Astrophysical Masers:
Unlocking the Mysteries of the Universe
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Masers as probes of the gas dynamics close to forming high-mass stars

Luca Moscadelli[1], **Alberto Sanna**[2] **and Ciriaco Goddi**[3,4]

[1]INAF - Osservatorio Astrofisico di Arcetri
Largo E. Fermi 5, I-50125, Firenze, Italy
email: `mosca@arcetri.astro.it`

[2]Max-Planck-Institut für Radioastronomie
Auf dem Hügel 69, D-53121, Bonn, Germany
email: `asanna@mpifr-bonn.mpg.de`

[3]Research Institute for Mathematics, Astrophysics and Particle Physics, Radboud University,
Heyendaalseweg 135, 6525, AJ Nijmegen, The Netherlands
email: `C.Goddi@astro.ru.nl`

[4]Leiden Observatory,
PO Box 9513, 2300 RA Leiden, The Netherlands

Abstract. Imaging the inner few 1000 AU around massive forming stars, at typical distances of several kpc, requires angular resolutions of better than $0\farcs1$. Very Long Baseline Interferometry (VLBI) observations of interstellar molecular masers probe scales as small as a few AU, whereas (new-generation) centimeter and millimeter interferometers allow us to map scales of the order of a few 100 AU. Combining these informations all together, it presently provides the most powerful technique to trace the complex gas motions in the proto-stellar environment. In this work, we review a few compelling examples of this technique and summarize our findings.

Keywords. Stars: formation, masers, instrumentation: interferometers

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1. Introduction

Low-mass ($\sim$1 $M_\odot$) stars form through disk/jet systems (see, for instance, Lee *et al.* (2017)), whereas accretion disks are a natural consequence of the collapse of a rotating molecular core by angular momentum conservation, and jets help removing the excess of angular momentum, allowing the infalling gas to accrete onto the protostar. The formation route could be different for massive ($\geqslant$ 8 $M_\odot$) young stellar objects (YSO), since they reach the ZAMS while still accreting and emit energetic UV radiation that could have a strong impact (via photoionization and radiation pressure) on preexisting disk/jet systems (see Beltrán & de Wit (2016), for a recent review). In order to resolve the kinematics of disks/jets around individual YSOs, an angular resolution of $\leqslant 0\farcs1$ is required, approached only by most recent, millimeter interferometers (ALMA, NOEMA). The demand for very high ($\sim$1 mas) angular resolution is naturally met by Very Long Baseline Interferometry (VLBI) observations of molecular (water and methanol, in particular) masers, which are commonly observed nearby (at radii of 100–1000 AU from) high-mass YSOs. Multi-epoch VLBI observations allow the measurement of the maser proper motions with high ($\sim$1 km s^{-1}) accuracy, providing the full 3-D distribution of (masing) gas velocities nearby the forming star. Since a decade, this technique has been successfully used to search for disks and jets around high-mass YSOs (Moscadelli *et al.* 2011; Sanna *et al.* 2010; Goddi *et al.* 2011). In the following, we present recent results from two main programs undertaken by our group.

