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High-Mass Star Formation and Maser VLBI

Luca Moscadelli*
INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
E-mail: mosca@arcetri.astro.it

Ciriaco Goddi
Joint Institute for VLBI in Europe, Postbus 2, NL-7990 AA Dwingeloo, the Netherlands
E-mail: goddi@jive.nl

Alberto Sanna
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
E-mail: asanna@mpifr-bonn.mpg.de

Riccardo Cesaroni
INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
E-mail: cesa@arcetri.astro.it

The physical processes leading to the formation of massive ($\geq$8 $M_\odot$) stars could be different from those at work in low-mass star formation. To investigate the accretion and ejection processes in high-mass Young Stellar Objects (YSO), it is essential to achieve angular resolutions of $\lesssim 0\farcs1$, which, corresponding to linear scales of $\sim$100 AU at the typical distances of massive star forming regions, allow us to resolve the gas kinematics around single objects. In this respect, Very Long Baseline Interferometry (VLBI) of the intense, interstellar molecular masers, often observed in proximity of high-mass YSOs, offers a unique diagnostic tool, allowing us to derive the 3-D gas kinematics at distances of 10–10^3 AU from the forming star. In this talk, we review some of the main achievements of maser VLBI applied to the study of massive Star Formation (SF).

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*Speaker.

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1. Introduction

The formation of isolated low-mass (M $\sim 1\, M_{\odot}$) stars is now understood quite well. It proceeds through (1) mass accretion onto the protostar through a Keplerian disk, an expected result of angular momentum conservation, and (2) ejection of material via a jet collimated along the disk axis, which removes angular momentum from the disk allowing matter to accrete onto the star. Jets are generally modeled as magnetocentrifugally driven winds, powered by the rotation and gravitational energy and channeled along the magnetic field lines either from the disk inner edge ("X-wind", [15]), or across a much larger (up to 100 AU) portion of the disk ("Disk-Wind", [10]).

The formation of more massive stars could require substantially different accretion/ejection processes. For the mass accretion rates predicted by theory (e.g., [14]), the accretion time becomes longer than the protostar contraction time for masses $\geq 8\, M_{\odot}$. At this point, the star reaches the ZAMS and, as a consequence, its radiation pressure would be sufficient to halt the inflow [17], thus preventing further increase of the stellar mass. A number of scenarios of high-mass star formation have been put forward to solve this "radiation pressure" problem: much higher mass accretion rates, competitive accretion [2] and/or star mergers [3] in clusters.

However, recent 3-D, radiation hydrodynamic simulations of high-mass SF seem to indicate that accretion disks and collimated outflows could be an effective route also in the assembling of very massive stars, up to $\approx 140\, M_{\odot}$ (e.g., [7]). The disk geometry focuses the accretion flow onto the equatorial plane, allowing the accreting material to overcome the strong radiation pressure and reach the stellar surface. These models predict also beaming of the stellar phothons into the lower-density outflow cavity, which contributes to alleviate the radiation pressure in the equatorial plane. The size of accretion disks around high-mass YSOs is predicted to be on the order of only a few 100 AU, whereas clustering of multiple forming stars should occur on scales of 10^3 AU (e.g., [6]).

From all the above it is clear that, to improve our understanding of the accretion and ejection processes in high-mass YSOs, it is essential to image linear scales as small as 10–100 AU (requiring angular resolutions $< 0\farcs1$ at the typical distances > 1 kpc of massive star forming regions) to resolve the gas kinematics around single objects. To this purpose very useful diagnostic tools are the intense molecular (in particular SiO, H_2O, and CH_3OH) masers often observed in proximity of the high-mass YSOs. Thanks to their high brightness temperature ($\geq 10^9$ K), molecular masers can be targets of VLBI observations, which, achieving sub-milliarcsec angular resolutions, permit us to derive the proper motions of the maser "spots" (i.e., the single maser emission centers) and access the full 3-D gas kinematics. Combining maser VLBI data with (subarcsecond) interferometric observations of thermal (continuum and line) emissions, one can get a very detailed view of the gas kinematics and physical conditions near the forming star. Such a study has been performed so far only towards a small number of objects. In the following we illustrate some of the most remarkable results of maser VLBI applied to high-mass SF.

