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The dynamics of red supergiant winds

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Abstract. During the red supergiant (RSG) stage of massive star evolution, emission from dust and molecules allows the copious stellar winds to be studied in great detail. This help us understand not only the evolutionary stages of the star (which are highly dependent on mass loss rates), but also the morphology of the eventual supernova remnant. Maser emission from OH and H_2O has been mapped with milli-arcsec resolution (using MERLIN and the EVN/global VLBI) around RSG including VY CMa, S Per and VX Sgr. The H_2O masers originate in clouds accelerating away from the star and OH mainlines masers interleave the outer parts of the H_2O maser shell. Zeeman splitting of OH maser lines reveals the orientation and strength of stellar-centred magnetic fields.

1. Clumpy mass loss

The inner H_2O maser shell radius is $\sim$5 R_*, just outside the dust formation zone (Greenhill et al. 1995). The H_2O masers around S Per form an almost

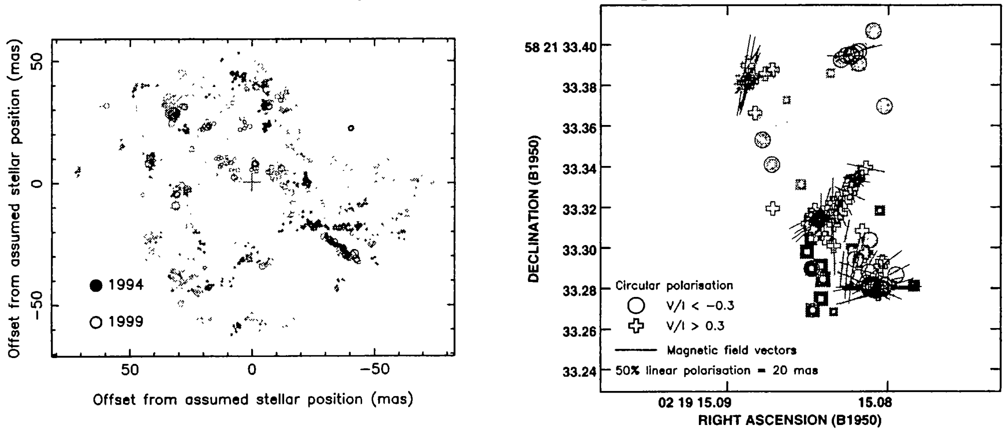

Figure 1. Each spot marks the position of a patch of maser emission from S Per, paler indicating more blue-shifted. (*left*) H_2O maser monitoring. (*right*) OH 1665 MHz masers observed in 1999.

spherical shell, shown in Fig. 1(*left*). The streaks and groups of spots represent emission sampled at 0.1 - 0.2 km s^{-1} intervals through H_2O maser clouds.Many of the same clouds can be identified in observations made 5 years apart showing internal turbulence as well as bulk outflow. The clouds are typically 15-20 au in diameter and 50× denser than their surroundings (Richards et al. 1999) at a gas temperature $T_g \sim$1000 K (Yates et al. 1997). Measurements of proper motions in S Per and VX Sgr (Murakawa priv. comm.) show systematic expansion but no significant rotation.

Fig. 1 (*right*) shows OH mainline masers on a similar scale to the H_2O masers. The OH shell also overlaps the H_2O shell in VY CMa and VX Sgr.
1. How is OH produced in this region, well-shielded from interstellar UV – chromospheric radiation? – dissociative shocks from stellar pulations?
2. How are OH masers pumped at such high densities and temperatures?
The problem is tackled using models including the measured velocity gradients. Fig 2. shows the maser gain for both mainline transitions, based on an OH cloud size of 10 au and a number density of 3.6×10^{13} m^{-3}. This assumes the OH masers originate in less dense regions between the H_2O clouds with a lower dust-gas collision rate at T_g = 400 K. An optical depth of -10 corresponds to an amplification factor of 2.2×10^5; for smaller values the masers are unsaturated, consistent with the observed velocity gradient and variability.

2. Axisymmetric winds and magnetic fields

The H_2O masers are tangentially beamed, indicating acceleration whilst the OH masers are radially beamed but attain the highest expansion velocities. Fig. 1 shows the H_2O masers are brightest in regions corresponding to equatorial belts in the near-spherical global distributions, while OH masers prefer the polar directions; this is typical for RSG. OH masers often show strong Zeeman splitting and some clouds can be 100% circularly polarised. This can be interpreted by combining the effects of magnetic- and velocity-field gradients in a clumpy medium (Cook 1966). In VX Sgr the OH 1612 masers (Szymczak & Cohen 1997, Szymczak et al. 2001) indicate a magnetic field of $\sim$-1 mG at $\sim 100R_*$.

