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First results from VLBA survey of water masers towards low-mass YSOs: the Serpens core and RNO 15-FIR.

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Abstract. This article reports first results of a long-term observational program aimed to study the earliest evolution of jet/disk systems in low-mass YSOs by means of VLBI observations of the 22.2 GHz water masers. Up to now we collected data for the cluster of low-mass YSOs in the Serpens molecular core and for the single object RNO 15-FIR. Towards Serpens SMM1, the most luminous submm source of the Serpens cluster, the water maser emission comes from two small ($\leq$ 5 AU in size) cluster of features separated by $\approx$25 AU, having line of sight velocities strongly red-shifted (by more than 10 km s^{-1}) respect to the LSR velocity of the molecular cloud. The two maser clusters are oriented on the sky along a direction that is approximately perpendicular to the axis of the radio jet observed with the VLA towards SMM1. The spatial and velocity distribution of the maser features let us favour the interpretation that the maser emission can be excited by interaction of the receding lobe of the jet with dense gas in the accretion disk surrounding the YSO in SMM1. Towards RNO 15-FIR, the few detected maser features have both positions and (absolute) velocities aligned along a direction which is parallel to the axis of the molecular outflow observed on much larger angular scales. In this case the maser emission likely emerges from dense, shocked molecular clumps displaced along the axis of the jet emerging from the YSO. The protostar in Serpens SMM1 is more massive than the one in RNO 15-FIR. We discuss the case where an higher mass ejection rate can generate jets sufficiently powerful to evacuate along the direction of motion, close to the YSO, the densent portions of circumstellar gas. In that case, the excitation conditions for water masers might preferably occur at the interface between the jet and the accretion disk, rather than along the jet axis.

Key words. low-mass star formation – water masers – jet – disk

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1. Introduction

Water masers at 22.2 GHz are well known to be associated with outflow phenomena and with the earliest evolutionary phases of star formation. Using the Nobeyama 45-m telescope, Furuya et al. (2001) performed a multi-epoch H_2O maser survey and revealed that the maser activity is high during the earliest stages of low-mass star formation, namely, Class 0 phase. The survey also showed that the maser activity fades towards Class I, namely the end of the main accretion and outflow phase, and completely disappears after the pre-main sequence evolution (Class II) when the star is optically visible and no significant accretion is occurring.

There are only a few published VLBI water maser studies towards low- and intermediate-mass young stellar objects (Claussen et al. 1998; Furuya et al. 2000; Patel et al. 2000; Seth et al. 2002). These VLBA studies indicated that the water masers trace predominantly knot and shock structures at the base of and along the protostellar jets, and, eventually, can also emerge from parts of the protostellar disks. Since two years, we have been using the VLBA to observe 22.2 GHz water maser emission towards a sample of low-mas YSOs in different evolutionary stages (from Class 0 to Class I) with the final aim to study the evolution of the disk/jet system as traced by the water masers. In this paper we report the results of the first two sessions of VLBA multi-epoch observations towards the cluster of low-mass YSOs in the Serpens molecular core and towards RNO 15-FIR.

2. Observational Results

2.1. Serpens core

For the Serpens molecular core, Fig. 1 and 2 show a collage of previous interferometric observations with our VLBA maps. Fig. 1a is the 99 GHz map obtained by Testi & Sargent (1998) using the OVRO (Owens Walley Radio Observatory) interferometer. Over a region of size about $5' \times 5'$ many 3 mm condensations are visible, suggesting that the process of fragmentation and collapse of the molecular cloud is in a very active phase. Interferometric molecular line observations (Hogerheijde et al. 1999) reveal that typical condensation masses are in the range 1–10 $M_\odot$ and gas temperatures are ≤ 50 K. Most of the massive condensations visible in the Testi & Sargent (1998) 3 mm map are thought to harbour a low-mass protostar accreting matter from the surrounding molecular envelope.

Fig. 1b shows the OVRO HCN $1 \rightarrow 0$ map by Hogerheijde et al. (1999) towards the two Serpens YSOs SMM3 and SMM4. Towards both sources, the *HCN* emission is extended along the same direction (indicated with an arrow) of a larger scale H_2 jet, and likely traces ambient gas shocked by the fast outflow emerging from the protostar. The red crosses give the position of the 22.2 GHz water masers observed in this region using the VLA just a few days before the VLBA observations.

