Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Water masers high resolution measurements of the diverse conditions in evolved star winds

A. M. S. Richards[1], Y. Asaki[2], A. Baudry[3], J. Brand[4], L. Decin[5], S. Etoka[1], M. D. Gray[6], F. Herpin[3], R. Humphreys[7], B. Pimpanuwat[1], A. P. Singh[8], J. A. Yates[9] and L. M. Ziurys[8]

[1]JBCA, Dept. Physics & Astronomy, University of Manchester, UK.
email: a.m.s.richards@manchester.ac.uk

[2]JAO, Chile, NAOJ, Chile, Department of Astronomical Science, SOKENDAI, Japan

[3]Université de Bordeaux, Laboratoire d'Astrophysique de Bordeaux, France

[4]INAF, Bologna, Italy

[5]Institute of Astronomy, KU Leuven, Belgium

[6]NARIT, Chiang Mai, Thailand

[7]Minnesota Institute for Astrophysics, University of Minnesota, USA

[8]Dept. of Chemistry, The University of Arizona, USA

[9]Dept. Physics & Astronomy, UCL, UK

Abstract. We compare detailed observations of multiple H_2O maser transitions around the red supergiant star VY CMa with models to constrain the physical conditions in the complex outflows. The temperature profile is consistent with a variable mass loss rate but the masers are mostly concentrated in dense clumps. High-excitation lines trace localised outflows near the star.

Keywords. masers, stars: massive, mass loss

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1. Water masers around evolved stars

Over 100 H_2O maser transitions are predicted, about half of which lie in ALMA bands. Fig. 1 shows the predictions of Gray *et al.* (2016) for combinations of gas temperature (T_k) and number density (n) optimising the maser amplification for lines imaged around VY CMa. Maser components in spectral channels can be fitted with accuracy ≈ (beam size)/(signal to noise ratio). Coincidence/avoidance of different masers constrains physical conditions in clumps, diffuse gas and directed outflows in the winds at an order of magnitude higher resolution than is possible with thermal lines. Only H_2O masers trace O-rich stellar winds from a few stellar radii $R_\star$, along with SiO masers, to hundreds $R_\star$, interleaving OH mainline masers.

2. Mass loss from VY CMa

VY CMa is a massive red supergiant, stellar radius ($R_\star$) 5.7 mas (Wittkowski *et al.* 2012), whose mass loss rate has varied between $5{\times}10^{-5}$–10^{-3} $M_\odot$ over centuries (Decin *et al.* 2006). Much of the wind is concentrated in dusty clumps, plumes and discrete ejecta seen by HST in scattered light e.g. Humphreys *et al.* (2021), and by ALMA e.g. Fig 2. OH mainline masers, favoured at $n < 10^{14}$ m^{-3}, T_k <500 K, interleave the outer 22-GHz H_2O maser clumps which need hotter, denser conditions, whilst OH

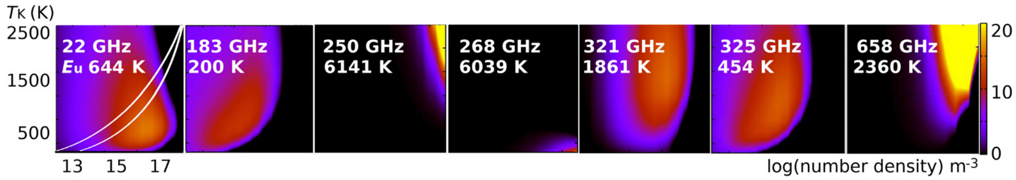

Figure 1. Colour scale: H_2O maser (negative) optical depth models (Gray *et al.* 2016). Labels: transition frequency and upper energy level. n assumes a fractional H_2O abundance $4{\times}10^{-5}$. The radiation temperature is set to 50 K except for 268 GHz, where it is 1250 K (also see Baudry, these proceedings).

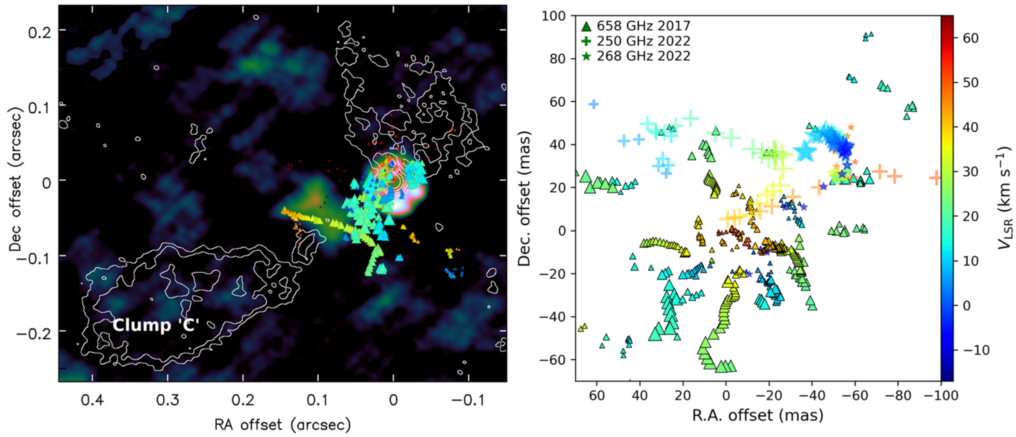

Figure 2. ALMA results: VY CMa is at [0,0]. Left: Contours: 650-GHz continuum emission. Background colour scale: integrated 658-GHz maser emission at 15-mas resolution (Asaki *et al.* 2020) observed in 2017. Components: lower-resolution 658 GHz observations (Richards *et al.* 2014) observed in 2013. Right: components fitted to the 15-mas 658 GHz masers and to lower-resolution 250 and 268 GHz masers.

and 183-GHz H_2O masers are associated with the SW clump whose dust is seen only in scattered light (Richards *et al.* 2018). Analysis of the overlaps and avoidance of 321, 325 and 658-GHz masers observed contemporaneously (Richards *et al.* 2014, 2018) broadly support the temperature – wind distance model of Decin *et al.* (2006) but suggest that much of the masing gas is concentrated in clumps with higher than average number densities. Fig 2, left shows an arc of 658-GHz masers, observed at ∼100-mas resolution in 2013, curving around clump ‘C’ (O Gorman *et al.* 2015). The masers appear partly resolved-out in the high-resolution 2017 data, supporting a shock origin which can lead to a large maser beaming angle even for strong amplification (Richards *et al.* 2010).

Fig 2, right, shows ‘spokes’ of high resolution 658-GHz masers appearing to emanate from the star in all directions, suggesting clumps with strong velocity gradients. The 250-GHz and 268-GHz emission comes from the highest-energy level H_2O masers yet imaged (see Baudry *et al.* 2023 for other stars) and is concentrated to the N and NE. The observational spectral and angular resolution was too low to confirm the maser nature of this 250-GHz emission but the 268-GHz masers have a brightness temperature $>5{\times}10^5$ K and are entirely confined to a bow-shock-like arc suggesting a recent ejection (see also Singh et al. in prep).

In future we will use multi-transition observations of a more symmetric CSE to infer wind conditions in 3D on $R_\star$ scales to inform models of chemistry and dust formation/evolution.

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