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The infrared environments of masers associated with star formation

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Abstract. The near infrared (1–2 μm) and the thermal infrared (3–25 μm) trace many of the environments in which masers are thought to reside, including shocks, outflows, accretion disks, and the dense medium near protostars. After a number of recent surveys it has been found that there is a higher detection rate of mid-IR emission towards masers than cm radio continuum emission from UC HII regions, and that the mid-IR emission is actually more closely cospatial to the maser locations. A high percentage of water and methanol masers that are not coincident with the UC HII regions in massive star forming regions are likely to be tracing outflows and extremely young high mass stars before the onset of the UC HII region phase. After a decade of groundwork supporting the hypothesis that linearly distributed class II methanol masers may generally trace accretion disks around young massive stars, compelling evidence is mounting that these masers may generally be associated with outflows instead. Substantiation of this claim comes from recent outflow surveys and high angular resolution mid-IR imaging of the maser environments.

Keywords. masers, accretion disks, ISM: jets and outflows, stars: formation, stars: early-type, infrared: ISM

In the proceedings of the last maser meeting in Brazil in 2001, I discussed the largely untapped potential of the infrared spectral regime as a tool for understanding the nature of the circumstellar environments of masers associated with star formation (De Buizer 2002a). In that article, I described the early stages of the work I had started using the infrared (IR) to study maser environments, and gave several possible paths for future work in the field. In the intervening years since that meeting and this one, I have explored several of those paths in detail, and will present in this article some of the highlights of that work.

1. The close association of masers and IR emission

In the Brazil proceedings article I described how the near infrared (1–2 μm) and the thermal infrared (3–25 μm) trace everything from the direct photospheric emission from young stellar sources to the relatively cool dusty environments that can be distributed far from their parent stars. The thermal infrared in fact has been shown to trace dusty circumstellar environments from temperatures of $\sim$1500 K at 3 μm, which is very close to a star and near the dust sublimation temperature, to cool dust tens of thousands of AU away at wavelengths near 25 μm. Because of this, it was suggested that the IR would be a good tracer of the emission from many of the environments in which masers were thought to reside: shocks fronts, outflow shocks, and accretion disks.

But how well does the infrared trace the environments of maser emission? There now exist a number of studies at several different wavelengths to help address this question. Since it is easiest to obtain radio continuum observations of maser regions, the most common studies of maser environments have traditionally involved searches for ionized gas emission in the form of ultracompact (UC) HII regions and partially ionized outflows. Well before the Brazil meeting it was known that the percentage of maser sources directly associated with cm radio continuum emission was not very high, which was remarkable for a phenomenon that is suppose to trace young massive star formation.

From studies with reasonable detection limits at a variety of wavelengths, one can piece together the dominant wavelengths at which maser environments can be seen and studied. As mentioned above, the cm radio continuum detection rate towards methanol and water masers is low, and has been found to be about 20% from the recent surveys of Walsh *et al.* (1998) and Beuther *et al.* (2002). Whereas in the surveys of De Buizer *et al.* (2000), Walsh *et al.* (2001), and De Buizer *et al.* (2005) it was found that the detection rate of mid-IR (typically 10 and 18 μm) emission towards class II methanol masers is ∼70%, and towards water masers ∼80%. Coarser spatial resolution observations in the sub-mm and mm are showing detection rates approaching 100% towards both water and methanol masers (Walsh *et al.* 2003; Beuther *et al.* 2002). Hence, all masers appear to be more closely associated with regions of hot to warm (300-30K) thermal dust emission than ionized gas emission.

Furthermore, De Buizer *et al.* (2005) showed that mid-IR emission when detected in a maser region was more closely associated with actual maser locations than the radio continuum emission detected towards those same maser regions (i.e., Figure 1b). The survey of Hofner & Churchwell (1996) showed that the median separation between water maser and the radio UC HII regions they detected is ∼18800 AU. The median separation between water masers and mid-IR sources is ∼8700 AU (De Buizer *et al.* 2005). Therefore, not only is there a higher detection rate of mid-IR emission towards masers than cm radio continuum emission, mid-IR emission is actually more closely cospatial to the maser locations.