Fig. 1c and 1d report the spatial and line of sight velocity disribution of the water maser features detected respectively towards SMM3 and SMM4. A single feature has been detected in SMM4, blue-shifted by a few km s^{-1} respect to the LSR velocity of the ambient gas, $\approx$8.5 km s^{-1}. Towards SMM3, we observed six features which show an elongated, very small (≤ 1 AU in size) spatial distribution, lying approximately parallel with the RA axis. It is worth noting that, although the interested angular scale is much larger, the molecular outflow observed towards SMM3 is directed close to the Dec axis (see. Fig. 1b), hence at large angle from the axis of the water maser distribution. The maser features detected in SMM3 are stronly red-shifted, with a line of sight velocity 10 – 12 km s^{-1} higher than the LSR velocity of the ambient gas.

Fig. 2b shows the radio jet observed towards SMM1 by Curiel et al. (1993) using the VLA at 3.6 cm. It consists of three main components aligned along a southeast-northwest direction (P.A. = −53°), with the central and northwest components connected by a bridge of weaker emission. The central component appears elongated, having a deconvolved size of $200 \times \leq 60$ AU, with a position angle close to that of the radio jet. The red cross indicates the VLA position of the 22.2 GHz water

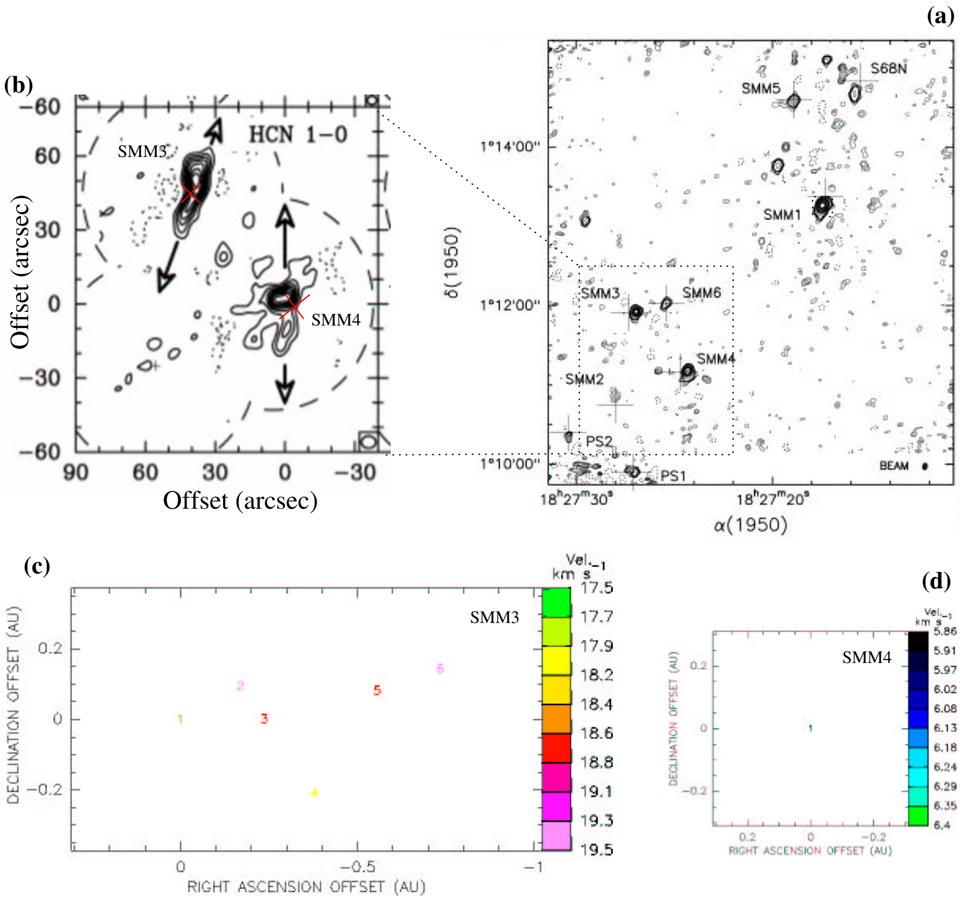

Fig. 1. VLBA results towards the Serpens molecular core. (a)OVRO 3 mm continuum mosaic of the Serpens core (Testi & Sargent 1998); crosses mark the position of the known submillimeter and far-infrared sources. The dotted rectangle in the lower-left corner of the panel delimits the region of the sky around the sources SMM3 and SMM4 shown expanded in the upper-left panel. The synthesized beam, $5\farcs5 \times 4\farcs3$ (FWHM), is shown as a filled ellipse in the lower right-hand corner. (b)OVRO HCN $1 \rightarrow 0$ image towards SMM3 and SMM4 (Hogerheijde et al. 1999). The arrows indicate the position angles of larger scale H_2 jets. The red crosses indicate the positions of the water masers deduced with the VLA shortly before the VLBA run. (c)Spatial distribution of 22.2 GHz water masers towards SMM3 as derived by our single-epoch VLBA observation. Each maser feature is identified with a label number. Different colours are used to distinguish the line of sight velocities of the features, according to the colour-velocity conversion code shown on the right-hand side of the panel. The positional coordinates are relative to the reference feature and are given in AU. (d)Same as panel "c", for SMM4.

masers, located close to the emission peak of the central component.

