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VLBI observations of H_2O masers towards high-mass Young Stellar Objects

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Abstract.
We have conducted multi-epoch VLBI observations of the 22.2 GHz water masers towards three massive star forming regions (Sh 2-255 IR, WB89-234, AFGL 5142). For the maser fetures persistent in time, accurate values of the proper motions are derived. The comparison of the VLBI 22.2 GHz maps with the highest-resolution images of the sources Sh 2-255 IR and WB89-234 in several thermal tracers, may suggest that the water masers are most likely tracing the inner portion of the molecular outflows detected at much larger-scales. This interpretation is also confirmed by the results obtained by fitting to the data two different kinematical models, a Keplerian disk and a conical outflow.
Towards AFGL 5142 the water maser features are distributed in two different structures, whose axes are nearly perpendicular to each other. A possible interpretation is that the maser emission is tracing the disk/jet system nearby the forming YSO.

1. Introduction

The star formation process is better understood for low-mass stars ($\sim$1 $M_\odot$) than for high-mass stars ($\geq$ 10 $M_\odot$). Massive stars are rare, form on much shorter timescales ($\sim 10^5$ yr) and are found at larger distances (typically several kiloparsecs) than their low-mass counterparts. They also spend all of their pre-main-sequence phase deeply embedded in their natal molecular cloud.

High-angular resolution observations of the 22.2 GHz water masers, commonly observed toward regions of high-mass star formation, have shown that they may originate at distances $\leq$100 AU from the Young Stellar Object (YSO). Multiepoch VLBI observations, reaching spatial resolutions of $\sim$1 AU, allow to determine accurate proper motions of the 22.2 GHz masers, which, combined with the line-of-sight velocities derived via the Doppler effect, permit to obtain the 3-dimensional velocity distribution of the masing gas.

So far, only a relatively small number ($\sim$10) of intermediate and/or high-mass YSOs have been studied with this technique, suggesting that the water masers are preferably associated to collimated flows of gas (jets) found at the base of larger-scale molecular outflows (IRAS 20126+4104 Moscadelli et al. 2000; W3-IRS5, Imai et al. 2000; W75N-VLA1, Torrelles et al. 2003), and, in a few cases, linear clusters (size $\sim$10-100 AU) of masers have been interpreted in terms of accretion disks (e .g., NGC 2071, Seth et al. 2002; AFGL 5142, Goddi et al. 2004). Torrelles et al. (2001, 2003) have recently observed two cases where water masers are distributed along circular expanding arcs (radius 62 AU for Cepheus A, 160 AU for W75N), interpreted as being due to a spherical ejection of material from a YSO located at the circle center: these works demonstrate that clusters of water masers close (within hundreds of AU) to the YSO may partecipate to expanding motions, likely driven by wide angle winds.

Multiepoch VLBI observations of H_2O masers towards a larger number of massive YSOs are needed to establish which of the two interpretations, (wide-angle or collimated) winds and rotating disks, may explain the kinematics traced by water masers in the close proximity of a massive YSO.

2. Observational results

Three candidate as high-mass YSOs (Sh 2-255 IR, WB89-234, AFGL 5142) were observed in the $6_{16} - 5_{23}$ H_2O maser line using the European VLBI Network (EVN) at three epochs (June, September and November 1997). Details on the observations and the data reduction are reported in Goddi et al. (2004). Follow-up, more sensitive observations were conducted towards AFGL 5142 with the Very Long Baseline Array (VLBA) at four epochs (from October 2003 to February 2004). The VLBA observations were performed in phase-reference mode, allowing to derive absolute position of the maser emission.

The high-mass star forming complex Sh 2-255 IR (at a distance of 2.5 kpc) was imaged by Miralles et al. (1997) at NIR and mm wavelengths, revealing a cluster of 50 NIR sources associated with IR H_2 jets and molecular outflows. The reddest NIR source (NIR 3) was found to coincide in position with the VLA 15 GHz continuum source Sh 2-255-2c (Rengarajan et al., 1996). The upper panel of Figure 1 shows the Brγ hydrogen recombination line map of Howard et al. (1997), which shows an ionized jet (seen also in the H_2 2.12 μm line) emerging from the position of Sh 2-255-2c. The radio to infrared emission properties of Sh 2-255-2c/NIR 3 suggest the presence of a high-mass YSO of ZAMS spectral type B1. 22.2 GHz water maser VLA observations (unpublished data kindly provided by R. Cesaroni) at two epochs (March 1990; August 1991) reveal three emission centers over a region of a few arcsecs (see middle panel of Figure 1), with the strongest maser feature ($\approx$30 Jy) found to coincide with Sh 2-255-2c. The lower panel