2. Using masers to pin-point extremely young massive stars

A large subset of water and class II methanol masers are found in regions of massive star formation, but are not coincident with the UC HII regions found there. What are these masers tracing?

In the case of the G29.96-0.02 region, the methanol and water masers are offset from the cometary UC HII region and were instead found to be coincident with a hot molecular core discovered in the ammonia line images by Cesaroni *et al.* (1994). Many hot molecular cores are high mass protostellar objects (HMPOs) which are at an extremely early stage of massive stellar birth. A HMPO consists of a massive protostar surrounded by a thick envelope of accreting dust and gas. They are compact sources seen in radio-wavelength ammonia (or molecular line) images but are so young that they have not had time to ionize their surroundings, and hence typically have little to no detectable radio continuum emission of their own. Other cases similar to G29.96-0.02, where masers were found associated with hot molecular cores (HMCs) and offset from UC HII regions, lead to the idea that some maser species may generally trace these very young sources at the earliest stages of massive star formation.

Some of the first models of the HMPO phase of massive star formation that were constructed (e.g. Osorio *et al.* 1999) showed that by changing parameters such as spectral type, accretion rates, and core radius, one can construct a variety of model spectral energy distributions (SEDs) for HMPOs. Throughout an array of physically reasonable parameter space, the SEDs peak around 80 μm on average. On the Rayleigh-Jeans side of the SED (>80 μm), there is little change in the shape of the SED when parameters are changed. However, on the Wien side of the SED (<80 μm), there is considerable change in