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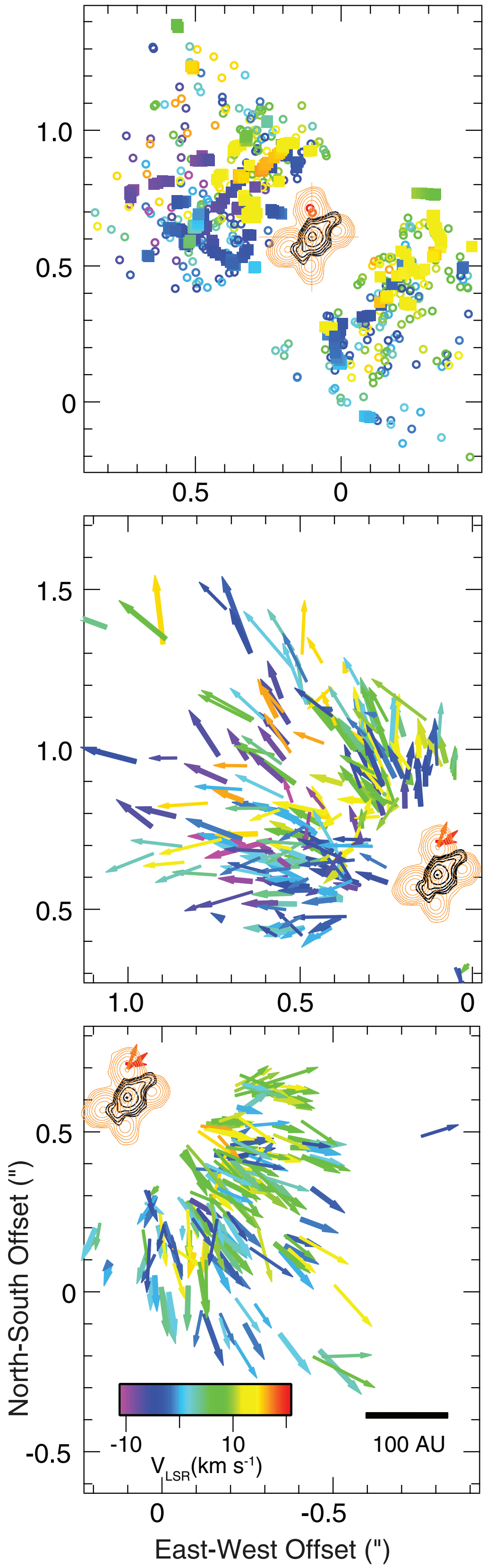

