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The Relationship Between Masers and Massive Star Formation: What Can Be Learned from the Infrared?

James M. De Buizer

Cerro Tololo Inter-American Observatory, National Optical Observatory, Casilla 603, La Serena, Chile.

Abstract. The infrared represents an alternative wavelength regime in which to study the environments of maser emission, while at the same time complementing the information obtained through radio techniques. The near infrared (1-2 μm) yields information on outflows, shocks, and reflected dust emission, while the thermal infrared (3-30 μm) yields information on the thermal dust distribution around stars. Thus, the infrared regime yields important clues in determining whether masers exist in shocks, outflows, circumstellar accretion disks, or in the dense medium close to protostars.

1. How Does Infrared Complement Radio?

Observations of centimeter radio continuum sources in the vicinity of galactic masers established the idea that masers are related to young massive stars. However, massive stars of spectral types later than B3 do not generate enough ionizing flux to create observable UCHII regions, given the sensitivities of modern centimeter radio telescopes and the kiloparsec distances to typical massive star forming regions. Furthermore, accurate astrometry from connected element interferometers has shown that masers are often not coincident with UCHII regions. Therefore, in order to figure out exactly how masers are related to young massive stars, and to observe the environments of the masers, one needs to observe at wavelengths other than centimeter. However, there is generally large extinction due to dust and gas in the environments near massive stars that are in the process of forming. This makes observing young massive stars difficult or impossible at wavelengths less the 1 μm. One could use far-infrared and submillimeter instruments, but these technologies presently do not have the spatial resolution to give detailed information on the maser environments close to young stellar sources. This means that the near and thermal infrared are presently the best alternative ground-based spectral regimes in which to study the formation of the individual massive stars and their nearby environments, and how they relate to maser emission.

In star forming regions, near infrared (1-2 μm) photons are usually photospheric emission or reflected and scattered photospheric emission off of dust near a star. The near-infrared regime is valuable because observations can peer through the extinction near newly forming stars, if the stars are not too embedded. The thermal infrared (3-30 μm) refers to the spectral regime which one looks at heat wavelength information. When referring to star formation regions, the thermal infrared traces heat radiation emitted from circumstellar and near-stellar dust. This spectral regime traces dust temperatures between 1000 K at 3 μm (close to the temperature of dust sublimation) to the relatively cool temperature of 100 K at 30 μm. The thermal infrared is even less affected by extinction than the near-infrared, making it a powerful probe of star formation regions. Therefore, using the infrared one can study the dust distribution and environment near a young massive star over a rather broad range – from the photosphere and hottest material close to a star, out to the coolest material distributed far from a stellar source.

2. Maser Locations and Infrared Observations

2.1. Embedded Sources

One scenario for the location of masers is in the near stellar environments of deeply embedded protostars. The work of Cesaroni et al. (1994) showed that there was a coincidence between clumps of ammonia emission and water masers that are offset from UCHII regions. These water masers may be marking the locations of "hot molecular cores" which may contain deeply embedded protostars that are so young that they do not have observable UCHII regions. Cesaroni et al. (1994) showed that these sources should have temperatures between 50 and 165 K. If these cores have temperatures greater than 100 K, they can be seen and studied in the thermal infrared. Figure 1a shows the direct detection of a hot molecular core at thermal infrared wavelengths from Gemini North (De Buizer et al., in print).

More hot cores could be found by searches in the thermal infrared looking for sources that are coincident with masers groups that are offset from, or do not lie near, radio continuum emission. Collaborations with radio astronomers will be needed for follow-up ammonia observations to confirm that they are indeed hot molecular cores. Using this combined information, models for the earliest stages of massive star formation can be constrained. Thermal infrared fluxes alone can refine massive star formation models like those of Osorio et al. (1999).

2.2. Circumstellar Disks

Another scenario for the location of masers is in circumstellar disks around young massive stars. The work of Norris et al. (1993) originally showed that there was a strong tendency for methanol masers to be distributed in linear patterns, and in some cases, there are velocity gradients along these distributions. It was determined that the simplest explanation for this phenomenon was that the masers are located in edge-on circumstellar disks. Likewise, in a small number of cases the spatial and velocity distributions of water and OH masers have been best described as existing in disks (Brebner et al. 1987; Torrelles et al. 1996; Slysh et al. 1999). If masers do exist in disks, then they would be best seen in the infrared. De Buizer et al. (2000) performed the first survey to detect circumstellar disk candidates at thermal infrared wavelengths. An example is shown in Figure 1b, and a full discussion of these sources and their likelihood of being actual circumstellar disks is given in De Buizer et al. (2000).

