# Methanol Masers: Tracers of Outflows ?

By VINCENT MINIER[1], ROY S. BOOTH[1], SIMON P. ELLINGSEN[2], JOHN E. CONWAY[1] AND MICHELE R. PESTALOZZI[1]

[1]Onsala Space Observatory, 439 92 Onsala, Sweden
[2]School of Mathematics and Physics, University of Tasmania, Australia

We have evidence that some 6.7 and 12.2 GHz methanol masers may trace outflows emerging from protostars. The methanol masers could trace either well collimated outflows or more randomly distributed clumps formed by ionised stellar winds. We present preliminary proper motion studies of 12.2 GHz methanol masers. First results show that the proper motions of the maser components in G9.62+0.20 are consistent with masers forming in an outflow rather than a disk.

## 1. Introduction

Previous high resolution imaging of 6.7 and 12.2 GHz methanol maser sources has been conducted in the Southern hemisphere using the Australia Telescope Compact Array (ATCA) at 6.7 GHz and the Parkes-Tidbinbilla Interferometer (PTI) at 12.2 GHz. Norris et al. (1988, 1993, 1998) and Phillips et al. (1998) found that in many sources, the 6.7 and 12.2 GHz maser features were aligned and exhibited linear velocity gradients. They argued that the linear structures were consistent with rotating disks of masers seen edge-on. The derived values of the radii of these disks and the approximate enclosed masses deduced by assuming Keplerian rotation, were 500 to 2000 AU and 3 to 100 $M_\odot$, respectively.

We began a Northern hemisphere campaign to observe methanol masers in 1997 when several telescopes of the European VLBI Network (EVN) were equipped with 6.7 GHz receivers. In order to clarify the nature of the 6.7 and 12.2 GHz methanol maser sites, i.e to investigate the possibility that these masers arise from ordered structures such as disks or shocks, Minier et al. (1998, 1999, 2000) have conducted VLBI observations at 6.7 and 12.2 GHz (EVN at 6.7 GHz in May 1997 and November 1998; VLBA at 12.2 GHz in July 1997, November 1998, and January 1999) toward 14 star-forming regions: NGC7538, S252, W75N, W48, G31.28+0.06, S231, S255, S269, MonR2, G9.62+0.20, Cep A, W51, G59.78+0.06 and G29.95-0.02.

In 10 of these sources, the methanol masers show elongated morphologies in the VLBI map and exhibit linear velocity gradients (see Minier et al. 2000, hereafter paper 1). These linear structures have lengths of 50 to 1300 AU. We consider whether these structures are consistent with circumstellar disks. Assuming that we see the whole diameter of a Keplerian disk then we derive sub-solar central masses with the exception of W48. However, it is possible that we only see masers in a fraction of the disk that lies in front of a young massive star. Assuming that the Keplerian disks have diameters of 1000 AU, then the derived enclosed masses vary from 1 to 75 $M_\odot$.

In the present paper, we argue that other models such as outflows could explain some linear structures as well as more complex morphologies described in paper 1. Indeed in sources like NGC7538, we could be observing a disk with an associated outflow (see Minier et al. 1998). Preliminary results on proper motions are presented in order to discriminate between the possible models.

## 2. Tracing outflows

The relatively narrow ranges of size and velocity, found in paper 1 for 10 sources, suggest a common mechanism. However, the disk model as argued by Norris et al. (1998) is in a few cases inconsistent with complementary infrared and radio observations. Indeed, elongated morphologies and linear velocity gradients are also expected in the case of masers tracing bipolar outflows (Shu et al. 1991; Te Lintel Hekkert et al. 1992). Although there is no theoretical support for Class II methanol masers forming in such environment, the observed linear morphologies could trace collimated outflows originating from a protostar. The methanol could be injected into the molecular gas via evaporation of the icy mantles of dust grains driven by weak shocks (Hartquist et al. 1995). The masers could still form after FIR radiative pumping within the shocked regions created by the interaction of the outflows with a dense $H_2$ environment ($n_{\rm H} = 10^7$ cm$^{-3}$).