Fig. 2c shows the water maser map derived with four epochs of VLBA observations towards SMM1. Therteen water maser features are detected and for five of them, observed at two or more epochs, (relative) proper motions are measured. Maser features are concen-

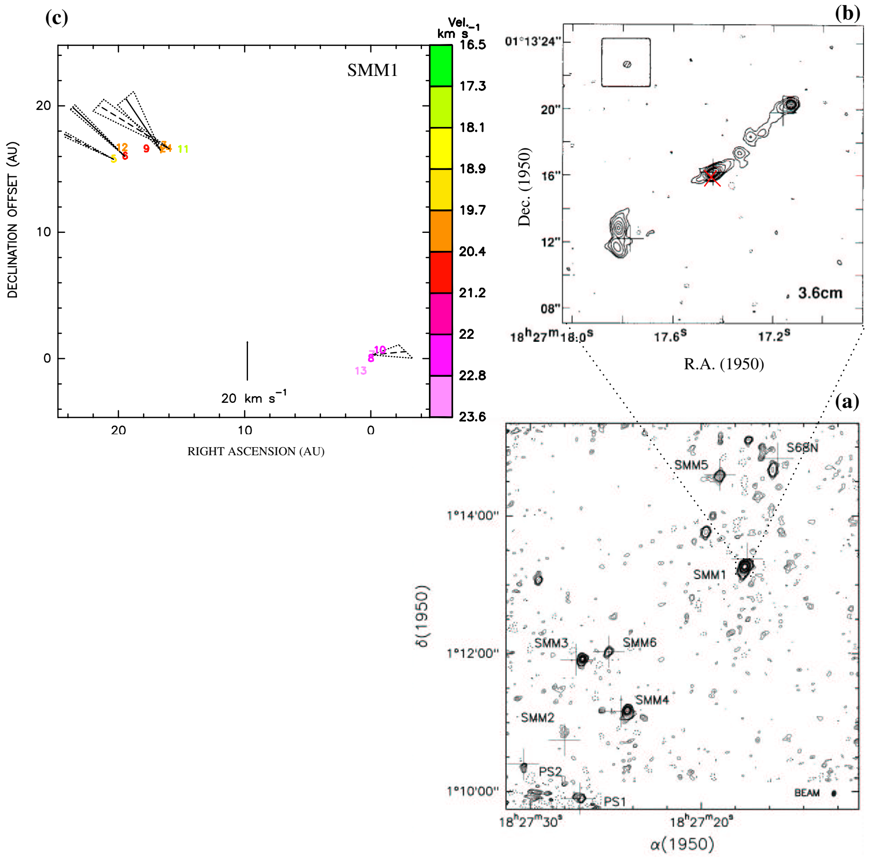

Fig. 2. VLBA results towards the Serpens molecular core. (a) see caption of Fig. 1 (b)VLA 3.6 cm map of the radio jet towards SMM1 obtained by Curiel et al. (1993). The black crosses mark the position of the three main components visible in the VLA map at 6 cm. The red cross indicates the water maser position derived with the VLA shortly before the first epoch of VLBA observations. The synthesized beam shape is shown in the upper left of the panel. (c)Spatial distribution and proper motions of the water maser features towards SMM1 derived with our four-epoch VLBA observations. Each maser feature is identified with a label number. Different colours are used to distinguish the line of sight velocities of the features, according to the colour-velocity conversion code shown on the right-hand side of the panel. The positional coordinates are relative to the feature with label number "8", used as reference, and are given in AU. The arrows report the measured proper motions, with dashed lines used in case of more uncertain values. The measured proper motions are all relative to the reference feature "8". The dotted triangles drawn around the proper motion vectors represent the amplitude and orientation uncertainty. The amplitude scale of the proper motions is given at the bottom of the panel.

