Cosmic Masers – from OH to H_0
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The infrared environment of methanol maser rings at high spatial resolution

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Abstract. The recent discovery of methanol maser emission coming from ring-like distributions have lead to the plausible hypothesis that they may be tracing circumstellar disks around forming high mass stars. In this article we discuss the distribution of circumstellar material around such young and massive accreting (proto)stars, and what infrared emission geometries would be expected for different disk/outflow orientations. For four targets we then compare the expected infrared geometries (as inferred from the properties of the maser rings) to actual high spatial resolution near-infrared and mid-infrared images. We find that the observed infrared emission geometries are not consistent with the masers residing in circumstellar disks.

Keywords. Masers, stars: formation, stars: early-type, circumstellar matter, infrared: ISM, instrumentation: high angular resolution

1. Infrared Observations of Young Stellar Objects

The first infrared observations to resolve disks around stars were of debris disks (e.g., Telesco et al. 1988, Jayawardhana et al. 1998). Debris disks are circumstellar disks that occur around stars with more evolved, (post)planet building disks. Since one can directly view a debris disk in its infrared dust emission it appears as an elongated ellipsoidal structures whose “flatness” is a function of the viewing angle of the disk. However, at earlier stages of star formation, such circumstellar disks are likely to be actively accreting on to their parent stars, and are thus much more massive and dense. In fact, accretion disks around very young stars began to be found, not by their direct emission, but by their scattered and reflected emission off of their upper and lower disk surfaces. Originally discovered in the optical (e.g., McCaughrean & O’Dell 1996), these “silhouette” disks demonstrated that if a disk is large and dense enough, it could be optically thick even at infrared wavelengths (e.g., Cotera et al. 2001). These sources are typified by a “dark lane” demarcating the disk itself, between to “lobes” of scattered/reradiated emission demarcating the upper and lower flared disk surfaces.

However, all of these observations were of disks around low-mass stars. The first claims of infrared detections of circumstellar disks around young massive stars (Stecklum & Kaufl 1998, De Buizer et al. 2000) were made, in part, on the assumption that the disk would appear as an elongated structure in its infrared dust emission, similar to what was seen with debris disks around low-mass stars. However, higher resolution follow-up observations (De Buizer et al. 2002) proved that these were not disks, and it was soon after realized that disks accreting onto young massive (proto)stars would be optically thick in the infrared as well, and would be even more dense and massive than those accreting onto low-mass protostars. Furthermore, in order to have a large enough reservoirs of material to accrete to such high masses, massive stars must form in the densest parts of giant molecular clouds, which are extremely obscured environments. Moreover, the earliest stages of massive star formation are deeply self-embedded; the (proto)stars are surrounded by massive and dense accretion envelopes, as well as the aforementioned circumstellar disks, which are believed to be large, thick, and flared.

Due to the high amount of obscuration, one would have no hope of observing these stages of massive star formation at even mid-infrared wavelengths if not for their bipolar outflows. Disk accretion is accompanied by outflow, and it is this outflow that punctures holes through the obscuring material surrounding a forming massive star. The outflow axis is oriented perpendicular to the disk, and the outflow starts out narrow and collimated. At such early stages of formation, we may only detect the presence of the massive young stellar object at infrared wavelengths if we are lucky enough to have a line of sight looking down the outflow axis. We could then see into the envelope, and view the scattered/reprocessed dust emission off of the cavity walls, and if the angle is just right, we may see down into the central disk or (proto)star. Such a chance alignment is rare, and it is in part due to this geometrical effect that detecting massive young stars in the infrared is so difficult. However, over time the young stellar object evolves and the outflow angle widens (Shu & Adams 1987). With the widened outflow, comes a large range of angles that allow for a higher probability of detection in the infrared. At some point the angle is so wide, that the distinction between what is the outflow cavity surface and what is the surface of the flared disk is blurred.

This notional sequence of events has been supported by several studies in the recent decade. For instance, observations of the earliest stages of massive star formation with collimated outflow cavities emitting brightly in their mid-infrared continuum emission were first identified by De Buizer (2006). The first claim of a candidate infrared "silhouette disk" around a massive star was made by Chini et al. (2004) demonstrating the later stages where the outflow has widened considerably (though whether the mass of the central object is high mass is the subject of debate, e.g. Sako et al. 2005). In addition to these observations, radiative transfer models of Alvarez et al. (2004) and Zhang & Tan (2011) also produce these geometries; the first showing the results of the earliest stages of collimated outflow cavities, and the second for more open-angled outflows.

