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LETTERS

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A Possible Origin of 6.7 GHz Linear Methanol Maser Sources

Ye Xu ⋆

Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030
Urumqi Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012

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Abstract We present a model which explains the observed multi-linear spatial structures with different velocity gradients of the $5_0-6_1A^+$ methanol line at 6.7 GHz. We consider this and other hypotheses and conclude that the methanol maser emission probably comes from some thin rings variously inclined to the line of sight.

Key words: masers — stars: circumstellar matter — stars: formation

1 INTRODUCTION

Newly formed massive stars are obscured by dust, and their clearest signature is often at radio frequencies from strong maser emission. Methanol maser emission arises from several transitions, the strongest being the $5_0-6_1A^+$ line at 6.7 GHz, which is also the second strongest Galactic masers of any molecule, first reported by Menten (1991) and recognized as typical of Class II masers. Class II methanol masers are always found in regions of recent massive star formation and many of them are associated with known ultra-compact (UC) HII regions — a very early phase of the star formation process. Stars earlier than type B2 also give rise to bright hydroxyl and water masers. However, hydroxyl and water masers can also be found in the later stages of a star's life, and interstellar water masers also occur around young stars later than type B2. Hence, only methanol masers are unique indicators of massive star-forming regions. At present extensive surveys have yielded more than four hundred 6.7 GHz maser sites (Caswell et al. 1995; van der Walt et al. 1995, 1996; Ellingsen 1996a; Lyder 1997; Walsh et al. 1997; Slysh et al. 1999; Szymczak & Kus 2000). The widespread occurrence and high intensity of the 6.7 GHz maser line makes it one of the best traces of star-forming regions at present. Observations revealed that they frequently have several different linear spatial structures with different velocity gradients along them (Norris et al. 1993, 1998; Phillips et al. 1998; Minier et al. 2000). This surprising result is in contrast to OH and H_2O masers, where no maser in a star formation region has ever been observed to have the tightly collimated linear structures which seem relatively common in methanol masers, although a few OH and H_2O sources do have a roughly elongated morphology, and linear structures are seen in high velocity masers.

⋆ E-mail: xy@center.shao.ac.cn

2 PREVIOUS MODELS

A number of possible models such as collimated jets, shock fronts, and circumstellar disks can be constructed to explain the lines of masers with linear velocity gradients (Norris et al. 1993, 1998; Sobolev et al. 1997; Minier et al. 2000).

Linear morphologies and linear velocity gradients are expected in the case of masers tracing bipolar outflows, but there is no theoretical support for Class II methanol masers forming in such environment. Outflows of gas with velocities of a few km s^{-1} are common in star formation regions, but they are broad and uncollimated. On the other hand, narrow collimated jets are associated with high-velocity flows. Observations indicated that the distribution of the masers is highly linear and they do not have a wide velocity range. Furthermore, a double-sided jet, needed to produce the observed feature, is almost never seen in stars. Thus, there is no observational or theoretical support for the methanol lines to represent highly collimated outflows or jets.

Another possibility to explain the line of masers is to consider that they form in the layer between the ionization and shock fronts surrounding the UC HII region. The shock can align the clumps and lead to formation of somewhat organized structures, but it does not produce the observed smooth velocity gradients.

