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CH_3OH and H_2O maser associations at very high angular resolution

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Abstract. 6.7 and 12.2 GHz CH_3OH (methanol) and 22.2 GHz H_2O masers are believed to be good tracers of the earliest phases of high-mass star formation. Interferometric and VLBI (Very Long Baseline Interferometry) observations have shown that water masers are predominantly associated with the innermost portions of the jets/outflows emerging from (proto-)stellar objects. On the other hand, the astrophysical environment traced by the 6.7 GHz (and the associated 12.2 GHz) CH_3OH masers is still to be more precisely determined. So far, most high-resolution studies have focused either on CH_3OH or on H_2O masers and little is known on their connection, wehereas it would be important to study both types of maser emission in the same object. The goal of our long-term project is to perform interferometric and VLBI observations of H_2O and CH_3OH masers towards a selected sample of high-mass YSOs where **both** maser types have been detected. This work presents preliminary results obtained for a few objects of our sample, and discusses possible implications.

Keywords. masers, techniques: interferometric, ISM: jets and outflows

1. Introduction

Survey of both 6.7 GHz CH_3OH and 22.2 GHz H_2O masers in massive star forming regions (Walsh *et al.* 1998; Beuther *et al.* 2002; De Buizer 2003) evidence that both maser species trace the earliest evolutionary stages of the high-mass star forming process. Emission of these two maser transitions is found to be commonly associated to massive, dusty mm cores, and, in most cases, with mid-infrared sources; conversely, only a minor fraction of the maser features are seen to correspond in positions with cm continuum emission, indicating that the 6.7 GHz and 22.2 GHz masers are preferably tracing a pre-UC HII phase. However, the quoted surveys, conducted with an angular resolution in the maser and continuum emissions $\geqslant 1''$, present us with a complex picture, where each of the two maser types are likely to trace different Young Stellar Object (YSO) environments and/or evolutionary phases.

On the other hand, VLBI observations evidence that, towards many YSOs, methanol and water masers are likely to trace well-defined kinematic structures (Torrelles *et al.* 2003; Moscadelli *et al.* 2005; Minier *et al.* 2000). To investigate the nature of the maser birthplaces and to test the utility of the maser observations as indicators of the evolutionary phase of massive YSOs, since a few years we have started a project aiming to first look for *true* associations of 6.7 GHz and 22.2 GHz masers (i.e., the cases when *both* masers are excited by the same YSO), and, then, derive the kinematics of both maser types using VLBI. This work presents recent (and still preliminary) results obtained for two among the best studied massive YSOs, IRAS 20126+4104 and G24.78+0.08, in each of which sources both 6.7 GHz and 22.2 GHz masers are observed.

2. Observational Results

2.1. *IRAS 20126+4104*

IRAS 20126+4104 is a luminous ($\sim 10^4$ $L_\odot$) YSO located at a relatively small distance (1.7 kpc). To date, it is one of the best example of a high-mass protostar associated with a Keplerian disk and bipolar outflow/jet. SiO and H_2 images (at angular scales of $\sim 10^4$ AU) of a bipolar jet (powering a larger scale molecular outflow) has been obtained by Cesaroni *et al.* (1997); Cesaroni *et al.* (1999). Such jet has been traced down to scales as small as a few 100 AU by means of VLA observations of the 3.6 cm continuum emission (Hofner *et al.* 1999) and (single-epoch) VLBA observations of the H_2O maser spots (Moscadelli *et al.* 2000). Recently, PdBI (Plateau de Bure) 3.2 mm and 1.3 mm observations in the $C^{34}S$ and CH^3OH lines and in the continuum emission (Cesaroni *et al.* 2005), indicate the existence of a Keplerian circumstellar disk approximately perpendicular to the jet, and let one infer a mass for the central object of ~ 7 $M_\odot$.

In order to investigate the geometry and the kinematics of the water maser jet, we have observed the 22.2 GHz emission in IRAS 20126+4104 at three different epochs using the Global (EVN + VLBA) array (Moscadelli *et al.* 2005). Figure 1a shows all the H_2O maser features detected in the region both with the Global VLBI experiment, and with previous VLBA (Moscadelli *et al.* 2000) and MERLIN (Edris *et al.* 2005) observations. Also shown are the OH maser emission peaks, which according to Edris *et al.* (2005) mark the plane of the circumstellar disk. The maser features are overlaid on top of the contour map of the 3.6 cm continuum emission imaged by Hofner *et al.* (1999), corresponding to the inner ionised part of the jet/outflow.

