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The innermost regions of massive protostars traced by masers, high-resolution radio continuum, and near-infrared imaging

Fabrizio Massi[1], **Luca Moscadelli**[1], **Carmelo Arcidiacono**[2] **and Francesca Bacciotti**[1]

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

[2] INAF - Osservatorio Astronomico di Bologna,
Via Piero Gobetti, 93/3, I–40129 Bologna, Italy
email: `carmelo.arcidiacono@oabo.inaf.it`

Abstract. Whether high-mass stars ($M > 7M_{\odot}$) emerge from a scaled-up version of the low-mass star formation scenario, i. e. through disk-mediated accretion, is still debated. We present the first results of an observational programme aimed to map the innermost regions of high-mass stellar objects by combining together high-spatial resolution maser and radio continuum observations, and near-infrared imaging.

Keywords. masers, stars: formation, infrared: stars

Disks and jets play a major role in the early evolution of low-mass stars, but their role in high-mass ($M_* > 7M_{\odot}$) star formation, if any, is still unclear. This is because high-mass young stellar objects (HMYSOs) are rare and difficult to observe. Recent calculations indicate that magnetic fields could be less efficient than in low-mass YSOs in collimating outflows, since magnetic collimation could be weakened by gravitational fragmentation of the accretion disk and by thermal pressure of the ionised gas at the base of the jet (Peters *et al.* 2011). In addition, outflows from HMYSOs could be intrinsically less collimated if driven by radiation pressure rather than by coherently rotating magnetic fields (Vaidya *et al.* 2011). Finally, OB-type stars emit powerful stellar winds, and if these were already present during the accretion phase they would contribute to the associated outflows.

Although mm interferometric observations in typical molecular outflow tracers (^{12}CO, ^{13}CO, SiO, HCO$^+$) have resolved a few individual high-mass protostellar outflows, the sampled scales are tens to hundreds times larger than model-predicted disk sizes (~ 100 AU) and do not allow investigating the launching regions of the flows. Much higher spatial resolution is then needed to determine the physical nature (e.g., stellar- vs. disk-wind, ionised vs. neutral) and the geometry (wide-angle vs. collimated) of the mechanism powering the associated molecular outflow. To tackle these limitations and better constrain models of high-mass star formation, we have recently started an observational programme of massive protostellar outflows. We have been investigating both the molecular and ionised components in these outflows with unprecedented angular resolution and sensitivity, by complementing multi-epoch VLBI observations of water masers, with high-angular resolution, multi-frequency (6, 13, and 22 GHz), deep imaging (rms noise 6–10 $\sim \mu$Jy) of radio continuum emission with the JVLA. A sample of 40 HMYSOs was selected from the BeSSeL (Bar and Spiral Structure Legacy; Reid *et al.* 2014) survey of water masers over the Galactic disk, which met all the following criteria: 1) strong

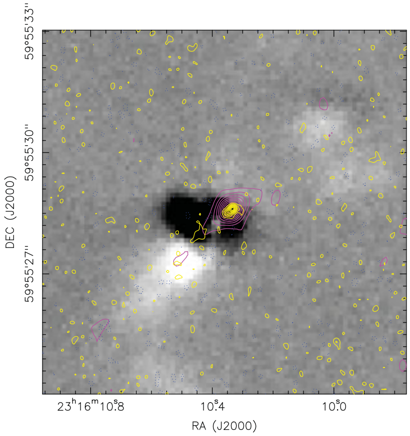

Figure 1. Continuum subtracted, pure line emission H_2 image of G111.25–0.77, overlaid with *purple* and *yellow contours* (see the on-line version) representing the JVLA A-Array continuum at 13 and 22 GHz, respectively (Moscadelli *et al.* 2016). A few H_2 knots SE and NW of the compact radio source clearly delineate a collimated jet with the same orientation as the innermost radio emission (observed at higher angular resolution). The black area is an artifact of continuum subtraction and indicates that the NIR counterpart of the radio source exhibits an SED rising with wavelength, a landmark of young stellar objects.

water masers; 2) associated sources with bolometric luminosity corresponding to ZAMS B3–O7 stars ($M_* > 7M_\odot$); 3) objects that, in previous surveys, had gone undetected or only showed compact (size $\leqslant$ 1 arcsec) and weak (flux $\leqslant$ 650 mJy) radio continuum emission (to exclude extended and more evolved HII regions). This sample was observed with JVLA in three different runs (for details see: Moscadelli *et al.* 2016). A comparison of radio continuum morphologies and water maser spatial and velocity distributions shows that 5 out of a sub-sample of 11 HMYSOs drive a collimated (conical) outflow. The derived outflow momentum rates are in the range $10^{-3} - 10 M_\odot$ yr^{-1} km s^{-1}, among the highest values reported in the literature. Radio continuum morphology and maser velocity patterns are more difficult to understand in the remaining 6 sources.

However, critical information on jet collimation can ultimately only be obtained by linking the sub-arcsec structure (closer than 100 AU for the examined targets) to the outflowing gas pattern on a scale of $10^2 - 10^5$ AU from the driving source (i. e., up to 0.5–1 arcmin), a region which is still heavily embedded in dust and gas. To investigate this region we carried out very deep observations of a sub-sample of 4 HMYSOs from the BeSSeL survey, located at distances $d < 4$ kpc, through the H2 narrow-band filter by exploiting one of or both LUCI NIR cameras in parallel mode at the Large Binocular Telescope in Arizona. H_2 line emission at 2.12 μm has been routinely used to trace collimated gas outflows from YSOs. We detected H_2 line emission apparently associated with all the targeted compact radio sources. The most remarkable case, G111.25–0.77, is shown in Fig. 1. Our results confirm the presence of collimated jets in the vicinity of newly formed high-mass stars, pointing to a scaled-up version of low-mass star formation.

References

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