trated in two small clusters (size ≤ 5 AU), separated on the sky by ≈25 AU along a northeast-southwest direction (P.A. ≈ 50°). The two clusters appear to move away from each other, as indicated by the (relative) transverse velocities measured for features in the northeast cluster, having similar amplitudes (30–40 km s^{-1}) and concorde versus of motion, directed away from

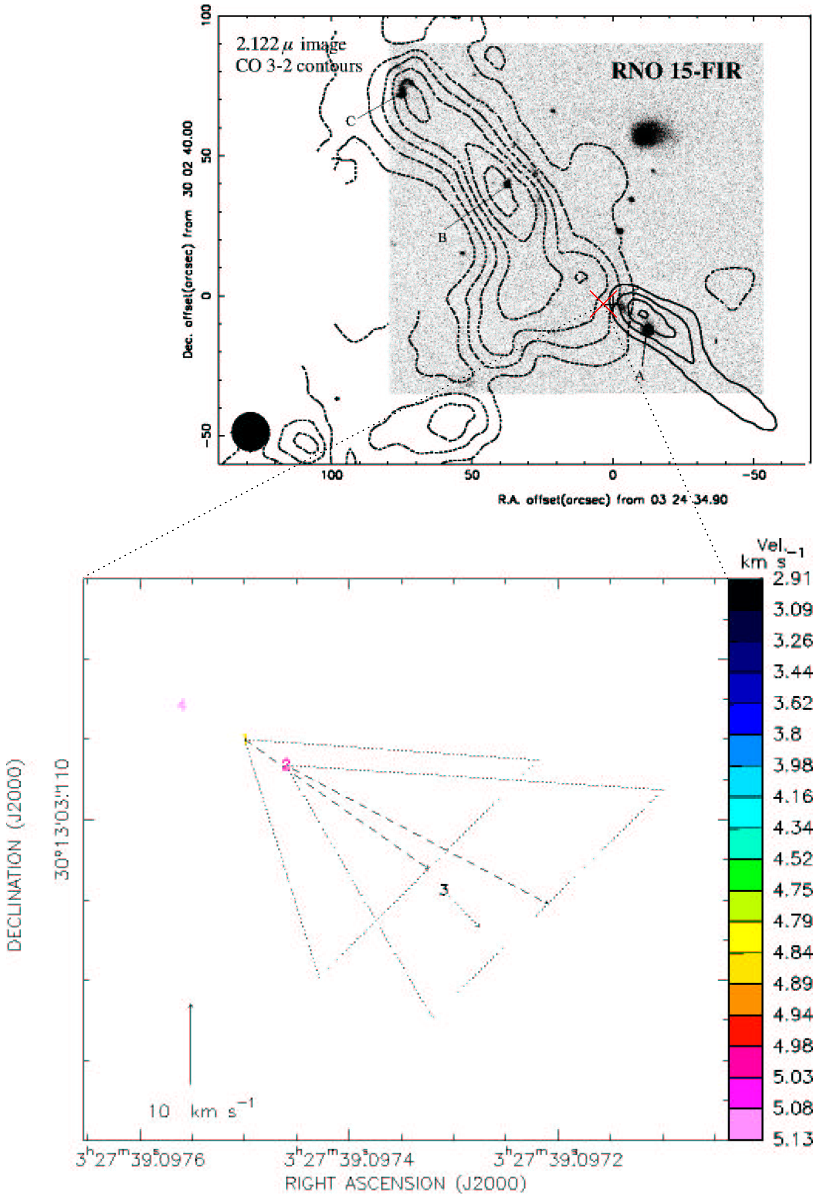

Fig. 3. VLBA results towards RNO 15-FIR. The top panel shows a H_2 2.12 μm image (gray scale) of the RNO 15-FIR outflow region (Davis et al. 1997b) with, overlaid, a contour map of the CO 3 $\rightarrow$ 2 integrated intensity measured by Davis et al. (1997a) using the James Clerk Maxwell Telescope (JCMT). The blue-shifted flow lobe is reported with full lines, the red-shifted lobe with dashed lines. The three brightest, compact H_2 knots are denoted with the letters "A", "B" and "C". The black cross marks the IRAS position of RNO 15-FIR. The red cross gives the absolute position of the 22.2 GHz water masers as deduced with our phase-reference VLBA observations. The bottom panel shows the water maser map derived with two epochs of phase-reference VLBA observations. Feature positions and line of sight velocities are indicated with the same notation used for the water maser maps of the Serpens region (see caption of Fig. 1). The dashed arrows indicate the measured (absolute) proper motions. The dotted triangles drawn around the proper motion vectors represent the amplitude and orientation uncertainty. A dotted arrow is used for representing the proper motion of the feature with label number "3" to indicate that is at most uncertain, with SNR $\leq$ 1. The amplitude scale of the proper motions is given at the bottom left-hand corner of the panel. The plot axes give absolute, RA and DEC coordinates.

the southeast cluster. All the maser features are strongly red-shifted respect to the LSR velocity of the ambient gas, by 10 – 12 km s^{-1} the one belonging to the northeastern cluster, and by 14 – 15 km s^{-1} those in the southwestern cluster.