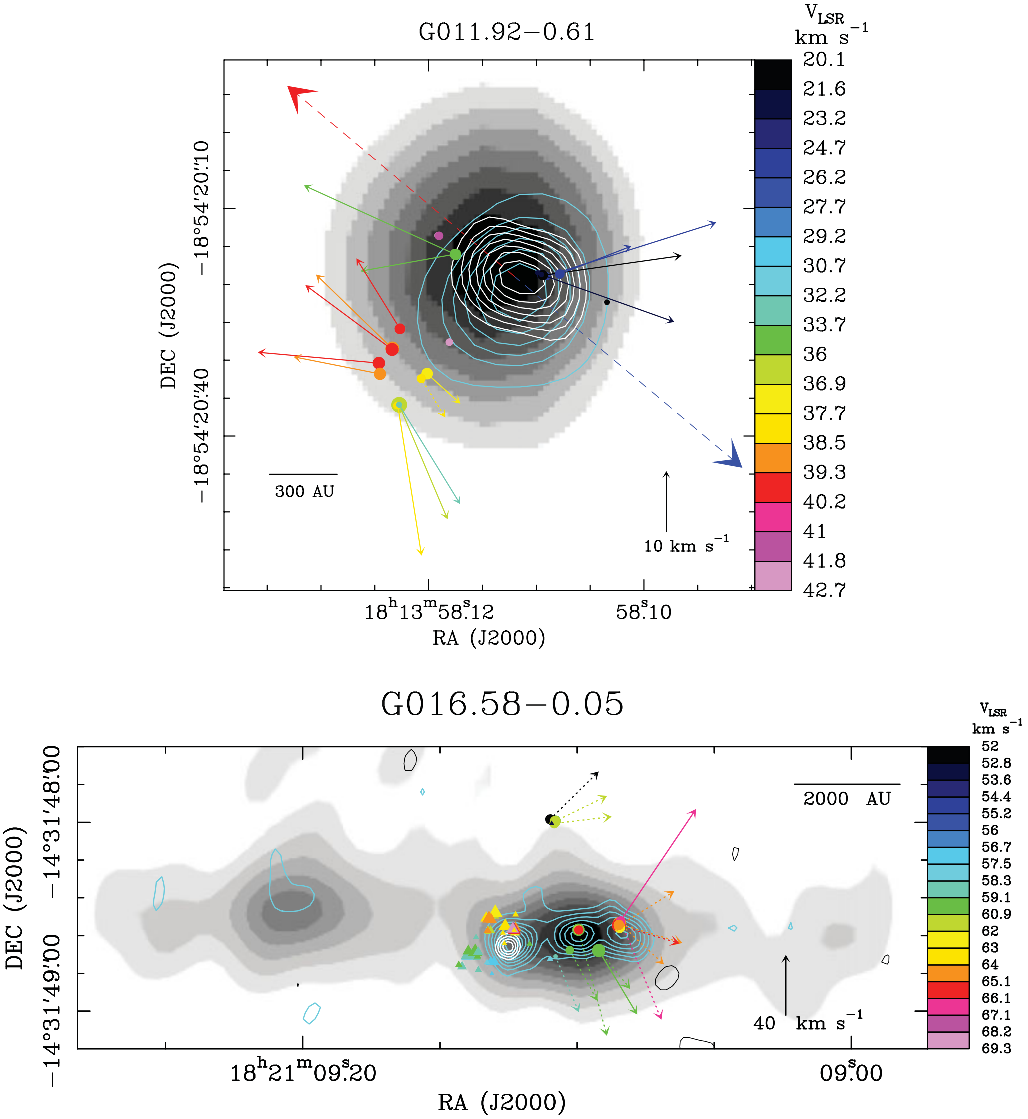

Figure 1. Radio continuum and maser emission towards G011.92−0.61 (upper panel) and G016.58−0.05 (lower panel). In both panels, the JVLA continuum at 6, 13, and 22 GHz is represented by the gray-scale image, cyan and white contours, respectively. Colored dots and arrows give the positions and the proper motions of the 22 GHz water masers, with colors denoting maser "Local Standard of Rest" velocities ($V_{\rm LSR}$). The amplitude scale for the maser velocity is indicated by the *black arrow* in the bottom right of the panels. In the lower panel, colored triangles mark the positions of the 6.7 GHz methanol masers. (See the on-line version of the figure; see Moscadelli *et al.* (2016), Figs. 2 and 4, for further details.)

2. Survey of massive (proto)stellar outflows using water masers

Since a few years, we have started a survey of massive protostellar outflows with the specific goals of both achieving an angular resolution sufficient to resolve individual YSOs and targeting relevant, complementary flow components. We use VLBI of water masers to determine the 3-D velocities of the molecular component of the flow on scales of 10–100 AU, and sensitive (rms noise ≈ 5–10 μJy) JVLA continuum observations to study the ionized emission. Our sample are 40 luminous (B3–O7 ZAMS type) YSOs with accurate distances measured by trigonometric parallaxes (from the BeSSeL† survey). The JVLA observations are performed at 6 and 13 GHz with the A-Array and at 22 GHz with the B-Array, obtaining comparable angular resolutions in the range $0''.2$–$0''.4$.

