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Methanol Masers and the Circumstellar Disk Hypothesis

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Abstract. It is not certain whether or not all massive stars form circumstellar disks. The earliest stages in the life of a massive star, when such disks would form, are poorly understood. Recent radio observations of methanol maser emission around young massive stars strongly suggest the existence of disks around these objects. This paper contains a review of what is known about masers and how they relate to massive stars. It discusses the hypothesis that methanol masers trace circumstellar disks around young massive stars, and presents the mid-infrared observations that may lend support to this hypothesis.

1. Introduction

Massive stars are extremely important astronomical objects on both the smallest and largest scales. From the moment they form photospheres, massive stars are violently changing their environment. They produce copious amounts of photons with wavelengths shorter than the Lyman continuum limit, and thus ionize the interstellar gas around them. They can heat material out to large distances in the clouds from which they formed, and in the process enrich the interstellar medium with molecules through evaporation of dust grain mantles. They may have powerful outflows which shock and churn the interstellar medium. Massive stars live fast and furious, and end their lives just as spectacularly. They explode as supernovae, releasing as much energy in the process as they had produced over their entire lives. Supernovae are invaluable alchemists. They produce the heavy elements that are otherwise impossible to create by normal stellar fusion processes. The force of their explosions spread these heavy elements throughout large distances in a galaxy, enriching the interstellar medium and thereby affecting later generations of stellar chemistry. These supernovae generate disruptive shock waves, which may in turn spark the formation of the next generation of stars. In this way, massive stars are responsible for the creation and distribution of elements in a galaxy, and are therefore ultimately responsible for the chemical building blocks necessary for the creation of other stars, planets, and life as we know it.

Two of the most fundamental questions in astronomy are: *How do stars form?* and *How do planets form around these stars?* Much has been done both observationally and theoretically to understand the phenomena associated with these questions. However, despite the importance of massive stars, most of these studies have focused on stars that are similar to our Sun in mass or smaller. It still remains unclear exactly how massive stars form. Studies have led to a four stage hypothesis for the formation of low mass stars: (1) the formation of a core of material within a molecular cloud, (2) the inside-out collapse of the core creating a protostar, (3) the development of an accretion disk and bipolar outflow, and (4) the end of infall, revealing a newly formed star and a circumstellar disk. It is from these disks that planets are assumed to form. While this scenario has worked well to explain star formation for low mass stars, it is not clear if it is applicable to massive star formation. We still do not know if massive stars form by accretion or by stellar mergers. Consequently, we do not know if the formation of circumstellar disks and outflows are a general characteristic of massive star formation. Furthermore, young massive stars are often associated with masers. We are only just now beginning to understand how masers of different species relate to the physical processes that occur during the formation and earliest evolutionary stages of massive stars.

2. Masers and Their Environment

Masers are naturally occurring molecular lasers that only exist under certain conditions and in very confined regions near newly forming stars. They are usually detected as extremely intense and narrow radio spectral lines. Interferometric mapping has revealed that maser emission is emitted from many individual 'maser spots'. Typically found in groups, maser spots each have their own well-defined velocity, and each comes from a region with a projected size on the order of 1 AU. There are four conditions necessary for the creation and continued existence of a maser. First, the interstellar medium through which the maser emission passes must be rich in molecular material. Second, a majority of the population of molecules involved must be in an excited state. This is referred to as a 'population inversion', which is produced by either radiative or collisional processes. We refer to any mechanism which creates a population inversion as a 'pump'. Third, there needs to be a large column density of material through which the maser emission passes. Large column densities lead to large maser gains. And fourth, there needs to be velocity coherence of the molecules. Maser photons will only interact with molecules whose transition frequency has not been Doppler shifted outside the linewidth of the maser transition.

There are several different molecules which exhibit maser action. The first observed astronomical maser was found by Weaver et al. 1965 in the 1665 MHz mainline transition of the hydroxyl (OH) radical. Shortly thereafter Cheung et al. 1969 discovered the 22 GHz water maser, and Ball et al. 1970 detected the first methanol (CH_3OH) maser at 834 MHz. While water and hydroxyl masers have been well studied since their discovery, only in the recent decade has the nature of the methanol maser begun to be seriously explored. Observations have lead to the ideas that hydroxyl and water masers are associated with infall (Reid et al. 1980; Forster & Caswell 2000), outflow (Felli, Palagi, & Tofani 1992; Claussen et al. 1998), and circumstellar disks (Brebner et al. 1987; Slysh et al. 1999), as well as the density-enhanced regions between the shock and ionization fronts that lie close to, and are created by, a massive star (Cook 1966; Gaume & Mutel 1987). Since there is evidence supporting each of these scenarios, it is likely that water and hydroxyl masers trace a variety of stellar phenomena. As we will see in this paper, methanol maser excitation may be linked to several different stellar processes as well.

