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Using Methanol Masers to Probe High Mass Star Forming Regions

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ABSTRACT Compared to low mass stars, the formation of high mass stars is not well understood. To understand better how high mass stars form, we can utilize masers, naturally amplified point sources of microwave radiation. One example is the methanol maser, which falls into two categories. Class I methanol masers form in the bipolar outflows from the protostar, and Class II masers form in the accretion disk. Their compact size and intensity make them an excellent source of information about the process of high mass star formation. We compiled a modest database of Class I and II methanol masers through a literature search to investigate the morphology of methanol masers in star forming regions and measure the distances of these masers from potentially associated infrared sources.

INTRODUCTION

While the Sun is the star with which we are most familiar, our galaxy is home to a large variety of stars (see, e.g., Gaia collaboration, Brown et al. 2018). Of these, stars with masses greater than eight times that of our Sun are designated as high mass stars. Although high mass stars constitute only a small fraction of the stellar population, they play an outsized role in the Interstellar Medium, injecting vast amounts of energy and matter into their surroundings, and influencing significantly the composition and subsequent evolution of the Interstellar Medium (McKee & Ostriker 2007). Yet, while the basic process by which stars like our Sun form is well established, there is much left to learn about the formation of high mass stars (Motte et al. 2018).

The Interstellar Medium is comprised mostly of hydrogen gas (with a smaller fraction of helium gas mixed in) and dust (usually silicon or carbon based). This is where stars are formed (Rosen et al. 2020). The process begins when sub-parsec[1]

[1] Parsec (pc): A unit of distance frequently used by astronomers. 1 pc is equal to 3.26 Light Years.

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scale dense cores in Giant Molecular Clouds[2] collapse under their own self-gravity to form protostars; higher density regions at the center of the core that will eventually go on to become stars. As the infall of material continues, an accretion disk will form around the protostar, accompanied by bipolar outflows of gas. The inner edge of the disk provides material for the protostar, fueling its formation. For low mass stars like our Sun, observations have been very successful at establishing this basic evolutionary sequence of star formation (Shu, Adams, & Lizano 1987).

For high mass stars, observational challenges make it very difficult to verify whether they form by the same process as low mass stars (Zinnecker & Yorke 2007). Since high mass stars are only a tiny fraction of the stellar mass spectrum, one would expect on statistical grounds for them to be farther away from us. Indeed, the nearest high mass star forming region of Orion is about 500 pc away, whereas the nearest low mass star forming region of Taurus is only 140 pc away. Yet another issue is that high mass stars tend to form in crowded clusters, and never in isolation (whether this has something to do with how they form is still an unsolved issue). This combination of large distances and crowded environments means that high mass star forming regions must be observed at very high angular resolution. Given their significant impact on the Interstellar Medium discussed above, astronomers continue to be engaged in a sustained effort to observe high mass star forming regions with the aim of establishing an evolutionary sequence of high mass star formation (e.g., Moscadelli et al. 2021). One of the best methods we have for observing the environment of high mass protostars is using radio telescope arrays (known as interferometers) to observe masers. Astrophysical masers (standing for Microwave Amplification by Stimulated Emission of Radiation) often occur naturally in star forming regions. As the name would suggest, the manner in which masers function is similar to that of lasers, with one prominent difference being the type of radiation emitted; masers are at microwave (radio) wavelengths. In masers, radiation is amplified to create a powerful point source. This is achieved through creating a population inversion; a situation in which more molecules are in a higher energy state, rather than a lower one (Figure 1).

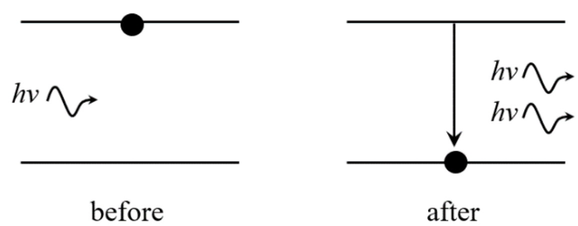

Figure 1. A diagram of the process of stimulated emission. Notice how the photons after emission are in phase and are producing coherent light in a single direction.