Our project has been awarded 60 hours of JVLA time during 2012 October and 2014 May, and we have recently presented the first results for a subset (11) of targets (Moscadelli *et al.* 2016). The large majority of the targeted water masers is detected in continuum at one or more frequencies. Most detections are weak ($\sim$100 μJy), compact or slightly resolved sources, likely pinpointing the YSO responsible for the maser excitation. For the subset of sources fully analyzed, the spectral indexes between 13 and 22 GHz are generally positive and consistent with ionized winds/jets. In a few cases, we also find clear negative spectral indexes, between 6 and 13 GHz, hinting at non-thermal emission.

Figure 1, upper panel, presents results of one typical case, G011.92$-$0.61, where the continuum emission is only slightly resolved and overlays on the cluster of water masers. Although no indication for an ionized jet can be obtained from the continuum morphology, a collimated flow is suggested by the distribution of maser proper motions, which all form small angles with the direction identified by the big arrows in the plot. This direction actually coincides with the axis of a collimated molecular outflow observed with the Submillimeter Array (SMA) at larger angular scales towards this YSO (Cyganowski *et al.* 2011). This is a nice example where the 3-D distribution of water maser velocities can help identifying collimated ejection from an high-mass YSO. Figure 1, lower panel, shows the opposite case, for the source G016.58$-$0.05, where the continuum emission (both at 6 and 13 GHz) is clearly elongated and witnesses the presence of an ionized jet, and the water maser proper motions are instead quite scattered in direction, and probably trace wide bow-shocks at the radio knots of the jet.

3. Disk/jet system in high-mass YSOs explored with methanol/water masers

G23.01$-$0.41 is a molecular clump excited by a late O-type YSO with a stellar mass of $\approx 20\ M_{\odot}$. SMA observations by Sanna *et al.* (2014) detect a collimated (^{12}CO(2-1)) molecular outflow at linear scales of $\sim$1 pc, emerging from a molecular core placed at the center of the outflow and elongated perpendicular to the outflow axis (see Fig. 2, left panel). Inside the molecular core, at linear scales of a few 1000 AU, recent JVLA sensitive observations reveal an ionized (thermal) jet, powering the larger scale molecular outflow (see Fig. 2, right panel). Multi-epoch VLBA observations have identified three distinct clusters of water masers, which spread over the radio continuum emission of the jet along a direction almost parallel to the jet and the molecular outflow. Maser spots of the central cluster draw an ark with diverging proper motions, and they are probably tracing a fast bow-shock of the jet impinging against dense molecular material near the YSO. The masers in the cluster to NE move parallel to the jet (see Fig. 2, right panel). The water maser data, taken a few years before the SMA and JVLA observations, have been our first (reliable) evidence of a jet emerging from the high-mass YSO in G23.01$-$0.41 (Sanna *et al.* 2010).

High-density (thermal) tracers (like the CH_3CN emission) reveal that the gas inside the molecular core is undergoing both expansion along and rotation about the outflow axis. (see Fig. 3, left panel). The presence of these two motion components emerges also

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† The Bar and Spiral Structure Legacy survey is a key Very Long Baseline Array (VLBA) project, which has measured parallaxes and proper motions of hundreds of methanol and water masers distributed across the Galactic disk (Reid *et al.* 2014)