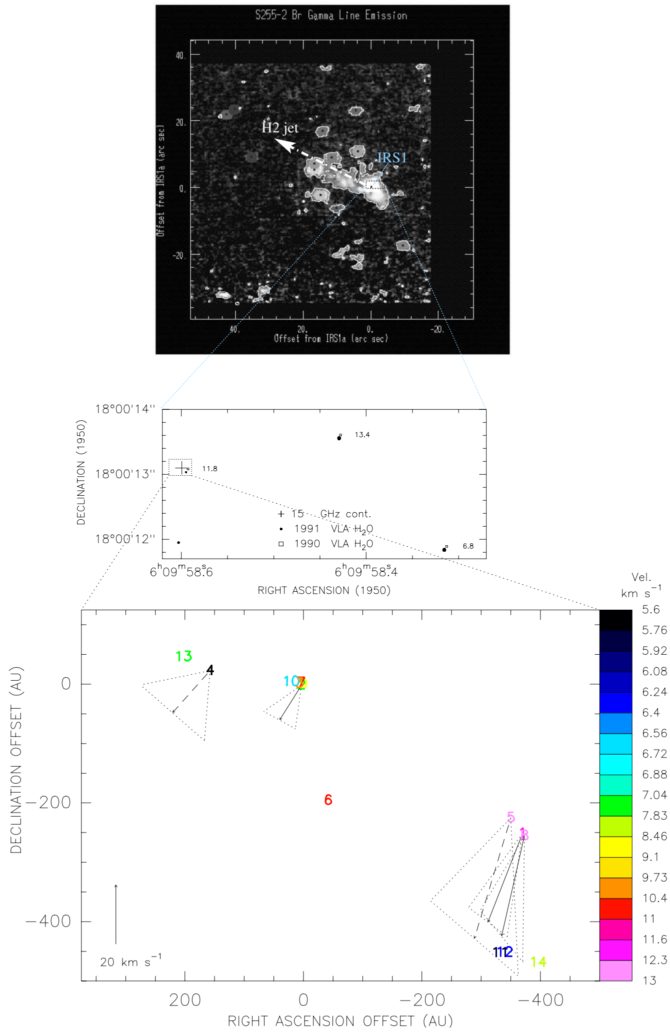

Fig. 1. Sh 2-255. (*Upper panel*) Brγ line minus continuum emission; the dashed arrow indicates the H_2 jet orientation. (*Middle panel*) Positions and LSR velocities of the 22 GHz maser features detected with the VLA in 1990 (*open squares*) and 1991 (*filled dots*); the cross indicates the VLA 15 GHz continuum source. (*Bottom panel*) VLBI 22 GHz water maser features, with different colours used to distinguish the line of sight velocities; the arrows indicate the measured proper motions, with dashed lines used in case of features detected at only two epochs; the dotted triangles drawn around the arrows represent the orientation uncertainty of the proper motions.