The third hypothesis, a protostellar disk, was proposed by Norris et al. (1993, 1998). If we are observing these disks nearly edge-on, then this provides an explanation for the linear structures. The high density of neutral material in the disk shields the fragile molecules within it from the ultraviolet photons in the surrounding HII region, so the interior of the disk remains un-ionized. Masers within the disk that radiate in the plane of the disk will beam their emission through this neutral material into the interstellar medium. This model also predicts that masers should show a simple velocity structure because the maser velocities should be roughly consistent with the Keplerian rotation. However, extensive surveys have shown the 6.7 GHz masers to be extremely common in regions of star formation of the Galaxy, which often show OH maser emission. More than 70% of methanol maser sources are associated with OH masers (Szymczak & Kus 2000), but OH masers often form outside the HII region and the maser spots of both methanol and OH project at similar positions in some regions of formation of massive stars. (Menten et al. 1992; Bloemhof et al. 1992; Caswell 1997; Minier et al. 2000). So, it is uncertain whether all the methanol masers with line structures originate from protostellar disks. On the other hand, observations also indicated that in some sources the conditions are favorable for methanol maser emission, but not OH (Caswell 1996). This suggests that the 6.7 GHz methanol masers are more widespread than OH masers in star formation regions. If methanol masers arise in circumstellar disks, we can see the maser emission only when these disks are observed nearly edge-on, which certainly greatly decreases the detection rates of methanol masers, and so the number of methanol maser sources would be significantly less than those of the OH in regions of formation of young massive star. This is in contrast to the above observational evidence. Furthermore, it is difficult to explain the multi-line structures with different velocity gradients along the lines observed by Minier et al. (2000). Maser emission perpendicular or inclined to the disk would be absorbed when they pass though the HII region which is likely to be optically thick at centimeter wavelengths (Hollenbach et al. 1994). Only those lying in the plane of the disk could be detected, as these maser emissions would pass through the neutral material into the interstellar medium, and so the projections of maser spots should be roughly on the same line, not several separate lines, although the methanol masers might occur in the same disk at different radii.

3 NEW MODEL

If we consider only the gravitational effect from a central star, the material from the molecular envelope outside the HII region around the star will gradually fall onto its equatorial plane due to the gravitational force perpendicular to the plane. If a blob, at a distance of 1000 AU, is in Keplerian motion around the star, and is inclined at an angle i to the equatorial plane (see Figure 1), then the time for the blob to reach the plane would be about 10^4 years, assuming $i \sim 30^\circ$ and the mass of the young star $\sim 10\ M_\odot$. However, radiation pressure and gas pressure would make the period longer, even up to 10^5 years. Hence, quite a lot of the matter of the molecular envelope may not reach the plane in that time. There is evidence that the lifetime of the maser phase is quite short ($< 10^4$ yr) and interstellar masers only occur in the first 10^5 years of the formation of stars, which means that many maser sources may spend their whole lifetime in directions away from the equatorial plane. The molecular envelope might gradually turn into separate *rings* with various inclinations relative to the equatorial plane during the maser phase.

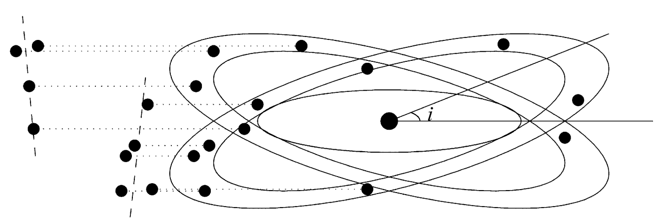

Fig. 1 Multi-ring model of masers. Filled circles and the inside ellipse mark masking regions and the equatorial plane of the central star, respectively. The maser emission might only be observed from the near sides of the tilted rings and the emission from the far sides might be undetected due to absorption by the intervening HII region. The projections of maser spots fall on two different lines with different velocity gradients along them, as in the results of Minier et al. (2000).