3. The Methanol Maser

One of the most exciting hypotheses for the location of masers is in circumstellar disks. As we have discussed, there are a few instances where water and hydroxyl masers are thought to trace disks. Recent observations of 6.7 and 12.2 GHz methanol masers have lead to the hypothesis that they preferentially lie in circumstellar accretion disks around massive stars (Norris et al. 1993, 1998, Phillips et al. 1998). These studies have shown that groups of methanol maser spots tend to be distributed in lines or arcs in about 40% of the sites of methanol maser emission. Furthermore in a limited number of cases, there exists a well defined increase or decrease in velocities measured across the linear distribution of maser spots, indicative of rotation.

Circumstellar disks are excellent locations for maser emission. There is a high density of molecular material, plenty of radiation from the central star for pumping the molecules, and because the knots of material in the disk are caught up in the rotation, there is also velocity coherence. It is believed that if methanol maser spots form in rotating linear patterns, then the simplest explanation is that they exist in, and delineate, edge-on circumstellar disks. Why only edge-on disks? A primary reason would be that there is greater column density through the plane of the disk, which allows for more amplification, which in turn creates easily detectable methanol masers.

The circumstellar disk hypothesis is controversial and has its opponents. Some claim that linear distributions of masers can be caused by a variety of phenomena. Moreover, since there are only a small fraction of masers sites displaying velocity gradients along the spots, rotation may not be a general feature of methanol masers. These opponents advance the shock or outflow hypotheses. Some authors believe that shocked material associated with the expanding regions of ionized gas created by massive stars (a.k.a. UCHII regions) can have just the right density for the existence of masers (e.g. Menten et al. 1988). If this is the case, the masers could be pumped radiatively or by the dissipation of the relative kinetic energies of the shocked and unshocked gas. Furthermore, there would be collective motion of the material for velocity coherence. The same holds true for the outflow hypothesis. If the masers were created by the shock associated with an outflow impinging on the interstellar medium, a similar circumstance could arise. The methanol masers may exist in the outflowing molecular material near the star as well, where the material can be radiatively pumped, and where there is velocity coherence.

4. Mid-Infrared Observations

The high spatial resolution radio observations of the individual methanol masers were primarily performed in the southern hemisphere, and until recently there had been no complementary data at other wavelengths. This has slowed the progress of figuring out which of the excitation scenarios discussed in the last section are responsible for the methanol maser emission. It is difficult to ascer-

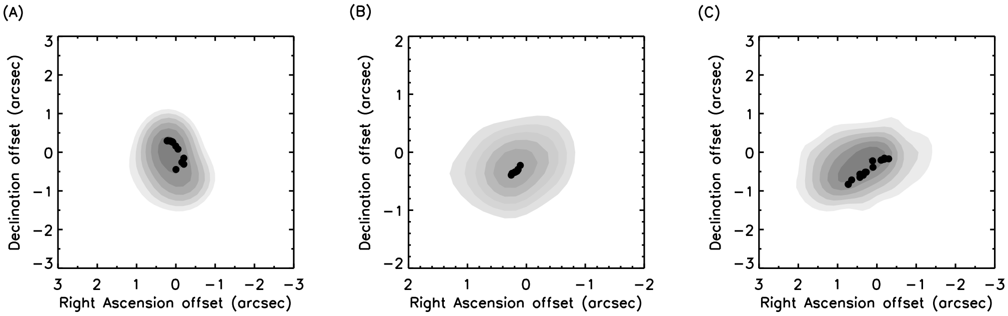

Figure 1. Greyscale contours of the three resolved mid-infrared sources from De Buizer et al. (2000) with methanol masers overplotted as filled black circles. In each case the mid-infrared dust emission is elongated at a similar position angle as the associated linear maser distribution: (A) G309.92+0.48, (B) G323.740-0.263, (C) G339.88-1.26.

tain what stellar process maser emission is tracing when it is not known where the locations of the associated massive stars are with respect to the maser spots. Only in recent years have researchers looked for and imaged the radio continuum from the UCHII regions produced by massive stars. It was discovered that many sites of methanol masers have no detectable radio continuum emission (e.g. Walsh et al. 1998). Imaging at another wavelength was needed to find the associated young stellar sources. Optical imaging is not useful because massive stars evolve so quickly that they stay heavily embedded in their birth clouds, even after they reach the ZAMS, and thus are totally obscured visually during these formative years. However, because infrared radiation is much less affected by extinction than visible radiation, infrared images can probe through the cool obscuring dust. Furthermore, mid-infrared images (5-25 μm) can trace the radiation from the $\sim$ 200 K dust close to the stellar sources associated with the methanol masers, and could even detect circumstellar disks around these stars if they exist. The first mid-infrared survey of massive stars associated with maser emission was conducted by De Buizer, Piña, & Telesco (2000). The main thrust of this work was to locate the stellar sources associated with the methanol masers and determine what stellar process or processes methanol maser emission is tracing.