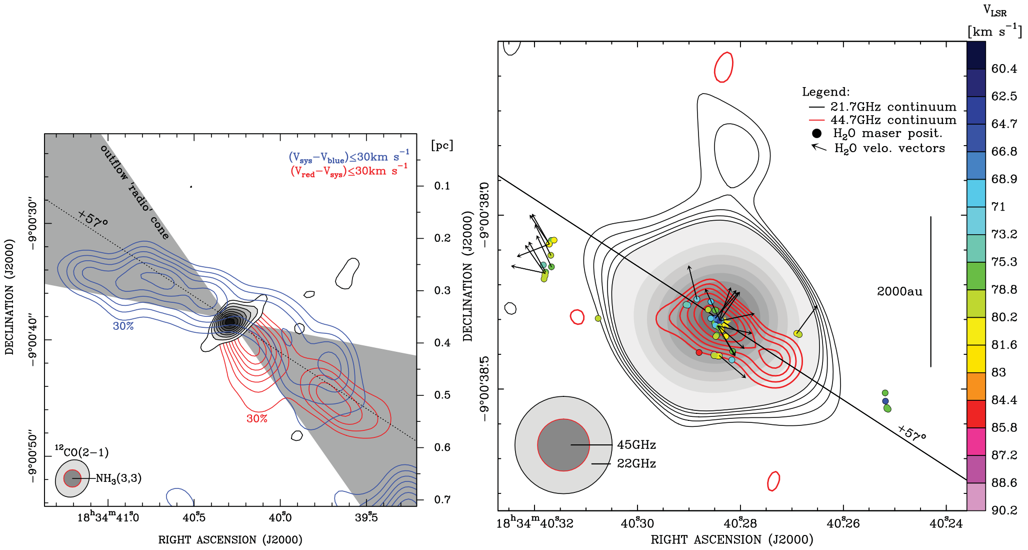

Figure 2. Comparison of the outflow tracers across different linear scales in G23.01−0.41. *Left:* Blue and red contours show SMA maps of the blue- and redshifted ^{12}CO(2-1) emission integrated over a $V_{\rm LSR}$ range up to 30 km s^{-1} from the systemic velocity. Gray contours at the center of the bipolar outflow represent the emission of warm gas traced with NH3 (Codella *et al.* 1997). The gray cone indicates the opening angle of the radio jet. *Right :* Overlay of the JVLA 22 GHz continuum (black contours and gray scale) with the 44 GHz continuum residual map (red contours). Colored dots and black arrows give positions and velocities of the water masers. (See the on-line version of the figure; see Sanna *et al.* (2016), Fig. 2, for further details.)

clearly from position-velocity plots along slices parallel and perpendicular to the outflow axis (see Sanna *et al.* (2014), Fig. 3). The 6.7 GHz masers originate at radii of 100–2000 AU from the forming star (see Fig. 3, right panel) and their 3-D velocities trace a combination of expansion and rotation, consistent with the kinematic pattern from thermal lines. The distribution of the 3-D 6.7 GHz maser velocities, moving radially outward across the equatorial plane and collimating at closer angles with the jet axis at (relatively) larger quotes, reminds that of a rotating disk-wind, qualitatively similar to the disk-wind traced with the SiO masers in Orion-KL Source I (Matthews *et al.* 2010; Greenhill *et al.* 2013).

Towards the ultra-compact (UC) H ii region NGC7538 IRS1, we have recently accumulated several pieces of evidence that the 6.7 GHz masers are tracing accretion disks around high-mass YSOs (Moscadelli & Goddi 2014). In this region, the methanol masers show two elongated distributions (labeled in Figure 4 with letters A and B+C, respectively) of size of ≈ 500 AU. We used four epochs of European VLBI Network (EVN) observations for: 1) studying the very regular change of maser $V_{\rm LSR}$ with position; 2) measuring the maser proper motions, mostly found to be closely aligned with the maser linear distributions, consistent with planar motion seen (almost) edge-on; 3) deriving the line-of-sight accelerations of many maser features, also varying regularly with maser position. We have complemented the maser data with JVLA B-Array observations of the NH$_3$ line (Goddi *et al.* 2015) from this region, finding that the NH$_3$ $V_{\rm LSR}$ distribution is in good agreement with the maser 3-D velocity pattern. Finally, for each of the two linear maser clusters, we have reproduced our set of observations with a simple kinematic model of a rotating disk in centrifugal equilibrium, constraining the mass of both the disk and the central star. Our hypothesis that the 6.7 GHz masers in NGC7538 IRS1 emerge from