For instance, the methanol masers in W75N are coincident with the radio continuum emission VLA1 that is believed to power an ionised stellar wind outflow (Torrelles et al. 1997). The elongated morphology of the continuum emission with a position angle of $43^o$ follows the linear morphologies of the OH and $H_2O$ masers (Torrelles et al. 1997). The methanol masers coincide in space and in velocity with the north part of the OH maser line. The linear structure (Group A in Fig.5 in paper 1) has a position angle of $42^o$. There is also a clear linear velocity gradient along group A. Such a velocity gradient is expected in a well collimated outflow created by a high velocity stellar wind blowing into the surrounding material at rest (Shu et al. 1991).

Moreover, the outflow model could also explain the more randomly distributed maser components. It is for example striking that many groups of maser components in NGC7538 coincide in space with the resolved clumps in the uniformly weighting map of the 22 GHz radio continuum emission (see Gaume et al. 1995 and Figure 1) although the main features do appear to delineate a disk (paper 1). Assuming that the radio continuum emission is produced by a bipolar outflow, the masers mark the position of dense and compact clumps within the outflow.

To summarise, the outflow model is an alternative way of explaining the methanol maser distribution in the VLBI maps. Unlike the disk model (Norris et al. 1998), the outflow scenario unifies in a reasonable model both lines of masers with a linear velocity gradient and more complex distributions of masers.

## 3. Proper motion of 12.2 GHz methanol masers

G9.62+0.19 hosts the most powerful 6.7 GHz methanol maser (~5000 Jy). The 12.2 GHz methanol masers are also bright and exhibit a spectrum very similar to the 6.7 GHz maser spectrum. They delineate in the VLBA map two lines of masers separated by ~600 AU (see paper 1). This distance is equal to the diameter of the hyper compact HII region that coincides with the masers (component E in Hofner et al. 1996). In Figure 2, the proper motions of the groups of masers forming the two lines are presented. The arrow length is proportional to the amplitude in mas of the proper motion. The proper motions are measured with respect to the centroid of all the groups of masers observed in both of May 1995 and November 1998 epochs. Note that the methanol maser components are indeed continuously distributed within the cluster they trace. The position of a maser component is the averaged position of velocity channel emissions over ~0.2 km s$^{-1}$ or within 1 mas$^2$. The proper motions are roughly perpendicular to the lines and in opposite directions. They suggest that the two lines of masers are tracing *expanding shock fronts* or *wide-angle outflows* rather than two disks.

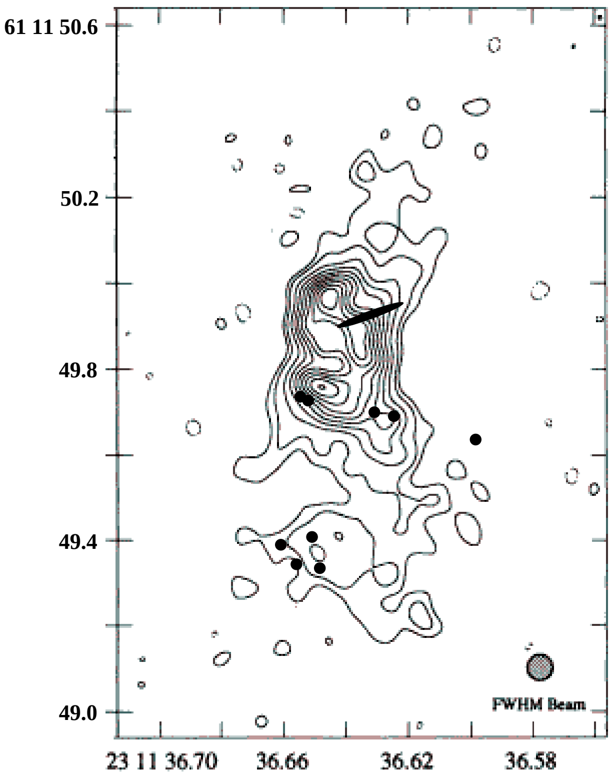


FIGURE 1. NGC7538-IRS1: Contour map of the uniformly weighted images of the 1.3 cm radio continuum taken from Gaume et al. (1995). The black symbols (circle and ellipse) mark the position of the 6.7 GHz methanol masers taken from Minier et al. 2000