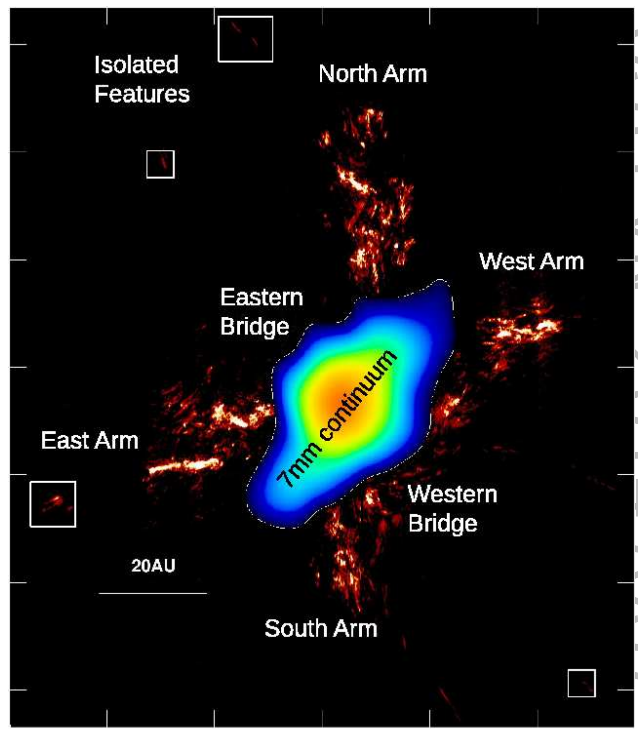

Figure 1: Maser kinematics in Source I. **Left Panel)** Top: SiO v=0 and H_2O masers (*open circles* and *squares*, respectively – [5]), velocity-integrated SiO v=1 masers (*red contours* – [4]), and 7 mm continuum (*black contours* – [11]), as mapped with the VLA. Middle: expanded view of SiO v=0 maser proper motions in the northeastern lobe of Source I. Bottom: expanded view of the southwest lobe. Colors denote maser V_{LSR} as indicated in the wedge on the bottom left corner of the bottom panel. **Right Panel)** Combined (velocity-integrated) SiO v=1 and v=2 maser emission distribution (*red-tone image*) observed with the VLBA [8], and 7 mm continuum (*color map*) imaged with the VLA [11].

2. Source I in Orion BN/KL

The closest (415 pc) and best studied high-mass YSO is Source I in the Orion BN/KL region. The continuum emission of Source I, imaged at 7 mm with the Very Large Array (VLA) by [11], is highly elongated and consistent with an accretion disk ionized by a YSO of $\approx$10 $M_{\odot}$. This source has been monitored by [8] with the Very Long Baseline Array (VLBA) in vibrationally-excited SiO maser transitions every month for over three years, and a movie of the 3-D molecular gas flow was created. The SiO masers are distributed symmetrically around the ionized disk, outlining four radial arms connected by two tangential bridges. The pattern of SiO maser proper motions evidences that material in the bridges rotates about the disk axis, whereas gas in the arms streams radially away from the star. Thus, the vibrationally-excited SiO masers are tracing both a compact rotating disk and a wide-angle wind emanating from the disk at radii < 100 AU (Fig. 1, right panel), which can be modeled in terms of a magnetocentrifugally driven wind [16]. VLA imaging of ground-state SiO maser transitions, probing larger scales, shows that the wide-angle wind collimates into a bipolar outflow at radii of 100–1000 AU (Fig. 1, left panel) [5]. This study has provided direct evidence for the formation of a massive star via disk-mediated accretion and revealed for the first time the launch and collimation region of an outflow from a rotating compact disk on scales comparable with the Solar system.

3. G23.01-0.41

The results recently obtained towards the high-mass YSO G23.01-0.41 by [13, 12] provide a good example of the sinergy between maser VLBI and interferometric observatons of the thermal line and continuum emissions. The bolometric luminosity of the region of $\approx 4\ 10^4\ L_{\odot}$ corresponds to that of a ZAMS O9.5 star of $\approx 20\ M_{\odot}$. On scales of a few 0.1 pc, a collimated bipolar outflow is revealed in the main CO isotopomers, as well as in the SiO(5-4) line, using the Submillimeter Array (SMA) (see Fig. 2, panel a). At the center of the outflow, on scales of a few 10^3 AU, the distribution of dense gas and dust (traced by typical hot-core tracers) is significantly flattened and elongated perpendicular to the axis of the bipolar outflow, indicating the presence of an envelope/disk surrounding the YSO (see Fig. 3, left panel). Multi-epoch VLBI observations of the water 22 GHz and methanol 6.7 GHz masers in this source have allowed us to determine the maser 3-D kinematics at radii of 10^2–10^3 AU, which is fully consistent with the SMA results and reveals also new interesting features. Water masers are concentrated in three main clusters, aligned (across $\approx$6000 AU) along a NE–SW direction approximately parallel to the axis (PA = 58°) of the SMA CO outflow (see Fig. 2, panel b). The water masers in the NE cluster have proper motions forming small angles with the axis of the maser distribution and directed away from the central cluster (see Fig. 2, panel c). These two findings suggest that the water masers are tracing a jet emitted by the YSO and driving the motion of the larger scale molecular flow.

