared studies of the massive protostellar object S140 IRS 1. S140 is a HII region at the south-east edge of the L1204 dark cloud, located at a distance of ~ 900 pc (Crampton & Fisher 1974). This cloud contains a small cluster of highly obscured, optically invisible infrared sources, originally detected by Rouan et al. (1977). The 20 μm observations by Beichman et al. (1979) revealed three individual infrared sources in this region. The brightest source is called IRS 1, the two other sources IRS 2 and IRS 3 are located $\sim 17''$ north and $\sim 9''$ east of IRS 1. The infrared spectra of these sources are rising steeply between 10 μm and 50 μm (Lester et al. 1986), demonstrating that they are deeply embedded young stellar objects associated with circumstellar material. IRS 1 has a luminosity of $L \approx 5 \times 10^3\,L_\odot$ and its mass is estimated to be $\sim 10\,M_\odot$. S140 IRS 1 is the source of a strong molecular CO outflow (e.g. [??]) with position angles of $\sim 160°$ and $\sim 340°$ for the blue- and red-shifted outflow outflow lobes, respectively. The low-velocity blue-shifted CO emission also shows a weak extension north-east of IRS 1, at a position angle of $\sim 20°$.

Observations and Results

Speckle interferograms in the near-infrared K' band were obtained with the 6 m telescope at the Special Astrophysical Observatory (SAO) in Russia. The image was reconstructed using the bispectrum speckle interferometry method (Weigelt et al. 1991) and has a diffraction-limited resolution λ/D of 76 mas, corresponding to $\sim$ 70 AU at the distance of S140 IRS 1. The large central figure shows our reconstructed image. With the exception of the diffraction rings around point sources, all features seen in our image are real. In Figure 2 we have marked all the features that we will discuss below.

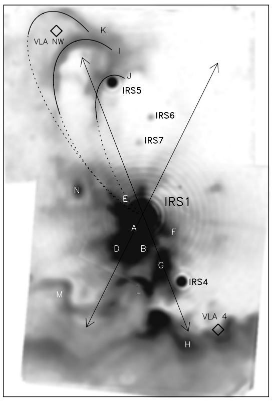

Figure 2: Greyscale representation of our K'-band image of S140 IRS 1. The features discussed in the text are marked in this image. The curved lines show the shapes of the jet-driven outflow cavity models described in the text. The rhombs mark the positions of the VLA sources 4 and NW. The long arrows indicate the four major outflow directions. North is up and east is to the left.

• Central part

Bright extended emission (**A–D**) is seen pointing from IRS 1 towards the south-east. While the structure of the emission is very clumpy, its general shape follows a well-defined direction with a position angle of $154° \pm 3°$. This structure probably is a partially evacuated cavity in the circumstellar envelope around IRS 1, which has been excavated by the blue-shifted south-eastern $(160°)$ molecular outflow lobe. Perhaps, the clumpiness indicates the presence of individual bullets or unresolved bow shocks in a jet that drives the outflow. No infrared emission is seen in our image in the direction of the red-shifted $(340°)$ CO outflow lobe, probably due to high extinction in the north-western part of the circumstellar material around IRS 1.