Twenty-one sites of methanol maser emission were imaged by De Buizer et al. (2000) at 10.46 and 18.06 μm, ten of which have their masers distributed in a linear fashion. Only in three of the ten sites were mid-infrared sources resolved at the location of the linearly distributed methanol masers. However, all three resolved sources are elongated in their thermal dust emission at the same position angles as their methanol maser distributions (Figure 1).

Modeling of methanol masers by Sobolev, Cragg, & Godfrey (1997) have lead to the conclusion that methanol masers can be effectively pumped via mid-infrared photons from warm dust near stellar sources. De Buizer et al. (2000) find that the physical size of the regions containing methanol masers seem to be smaller than the resolved mid-infrared emitting regions of the associated stellar sources. Moreover, the mid-infrared source peaks coincide with the methanol masers, a necessary condition if the masers are tracing disks.

All three resolved and elongated mid-infrared sources have mid-infrared companions which lie at approximately the same position angle as the methanol maser distributions. These companions are on the order of 10,000 AU from their counterparts, and are not visible in Figure 1. While they may not be gravitationally bound binaries, the two stars might be coeval. Wide binaries could form via the growth of an instability in the outer parts of a massive circumstellar disk (Bonnell 1994). In this formation scenario, the spin axes of the stars would always be aligned, and consequently circumstellar disks would be coplanar to the position angle of the binary. Recent observational evidence suggests that binaries with circumstellar disks may preferentially form in such a way as to produce this coplanarity (Monin, Menard, & Duchene 1998; Jensen, in preparation).

Are these elongated mid-infrared sources circumstellar disks? I will summarize the evidence, which is circumstantial, but convincing. First, the mid-infrared peaks are coincident with the methanol masers. Second, the dust elongations seen in the mid-infrared are at the same position angle as the linearly distributed methanol maser spots. Third, there is theoretical evidence that methanol masers require mid-infrared photons for pumping. All three maser distributions are contained within these mid-infrared elongations, and circumstellar disks radiate copious amounts of mid-infrared photons. Fourth, the resolved sources may be binary in nature. These pairs of sources lie at similar position angles as the methanol masers, and there is observational evidence that wide binaries with disks tend to be coplanar. And finally, one of the three sources has a well-defined velocity gradient along the maser spots in the linear distribution, which may be caused by rotation. The simplest way to explain the nature of these elongated mid-infrared sources is that they are indeed circumstellar disks.

5. Planets and Disks around Massive Stars

The notion that planets form and exist around massive stars may be evidenced by the first ever discovery of extra-solar planets, detected around the pulsar PSR1257+12 (Wolszczan & Frail 1992). These planets could have formed before or after the supernova explosion that left the pulsar we see today. Though the current idea is that planets form after a supernova, this scenario is not without its problems. Although controversial, there is some theoretical evidence that planets could survive a supernova explosion (Postnov & Prokhorov, 1992). This would imply that the planets can form much earlier in the lifetime of a massive star, just as the case for low mass stars. It is believed that accretion disks eventually become planet-building disks in the low-mass star formation paradigm. Therefore, the first step towards resolving the question of whether or not young massive stars can form planets is to first find out if they form circumstellar disks.

Though the data is still limited, the results of De Buizer et al. (2000) suggest that circumstellar disks do indeed form around young massive stars. Moreover, methanol masers may trace circumstellar disks more often than any other maser species. However, De Buizer et al. (2000) conclude that there are several methanol maser groups in their survey which most likely do not trace circumstellar disks. They find that some linearly distributed methanol masers may best be described as existing in shocks or outflows. Nevertheless, outflows are indirect evidence for the existence of circumstellar disks around massive stars because the disks serve as a collimator of stellar winds.

All of these results show that methanol masers are important tools which aid in the search for circumstellar disks around massive stars. Whether the masers directly trace disks, or indirectly tell us of the existence of a disk from tracing an outflow, they provide important collaborative evidence for the existence of circumstellar disks around massive stars. These studies also give us much needed insight into the early evolution of massive stars and suggest that these stars may indeed form in a similar fashion as their low mass counterparts.

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