The expansion velocity of a maser component is $v_{exp} = \frac{\lambda}{t \times cos\phi}$ where $\lambda$ is the measured value of the proper motion, $t$ is the time elapsed between May 1995 and November 1998, and $\phi$ is the angle between the direction of the proper motion and the plane of the sky. The mean value of $v_{exp}$ with $\phi$=0$^o$ is 4 km s$^{-1}$. Assuming that the centroid of the maser groups is the centre of the hyper compact HII region, the age of the hyper compact HII region expanding at a constant speed of $v_{exp}$ is ~300 AU/$v_{exp}$ i.e ~400 years which is very young and unlikely. Assuming that the proper motions trace a bipolar outflow instead of ionising fronts, the mean velocity of the outflows ($4/cos\phi$ km s$^{-1}$) is consistent with the velocity of CO outflows within similar star-forming regions. However, further VLBA observations are needed to confirm the proper motions.

## 4. Conclusions

Although the protostellar disk model proposed by Norris et al. (1993) is a likely explanation of the lines of methanol masers with a linear velocity gradient along them, it is inconsistent with more complex methanol maser distributions than a single elongated structure. We have presented some evidence that 6.7 and 12.2 GHz methanol masers trace outflows emerging from protostars. This scenario is based on interferometric observations of methanol maser sites and the comparison of their location with those of outflows taken from detailed studies available in recent publications. The methanol masers could

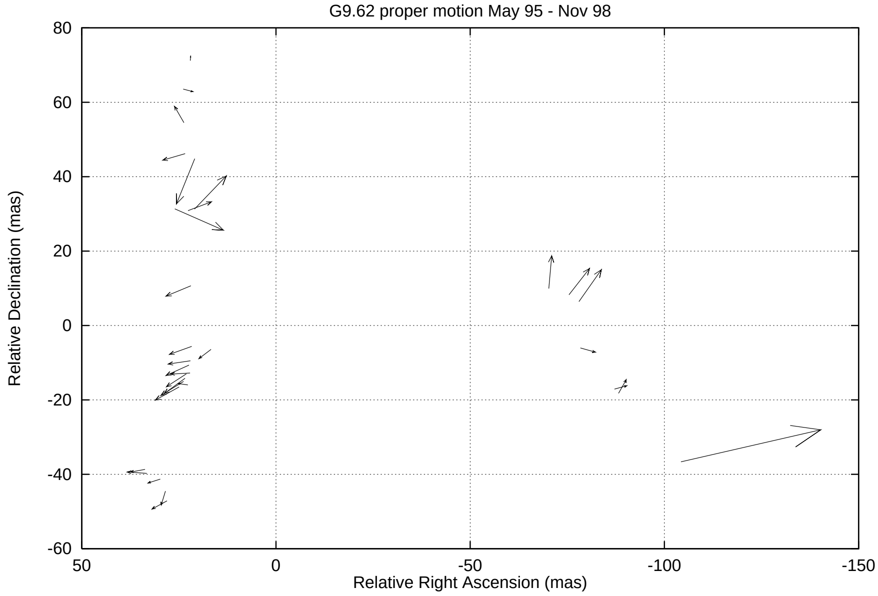


FIGURE 2. Proper motion of the 12.2 GHz methanol masers in G9.62+0.20. The size of the arrow is 10 times proportional to the amplitude in mas of the proper motion.

trace either well collimated outflows (e.g W75N) or more randomly distributed clumps formed by ionised stellar outflows interacting with the ambient material (e.g NGC7538). Additionally, preliminary proper motion studies of G9.62+0.20 show that the maser components do not move along the lines as expected in a disk. On the contrary they move in a direction perpendicular to the lines they delineate. A likely interpretation is that the methanol masers trace weakly shocked regions resulting from the interaction of a bipolar outflow with the surrounding environment.

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