Observations of a Compact (<1000 AU) MYSO Cluster with HST

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Abstract

Observations show that most, if not all, massive stars form in clusters. This combination of massive stars and clusters has led to the suggestions that massive stars form by coalescence after stellar collisions or by enhanced accretion due to the gravitational potential of the cluster instead of the accretion through a disk embedded in an isolated natal cloud that is the current paradigm for low-mass star formation. We have been studying the massive young stellar objects (MYSOs) in the nearest star-forming regions using 2 μm polarimetry with the 0.2" resolution of the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on Hubble Space Telescope (HST). These stars, which are still embedded in dense envelopes, have cones of scattered light along their outflow axes. Through polarimetry we can infer the orientation and illuminating star of each observed outflow; thanks to our good spatial resolution we can also observe twists in the outflow axes (possibly due to precession) and other asymmetries and irregularities that indicate the outflows are episodic or are influenced by neighboring stars. Mon R2 IRS3 is one of the most interesting of our targets. This compact stellar group is found near the center of the Mon R2 star cluster just east of the well-known Mon R2 IRS1 H II region. The region is also known for its massive molecular outflows (e.g., Wolf et al. 1990), the source(s) of which may no longer be actively ejecting mass and which cannot be identified with any of the currently known YSOs. In IRS3 itself at least three early B stars (total luminosity 1.4 x 10^4 $L_\odot$) are found within a core of <1.2" (<1000 AU). Our polarimetry shows that the outflow axes of the two brightest stars are perpendicular in the plane of the sky, although much of the dust appears to envelop all the IRS3 cluster (20"). Moreover, the brightest star is sufficiently embedded in its envelope plus disk that it appears extended at the NICMOS resolution. We will discuss the three stars and their interaction using models of our data and archival NICMOS images at other wavelengths. Clearly high spatial resolution is needed to distinguish these MYSOs. Stars of much younger ages than those in Mon R2 will not be visible in the near infrared; instead observations will need to be done with mm interferometers such as ALMA.

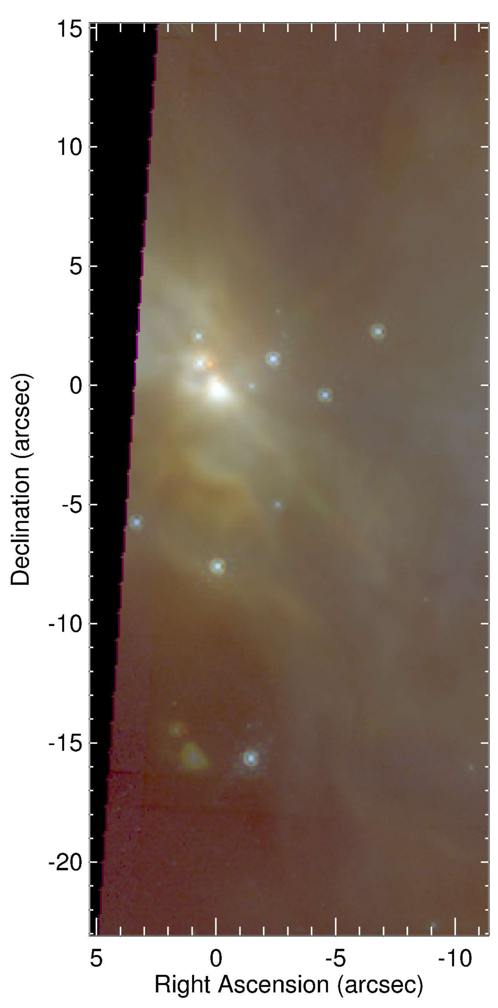

Fig. 3. We downloaded these same MonR2 data from the HST archive and reduced the frames containing IRS3 and environs, which we plot here (blue is the F110W filter, green is F165M, and red is F207M, all log stretch). Unfortunately, these NICMOS images do not include the extensions of IRS3 to higher right ascensions that are seen in the 2MASS images. At a distance of 830 pc, the separation of the two brightest stars corresponds to a separation of ~720 AU in the plane of the sky. The total luminosity of this compact group is ~1.4 x 10^4 $L_\odot$ (Henning et al. 1992).