All of these tracers agree very well with the model proposed by Moscadelli *et al.* (2000), according to which the H_2O masers are located at the interface between a conical jet and the surrounding quiescent material, and are flowing along the surface of a such a jet with velocities directed outward from the central YSO. As expected, the vertex of the cone – i.e. the putative position of the YSO powering the jet – falls very close to the peak of the 3.6 cm continuum emission and in between the two OH maser peaks denoting the disk. The conical jet model is fully confirmed by the proper motions of the H_2O maser features, shown in Figure 1b. All the detected H_2O features move with high velocities ($50 - 100$ km s^{-1}), and, although forming a small angle with the jet axis, have directions of motion diverging from the YSO position.

Recently, we performed a single-baseline VLBI observation using the antennae of Medicina and Noto to determine the accurate position of the 6.7 GHz CH_3OH masers in IRAS 20126+4104. Within an accuracy of ~ 50 mas, we found them to originate close to the blue-shifted OH maser peak (see Figure 1b). That may indicate that also the 6.7 GHz masers, as it has been already suggested for the OH masers, might originate from dense and relatively warm gas rotating around the massive YSO in a toroid/disk structure. If this is the case, full-array VLBI observations of the 6.7 GHz (or the associated 12 GHz) CH_3OH masers might achieve enough angular resolution and sensitivity to investigate the velocity field of the accretion disk predicted in IRAS 20126+4104.

2.2. *G24.78+0.08*

G24.78+0.08 is a cluster of massive (proto)stars in different evolutionary stages. The most evolved of these YSOs (G24 A) shows a compact VLA emission at 1.3 cm (Codella *et al.* 1997), on top of which several species of molecular masers have been detected: H_2O 22.2 GHz and OH 1.6 GHz masers observed with VLA by Forster & Caswell (1989); CH_3OH 6.7 GHz masers, observed with the ATCA (Australian Compact Array) by Walsh *et al.* (1998). With an angular resolution of a few tenths of arcsecond provided by these

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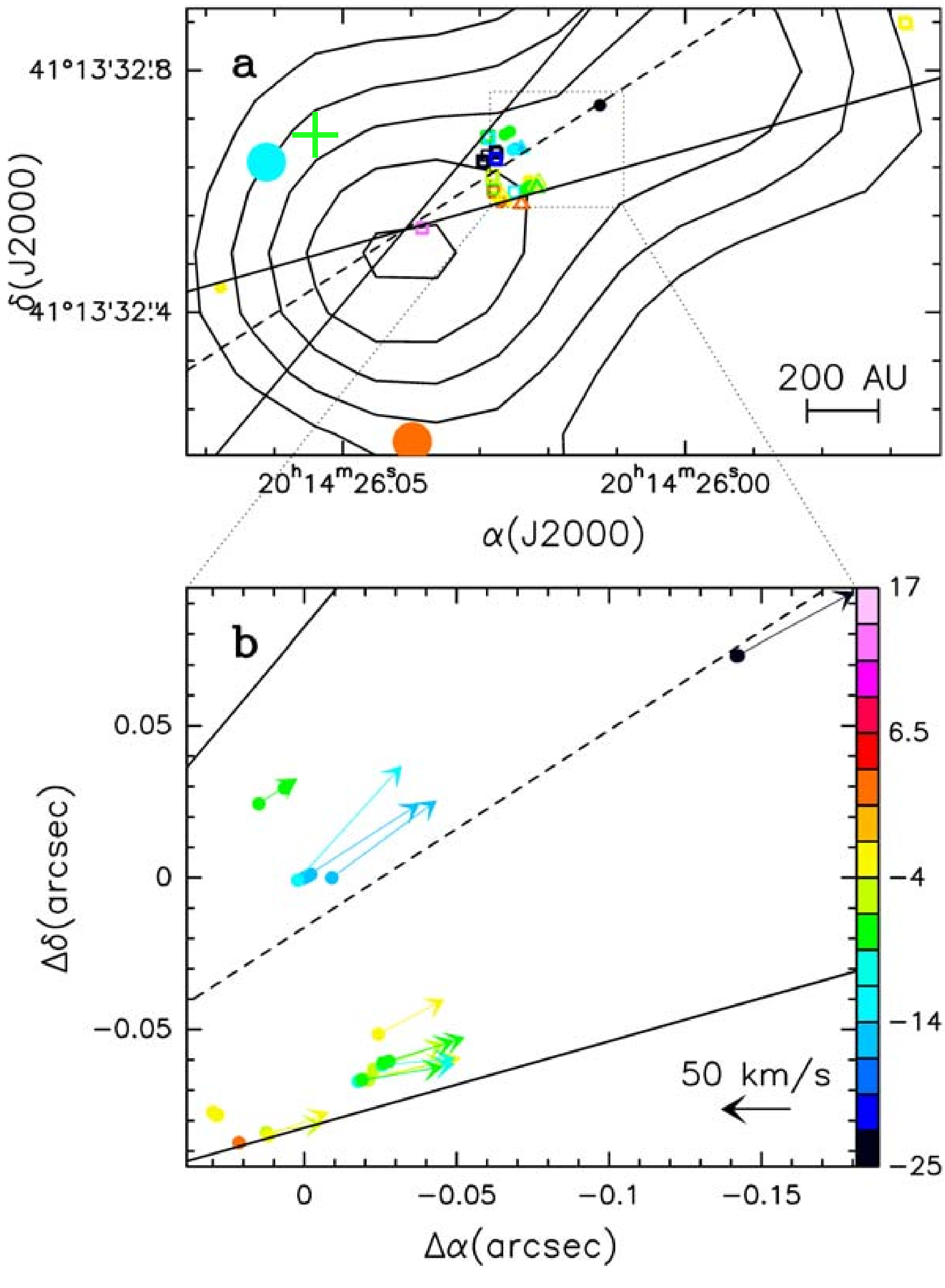

