OH masers and the structure of Mira/Red Supergiant winds

By A.M.S. RICHARDS[1], R.J. COHEN[1], K. MURAKAWA[2], J.A. YATES[2], H.J. VAN LANGEVELDE[3], M.D. GRAY[4], M.R.W. MASHEDER[5], AND M. SZYMCZAK[6].

[1]JBO Manchester, [2]Hertfordshire, [3]JIVE, [4]Cardiff, [5]Bristol, [6]Torun.

Multi-epoch milli-arcsecond resolution observations of OH and H_2O masers have been made with the EVN/global VLBI and MERLIN. OH mainline masing can start at a few tens of R_*, overlapping the H_2O maser zone. The OH wisps and clumps are usually sparsely distributed, and significantly polarised. MERLIN data show the red-shifted OH is often less linearly polarised than blue-shifted emission. This, and the presence of OH close to the star, suggest a significant degree of ionisation in this region. OH proper motion measurements will be used to relate the wind dynamics to the magnetic field and other causes of clumpiness and asymmetry.

1. Introduction

The traditional 'onion skin' model for O-rich AGB or red supergiant (RSG) stellar winds contains SiO, H_2O and OH masers at increasing distances from the star (e.g. Goldreich & Scoville 1976). In the simplest interpretation the velocity and chemistry of the outflow are not expected to change after the formation of dust at a few R_*. However Chapman & Cohen (1986) showed that the masers around VX Sgr form roughly spherical shells as predicted but the wind is accelerating up to $\sim 1''$ ($\sim 100R_*$) from the star.

Typical OH 1612 MHz masers change very little over a decade. Individual H_2O maser clouds may disappear but the emission retains a shell-like appearance. OH mainline masers tend to be most variable in velocity and intensity and least symmetrically distributed. MERLIN observations of OH mainline masers (e.g. Szymczak et al. 1999; Richards et al. 1999) show that they can occur as close as $\sim 8R_*$ from the star but the thickness of the OH mainline maser shell is barely resolved. Zeeman splitting of the OH lines shows the magnetic field in the CSE is a few mG, strong enough to influence the wind dynamics (e.g. Chapman & Cohen 1986). Faraday rotation/depolarisation of red-shifted mainline OH emission suggests there is a significant free electron density in the inner CSE (Szymczak et al. 1999).

We are monitoring OH and H_2O masers using the EVN and MERLIN in order to

(*a*) Locate and measure OH mainline masers interleaving the H_2O maser clouds;

(*b*) Compare maser observations with high resolution IR data (e.g. Monier et al. 1998) to see if changes in dust surface properties can explain the acceleration;

(*c*) Measure the maser proper motions and combine these with the Doppler velocity information to establish the 3D kinematics of the stellar wind;

(*d*) Measure the magnetic field and relate this to the observed dynamics;

(*e*) Look for any systematic red/blue shifted asymmetry at high resolution;

(*f*) Investigate maser variability over the stellar pulsational cycle;

(*g*) Develop models for maser physics and the chemistry producing OH near the star;

(*h*) Use these results to constrain density, temperature etc. in different regions of the wind and test models involving small-scale clumpiness and large-scale bipolarity;

(*i*) Compare objects to distinguish evolutionary stages (eg Mira, SRb) from reversible changes (eg caused by superperiods or thermal pulses).

The EVN, augmented by several US antennas, was used to observe two high-mass red supergiants in 1997. Initial results for S Per confirmed (a) and also showed that the OH maser clouds are somewhat resolved on VLBI scales (Masheder et al. 1999).

The following year we started monitoring a sample of half a dozen AGB stars. The 1665 and 1667 MHz transitions were observed simultaneously in RHC and LHC and the data were correlated using the VLBA correlator at Socorro. In addition we undertook complementary MERLIN H_2O and full OH polarisation observations. The resolution of the EVN at 1.6 GHz is similar to MERLIN at 22 GHz and milli-arcsec position accuracy is achieved by fitting Gaussian components. Where possible, comparison with phase-referenced MERLIN OH maps is used to determine absolute positions of EVN data to within about 10 mas. OH and H_2O maps are aligned by attempting to establish the stellar position at the centre of expansion and at the greatest angular separation from masers at velocities close to V_*.