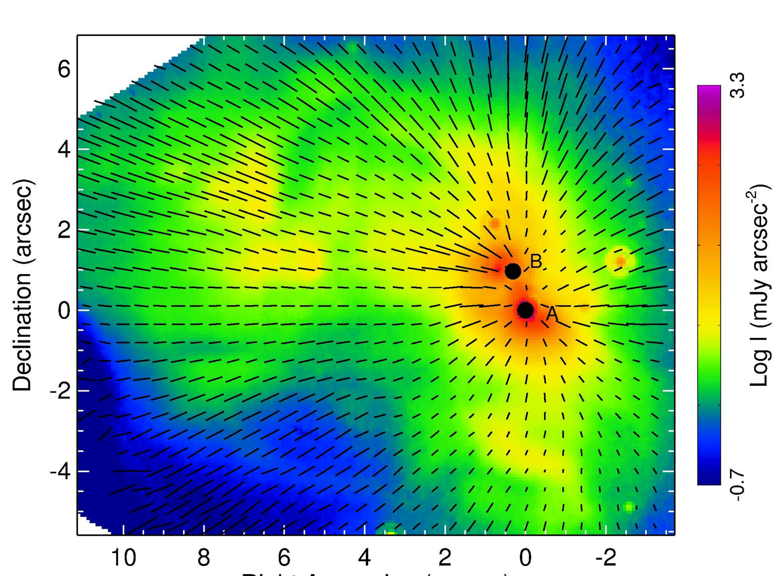

Fig. 6. Star B is almost as bright as star A (magnitude 9.46 vs. 9.23 at 2.0 μm), and since it is 12% polarized, its diffraction pattern and instrumental scattered light are also polarized. Consequently, we removed its point spread function (PSF) by subtracting the image of the very red PSF standard star (Oph N9) that we also used for the coronagraph imaging. Now the locations of both stars A and B are blocked out by black dots and their PSFs should not contribute appreciably to the images.
Here we plot the perpendiculars to the polarization vectors, since these should point to the illuminating star. We see that although the southern lobe is indeed illuminated by star A (as was previously modeled), the much larger east lobe is illuminated by both stars A and B.

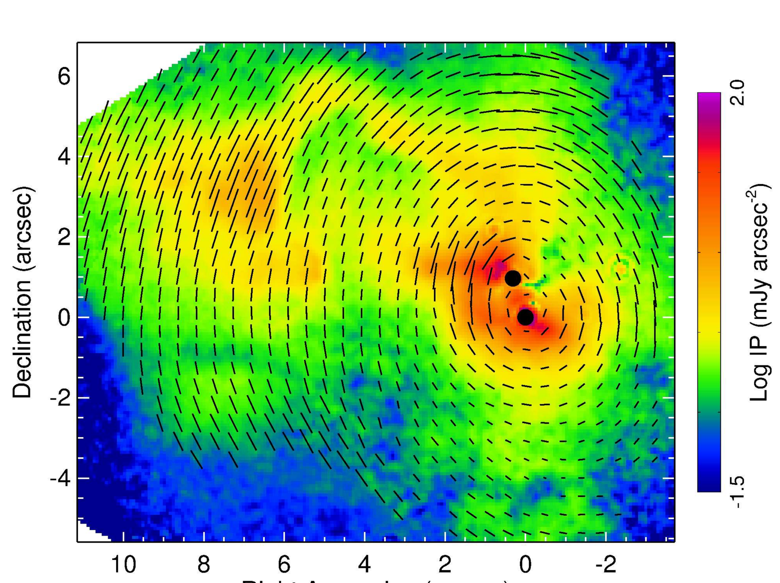

Fig. 8. Plot of the polarized intensity. The big lobe east of star B is even more prominent. The position angle of this lobe is very similar to the polarization position angle, θ, of star B (θ = 167°) minus 90°. We infer that a small disk (<100 AU) might be present around star B even though star B is not an X-ray source; the axis is pointed toward the Earth on the east side. The opening angle for the outflow is very large, almost 180°, and the outflow is either episodic or it is warped and clumped by the molecular cloud in which IRS3 is embedded.