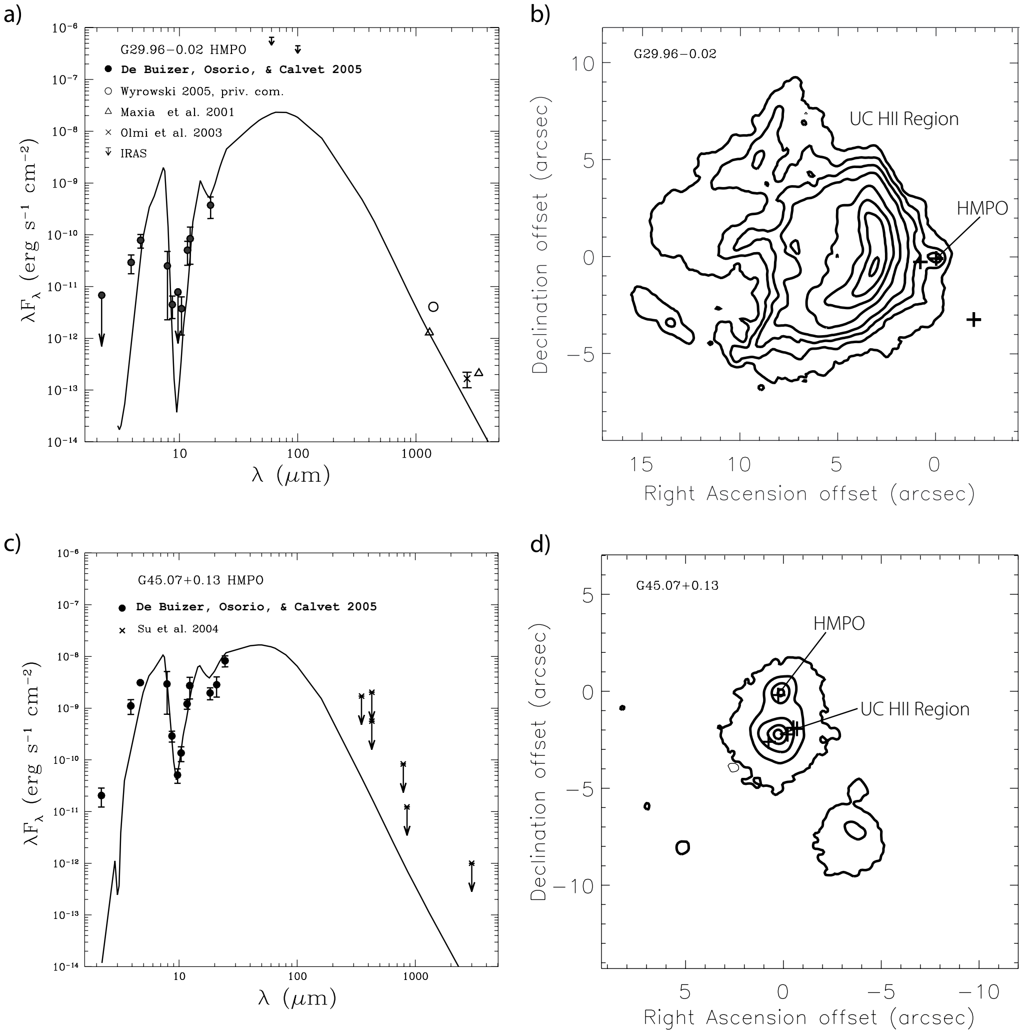

Figure 1. **(a)** Observed and model SEDs for the G29.96-0.02 HMPO. The different symbols represent the observed values of the flux densities from the references indicated. Error bars are 3–σ for the IR data. Upper limits are represented by arrows. The solid line represents the best fit model obtained with $L_\star = 1.8 \times 10^4$ $L_\odot$, the equivalent luminosity of a B0 star. **(b)** A contour plot of the 11.7 μm image of the G29.96-0.02 field with the extended mid-IR emission from the UC HII region and compact mid-IR emission of the HMPO indicated. Plus signs represent the location of water masers from Hofner & Churchwell (1996). The masers are not associated with the UC HII region, but some are associated with the HMPO. **(c)** Same as in (a) but for the G45.07+0.13 HMPO. The solid line represents the best fit model obtained with $L_\star = 2.5 \times 10^4$ $L_\odot$. **(d)** Same as in (b) but for G45.07+0.13. In this case, there are some water masers associated with the UC HII region, however the clump of masers to the north are associated with a HMPO.

SED shape with the variation of each parameter, especially if one could observe the mid-IR emission of these sources (see Figure 1a and 1c). The most noticeable changes in the HMPO SEDs are between 3 and 30 μm, and in the depth and shape of the 10 μm silicate feature. This modeling showed that the mid-infrared could be key to understanding the properties of the youngest massive stars, if we could detect the mid-IR emission from such embedded and distant objects.

To see if we could indeed detect these HMPOs in the mid-IR and test the hypothesis that masers offset from UC HII regions may be associated with HMPOs, I began my search in the mid-IR with the prototypical source, G29.96-0.02. These observations led to the first confirmed direct detection of a HMC at mid-IR wavelengths (De Buizer *et al.* 2002a), proving that indeed some HMPOs are bright enough to observe in the mid-IR. To further test the hypothesis that non-radio continuum emitting sources of maser emission could be associated with HMPOs, a mid-infrared study of several fields from the survey of water maser and UC HII regions of Hofner & Churchwell (1996) was performed in an attempt to find more mid-infrared bright HMPOs. Concentrating on the fields that have UC HII regions with water masers well offset, this survey led to the detection of mid-infrared emission from the locations of two HMPO candidates, G11.94-0.62 and G45.07+0.13 (De Buizer *et al.* 2003). These observations seemed to support the idea that in some cases masers can indeed be used to find the locations of HMPOs.

At the Brazil meeting I claimed that these mid-IR-bright sources held the promise that, if one could perhaps create a well-sampled SED from observations of a HMPO at many wavelengths in the mid-infrared, the data could then be fit with the new HMPO models to derive accurate physical parameters, such as mass, luminosity and accretion rate for these youngest massive stars.

This was attempted by De Buizer, Osorio, & Clavet (2005), for the three above mentioned sources: G29.96-0.02, G11.94-0.62, and G45.07+0.13. Though the modeling performed on these sources led to relatively accurate luminosities, degeneracies and a large number of free parameters prevent the accurate assessment of physical parameters from SED modeling alone and can only constrain such parameters. More recent and more detailed SED modeling of YSOs by Robitaille *et al.* (2007) have come to the same conclusion.