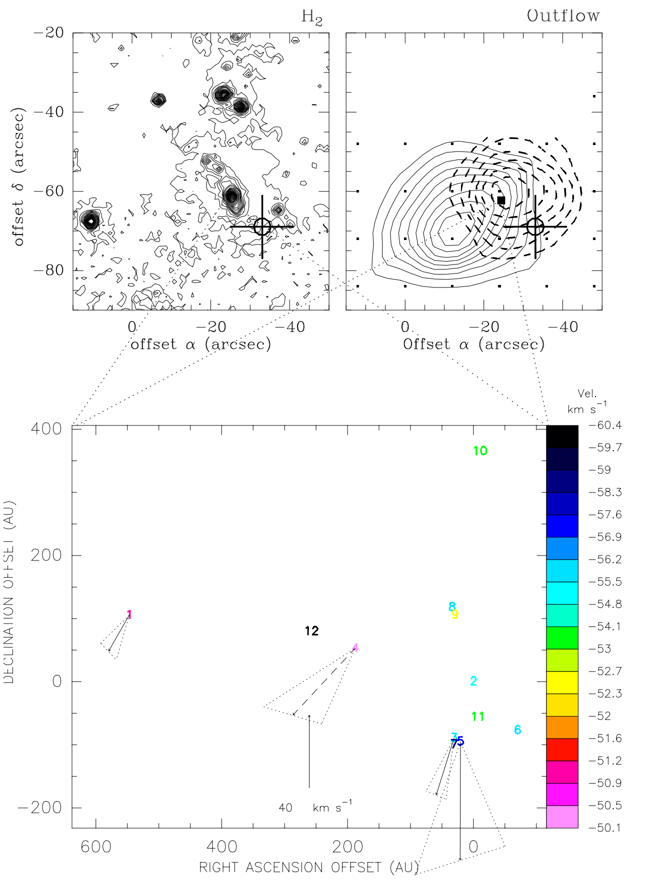

Fig. 2. WB89-234. (*Upper panels*) TIRGO H_2 2.12 μm image (*left*); blue (*dashed lines*) and red (*solid lines*) lobes of ^{12}CO(1–0) wing emission (*right*); the big cross and the filled square indicate respectively the Effelsberg and VLA positional uncertainties of the H_2O maser. (*Bottom panel*) VLBI 22 GHz water maser features (see the caption of Fig. 1).

of Figure 1 reports the positions and velocities of the 22.2 GHz maser features as derived by our multiepoch EVN observations.

Maser features show an elongated spatial distribution of size ≈700 AU whose major axis is oriented appressimately parallel with the axis of the (Brγ and H_2 2.12 μm) ionized jet observed at arcsec-scale. All the measured *relative* proper motions, approximately perpendicular to the jet axis, suggest that water masers can trace an expansion motion, characterized by (relative) transversal velocities (in the range 10 – 40 km s^{-1}) large compared to the spread of radial velocities (≈7 km s^{-1}).

WB89-234 (at a distance of 5.8 kpc) was first found by Wouterloot et al. (1989) in a survey of CO emission towards IRAS sources in star forming regions, and subsequently studied in detail by Brand et al. (1998). The upper panels of Figure 2 show that the H_2O maser (whose absolute position is derived from VLA observations; Brand & Wouterloot, unpublished) is found at the center of a CO bipolar outflow and coincides with a NIR source (imaged in J, H, K bands, and in the H_2 2.12 μm line), which probably identifies the embedded exciting YSO. The 22.2 GHz maser features detected in our EVN map (lower panel of Figure 2) are distributed across an area of diameter ≈900 AU, and there is no preferential direction of elongation for the maser spatial distribution. All the measured *relative* proper motions have similar northwest-southeast orientation (close to the direction of the molecular outflow), with amplitudes (in the range 20 – 60 km s^{-1}) large compared with the spread of line of sight velocities (≈10 km s^{-1}).

Previous observations towards the star forming region (SFR) AFGL 5142 strongly suggest the presence of a high-mass YSO (at $\alpha(1950) = 05^h27^m30^s$; $\delta(1950) = +33°45'40''$), whose position is indicated by compact, thermal continuum sources (observed with the VLA at 8.4 GHz and with OVRO at 88 GHz). The compact radio sources are located at the origin of a H_2 and SiO jet and at the center of a CO and HCO^+ outflow (Hunter et al., 1995, 1999) (Fig. 3, upper right panels). VLA NH_3-observations by Zhang et al. (2002) show a compact structure (diameter ~1800 AU), coincident in position with the 8.4 and 88 GHz continuum sources, interpreted as an unresolved rotating disk. The 22.2 GHz water masers in AFGL 5142 have been observed with the VLA at two epochs (1992, Hunter et al. 1995; 1998, Hunter et al. 1999), and found to be distributed within a few arcseconds from the continuum sources (Fig. 3, left upper panel). The lower panel of Fig. 3 shows the posi-