Figure 1. a) Map of the H_2O maser features detected towards IRAS 20126+4104 by Moscadelli *et al.* (2005) (small circles), by Moscadelli *et al.* (2000) (squares), and by Edris *et al.* (2005) (triangles), overlayed on a contour map of the 3.6 cm continuum emission (Hofner *et al.* 1999). Also shown are the OH maser emission peaks observed by Edris *et al.* (2005) (big circles). The grey tone denotes the LSR velocity of each feature according to the grey scale in the bottom panel. The solid lines indicate the conical jet that best fits the positions and 3-dimensional velocities of the water masers. **b)** Enlargment of the central region illustrating the locations and absolute proper motions (corrected for parallax, solar motion with respect to the LSR, and galactic rotation) of the H_2O maser features observed by Moscadelli *et al.* (2005). Offsets in R.A. and DEC are measured with respect to: RA(J2000)=20^h 14^m $26^s.0253$, Dec(J2000)=41^o $13^{'}$ $32^{''}.666$.

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interferometers, the maser spots of the three maser species ehxibit an elongated spatial distribution, approximately parallel with the axis of the ^{12}CO $(1 \rightarrow 0)$ molecular outflow observed towards G24 A using the PdBI by Furuya *et al.* (2002).

Recently, 1.4 mm PdBI 1-arcsecond angular resolution observations by Beltrán *et al.* (2004) have resolved the structure of the G24 A core. Figure 2a shows that the 1.4 mm continuum emission consists of two distinct subcores (labeled A1, the one towards southeast, and A2, towards northwest). In both subcores, the V_{LSR} gradient mapped in the CH_3CN line has a northeast-southwest direction, approximately perpendicular to the axis of the ^{12}CO molecular outflow. This fact suggests that the velocity gradient can be due to rotation of the gas in the subcores around the outflow axis. Figure 2a shows also the absolute positions (accurate within ∼50 mas) of the CH_3OH 6.7 GHz maser features as derived by recent EVN observations. It is clear that the 6.7 GHz maser emission stems from two distinct group of features, each one associated to either of the mm subcores. Both groups of maser features are elongated along a direction that agrees well with the axis of the velocity gradient measured in the CH_3CN 1.4 mm line.

Figures 2b and 2c show the line-of-sight velocities of the 6.7 GHz maser features, associated respectively to the A2 and A1 subcores. Across each maser group, the variation of V_{LSR} agrees with the velocity gradient observed in the harbouring subcore, with the red-shifted velocities to the northeast and the blue-shifted ones to the southwest. On the smaller angular scales traced by the masers, the V_{LSR} variation is significantly higher than the value measured with the thermal line (at much lower angular resolution) across the subcore diameter, which might be interpreted as a "speed-up" effect characteristic of "Keplerian" rotation.