This can be done through a number of pumping mechanisms (radiative, collisional) which maintain the inversion. When a molecule in the higher state is hit by a photon, the molecule will return to its lower energy state, emitting a second photon in the process. This is what is called stimulated emission. As these photons continue to interact with other molecules, the number of photons increases exponentially, creating amplified, focused radiation. This makes masers an incredibly useful source. When imaged via interferometric telescopes, they provide images with milliarcsecond resolutions; 1 arcsecond is 1/3600 of a degree on the sky.

Methanol (CH_3OH) masers are a common feature in star forming regions and can be separated into two classes. Class I CH_3OH masers form along the bipolar outflows of protostars, while Class II CH_3OH masers form in the accretion disks around protostars. They are incredibly bright and compact sources, which makes them very useful for observing distant astronomical sources at high angular resolution. The main objective of this project was to gather data from the literature on methanol maser observations in star forming regions. By recording their coordinates in the sky, we were able to measure how far away they lie

[2] Giant Molecular Clouds are clouds of gas in the Interstellar Medium that contain molecular hydrogen. They have sizes ranging from 20 to 200 parsec.

from protostars (as revealed by infrared observations) and investigate how these masers are aligned along disks and outflows in star forming regions (as revealed by high angular resolution observations). In the next section, we discuss the methods used to gather and organize the data.

METHODS

The objective of this project was to collect data on methanol masers in order to investigate their association with star forming regions and determine how they are arranged in disks and outflows. This was achieved by surveying papers from the NASA Astrophysics Data System (ADS) and accessing each paper's respective data products on the Set of Identifications, Measurements and Bibliography for Astronomical Data (SIMBAD) Database. Our search was confined to the years 2006-2020. Most modern surveys during this period have covered the important regions hosting maser sources, so the impact of not searching publications prior to 2006 should be minimal. After tabulating the surveys in an Excel file, we considered only those that had observed 20 or fewer maser sources so that the project could be completed over the summer; while this does mean our work cannot be considered a complete survey of all available observations, such a choice is unlikely to bias our conclusions unless large groups of masers are systematically nearer or farther from their associated sources. For the sources that had observed 20 or fewer maser sources, we searched the Right Ascension (RA) and Declination (Dec) of each maser on SIMBAD, in order to find any infrared sources within a radius of 60 arcseconds of the maser position; RA and Dec are described in the caption to Figure 3. Such infrared sources could potentially reveal the presence of the protostar with which the methanol masers are associated. We then calculated the distance between the maser and its associated infrared source in parsec (pc). These are projected distances in the sky, obtained by subtracting the RA and Dec of the maser and infrared sources. Finally, we picked out those maser sources that had been observed at high angular resolution in order to investigate how they are arranged in disks and outflows around the central protostar.

RESULTS

Our literature search resulted in a total of 146 methanol masers. A *sample* of our results, showing the position of each maser, and the distance from its associated IR source, is shown in Table 1. Out of these 146 masers, 51 were Class I methanol masers, the majority of which were associated with a frequency of 44 or 95 GHz. The remaining 95 were Class II, associated overwhelmingly with a frequency of 6.7 GHz. This is expected, as these are some of the most common maser lines for each respective class. We also noted whether these observations were carried out with a single dish, or with interferometers. Observations with interferometers would have significantly higher angular resolution than those carried out with a single dish and provide more detail on the observed region.

We then searched for IR sources potentially associated with these masers by looking at a listing of sources within 60 arcseconds in the SIMBAD database, and scanning these sources using the Aladin viewer. Of the overall total of 146 masers, 72 (49%) were associated with an IR source. When only considering Class II masers, 57 (60%) had such an association. A separate search was completed to define how many masers were from known star forming regions. Of the total 72 IR-associated masers, 70% were present in known star forming regions, while only 49% of IR-associated Class II masers had this association.