It is necessary to propose a model to interpret reasonably the observed results. First, methanol masers often emanate from the same region as OH masers, and the spectra of both commonly show emission confined to a very similar velocity range (Caswell 1997). For instance, in W3(OH), the maser spots of both OH and methanol appear to be distributed in an extensive, expanding partial shell or torus, girdling a compact HII region (Menten et al. 1992; Bloemhof et al. 1992) and in Cep A, the methanol masers have approximately the same velocities as the OH masers located at similar positions, indicating that the two types of maser are probably associated with each other (Minier et al. 2000). These results suggest that the methanol masers probably occur outside the HII region. Next, the frequently observed linear spatial structures with different linear velocity gradients indicate that the masers are also associated with some rotating disks or rings. In addition, the widespread occurrence of methanol masers suggests that there are a number of rings or disks tilted at different angles to the line of sight, which could have increased the rate of detection of the masers, while a clear linear velocity gradient along each line suggests rotating masers at a constant radius. Finally, in some cases the masers could trace only a fraction of the rings in front of the star, and therefore we may only see maser emission from the near sides of the rings. The maser emission of the far sides may be undetected due to the absorption by the HII region when passing through it. In W48 and G339.88–1.26 (Norris et al. 1993, 1998; Minier et al. 2000), each line of masers is more than 1000 AU in extent which is very probably shorter than the full diameter of the disk, and also exhibits a clear linear velocity gradient which suggests the masers to be located across a diameter of the HII region and at a constant radius. The result shows that these masers are indeed located in an edge-on thin ring outside the HII region. Hence, most probably there are a number of rotating rings outside the HII region, where the conditions are suitable to form methanol masers, with inclined at various angles with respect to the line of sight.

Zheng & Ling examined a possible excitation mechanism for 17 sources with the Class II methanol masers and concluded that the conditions in a warm molecular envelope outside the HII region are suitable to form the methanol masers (Zheng & Ling 1997). They argued that the masers arise in regions of methanol-rich gas within a cloud layer around the compact HII region, where the hydrogen number density is about 10^6 cm^{-3}; The free-free radio continuum emission with a brightness temperature of 10^3 K from the compact HII region provides a source of background radiation for amplification. Infrared objects with a brightness temperature of 100 K and photon rates of about 10^{53} s^{-1} associated with compact HII regions are reasonable sources of excitation.

We assume that the methanol masers lie in some of the thin rings which may have a wide range of radii and various inclination angles with respect to the line of sight which means we can see more edge-on rings than at other inclinations. Maser action will occur predominantly along those columns through which there is a maximum number of molecules with the same line-of-sight velocity, and therefore the most favored location of the methanol masers will be within the rings seen nearly edge-on and in the vicinity of the HII region where there is sufficient radiation to pump the masers.

In terms of rectangular coordinates centered at the center of a protostar a thin ring can be approximately written in the form

$$x^2 + y^2 + z^2 = r^2,$$

$$ax + by + cz = 0, \tag{1}$$

where a, b and c are the direction components of the normal vector of the plane $ax+by+cz = 0$, r is the radius of the ring (assuming the ring to be approximately circular). Assuming the line of sight is in the z direction (i.e. maser spots project at the $z = 0$ plane), we always see edge-on rings if the planes of the rings are parallel to z axis. So, the projections of the maser spots could exhibit a number of lines, and some of them may intersect each other or overlap, as shown in W48 and NGC 7538 (Minier et al. 2000).

Generally, most of maser rings are tilted, and so the maser spots would delineate a number of elliptical curves, rather than straight lines. If the major-to-minor axis ratio ρ of a ellipse is large enough, then the projections of maser spots would exhibit a roughly linear or elongated morphology. For simplicity, assuming that x-axis lies in the plane of a maser ring , the angle θ between the plane of the ring and $y = 0$ plane will satisfy the equation

$$\sqrt{1 + b^2/c^2} = \rho,$$

$$\tan\theta = c/b. \tag{2}$$

According to the observed results, ρ should be ≥ 10, and then we find $\theta \approx 6°$. This case has been observed in S231 (Minier et al. 2000) in which the masers exhibit two or more lines which may be caused by the projections of several different, almost edge-on maser rings with small inclination angles between the planes of the rings.