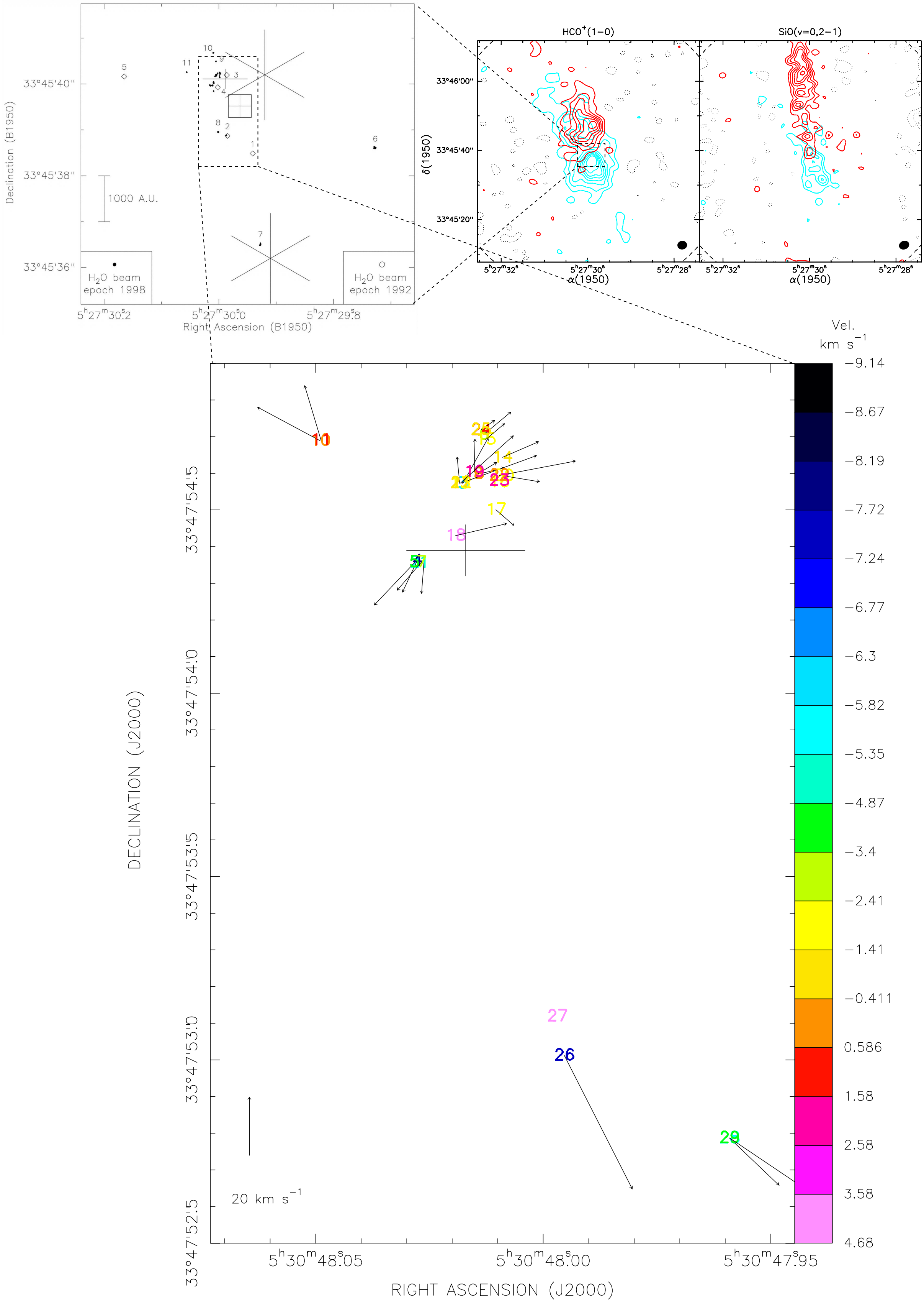

Fig. 3. AFGL 5142. (*Upper right panels*) Contour maps of the OVRO high-velocity molecular line emission for HCO^+ ($1 \rightarrow 0$) (*left*) and SiO (v = 0, $2 \rightarrow 1$) (*right*) (Hunter et al., 1999). (*Upper left panel*) Positions of the 22 GHz masers detected with the VLA in 1992 (*open squares*) and 1998 (*filled dots*); the boxed and the plain crosses indicate the OVRO 88 GHz and the VLA 8.4 GHz continuum sources, respectively (Hunter et al., 1995, 1999). (*Bottom panel*) VLBA 22.2 GHz water maser features; the derived maser positions and proper motions are absolute; the position of the 8.4 GHz continuum source (indicated by the cross) individuates the expected location of the YSO.