2. Infrared Imaging Tests of the Disk Hypothesis of Maser Rings

One phenomena that seems to be related only to massive star formation is the appearance of methanol maser emission. Milliarcsecond-scale very long baseline interferometry (VLBI) observations of massive star-forming regions with 6.7 GHz methanol maser emission resolve the discrete locations of the emission (known as "maser spots") and show a wide range of spot distributions. The maser spots can be distributed randomly without any regularity, however often they group into seemingly coherent structures like lines or arcs (e.g., Norris et al. 1993). We have recently completed a survey of 31 sources at 6.7 GHz using European VLBI Network (EVN) (Bartkiewicz et al. 2009). In addition to the curved and complex morphologies observed in other samples, we have discovered for the first time nine sources (29 % of the sample) with ring-like distributions with typical sizes having major axes of 0.2-0.3$''$. Though not apparent in the radio data, these ring-like structures strongly suggest the existence of a central stellar object and lead to the obvious question: *Are methanol maser rings tracing circumstellar disks around massive protostars?*

Because methanol masers are believed to be pumped by mid-infrared photons from dust (Cragg, Sobolev, & Godfrey 2002), if the masers are arising from gas in a dusty circumstellar disk, they would have to trace the inner few hundred AU radius at most, given any reasonable heating argument†. Furthermore, the presence of a circumstellar disk around a massive star is expected to be short-lived, owing to the generally more rapid evolution of massive stars at all phases (Povich & Whitney 2010) and the very caustic nature of the near stellar environment of a massive star. As such, it is believed that once accretion ends, the disk would summarily dissipate (i.e. there would be no analogous debris disk phase for massive stars). This means that if the methanol masers are within circumstellar disks, then they must trace a rather young stage of the massive star formation process where the disk is an active accretion disk and the massive young stellar object will be very self-embedded, and thus should have an appearance in the infrared as discussed in the previous section.

Consequently, there are expected spatial and morphological relationships that can be tested between what one sees in the infrared when looking toward methanol masers rings under the assumption that the rings are in disks and that they are associated with an early and obscured accretion phase of massive star formation:

Scenario 1: The more circular the maser ring, the more face-on the disk, meaning one would be looking right down the outflow axis into the outflow cavity. Therefore, the infrared emission should be unresolved or circularly symmetric with the peak of emission coincident with the maser ring center;

Scenario 2: Slightly elliptical rings would indicate a disk orientation close, but not quite face-on. In this case we would expect to either only see the blue-shifted outflow cavity, or just a hint of the red-shifted cavity (depending on disk/envelope extinction, outflow opening angle, and disk inclination). In this case, the maser ring center will be slightly offset from the infrared emission center in a direction given by the outflow axis.

Scenario 3: The more highly elliptical the ring, the closer to edge-on will be the disk. If detectable in the infrared, we would expect for moderately to highly elliptical maser rings to see something more like a silhouette disk in the infrared, where the maser ring would lie between two infrared bright sources (the outflow cavities), in the “dark lane” of the optically thick disk. Of course, if the source is extremely obscured and/or very close to edge-on, we may not expect any infrared emission to be detected at all.

3. The Experimental Design

Inspection of mid-infrared data from the *Spitzer* IRAC maps, GLIMPSE and MIPSGAL, revealed that all of our sources with ring-like morphologies coincide with unresolved mid-infrared sources within one pixel in a GLIMPSE map ($1.2''$). However, the resolutions of the *Spitzer* data ($2.3''$ at $8\,\mu$m, $7''$ at $24\,\mu$m) and 2MASS data ($2.5''$) are relatively poor. Therefore, we decided to obtain the highest spatial resolution near-infrared and mid-infrared imaging available to allow resolution of details on par with the scale of the maser rings (∼300 mas).

Using the Gemini 8-m telescopes, we obtained data with NIRI/Altair, an adaptive optics near-infrared instrument that can achieve resolutions better than ∼150 mas at 2 μm. The mid-infrared observations were made with T-ReCS, employing a method which fully characterized the system point spread function accurately enough to allow the imaging data to be reliably deconvolved, achieving spatial resolutions of ∼150 mas at 8 μm and ∼250 mas at 18 μm.

Since it was of the highest importance that we know precisely where the maser rings

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† Remember however, the flaring of the disk and the dense accretion envelope prevent one from viewing the mid-infrared emission coming directly from the disk for most, if not all, viewing angles.