Associated to the subcore A1, located southeastward of the EVN 6.7 GHz maser cluster, a group of 22.2 GHz water maser features was observed using the VLA by Forster & Caswell (1989). In order to measure absolute positions and proper motions of the water features, recently we have observed the 22.2 GHz masers using the VLBA in phase-reference mode, at four different epochs. Figure 3 present the spatial and line-of-sight velocity distribution of the 22.2 GHz masers as deduced from the analysis of the first of the VLBA epochs. Most of maser features appear to trace two distinct geometrical structures: 1) a circle (radius of ∼150 AU); 2) a linear structure (size of ∼2400 AU). The V_{LSR} range spanned by the water masers is slightly more extended than that of the 6.7 GHz methanol masers.

The circular structure detected by us in the water masers has size and V_{LSR} dispersion (∼6 km s^{-1}) quite similar to the shell of 22.2 GHz maser emission observed by Torrelles *et al.* (2003) in W75N. Measuring proper motions will allow us to determine the kinematics of the maser features and clarify whether the maser circle is expanding, as it is found for the source of Torrelles *et al.* (2003). Assuming that the detected maser circle were a wide-angle wind emitted by the YSO, its geometrical centre would pinpoint the YSO location. Measuring proper motions will allow us also to investigate the relationship between the circular and linear structure of maser features. Should the maser features of the circular and linear structure trace, respectively, an expanding and a collimated motion, we might have the chance of directly studying the connection between wide-angle and collimated outflows.

Reducing data of the first epoch, we could not detect the weak phase-reference calibrator and estabilish the absolute position of the 22.2 GHz masers. Hopefully, the weather condition of the following epochs (to be still analyzed) were better and we will be able to determine absolute positions. Comparing the 22.2 GHz water and 6.7 GHz methanol maser positions and velocities in this source promises to be particularly instructive for learning about the gas kinematics around a massive YSO.