The average distance from each maser to its respective IR source was 0.554 parsecs. Overall, a majority of the 6.7 GHz masers resided closer than 1 pc to their IR source. Masers of 44 and 95 GHz resided at a slightly larger distance from their IR source. We also looked at how these masers were aligned in disks and outflows. Class I masers are known to reside in outflows whereas Class II masers are found predominantly in accretion disks near the protostar.

Table 1. Selected Sample[3] of Methanol Masers and Associated Data

Maser Name	Right Ascension[4] (h m s)	Declination[4] (° ‘ “)	Maser Class (I or II)	Distance from associated IR source (arcsec)	(parsec)
G173.48+2.446	05 39 13.064	+35 45 51.34	II	12.64	0.104
G173.58+2.442	05 39 27.500	+35 40 43.00	I	23.26	0.192
G305.21+0.206	13 11 13.700	–62 34 41.39	II	17.83	0.354
G321.03–0.485	15 15 51.660	–58 11 18.00	II	30.67	0.877
G345.01+1.792	16 56 47.600	–40 14 25.80	II	7.06	0.103
G00.546–0.852	17 50 14.523	–28 54 31.25	II	3.64	0.048
IRAS18089–1732	18 11 51.290	–17 31 23.80	I	32.08	0.560
G34.256+0.155	18 53 18.000	+01 14 57.00	I	13.74	0.699
G34.258+0.154	18 53 18.629	+01 15 00.49	II	2.81	0.143
G38.037–0.300	19 01 50.470	+04 24 19.25	II	1.98	0.093
G49.489–0.369	19 23 39.813	+14 31 04.58	II	2.92	0.077
G59.633-0.192	19 43 49.963	+23 28 36.61	II	23.26	0.507
IRAS 20293+3952	20 31 11.970	+40 03 12.10	I	16.66	0.162
G80.861+0.383	20 37 00.971	+41 34 55.60	II	22.53	0.175
IRAS 23033+5951	23 05 24.560	+60 08 09.40	I	7.55	0.128

[3] Sample only, additional data available upon request.
[4] Epoch of Right Ascension (RA) and Declination (Dec) is J2000; RA and Dec explained in the caption to Figure 3.

Figure 2 shows an example of Class I methanol masers in an outflow; the outflow is traced by shocked H_2 emission and SiO line emission; the water masers in the figure likely indicate the position of the protostar. The Class I masers are arranged in an arc-shaped structure (upper right), where the outflow impacts the ambient interstellar gas. Figure 3 shows examples of Class II masers. The masers in the left panel appear to be in a complex distribution without any regular arrangement. The Class II masers on the right are seen arranged in a ring-like structure, with a dashed circle drawn to trace the ring. Each maser in the lower panel is color-coded so that its corresponding spectrum can be located in the upper panel. Note that the left panel actually shows two maser sites; the one located at the top left of the bottom panel has masers centered around 60 km/s in velocity in the upper left panel, whereas the one located at the bottom right of the bottom panel has masers centered around 72 km/s. For several additional sources in our literature search, Class I masers were seen in outflows, whereas Class II masers often appeared in arcs or rings along filaments of gas, evidently ringed around the forming protostar. Such patterns occurred multiple times, such as in the star forming regions of G034.3+00.1 and G017.6369+00.1568 (Bartkiewicz et al. 2016, Ouyang et al. 2019).

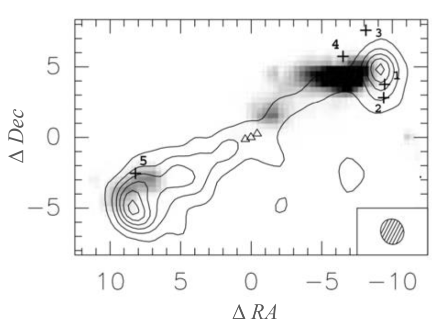

Figure 2. Class I methanol masers (shown by numbered plus signs) in the high mass star forming region IRAS 20126+4104 from Kurtz et al. (2004). Contours show the SiO (2–1) emission, while gray-scale shows H_2 emission. Triangles indicate water masers. The axis is marked in offsets from the reference position of RA 20h 14m 26.03s, Dec 41° 13' 32.5"; see Figure 3 for explanation of RA, Dec. The methanol masers appear to trace the edge of the shocked gas seen in H_2 emission.