tions and the velocities of the H_2O maser features as derived by our multi-epoch VLBA observations. We have derived *absolute* maser positions and proper motions, these latter being corrected also for the systematic effects of the earth, sun and galactic motion. On the basis of their spatial and velocity distribution, the VLBI maser features can be divided into two groups. Group I is found to be distributed (within ~300 mas) around the position of 8.4 GHz and 88 GHz continuum emissions (corresponding to the expected location of the YSO). Group II is distributed nearly perpendicular to group I, both northward and southward from the continuum emissions.

3. Discussion

Towards each observed YSO, the presence of an arcsec-scale molecular outflow has been established by means of different thermal tracers.

Sh 2-255 IR shows an elongated distribution of maser features, aligned along a direction close to the orientation of the molecular outflow. If maser features were tracing the inner portion of the jet, one would expect their tangential velocites to be directed mainly along the jet axis. However, all the measured *relative* proper motions are approximately perpendicular to the jet axis: a simple model of collimated flow does not appear to adequately describe the kinematics of the masing gas.

The spatial distribution of maser features detected towards WB89-234 do not show any preferential direction. However, all the measured proper motions have similar orientation, close to the direction of the molecular outflow, which might suggest that the maser motion is driven by the outflowing gas.

In order to perform a more quantitative analysis, we have fitted to the data 3-dimensional kinematic models. Following the current theory of star formation, two main kinematic structures should be found in the proximity of a forming star: an accretion disk and a jet/outflow system (driven by either wide-angle or collimated winds). We have tested the expansion vs rotation scenario by fitting the measured positions and velocities of the detected maser features with two kinematic models: 1) a Keplerian disk; 2) a conical outflow. The model fits indicate that the masers detected towards Sh 2-255 IR and WB89-234 might arise on the surface of a conical jet. The best fit solution is found in both cases for conical jets having large semi-aperture angles, supporting the occurence of large-angle winds.

Towards AFGL 5142 two distributions of masers, nearly perpendicular to each other, have been identified. Three possible interpretations are considered: 1) all the detected masers partecipate to a common expanding motion, as they were driven by an isotropic wind; 2) Group I and Group II of masers are associated with two distinct outflows, originating possibly from two individual YSOs; 3) the two groups are tracing a disk/jet system.

The first two hypotheses might be supported by the fact that, basing on the measured *absolute* proper motions, the two groups of masers seem to be flowing away from the expected position of the YSO. However, one might expect an isotropic wind to originate an expanding spherical shell and that appears inconsistent with the observed maser distribution, not showing any evidence of spherical structures. The presence of multiple outflows seems more realistic, since in other well studied high-mass protostars evidence has been found of a complex pattern for the gas outflowing form the central object(s) (e.g., Beuther et al. 2003), indicating the presence of binary/multiple star system. In the present case, higher sensitivity and resolution observations (from radio to near-infrared frequencies) are needed to test this interpretation.

We have further fitted a kinematic model where the Group I maser features emerge from the surface of a Keplerian disk. The best fit solution is found with the disk seen nearly edge-on and oriented on the sky parallel to the elongation axis of the Group I masers. The fitted value of the YSO mass ($M_{\rm YSO}$ = 14 $M_\odot$) is in agreement with the estimated bolometric luminosity of the SFR (4×10^3 $L_\odot$), indicating a central star of spectral type between B2 and B1, with an expected mass in the range 10–15 $M_\odot$. The range of disk radii traced by the maser emission (from ≈50 AU to ≈800 AU) is compatible with the disk sizes predicted by current models for an accreting disk around a high-mass protostar. This interpretation is also supported by the facts that the distribution of the Group II masers is elongated along a direction close to the axis of the large-scale (SiO and HCO^+) molecular outflow and that the measured proper motions clearly indicate that Group II masers are receding away from the YSO. Should this scenario be confirmed, AFGL 5142 would be one of the best examples of high-mass YSO, associated with a keplerian disk and a jet/outflow system.

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