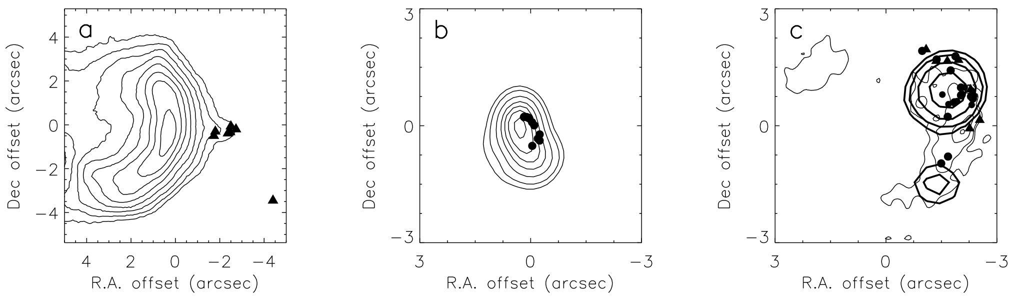

Figure 1. (a) A contour map of the cometary UCHII region G29.96-0.02 in 18 μm emission. We detect a thermal infrared source at the location of the water masers (triangles, Hofner and Churchwell 1996) which are offset from the UCHII region and coincident with a knot of NH_3 (4,4) emission (Cesaroni et al. 1994). (b) The 18 μm contours of G309.92+0.48, a resolved and elongated thermal infrared source, with methanol masers overplotted as dots. The thermal dust emission is elongated at a similar position angle as the associated linear maser distribution. (c) Thin contours show the location of our deconvolved 18 μm dust emission, and the thick contours show the location of 1.25 μm (J band) emission (Persi et al. 1996) for NGC 6334 F. The J emission may be light scattered off of the dust, however this filter contains many emission lines from shock-excited iron as well. These observations show that there is a warm density enhancement at the location of the masers (symbols), and perhaps the near-infrared emission is shock-related.

At the 1-10 kiloparsec distances of these star forming regions, high resolution imaging is essential in the thermal infrared in order to resolve sources that may have circumstellar disks. For those sources that are too far away or do not have disks that are extended, indirect evidence of the presence of disks can come from mapping outflows from these sources. If the outflow is perpendicular to the linear distribution of maser spots, this is good evidence that these masers exist in a disk. One way to accomplish this is to search for signs of outflow by mapping these regions in the near infrared with narrow band filters centered on spectral outflow indicators, such as the 2.12 μm H_2 and 1.64 μm [FeII] spectral lines (see Davis & Eisloffel 1995).

2.3. Edges of UCHII Regions

A further scenario for the location of masers is in the dense regions at the edges of UCHII regions. Density enhancements exist between shock and ionization fronts of expanding UCHII regions. Material can also be swept up to create a “bow-shock” at the head of a moving cometary UCHII region. A star sitting on the edge of a density gradient in a molecular cloud will create a cometary UCHII region as well, and the material near the head will be warm and dense. All of these situations may give rise to masers at the edges of UCHII regions. Some observations have supported this idea (Ho et al. 1983; Baart & Cohen 1985; Gaume & Mutel 1987), and the chemistry behind shock fronts was found to be a good location for maser emission (Elitzur & de Jong 1978). If the swept up or compressed material in these regions is warm enough, it can be observed in the infrared. Figure 1c is an 18 μm Keck image that shows water, OH and methanol maser excitation on a dusty UCHII region edge (De Buizer et al., in prep).

Further ground-based, high-resolution, infrared observations will be capable of studying these environments of maser emission. Observations with near-infrared spectroscopy can confirm the shocked nature of these regions by searching for the shock-excited [FeII] lines available at 1.25 μm and 1.65 μm as diagnostics.

3. Conclusions

The infrared regime is a valuable complementary tool to radio and millimeter observations. Infrared observations aid in the interpretation of activity in star formation regions containing maser emission. The near-infrared allows one to see photospheric emission from an exciting young massive star or to see this emission reflected off dust in the near stellar environment. Furthermore, there are spectral lines that allow one to perform useful spectroscopy and map outflows and shocks associated with maser emission. The thermal infrared allows one to probe through significant extinction in these regions and observe the hotter circumstellar material close to the exciting stellar sources. It also is a good probe of the warm, dense parts of UCHII regions. Presently, 8 to 10-m class telescopes and infrared instruments represent the best high-resolution alternative to the radio for studying the detailed environments of maser emission located in massive star forming regions.

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