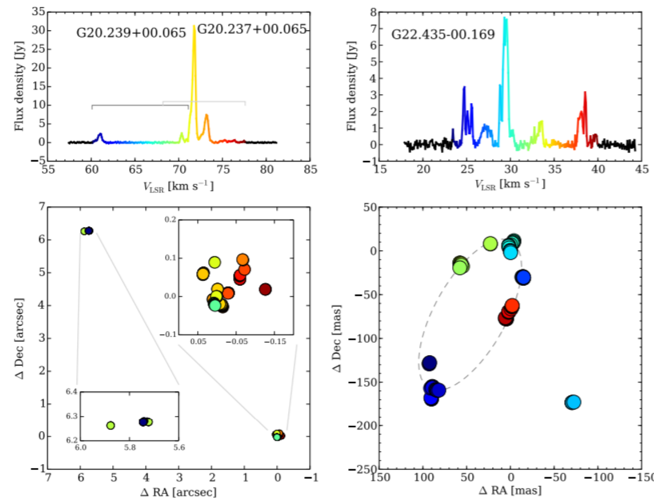

Figure 3. Figure showing various images of methanol masers from Bartkiewicz et al. (2016) observed at 6.7 GHz. The top two panels show the spectra of masers toward two locations, plotted as intensity *vs*. velocity. The velocities are expressed with respect to the LSR, the Local Standard of Rest, an inertial frame defined with respect to a known set of stars that appear to be fixed in the sky. The bottom panels show the morphology of the masers, a complex distribution without any regularity on the left, and a ring-like arrangement on the right. The images in the bottom panels are labeled in RA and Dec, where RA stands for Right Ascension, and Dec for Declination; these are coordinates used to locate objects in the sky, and are equivalent to longitude and latitude, respectively, on the Earth.

DISCUSSION

In order to gain an understanding of methanol maser characteristics and morphologies, a series of methanol masers from the literature were compiled into a modest database. Databases such as these are an important tool, as they allow a variety of masers to be efficiently gathered in one place, and easily accessible for a variety of uses.

Our literature search resulted in a reasonably representative sample of 51 Class I methanol masers (44 or 95 GHz), and 95 Class II masers (6.7 GHz). We then used this sample to look for potential association with a protostar by searching for infrared sources within 60" of the maser position. Overall, almost half of the total population of 146 masers appear to be in the vicinity of an IR source, although the proportion is higher when considering only Class II methanol masers (60%). Of course, it is entirely possible that setting an arbitrary limit of 60" to enable completion of the project over the summer has biased the statistics, so clearly this paper is a start and not the last word on this subject. Future projects should not only expand the region in which to search for associated sources, but also normalize it by the distance to the source. Even though the statistics may turn out to be different, our result that some methanol masers may not be associated with an IR source, though, is significant. It implies that some of these masers may be tracing a very early stage of the star formation process, before the protostar has revealed itself in the infrared. This is supported by the results of our search for known associated star forming regions; 70% of the total amount of IR-associated masers did indeed belong to a known star forming region. However, only about half of IR-associated class II masers were found in known star forming regions. This may imply that a significant portion of IR-associated class II masers tabulated in this survey are situated around extremely new or early-stage star forming regions in which the known tracers of star formation may not yet have manifested themselves.

In several instances, we were also able to locate the masers in disks and rings (for Class II masers) and outflows (for Class I masers). Such associations allow us to understand better the location of these masers in high mass star forming regions and their role in the star forming process itself.

In conclusion, our project reveals the potential of using masers to study high mass star formation, with the cherished goal of developing an evolutionary scheme for this process. Future work will focus on a deeper and broader search for associated IR sources and association with star forming indicators like disks and outflows.

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