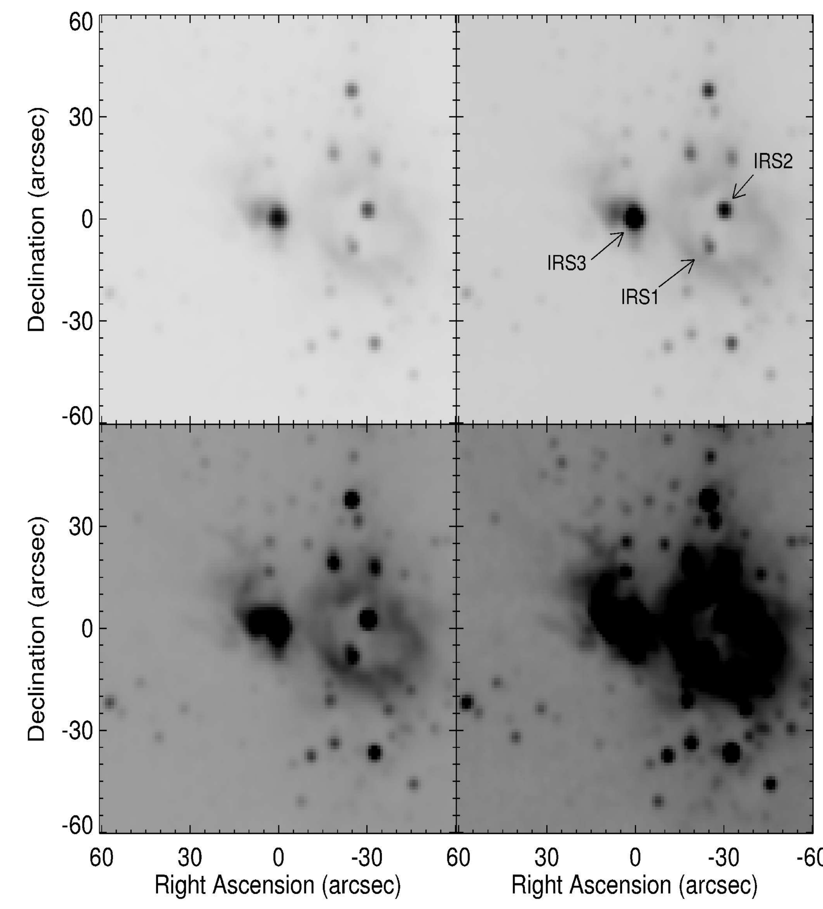

Fig. 1. To set the stage, we plot the 2MASS K_s band image in four stretches (all log scale). The 0,0 position is $6^h\ 7^m\ 47.86^s$ -6° 22' 56.0” (J2000). Molecular line maps show a central cavity surrounding IRS1 and IRS2 with the most gas to the northeast and southwest of the ring and at IRS3 (e.g., Tafalla et al. 1997; Giannakopoulou et al. 1997).