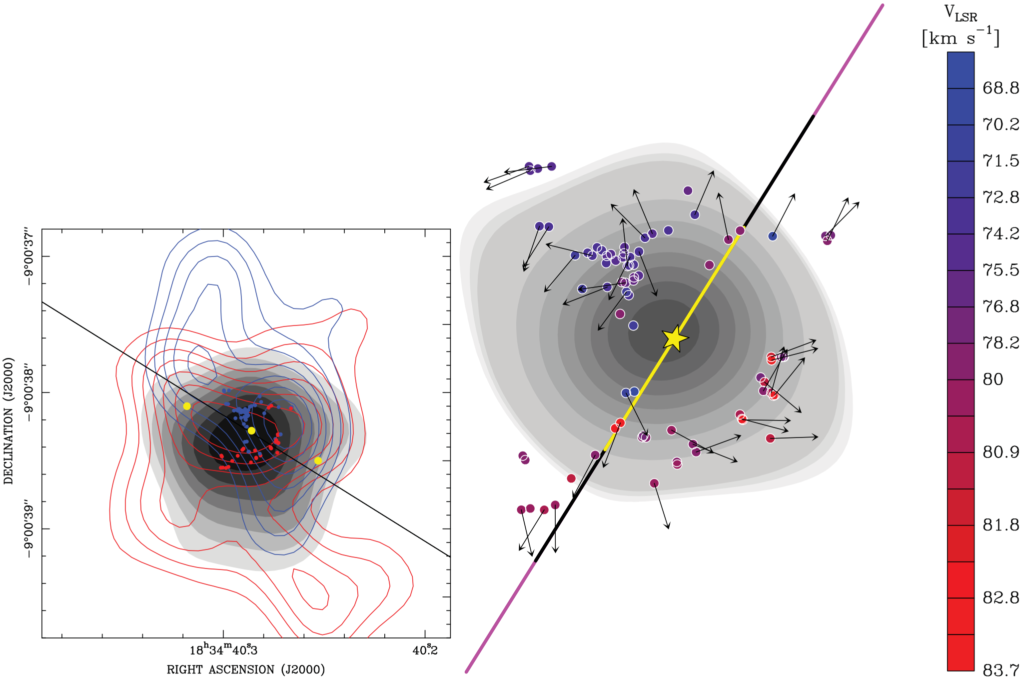

Figure 3. Rotation and expansion in G23.01−0.41. *Left:* The gray-scale image, and the blue and red contours show SMA maps of the CH3CN (12_3-11_3) emission at the systemic, and blue- and redshifted velocities, respectively. Big yellow and small, red and blue dots give the spatial distribution of the 22 GHz water and 6.7 GHz methanol masers, respectively. The NE-SW black line denotes the outflow direction. *Right:* Zoom on the 6.7 GHz methanol masers. The distribution of 6.7 GHz maser $V_{\rm LSR}$ is shown by white-encircled, colored dots, and the proper motion direction by black arrows. The gray scale image represents the JVLA 1.3 cm continuum. The colored axis denotes the disk mid-plane, where each colored segment spans 1000 AU in length. (See the on-line version of the figure; see Sanna *et al.* (2014), Fig. 1, for further details.)

accretion disks around two distinct high-mass YSOs (labeled IRS1a and b in Fig. 4), has been recently confirmed by JVLA A-Array observations of NH_3 and CH_3OH lines by Beuther *et al.* (2017). These authors find a velocity gradient, in (thermal) CH_3OH absorption, in correspondence of each of the two CH_3OH (maser) linear distributions. These velocity gradients, interpreted in terms of accretion disks, show an (approximately) E-W orientation, not very different from the PA of the maser structures observed at smaller scales.