A number of unsaturated masers might occur in some of the rings and they could not be detected due to their low flux density. If these unobservable masers amplify a background source which is either a radio continuum from the HII region or other maser emissions (Deguchi & Watson 1989; Boboltz et al. 1998), they could amplify the continuum flux to a observable level. Observations have shown that most of the methanol masers are associated with a detected UC HII region (Ellingsen et al. 1996b; Phillips et al. 1998), and during a radio flare, an unsaturated maser flare occurred in an almost face-on galaxy and its apparent luminosity is up to about $420\,L_\odot$, which is the third most luminous maser discovered so far (Falcke et al. 2000). For the complex sources, such as S269, W75N, G31.28+0.06 (Minier et al. 2000), they may be caused by confusion of the maser spots from these rings with various inclination angles with respect to the line of sight, some of them with a significant inclination angle, even face-on.

In a nearly edge-on ring the line of sight velocity is (Minier et al. 2000)

$$v = V_{\rm rot} \times \frac{l}{r} \times \cos\alpha + v_{\rm sys}, \qquad (3)$$

where $V_{\rm rot}$ and α are the rotational velocity and the inclination angle with respect to the line of sight, respectively. $v_{\rm sys}$ is the systemic velocity and l is the observed distance from the central star. Because the line of velocity is a linear function of l, in the case of rotating rings, a clear linear velocity gradient alone each line would be seen, as shown in Fig. 2, which can be written as (Phillips et al. 1998)

$$\frac{{\rm d}v}{{\rm d}l} = \sqrt{GM/r^3} \times \cos\alpha, \qquad (4)$$

where M is the mass of the star. If $M = 10M_\odot$, $r = 1000$ AU, then ${\rm d}v/{\rm d}l \approx 10^{-2}$ km s^{-1}AU^{-1}, and for different r the lines of masers will show different gradients. These cases have been observed in NGC 7538 and W75 (Minier et al. 2000).

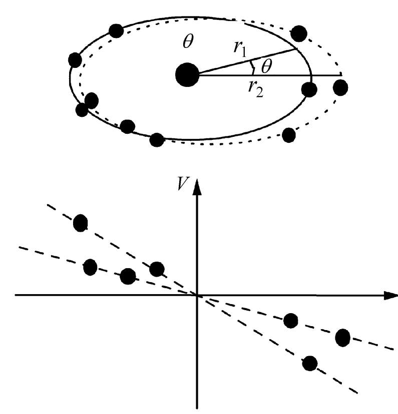

Fig. 2 Velocity vs. major axis offset ($v-l$) diagram. Small circles indicate masing regions. There are a quite small angle θ between the planes of the two rings. In the case of rotating rings, the line of velocity is a linear function of l, and therefore, a clear linear velocity gradient would be seen along each line and the lines of masers will also show different gradients for different r.

As mentioned above, the angle between the planes of some rings which form roughly parallel line structures should be quite small, and so the difference of the radial velocities along each line of the masers is mainly caused by the different radii of each ring. Therefore, from the observed changes of the radial velocities along each line in the same maser source, one could obtain the ratios of the radii among these rings. By using Eq.(3) we find

$$\frac{r_1}{r_2} \propto \left(\frac{\Delta v_1}{\Delta v_2}\frac{\Delta l_2}{\Delta l_1}\right)^{2/3}, \qquad (5)$$

where Δl_1 is the linear distance in projection between two maser spots along the same line. Δv_1 is the velocity difference between two spots along the same line. Δl_2 and Δv_2 are same as Δl_1 and Δv_1, respectively. If B, C and D in NGC 7538 come from three different rings, then the ratios of the radii among the three rings would be about 1: 1.1: 0.7. This could roughly determine the scale of the molecular envelope outside HII region, where the conditions are suitable to form methanol masers.

Hence, the multi-ring model manifests that we can not only see single linear structure with an approximate velocity gradient along it, but several separate linear structures with different linear velocity gradients along them. Furthermore, we can see more methanol maser sources with linear structures.

In short, those models such as collimated jets, shocks fronts, and circumstellar disks fail to explain the multi-linear spatial structures with different velocity gradients of the 6.7 GHz methanol masers. The evidence is strongly in favor of the conclusion that the observed results are the projections of the maser spots located in some of nearly edge-on rings outside the HII region.

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