Interestingly, of the three sources modeled in De Buizer, Osorio, & Calvet (2005), G11.94-0.62 has a luminosity to small to be a true HMPO. Though this source lies near an UC HII region, is cospatial with water maser emission, and has a deep silicate feature in the mid-infrared indicative of a highly embedded star, it is likely a young and embedded intermediate mass YSO. Hence, there exist intermediate mass YSOs that have similar observational characteristics to HMPOs that may contaminate HMPO studies.

From all of this, one can conclude that some masers offset from UC HII regions can indeed be associated with HMPOs. However, in De Buizer *et al.* (2005) it is shown that some of these masers are likely offset from known YSOs because they are associated with outflows, and some, as just mentioned, may be associated with less-massive embedded YSOs.

3. Maser disks vs. maser outflows

Some maser species, class II methanol in particular, have been suggested to be associated with circumstellar disks around massive young protostars. Norris *et al.* (1993) discovered that 45% of methanol masers groups tend to be distributed in the sky in linear structures. Occasionally these linearly distributed masers have apparent velocity gradients along the maser distributions that suggest rotation. Observations by Walsh *et al.* (1998) confirmed that methanol masers are linearly distributed in approximately half the cases, but that velocity gradients were not a general feature.

However, in the article by Norris *et al.* (1993) it was suggested that these linearly distributed methanol masers exist in, and delineate, edge-on circumstellar disks around massive stars. In Brazil I presented results from my low resolution (1.0–2.0") mid-IR imaging survey of star forming regions with methanol maser emission, which contained

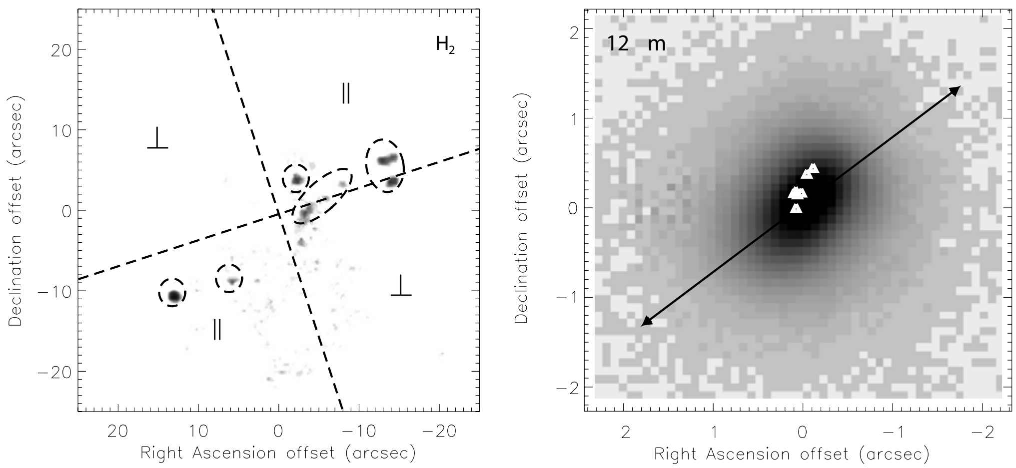

Figure 2. (Left) The H_2 line image from De Buizer (2003) of the ~50" field of G318.95-0.20 centered on the methanol maser location. The dashed straight lines intersect at the maser location and show the parts of the field perpendicular to (⊥) and parallel to (∥) the methanol maser distribution angle. Dashed ellipses show the location of real H_2 emission (other faint signatures are due to poor subtraction of continuum emission). The H_2 emission is distributed in the quadrants parallel to the linear methanol maser distribution angle. **(Right)** The 12 μm image of the ~5" field of G318.95-0.20. The methanol masers of Norris *et al.* (1993) are shown as white triangles. The mid-IR emission is elongated at the same angle as the methanol maser distribution, however this is the direction of the outflow seen in H_2. The arrow shows the direction of the SiO outflow (De Buizer *et al.* in prep). The similarity of the methanol maser distribution angle and mid-IR emission elongation angle with the outflow angle suggest that both the maser and the mid-IR emission are outflow related, and not directly tracing a circumstellar disk.