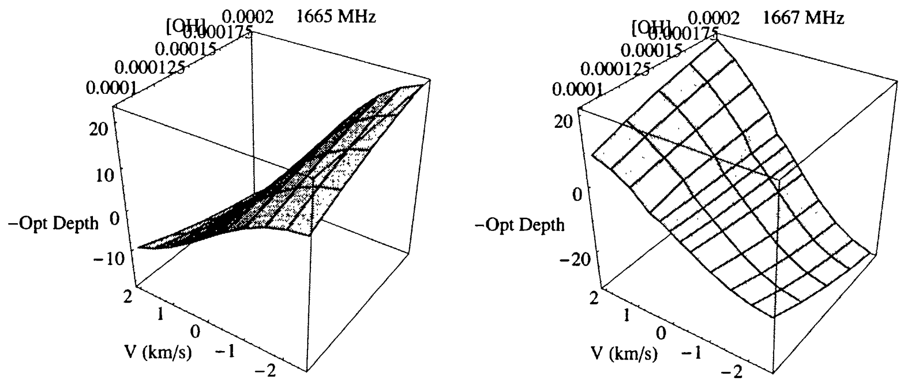

Figure 2. OH mainline maser gain (negative optical depth) under the conditions in the inner CSE of S Per. [OH] is the fractional OH number density and V is the doppler velocity relative to the cloud centre.

This is supported by EVN observations of OH mainline masers (Richards et al. 2000) and by the polar axis direction deduced from H_2O and OH maser velocity field asymmetries. This suggests a dipole field centred on the star at position angle $210° \pm 20°$, tilted at $\sim 65°$to the plane of the sky. In S Per at 1612 MHz only circular polarisation is found in just two clouds, suggesting a magnetic field pointing towards the observer. Its mainline masers (Fig. 1 *right*)show the magnetic field is stronger and more complex in regions closer to the star. Linear polarisation is seen in blue-shifted emission only, suggesting Faraday screening of the red-shifted masers by a significant free electron density in the inner CSE.

2.1. VY CMa

The OH masers around VY CMa extend several thousand au from the star in a similar distribution to that of the dust imaged in the NIR by Monnier et al. (1999) (Fig. 3). Irregularities seen in IR emission could originate in the interaction of the stellar wind with orbiting material. The H_2O masers, in the inner few hundred au, appear to be located in a flared disc, which can also be related to the IR SED (Efstathiou et al. 1990). The H_2O masers are mostly accelerating strongly away from the star (Richards et al. 1998). However a few clumps show tangential proper motions (on grey background). This may be revealing planetary or protostellar debris.

3. Conclusions

We have used radio and IR interferometry to examine the dynamics of stellar winds on scales from tens to thousands of au. The small-scale dynamics of the H_2O maser region are explained by intrinsically clumpy mass loss from the star. OH masers are found in between and outside R_*-sized H_2O-rich clouds, and require different physical conditions. The radially beamed appearance of the OH may be partly due to the velocity gradients required for maser pumping. The absence or distortion of linearly polarised emission from the far side of

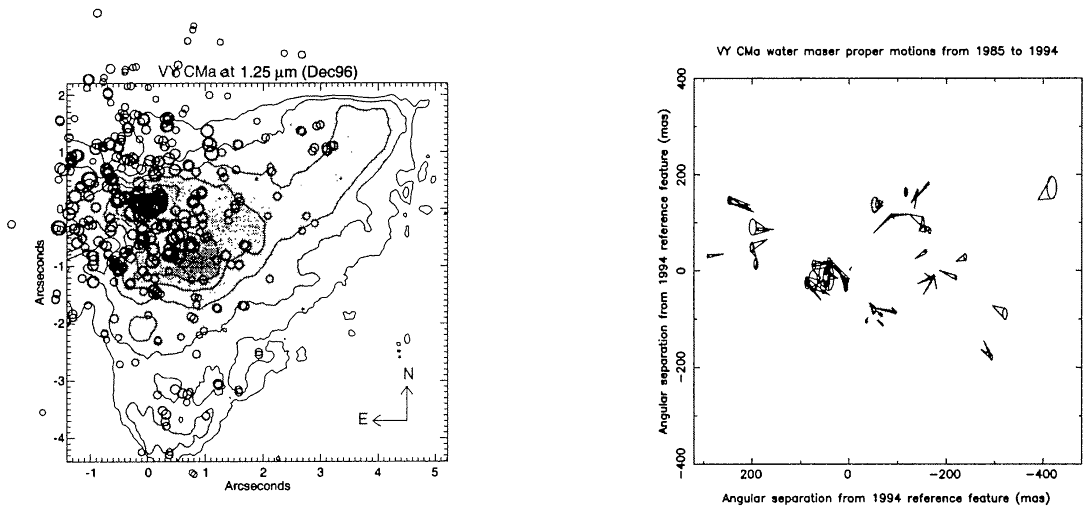

Figure 3. VY CMa: (*left*) The circles show the positions of OH main-line maser clouds superimposed on NIR emission (greyscale). (*right*) Proper motions of H_2O maser clouds between 1985 and 1993.

the CSE suggests a significant ionisation fraction which may be linked to the production of OH and other non-LTE chemistry.

Larger-scale asymmetries exist; in VX Sgr and S Per (10-20 solar masses) the H_2O masers are brightest at velocities close to V_* in an equatorial belt. The OH masers are brightest at more extreme velocities and around the polar axis. This appears to be aligned with a dipole magnetic field in VX Sgr. The magnetic field is strong enough to have a noticeable dynamic influence on the stellar wind and explain the axial symmetries we observe, especially if higher fractional densities of OH and electrons are associated near the star. VY CMa is more massive and has the only RSG or Mira wind in which we have detected significant (localised) rotation. This may be due to interactions between the outflowing stellar wind and rotating solid material, or other external factors linked to the irregular heart-shaped appearance of the OH masers and the vast surrounding dusty nebula.

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