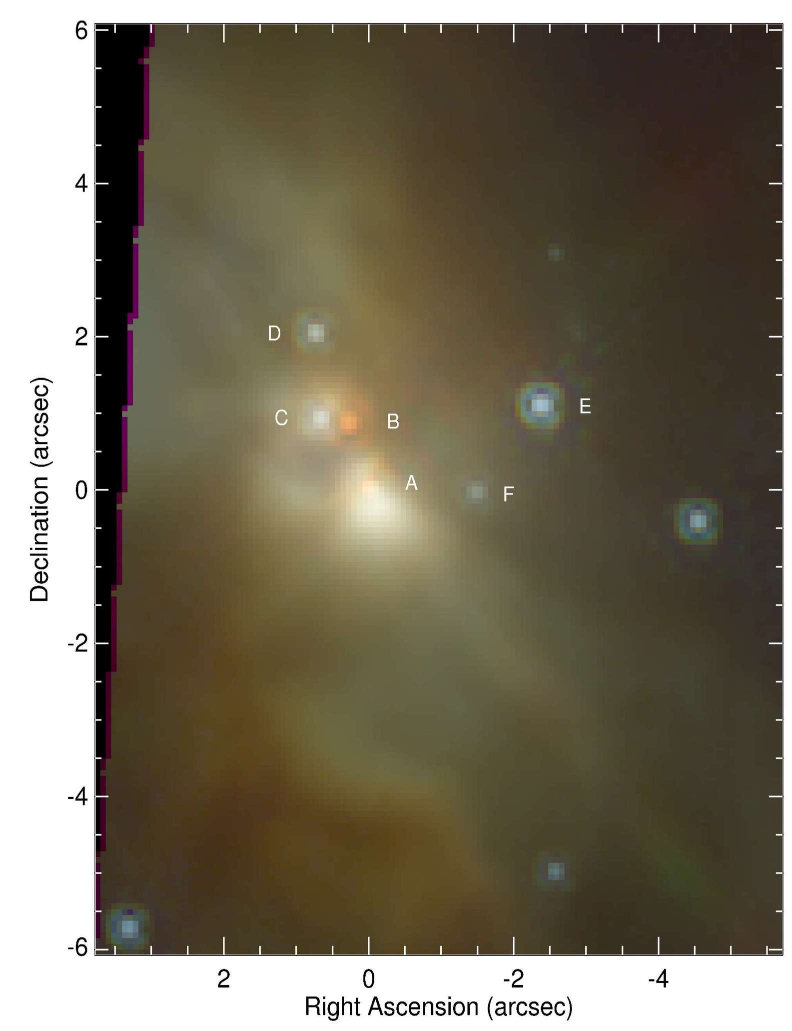

Fig. 4. This figure shows the central regions of IRS3 with the stars named in the order of K band brightness from the NIR speckle imaging of Preibisch et al. (2002). Preibisch et al. (2002) estimate that the masses of stars A, B, C, D, and E are in the ranges 12-15 $M_\odot$, 8-12 $M_\odot$, 5-10 $M_\odot$, 2-5 $M_\odot$, and ~1 $M_\odot$, respectively. Stars E, C, and A are X-ray sources with typical YSO X-ray properties (Preibisch et al. 2002).
From its red color, star B is clearly the most highly extincted. Star A, however, is present as a HST point source (i.e., exhibiting the first Airy bright ring of the HST PSF) only at 2.07 μm; at shorter wavelengths the stellar point source is obscured by the bright scattered light of the south scattering lobe. This lobe has been modeled as being tipped towards the Earth by ~ 45° (Alvarez et al. 2004). We suggest that some of the extinction of star B is due to the disk and envelope of star A.

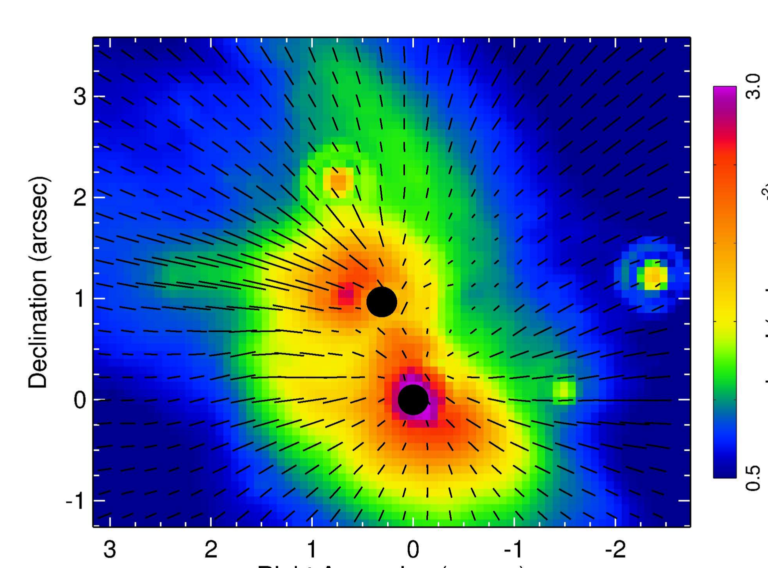

Fig. 7. Enlarged view of the center of IRS3. This image shows even more clearly that star A illuminates the south scattered light lobe and star B illuminates the east scattered light lobe. The polarization position angle of star A is 110°, almost perpendicular to the position angle of the south scattered light lobe (Alvarez et al. 2004 used a position angle of 198° for the outflow axis of their models).