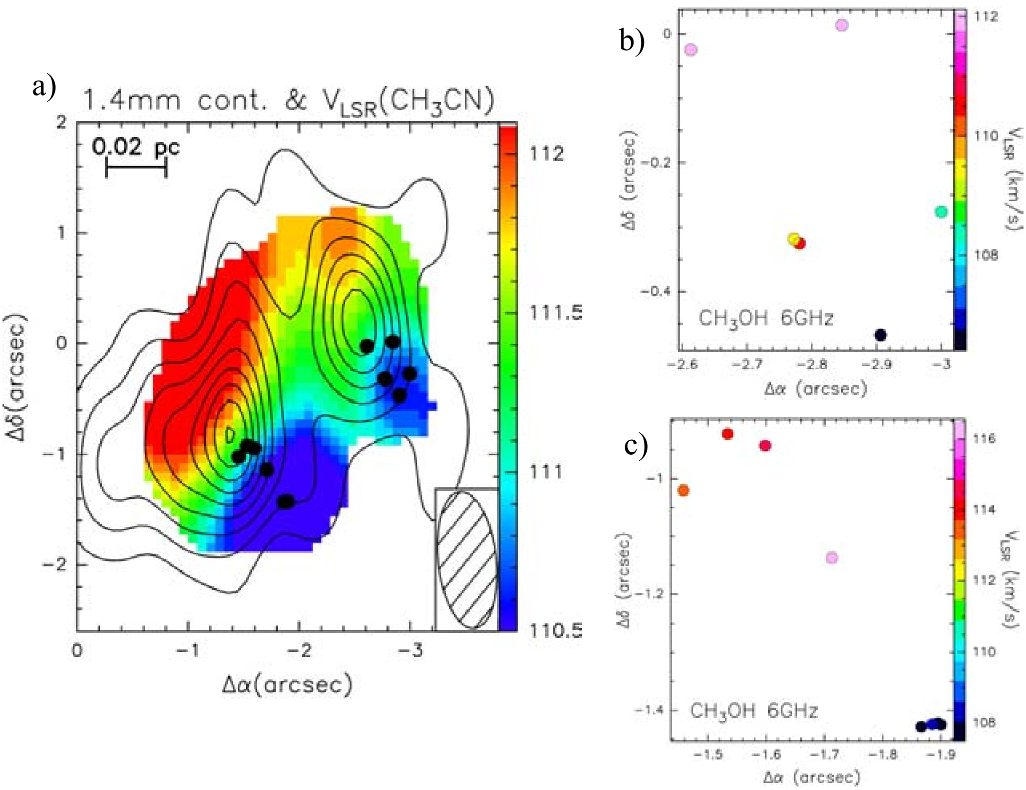

Figure 2. a) In grey scale is the map of the CH_3CN (12 → 11) line peak velocity towards G24 A obtained with a Gaussian fit (Beltrán *et al.* 2004). The contour levels in kilometers per seconds are indicated in the wedge to the right of the panel. Overlaid on the CH_3CN velocity map, it is shown the contour map of the 1.4 mm continuum emission. The black spheres indicate the positions of the CH_3OH 6.7 GHz masers, recently determined using the EVN. The position offsets are relative to: R.A.(J2000)=18^h 36^m $12^s.66$, Dec(J2000)= -07^o $12'$ $10''.15$. **b)** Positions and line-of-sight velocities of the 6.7 GHz maser features observed towards the subcore A2 (the one to the northwest). The grey tone denotes the LSR velocity of each feature according to the grey scale shown on the right-hand border of the panel. The position offsets are relative to: R.A.(J2000)=18^h 36^m $12^s.563$, Dec(J2000)= -07^o $12'$ $11''.170$. **c)** Positions and line-of-sight velocities of the 6.7 GHz maser features observed towards the subcore A1 (the one to the southeast). Colours have the same meaning and offsets are relative to the same position as described for panel b).

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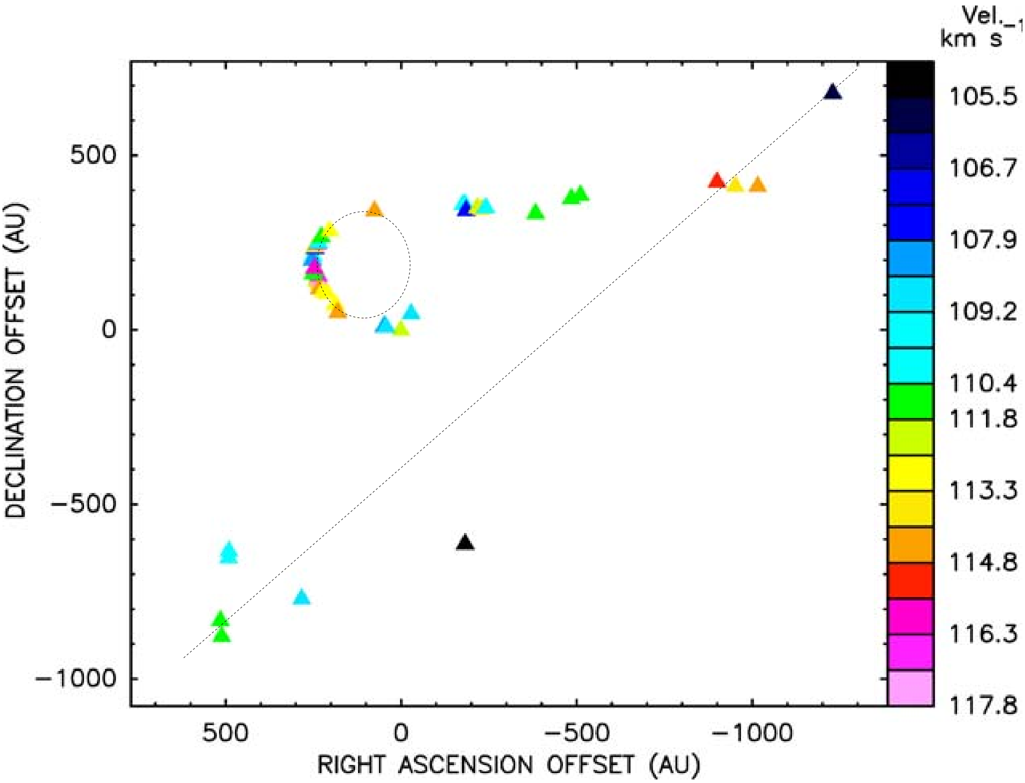

Figure 3. Positions and line-of-sight velocities of the 22.2 GHz masers associated to the G24 A core, as deduced from the analysis of the first epoch of our VLBA observations. The positional offsets are relative to the reference maser feature and are given in AU. The grey tone denotes the LSR velocity of each feature according to the grey scale shown on the right-hand border of the panel. The dashed circle and the dashed line evidence the main geometrical structures traced by the maser features.

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