2.2. RNO 15-FIR

The upper panel of Fig. 3 presents an H_2 2.12 μm image of the RNO 15-FIR outflow region (Davis et al. 1997b) with, overlaid, contours of the CO 3 $\rightarrow$ 2 integrated intensity map by Davis et al. (1997a). Several bright, compact H_2 knots lie along the axis of the *CO* outflow, and are found to have a good spatial correspondence with the peaks of the *CO* emission. These observations indicate the presence of an highly collimated (opening angle $\leq 10°$) jet/ouflow, directed at P.A.$\approx$32°. The IRAS position of RNO 15-FIR lies close to the *CO* outflow center. The bolometric luminosity of the region is only 8 $L_\odot$, implying a protostellar mass $\leq$ 1 $M_\odot$.

The red cross denotes the absolute position of the 22.2 GHz water masers (accurate to within 2 mas) derived by means of our phase-reference VLBA observations. The water maser VLBA map is shown in the lower panel of Fig. 3. Observing for only two epochs, we detected four maser features and for three of them, persistent over the two epochs, tentative values of the absolute proper motions are derived. The proper motions shown in Fig. 3 have been corrected by the earth and solar motions, and by the galactic rotation. The four maser features appear to distribute along a line, that also coincides with the direction of their motion. The most distant features are separated by only 1.4 AU. The amplitude of the measured proper motions is in the range of 10 – 40 km s^{-1}. The line of sight velocities of the maser features are within 1 – 2 km s^{-1} from the LSR velocity of the ambient gas, $\approx$4.7 km s^{-1}.

3. Discussion

Towards Serpens SMM1, the most intense submillimeter source of the Serpens molecular core, the maser emission is found to originate from two clusters of strongly red-shifted (more than 10 km s^{-1}) features separated by $\approx$25 AU. The measured relative transverse velocities of the maser features are directed parallel to the cluster-connecting line, which in turn is approximately perpendicular to the axis of the radio jet observed towards SMM1 on lenght scales of hundreds of AU. Basing on their spatial distribution, water masers might originate in the accretion disk surrounding the YSO. However, the measured maser (line of sight and transverse) velocities appear too large to be compatible with Keplerian rotation around a central mass $\leq$ 4 $M_\odot$. We suggest that the water maser emission can originate at the very base of the radio jet, tracing the interaction region of the red-shifted lobe of the jet with the dense material of the accretion disk. Since the jet is much faster than the gas rotating in the disk, the water maser kinematics would be driven by the jet.

Only a few (four) maser features are detected towards RNO 15-FIR. However, since *absolute* proper motions are measured, the data available is sufficient to make hypothesis on the water maser birthplace. The water maser features are distributed along a line, whose orientation on the sky coincides with the common direction of all the measured absolute velocities. Such a spatial and velocity distribution is expected if water masers trace a tightly collimated flow. Since the (VLBA) absolute postion we have derived for the water masers, locates them just at the center of the bipolar molecular outflow observed towards RNO 15-FIR (on angular scales of tens of arcsecs), and since the axis of the molecular outflow is parallel with the direction of elongation and motion of the maser features, we suggest that the water masers trace the innermost portion of the molecular outflow.

On the basis of the measured bolometric luminosities and temperatures, evolutionary models indicate that RNO 15-FIR and Serpens SMM1 share a comparable evolutionary stage, both of them being still Class O sources, even if more evolved than an average Class O protostar. Despite of that, we observe significant differences in the water maser spatial and velocity distribution between the two sources. The explanation for that is likely to be found in the quite different value of protostellar mass of the two YSOs, RNO 15-FIR being less massive than Serpens SMM1 by a factor of (at least) a few. An higher value of protostellar mass implies correspondingly higher values of mass accretion (and ejection) rates. If the jet emitted by the YSO is sufficiently powerful to sweep away the densest portions of circumstellar gas, eventually the molecular gas density along the jet axis becomes too low ($n_{H_2} < 10^7$ cm^{-3}) for the excitation of the water masers. In that case, however, water maser emission can still occur if the jet interacts with the dense material of the accretion disk.

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