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EVN observations of H_2O masers towards high-mass star forming regions

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Abstract. We have conducted Very Long Baseline Interferometry (VLBI) observations of the 22.2 GHz water masers towards three massive star forming regions. With three observing epochs, few distinct maser features were detected for each source. For features persistent in time, accurate values of the proper motions are derived. A preliminary analysis indicates that the kinematics traced by water masers is consistent with expanding motions, possibly driven by wide-angle winds.

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. High mass stars 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 maser features, 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 maser features have been interpreted in terms of accretion disks (e .g., NGC 2071, Seth et al. 2002; AFGL 5142, Goddi et al. 2004). Torrelles et

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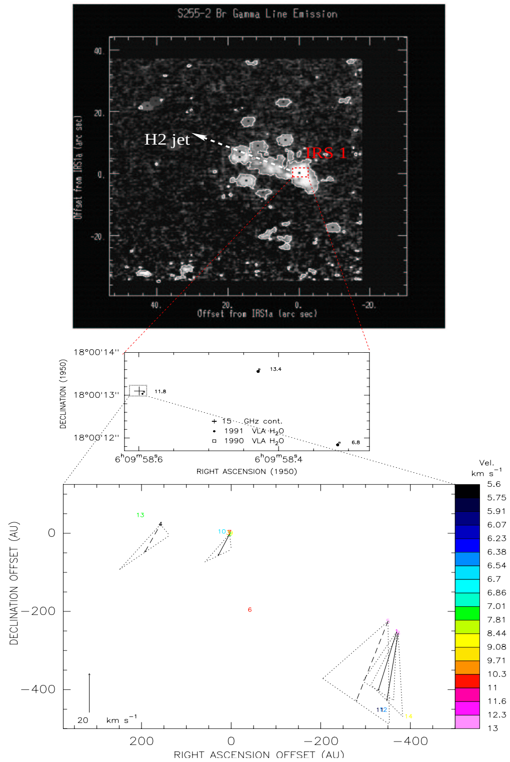

Fig. 1. Sh 2-255. (*Top*) Brγ line minus continuum emission; the arrow indicates the H_2 jet orientation. (*Middle*) Positions and LSR velocities of the 22 GHz maser features detected with the VLA in 1990 (open squares) and 1991 (filled dots); the cross indicates the VLA 15 GHz continuum source. (*Bottom*) 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 amplitude and orientation uncertainty of the proper motions.

al. (2001, 2003) have recently observed two cases where the water maser features 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 winds or 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, IRAS 23139+5939, WB89-234) 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 process are reported in Goddi et al. (2004).

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 near-infrared (NIR) and mm wavelengths, revealing a cluster of 50 NIR sources associated with Herbig-Haro (HH)- like objects, H_2 jets and molecular outflows. The reddest NIR source (NIR 3) was found to coincide in position with the Very Large Array (VLA) 15 GHz continuum source Sh 2-255-2c (Rengarajan et al. 1996). The upper panel of Figure 1 reports 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 Zero Age Main Sequence (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 spread over a region of a few arcsecs (see middle panel of Figure 1), with the strongest maser feature (≈30 Jy) found to coincide with Sh 2-255-2c. The lower panel 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 approssimately 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