Close inspection of the cluster at the center of the water maser distribution (which coincides with the compact 1.3 cm continuum emission – see Fig. 2, panel d) shows that the maser features draw an arc-like pattern (with radius of $\approx$500 AU) and the proper motions are diverging from the center of the arc. Thus these water masers do not appear to trace a collimated jet, but rather be accelerated by a fast, wide-angle wind emerging from the YSO, whose position might coincide with the arc center. The outward pressure exerted by the wide-angle wind onto the surrounding gas is also witnessed by the kinematics of the 6.7 GHz methanol masers, which are distributed at

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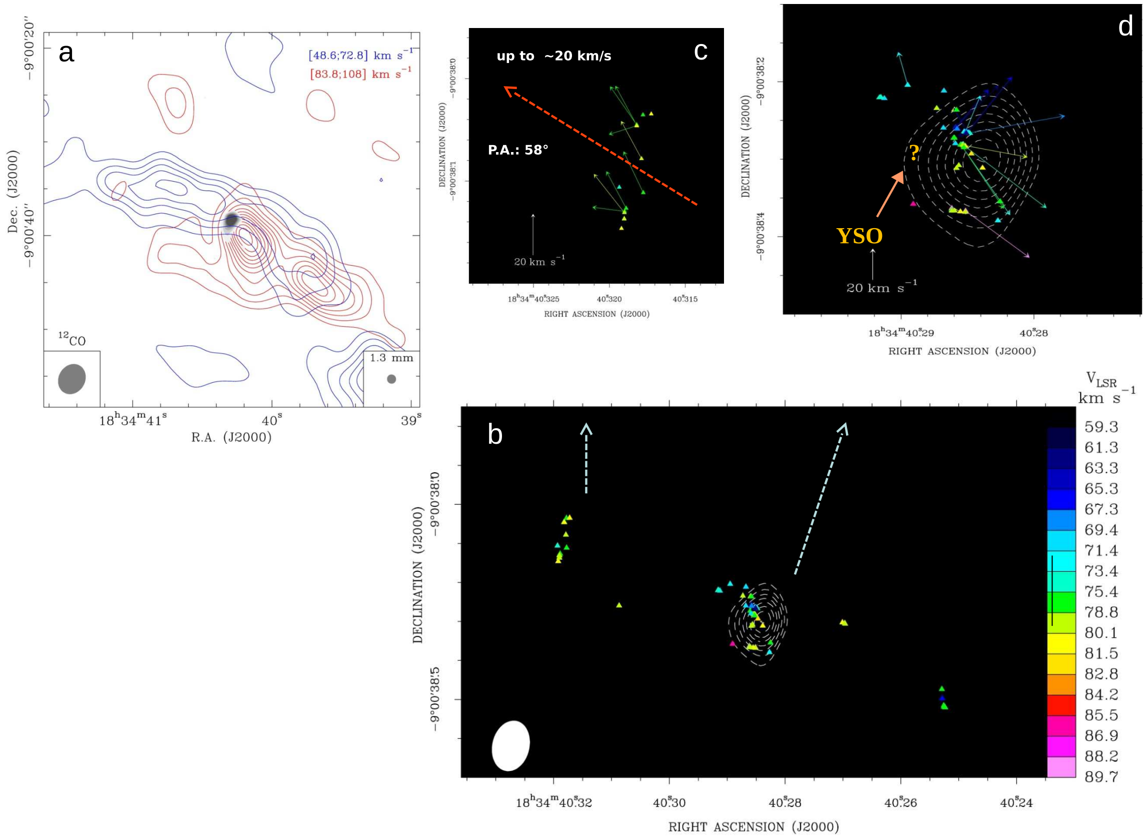