4. Conclusions

Molecular interstellar masers are *reliable* tracers of kinematic structures in high-mass YSOs. 22 GHz water masers invariably arise from (and trace the motion of) fast (20–100 km s^{-1}) shocks in (wide-angle) winds or (collimated) jets ejected from the massive (proto)stars. Depending on the shock properties, water maser velocities are well collimated about the local flow direction in compact, radiative shocks, or present a larger scatter, if emerging from wide-angle, (quasi)adiabatic bow-shocks. In a few well-studied objects, 6.7 GHz methanol masers are found to originate in the flattened, rotating disk/envelope of high-mass YSOs, at radial distances from a few 100 AU to a few 1000 AU. Methanol masers move at typical speeds of 1–20 km s^{-1}, and can show a complex pattern of 3-D velocities. They can trace not only the envelope/disk rotation but also expansion along directions both radial (close to the equatorial plane) and forming

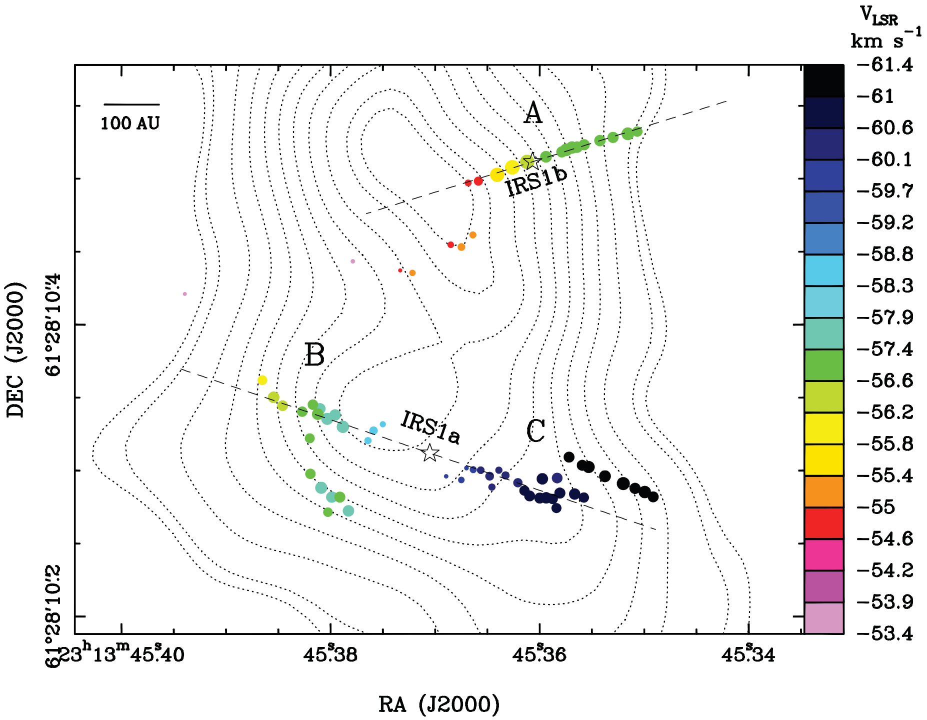

Figure 4. Methanol masers tracing accretion disks in the UC HII region NGC7538 IRS1. Colored dots give positions of the 6.7 GHz methanol masers, with colors denoting maser $V_{\rm LSR}$. Masers distribute in three elongated clusters labeled with letters "A", "B" and "C". The dashed lines show the linear fits to the spatial distributions of maser features in cluster A, and in the combined clusters B + C. The dotted contours reproduce the VLA A-Array, 22 GHz continuum. The stars labeled IRS1a and IRS1b mark the YSO positions, as determined from fitting a disk model to the maser positions, velocities and line-of-sight accelerations measured via multi-epoch EVN observations. (See the on-line version of the figure; see Moscadelli *et al.* (2014), for further details.)

small angles with the disk axis (at relatively higher quotes). Such a velocity pattern can be interpreted in terms of a (relatively slow) rotating disk-wind.

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