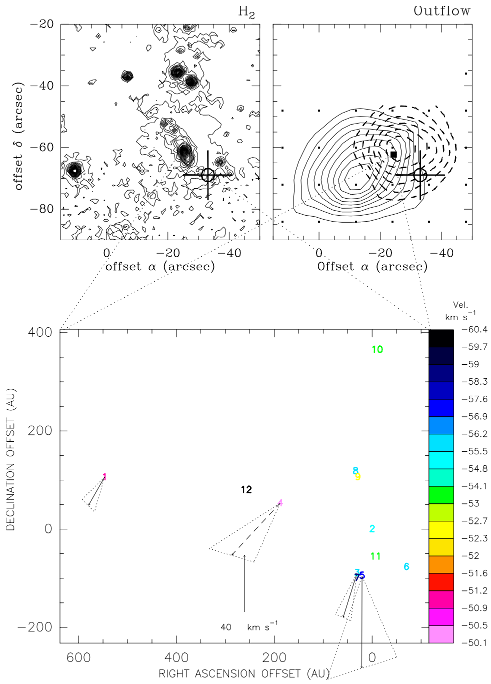

Fig. 2. WB89-234. (*Top left*) TIRGO H_2 2.12μm image of WB89-234. (*Top right*) PdB map of CO 2→1 emission (contours) overlapped with the PdB 1.2 mm continuum emission (gray scale); the big cross and the filled square indicate respectively the Effelsberg and VLA positional uncertainties of the H_2O maser. (*Bottom*) VLBI 22 GHz water maser features (see the caption of Fig. 1).

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 maps (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}).

IRAS 23139+5939 is included in the list of high-mass protostellar objects that Beuther et al. (2002) studied with angular resolution of ∼1 arcsec over an extended range of wavelengths (from cm to sub-mm) using both molecular line and continuum tracers. The upper right panel of Figure 3 shows the Plateau de Bure (PdB) map of CO 2→1 emission (*contours*) overlapped with the PdB 1.2 mm continuum emission (*gray scale*). The middle left panel of Figure 3 compares the position of a compact 3.6 cm continuum source with that of the 22.2 GHz masers, both emissions observed in 1992 with the VLA by Tofani et al. (1995). The lower panel of Figure 3 reports the positions and velocities of the EVN 22.2 GHz maser features. Most of the 22.2 GHz emission emerges from a roughly circular cluster of maser features whose diameter is ≈200 AU. The three tentative (based only on two epochs) proper motions are suggestive of a general expansion with (relative) velocities of tens of km s^{-1}.

3. Conclusion

Towards each observed YSO, the presence of a 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 IRAS 23139+5939 and WB89-234 do not show any preferential direction. In the first case, however, the CO outflow is nearly oriented along the line-of-sight

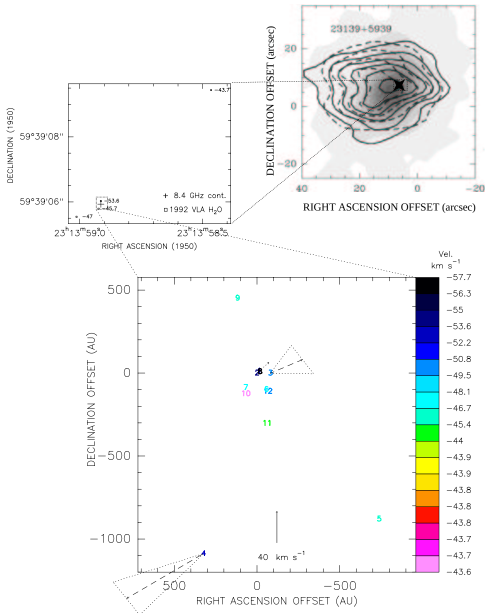

Fig. 3. IRAS 23139+5939. (*Top*) CO 2→1 emission overlapped with 1.2 mm continuum. (*Middle*) 22 GHz maser features (open squares) and 8.4 GHz continuum source (cross) detected with the VLA in 1992. (*Bottom*) VLBI 22 GHz water maser features (see the caption of Fig. 1).

and not spatially resolved on the sky-plane, so that the observed clustered distribution might reflect projection effects onto the sky-plane. The measured proper motions are suggestive of a general expanding motion. Towards WB89-234, all the measured proper motions have similar orientation, close to the direction of the molecular outflow, which then could be responsible for the maser excitation.

All the three sources show a good agreement of the line-of-sight velocity dispersion of the molecular outflow and the water masers.

This still preliminary analysis indicates that the motion of water maser features in the three observed YSOs present common features, which suggest that in all the cases maser clusters might be expanding. In order to test this interpretation more sensitive multi-epoch observations with the Very Long Baseline Array are required.

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