Figure 2: Panel a) The *red* and *blue contours* show the integrated emission of the ^{12}CO (2-1) line observed with the SMA towards G23.01-0.41 by [12]. At the center of the field it is reported the SMA 1.3 mm continuum map (*gray scale*). **Panel b)** 22 GHz water maser (*colored triangles*) spatial distribution observed with the VLBA, and VLA 1.3 cm continuum (*dashed contours*) [13]. Colors denote maser $V_{\rm LSR}$ using the color-velocity conversion code given on the rigth of the panel. **Panel c)** Maser proper motions (*colored arrows*) in the northeastern water maser cluster. **Panel d)** Maser proper motions (*colored arrows*) in the central water maser cluster.

radii from a few 100 AU to a few 10^3 AU, around the YSO (see Fig. 3, right panel). Although the pattern of 6.7 GHz maser proper motions is quite complex, one can note that both maser features with the smallest and largest (projected) distance from the outflow (and disk rotation) axis tend to have proper motions directed perpendicular to this axis. The velocity field of methanol masers can be simply explained in terms of a composition of slow (4 km s^{-1} in amplitude) motions of radial expansion and rotation about an axis approximately parallel to the water maser jet. Since the methanol masers trace gas adjacent to the water maser arc, it is very likely that the wide-angle wind is the agent responsible for their radial expansion. The rotational component can be seen by plotting the $V_{\rm LSR}$ of the emission peaks versus the corresponding position projected along an axis orthogonal to the jet. This is done for the methanol masers as well as the (CH_3CN (12-11)) thermal line (see Fig. 4). The resulting position-velocity distribution suggests Keplerian rotation around a 19 $M_\odot$ star (in good agreement with the value of stellar mass inferred from the bolometric luminosity of the region).