10 sites of linearly distributed masers. Three of these maser locations were coincident with young stellar objects with extended mid-IR emission elongated at the same position angle as their methanol masers distributions (De Buizer *et al.* 2000). These sources were suggested to be dusty circumstellar disks, thereby apparently adding credence to the disk hypothesis for linearly distributed masers. However, one of these sources was later observed at high angular resolution (<0.5") with Keck and found to be three individual mid-IR sources arranged in a linear fashion, and not a disk (De Buizer *et al.* 2002b).

To further test the maser/disk hypothesis, several sites of linearly distributed methanol masers were observed to search for outflows. According to the standard model of accretion, during the phase of stellar formation where the star is being fed from an accretion disk, it is also undergoing mass loss through a bipolar outflow. The bipolar outflows are perpendicular to the plane of the accretion disk, and along the axis of rotation. Wide-field images of the sites of linearly distributed methanol masers were obtained using the 2.12 μm H_2 (ν=1-0) S(1) line as the outflow diagnostic (De Buizer 2003). Surprisingly, in 12 of 14 fields where H_2 emission was detected the emission was not aligned perpendicular to the maser distributions as expected, but instead was parallel (Figure 2). This seemed to suggests that the methanol masers delineate outflows rather than circumstellar accretion disks.

The interpretation of the results from De Buizer (2003) remained ambiguous because 2.12 μm H_2 line emission can be excited both by outflow shocks and by UV excitation. The overall morphology of the H_2 emission seen in the fields imaged by De Buizer (2003) does not resemble the bipolar outflows seen around young, low-mass stars. It was cautioned that perhaps some of the H_2 emission was perhaps due to excitation from UV emission by other massive stars in the star forming region. Without additional evidence, it could not be said with certainty which mechanism is stimulating the H_2 emission near these high-mass protostars, nor definitively link the outflows to the methanol masers. However, 86% of the sources showed H_2 emission parallel to their maser distribution angles, and the probability of this occuring by chance is low. Nonetheless, there was sufficient doubt to justify observing these sources in an independent outflow indicator.

SiO is a good shock tracer because its abundance is enhanced by factors of up to 10^6 behind strong shocks (i.e., Avery & Chiao 1996). Using the JCMT to try to detect the presence of outflows in the SiO (6-5) transition, nine sources from the H_2 survey of De Buizer (2003) were observed and SiO emission was found in seven of those fields (Feldman *et al.* 2005). Many of the stronger detections have line profiles with a relatively narrow core on top of wide wings which are characteristic of outflows. To follow this up, five of these JCMT sources were recently observed with the Australia Telescope Compact Array (ATCA) to map out the outflows in the SiO (2-1) transition. Preliminary results from these observations show that the SiO emission is in all cases distributed at an angle close to that of the maser distribution angles and H_2 emission position angles for each source. In four of the five cases these SiO maps show clear signs of a single outflow with red- and blue-shifted lobes. In the fifth case the velocity structure is more complex, indicating perhaps multiple outflows are present, however the overall structure of the SiO is parallel to the maser position angle (De Buizer *et al.* in prep). These SiO observations clearly indicate that the H_2 emission observed in Buizer (2003) is indeed outflow related. These observations also lend convincing support to the idea that the methanol masers in linear distributions are directly associated in some way with the outflow from their parent stars.