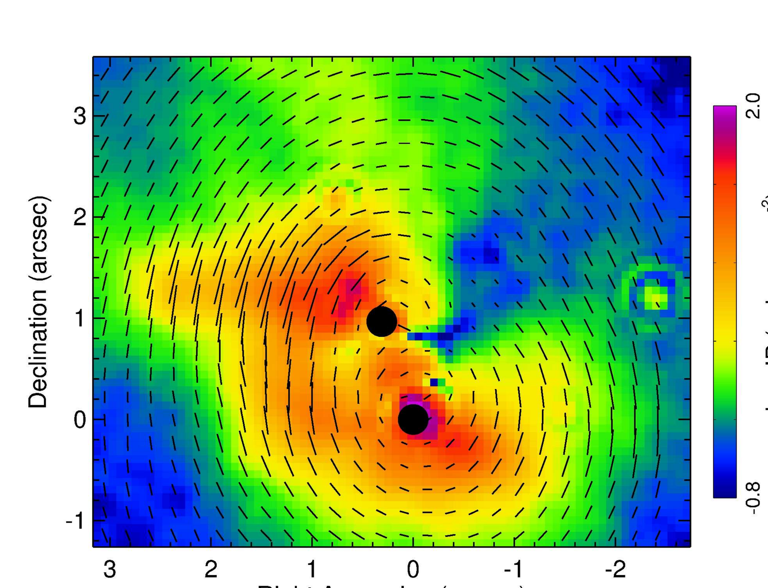

Fig. 9. Polarized intensity image of the central few arcsec. Preibisch et al. (2002) identified three small clumps to the northeast of star B as a narrow “jet” - the red spot just northeast of star B's center lies in the same direction but would require a transverse proper motion > 100 km/s to be their outermost clump.

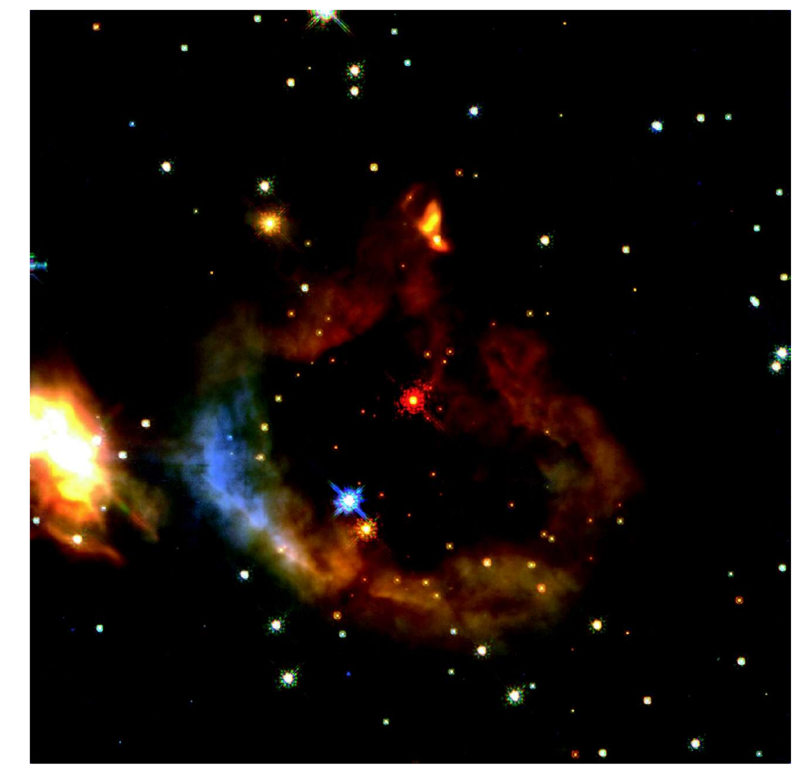

Fig. 2. In December 1997, the Mon R2 Cluster was imaged with NICMOS on HST (Program 7417, PI: M. Meyer) at 1.10, 1.60, 1.65, and 2.07 μm. Here we show the three color image from the Astrophysical Journal paper of Andersen et al. (2006). The large ring surrounding the cavity is an H II region ionized by the redder of the pair of stars at IRS1; however, two near infrared (NIR) polarization measurements show that the ring is also illuminated by the very red star, IRS2 (Aspin & Walther 1990; Yao et al. 1997). It is thought that IRS2 is much younger than the H II region and that it is a protostar. Because IRS3 is so very bright (K_s magnitude 6.6), it is saturated in the stretch employed in this figure.