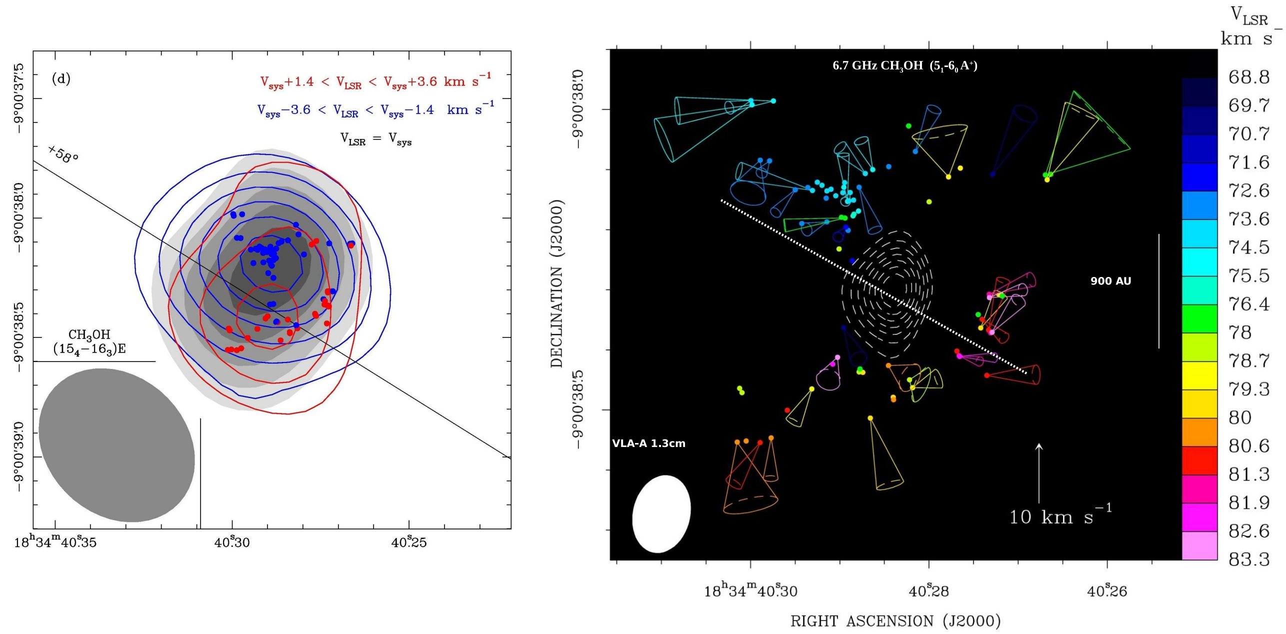

Figure 3: **Left Panel)** Map of the CH_3OH (15_4-16_3)E line emission observed with the SMA towards G23.01-0.41 by [12], with *gray*, *blue*, and *red contours* representing, respectively, the systemic velocity, and the blue- and redshifted wings of the line. *Blue* and *red dots* mark the positions of the blue- and redshifted methanol maser spots. **Right Panel)** Positions and proper motions (*colored dots* and *cones*, respectively) of the 6.7 GHz methanol masers derived with multi-epoch VLBI observations, and VLA 1.3 cm continuum (*dashed contours*) [13].

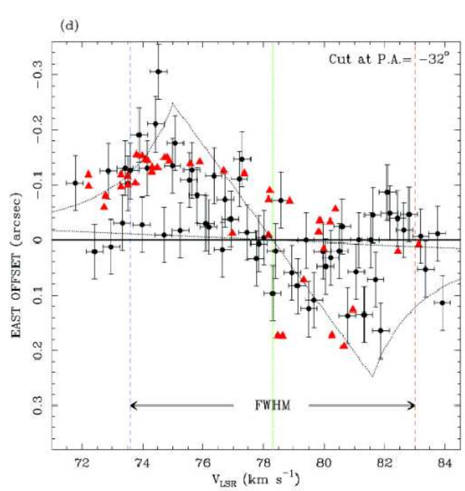

Figure 4: Distribution of the velocity channel peaks of the CH_3CN (12-11) line emission (*black dots*) projected along the direction (PA = -32°) perpendicular to the outflow axis [12]. *Red triangles* show the CH_3OH masers within 0.″25 from the continuum peak. The dotted pattern encompasses the region where emission is expected from a Keplerian disk rotating about a 19 $M_\odot$ star.

What is the nature of the wide-angle wind observed near the high-mass YSO in G23.01-0.41? If it were a disk-wind, it should be a scaled-up version by a factor of at least five with respect to that observed in Source I, where the flow is already recollimating at a distance of 100 AU from the star. Alternatively, a stellar wind emitted from a ZAMS O9.5 star would yield enough momentum to drive the fast, wide-angle motion of the central cluster of water masers.

4. G24.78+0.08 A1

The fit to the continuum spectrum between 6 cm and 1 mm (see Fig. 5, left panel) indicates that