Recent high angular resolution observations of individual young massive stellar objects with masers (De Buizer 2006, De Buizer 2007, and as yet unpublished data) have revealed that many sources that are elongated in their mid-IR emission are not disks, but instead are elongated in the direction of outflow. The best example of this is G35.20-0.74 (De Buizer 2006), which shows an outflow cavity in mid-IR continuum emission unmistakeably similar to the outflow jet seen at various other wavelengths. It is believed that sources such as these are too embedded to directly detect their accretion disks even at mid-IR wavelengths. However if the outflows clear away enough material in the natal cloud surrounding a massive young stellar object, we are then able to see these cavities and the mid-IR emission of the warm cavity walls. More developed bipolar cavities should exist where the material above and below the accretion disk is well-cleared as the opening angles of the outflow cavities widen. In this case the definition of what is the surface of a outflow cavity and what is the surface of a flared accretion disk may become blurred, and the source could appear as a mid-IR silhouette disk. These disks would be similar to the near-IR silhouette disks seen in Orion (i.e., McCaughrean *et al.* 1998). However, the accretion disks would still be so optically thick at their mid-planes that one could not detect the direct emission from the disk itself. Detections of such sources may have already been made; possible examples of such sources are the massive young stellar objects in M17 (Chini *et al.* 2004) and IRAS 20126+4104 (De Buizer 2007).

In the case of G35.20-0.74 the OH, water, and methanol masers appear to delineate the edges of these outflow cavity walls as seen in the mid-IR. Therefore, it is a possibility that the linear arrangements of water and methanol masers associated with other sources are tracing cavity walls where there are oblique shocks for the collisional pumping of water masers and a sufficient mid-IR thermal bath of photons to radiatively pump the methanol masers.

Observations in the mid-IR of massive young stellar objects that only show signs of emission from their outflow cavities may also help interpret the mid-IR emission from more embedded HMPOs. Some HMPOs are not mid-IR bright, while others are. In many cases this may simply be a temperature issue, i.e. that some HMPOs are too cold to be seen at mid-IR wavelengths. However, HMPOs that are detectable in the mid-IR may just be sources where the outflows from the central stars are more or less pointed toward us. In this way, we are seeing through the cavity and closer to the central heating source since the outflow is clearing out material along our line of sight. Therefore the mid-IR emission observed to be coming from HMPOs like G29.96-0.02 may be tracing beamed emission in outflow cavities and not reprocessed emission coming from the entire core, as is seen at longer wavelengths. If this is true, SED models of such sources would be influenced by this and could lead to poor fits unless accounted for.

4. Conclusions

A lot has been learned about the infrared environments of masers since the 2001 Brazil maser meeting. The IR regime has been shown to complement radio continuum observations and offer new insights into maser environments.

Methanol, hydroxyl, and water masers appear to be most closely associated with regions of hot to warm (300-30 K) thermal dust emission traced by mid-IR and sub-mm emission. As such, studies of the IR environments of masers will continue to offer much insight into the relationship between masers and the massive star formation process, *especially at high (<0.5") angular resolution* where one can hope to separate IR emission from disks, envelopes, outflows, and other nearby stellar sources.

It has been found that water and methanol masers offset from UC HII regions trace mid-IR sources that are in some cases HMPOs. Therefore masers that appear to be isolated from traditional massive star formation tracers such as radio continuum emission may be great locations to find more HMPOs. If enough observations are made over the full SEDs of HMPOs, physical properties of these sources can be derived from accretion models. However, such SED modeling alone can only place constraints and limits on most of these physical parameters.

Evidence is building that shows that linear distributions of methanol masers are not generally tracing disks around young massive stars. These maser distributions were found to be dominantly at the same angle as extended near-IR H_2 emission, which is a potential outflow indicator. Follow-up observations in the mm using SiO as an outflow tracer appear to confirm the notion that outflows are dominantly at the same position angles as the linear methanol maser distributions of massive young stellar objects. This further implies a *general, direct physical relationship between the methanol masers and outflows*, rather than disks, however these observations do not rule out the possibility that masers may trace circumstellar disks or other phenomena in some cases.

Finally, high-resolution imaging is showing circumstellar mid-IR continuum emission commonly comes from outflows, not disks. This mid-IR emission is often found to be co-spatial with masers, and therefore further suggests that there is a general tendency for masers, especially water and methanol, to be often directly associated with outflows.

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