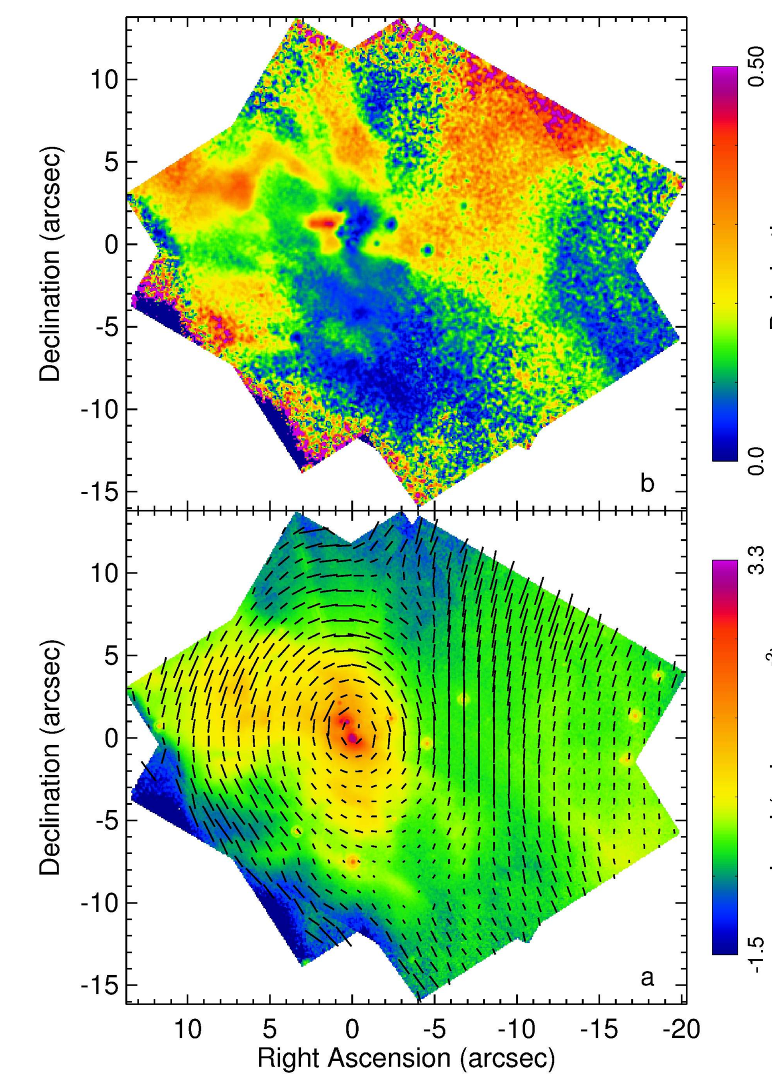

Fig. 5. In Aug. and Oct. 2006 (HST Program 10519), we measured the 2.0 μm polarization of IRS3 with NICMOS in two visits at different telescope orientations. We used NICMOS's capability for coronagraphic imaging to occult star A and also took images with IRS3 in the center of the array to determine the polarization of star A itself. This composite image includes the bright core of star A replacing the pixels of the coronagraph hole. The western third of the image is the ring surrounding IRS1 and IRS2. Stars A, B, and C are polarized at 9%, 12%, and 6%, respectively. (a) False-color plot of the log of the intensity (Stokes I) with polarization vectors proportional to the polarization. (b) Fractional polarization.

Conclusions

- High resolution imaging of Mon R2 IRS3 with HST shows the presence of multiple YSOs with outflows within 1”.
- From NICMOS polarization measurements we infer that star B is the illuminating star and source of the extensive outflow to the east of IRS3.
- As was previously known, star A is the illuminating star of the scattered light lobe immediately to its south.
- The polarization position angles of stars A and B are almost exactly perpendicular to the position angles of the associated scattered light lobes and probable outflows. Possible explanations are (a) multiple scattering in optically thick envelopes, or (b) dichroic absorption by dust grains aligned by a toroidal magnetic field in the YSO's disk.

Questions

1. Are the two stars A and B interacting? Are their outflows interacting?
2. The question of whether massive YSOs have true disks like low mass YSOs is still controversial. Do these stars have true disks as well as envelopes?
3. Are these outflows only NIR phenomena or do they have anything to do with the CO outflows mapped in the radio (which appear to have different centers)? There is blue-shifted CO associated with IRS3 (Giannakopoulou et al. 1997).
4. The NIR outflows both seem to be the blue-shifted lobes. Where are the red-shifted lobes? They're hidden by the dusty envelopes at NIR wavelengths, so their true structure isn't known.

Need for ALMA

1. The disk/envelope systems are seen in the NIR only as scattered light or as they affect the extinction. With ALMA we could detect the dense gas itself and determine the orientation of the two systems and whether there are gaps or clumps due to interactions.
2. If any telescope can detect a true disk (defined by Cesaroni et al. 2007 as "a long-lived, flat, rotating structure in centrifugal equilibrium"), ALMA will.
3. With the higher resolution of ALMA, one could pin down the geometry of the gas surrounding IRS3, including the locations of the blue and red-shifted CO and other molecules.
4.Red-shifted gas is not obvious at IRS3, although the observed lines have larger velocity widths than at other locations (Giannakopoulou et al. 1997). Sub-arcsecond spatial resolution is needed.

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