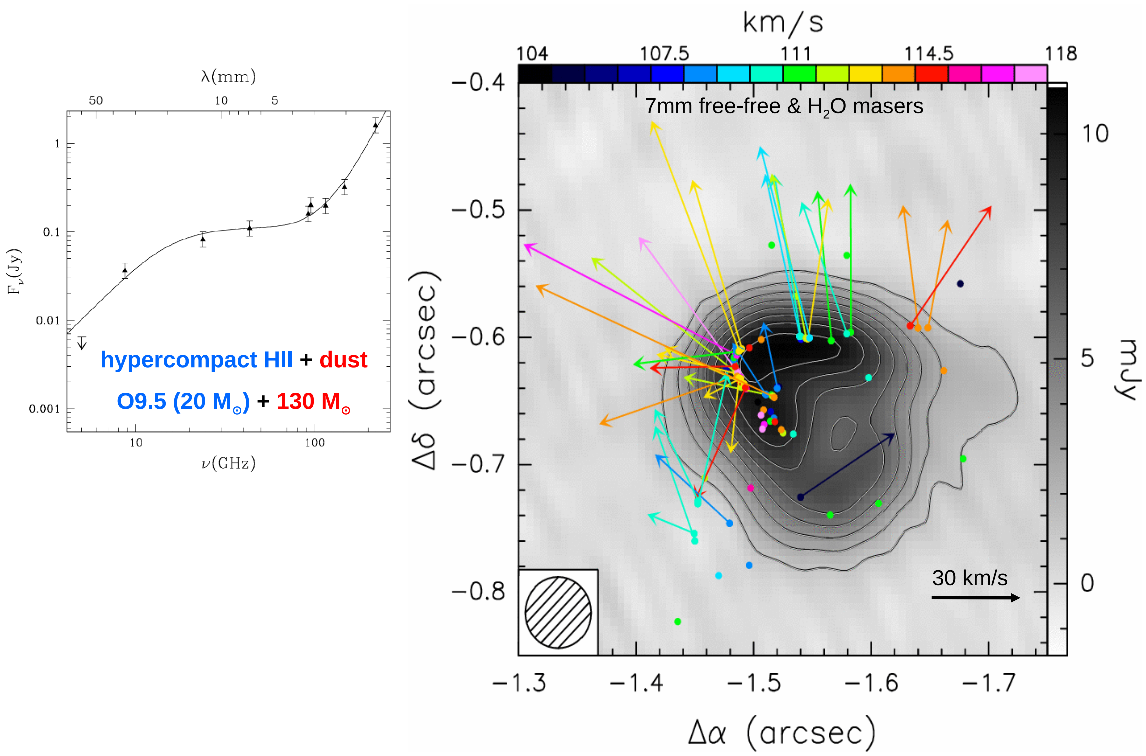

Figure 5: Left Panel) The radio SED of the source G24.78+0.08 A1 is well fitted in terms of a HC HII region, ionized by a ZAMS O9.5 star, embedded inside a massive (≈130 $M_\odot$), hot molecular core. **Right Panel)** Positions and proper motions (*colored dots* and *arrows*, respectively) of the 22 GHz water masers derived with multi-epoch VLBA observations by [9], and VLA 7 mm continuum (*gray scale* and *contours*) [1].

G24.78+0.08 A1 is a 20 $M_\odot$ YSO surrounded by a hypercompact (HC) HII region located at the center of a massive (≈130 $M_\odot$) hot-core. The 22 GHz water masers, monitored with multi-epoch VLBA observations by [9], are distributed along an arc at the border of the HC HII region (of radius ≈500 AU) and expand away from the center of the HII region with high velocities (≈40 km s^{-1}) (see Fig. 5, right panel). In this source, both the shell-like appearance of the HII region [1] and the maser expansion are well reproduced by a model where a strong stellar wind is blowing from the ZAMS O9.5 star exciting the HII region, pushes aside the ionized gas and confines it into a thin shell, and drives the fast motion of dense, shocked, molecular material (marked by the water masers), swept by the expanding ionization front. Both pressure- and momentum-driven solutions demand a high circumstellar gas density $n_{H_2} \sim 10^7$ cm^{-3} (in agreement with the excitation models for strong water masers) and a very short dynamical age $t_0 \approx 40$ yr.

5. Conclusions

Maser VLBI offers a unique tool to investigate high-mass SF at the smallest (∼10 AU) scales, unaccessible even to the new-generation millimeter interferometers. In the few objects studied so far using both maser VLBI and thermal interferometric observations, the maser 3-D kinematics and the V_{LSR} distribution of the (thermal) tracers of high-density gas complement each other, providing a picture of the gas motion around the forming star at radii from 10 to 10^4 AU. The results obtained seem to indicate that disks and jets could play an important role in the formation of more massive stars, as well. However, maser VLBI reveals also some new interesting kinematical features, whose significance for the stellar formation process has still to be deciphered. Are the wide-angle winds in G23.01-0.41 and G24.78+0.08 A1, traced with the water masers at radii of $\approx$500 AU from the YSO, witnessing the final expansion of the HII region and the conclusion of the accretion phase? Or are these just episodic ejection phenomena, possibly induced by a burst of mass accretion? To answer these questions, we need to increase the number of high-mass YSOs studied with milliarcsec resolution, selecting targets that span a sufficiently broad range of luminosities and evolutionary phases.

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