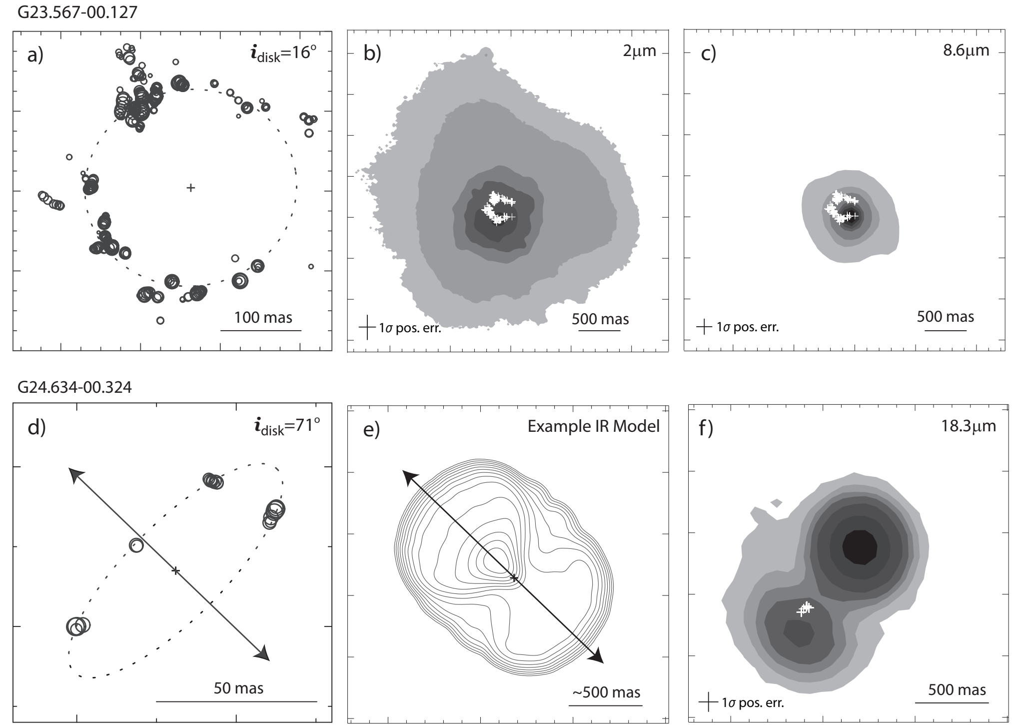

Figure 1. Results for G23.567-00.127 (a-c) and G24.634-00.324 (d-f). Methanol masers are shown as black open circles in panels a and d, and as white crosses in the other panels. Inferred disk inclinations from the maser rings are given in panels a and d (from fits by Bartkiewicz et al. 2009), with d also showing the angle (as projected on the sky) of the axis of the disk rotation/outflow expected (for panel a this axis is straight out of the page). The 1σ positional uncertainty between the maser positions and the infrared emission are given in the relevant panels. Panel e is not a fit to any of our data, but an example model of infrared emission from a massive young stellar object taken from Zhang & Tan (2011) for comparison.

are with respect to the dust emission in the infrared, we employed Gemini Observatory's high accuracy astrometric technique for our mid-infrared observations, which yields an absolute astrometry accuracy of 1σ=90 mas. For the near-infrared images, since the fields containing the science targets also contained near infrared stars from the 2MASS Point Source Catalog, we were able to use their measured positions to accurately define absolute astrometry of the NIRI images. A χ^2-minimization technique was used to register the 2MASS fields to the NIRI fields. This yielded an 1σ<150 mas error in the absolute astrometry of the near infrared images, where the actual errors are different for each source and dependent on the number of 2MASS stars on the NIRI field and their astrometric accuracy. Since we are comparing the offsets of infrared emission from the methanol masers, it should be stated that the absolute astrometrical error for the methanol masers are on the order of a few mas owing to the phase-referencing technique that was employed (Bartkiewicz et al. 2009). This means that when comparing the maser and infrared positions, the infrared astrometric errors quoted here for each source dominate in all cases.

4. The Results

Of the four methanol maser rings we observed in the infrared, none convincingly displayed the characteristics expected if the maser rings are indeed tracing circumstellar disks. We show the results for two of these in Figure 1. In the case of G23.567-00.127, the maser ring (Fig. 1a) is nearly circular, indicating that we should be looking almost straight down the outflow cavity (i.e., Scenario 1). This would imply that the infrared emission should be circularly symmetric with the infrared peak at the center of the maser ring. We see that the infrared emission peaks at 2 and 8.6 μm (Fig. 1b and c) do indeed lie near the maser ring center to within the positional errors, however the 2 μm morphology is fan-shaped as one would expect for the reflected light from a outflow cavity with a much more inclined geometry. In the case of G24.634-00.324, the maser ring is more highly elliptical (Fig. 1d), indicating that we should be seeing a more edge-on disk geometry, and perhaps a silhouette-like infrared morphology where the masers reside in the "dark lane" of the infrared emission (i.e., Scenario 3). Figure 1e shows the infrared emission geometry we would expected to see (adapted from the infrared models of Zhang & Tan 2011). We do indeed see this type of morphology in the infrared at 18.3 μm (Fig. 1f), as well as 8.6 μm (not shown), and the masers are coincident to within the positional errors with the dark lane. However the angle of the "silhouette disk" is almost 90° from the expected rotation axis as given by the maser ring (demonstrated by the arrow in Fig. 1d and e).

The other two sources in our sample have similar problems, leading to the conclusion that the *infrared emission from these sources does not seem to support the scenario where methanol maser rings trace circumstellar disks around young massive stars.*

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