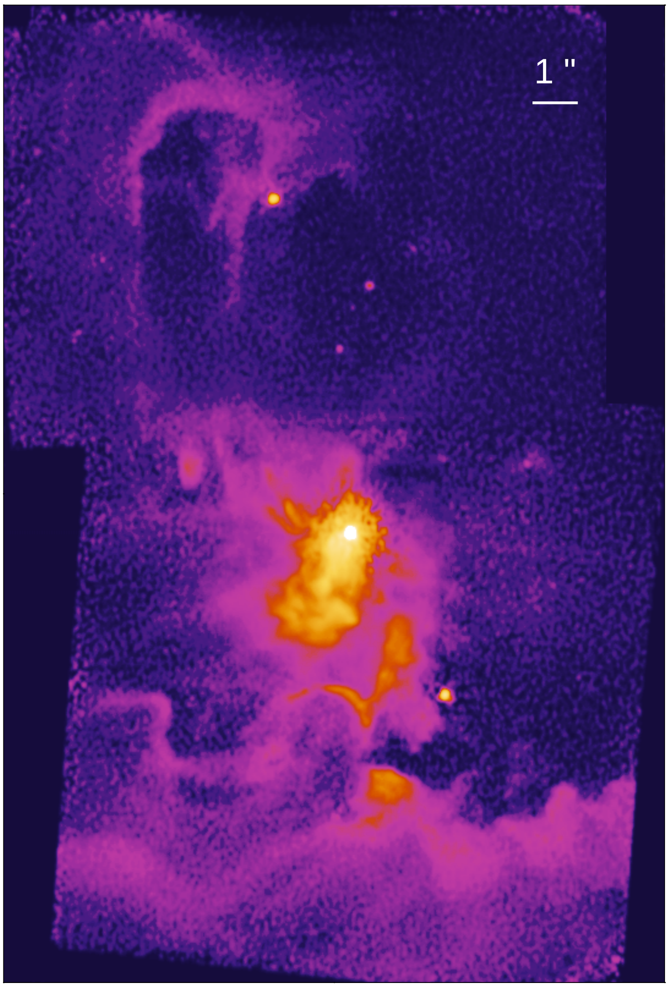

Figure 1: K'-band image of a $13'' \times 21''$ area centered on S140 IRS 1, reconstructed by the bispectrum speckle interferometry method. North is up and east is to the left. The image has a diffraction-limited resolution of 76 mas. The faintest structures visible in the image are 8–9 mag fainter than the central source IRS 1 (for example, the point source $4''$ north of IRS 1 is 8.0 mag fainter than the central source IRS 1).

• North-eastern region

Three prominent arcs of emission (**I, J, K**) can be seen approximately $10''$ north-east of IRS 1. The tips of these arcs have bow-shock like shapes and they point away from IRS 1 with position angles of $20°$, $25°$, and $10°$, respectively. (cf. Fig. 2). These arcs look like outflow cavities. We therefore compared their shapes with theoretically expected morphologies of outflow cavities, based on the semi-analytical model [??] for jet-driven propagating outflows with prompt entrainment at the head of the traveling bow shock. In Fig. 2 we show model curves overlaid on our image, which fit the observed arc structures in our image quite well.

This suggests that the observed arcs actually represent the limb-brightened flanks of elongated cavities that have probably been carved out by material flowing away from IRS 1. Interestingly, the orientation of these arcs closely corresponds to the direction of the blue-shifted CO emission north-east of IRS 1, at a position angle of $\sim 20°$.

• Southern part

The southern part of our image is dominated by clumpy diffuse emission. Most of this represents probably reflected light from the surface of the molecular cloud clump south of IRS 1. Note that the surface of the diffuse emission seems to show some kind of depression next to the mark **H** in Fig. 2. This structure could indicate the impact of material flowing from IRS 1 in the $\sim 200°$ direction. This is just the opposite direction to the symmetry axis of the north-eastern $20°$ arc. The location of the radio source VLA 4 near that feature, indicating the presence of ionized shocks from a collision zone [??], is a further indication that out-flowing material from IRS 1 collides with cloud material in this direction.

Discussion

Our image traces the violent interaction of material flowing away from IRS 1 in several directions with the surrounding cloud material. The brightest and most prominent features of diffuse emission trace the southern part of the previously known $160°/340°$ molecular outflow. The system of arcs north-east of IRS 1, the presence of the radio source VLA NW in this region, and the low-velocity wing in the molecular emission maps in this direction strongly support our assumption that the arcs are related to outflow activity in the $\sim 20°$ direction. There is also some evidence, although less convincing, for a flow of material in the opposite, i.e. $200°$, direction: the apparent depression in the surface of the cloud core in that direction, the location of the radio source VLA 4, and the extension of the low-velocity CO emission in that direction.

Taken together, the available data suggest the presence of two distinct bipolar outflow systems, one in $160°/340°$ direction and another one in $20°/200°$ direction, both originating from IRS 1. The most straightforward explanation for the presence of two distinct bipolar outflow structures would be that we see two independent outflows from two sources, i.e. that IRS 1 is a binary or multiple system. Interestingly, the detailed analysis of our image [??] showed marginal evidence that S140 IRS 1 is slightly extended; it might be a binary with a separation of $\sim$ 20 AU.

Another interesting result of our high-resolution study is the detection of the system of three arcs north-east of IRS 1. The projected distances of the tips of the arcs are increasing with their respective position angles. This morphology suggests that the direction of the individual flows that have created the individual cavities has changed with time. In the jet-driven scenario, this might be an indication for jet precession. Assuming a typical jet velocity of ~ 150 km/sec, we can estimate the kinematic ages of the three cavities (i.e. their projected length divided by the assumed jet velocity) and find ~ 240 years, ~ 300 years, and ~ 400 years, respectively. This implies that the outflow direction has changed by $\sim 15°$ within ~ 160 years. A possible explanation for jet precession would be a binary system in which the protostellar disk is misaligned with the orbital plane of the binary. This case was recently considered theoreticaly by [??], and it was found that in such a system the disk (and therefore also the jet) precesses with a period of the order of 20 binary periods. If S140 IRS 1 actually is a binary with a separation of $\sim$ 20 AU and a mass of $\sim 10\,M_\odot$ (see above), its Keplerian orbital period should be about 30 years. One therefore would expect a jet precession period of ~ 600 years. Since the observed structure of the north-eastern complex of arcs actually suggests changes of the outflow axis direction at time scales of a few hundred years, this model may be a good explanation of the S140 IRS 1 jet.

References

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