2. Examples of EVN OH maser observations of Miras

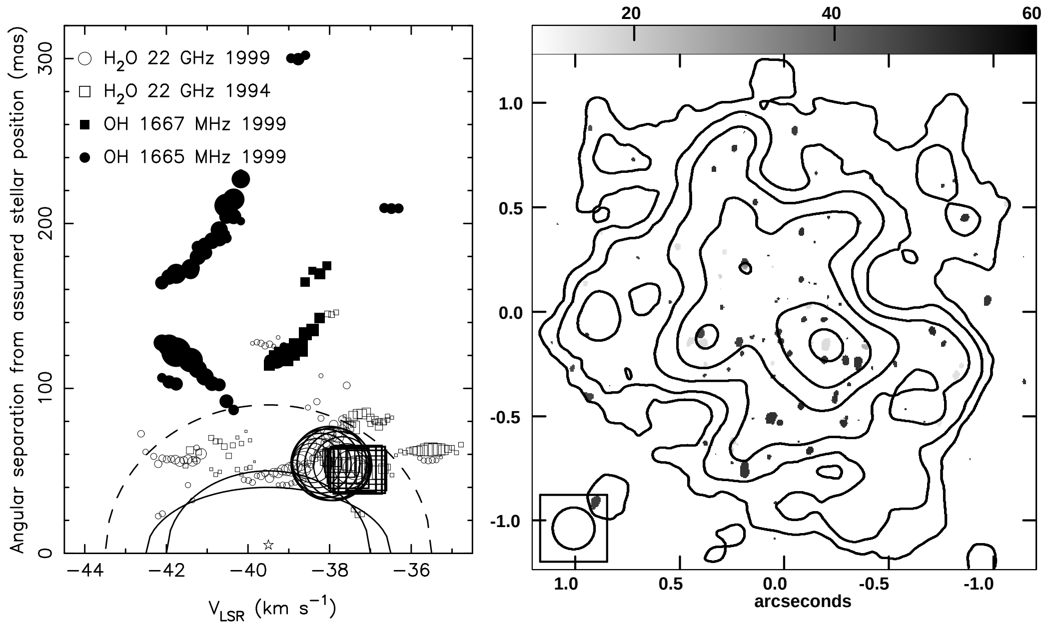

FIGURE 1. *Left* EVN OH and MERLIN H_2O maser components around U Ori. Symbol radius is proportional to flux density. The star marks V_*. The solid lines show ellipses fitted to the inner radii of the H_2O maser shells and the dashed line is the inner radius of the OH maser shell. *Right* IK Tau OH 1667 MHz masers. Contours show the integrated (zeroth moment) flux detected by MERLIN with the beam size at lower left. The grey scale, in km s^{-1}, shows the first moment of flux detected by the EVN.

22 GHz observations of U Ori in 1994 (Louridas 2000) and 1999 (Murakawa 2000, in prep) show the total angular size and velocity extent of the H_2O maser shell is similar at both epochs, but the detailed distribution is very different. The H_2O maser shell is very poorly filled which may be associated with an OH 1612 MHz flare (Pataki & Kolena 1974) from the inner CSE.

Fig. 1 (*Left*) shows the radial distribution of the masers. The brightest 22 GHz masers occur at a similar velocity and distance from the star at both epochs although maps show they are at very different position angles, vindicating the alignment method. The EVN

OH mainline mainline masers near the star overlap the outer half of the H_2O maser shell in position, from regions a few au in radius. They occupy a smaller velocity extent than the H_2O masers and peak close to V_*. Pre-1991 (low resolution) MERLIN data show a more complete mainline maser shell (Chapman, Cohen & Saikia 1991), of a similar angular size but a larger velocity extent, so the poor filling of the EVN OH maser shell suggests the front and back caps are being resolved out.

1612 MHz OH masers appear to form a fairly spherical shell around IK Tau, observed by Bowers et al. (1989) using the VLA, and Yates & Cohen (1994) used a statistical comparison of two epochs of H_2O maser data to measure expansion proper motions in all directions. However low-resolution MERLIN observations of the OH mainline masers (Kirrane 1987) suggested a biconical outflow. Observations in 1993 showed that, unusually, the most extended OH emission detected by MERLIN is highly red- and blue-shifted relative to V_*. Total intensity contours are shown in Fig. 1 (*Right*); fainter emission was found in a $6'' \times 5''$ region. In 1999 the EVN detected the most compact components. The brightest red-shifted maser component detected in 1993 and 1999 was used to align the maps and many other features also appear to have survived. Further EVN observations will be used to measure the mainline maser proper motions and compare their kinematics with MERLIN 22 GHz monitoring.

3. The magnetic field close to VX Sgr

Our EVN/Global VLBI observations found most of the compact OH mainline masers lie in a region of radius ~ 150 mas, at $-7.5 < V_{\rm LSR} < +22.0$ km s^{-1} (Fig. 2). The stellar velocity $V_* = 5.3 \pm 0.4$ km s^{-1}. The H_2O maser region is similar in total size and velocity extent (although much more evenly filled), suggesting that the OH mainline maser regions interleave the H_2O clouds, similarly but sparsely. Fainter 1667 MHz features (not shown; moderately red- and blue-shifted) occur up to 700 mas south of the peaks.

Chapman & Cohen (1986) found $B \approx -2$ mG using short baseline observations of the OH mainline masers. Later MERLIN observations of the 1612 MHz maser shell (Szymczak & Cohen 1997) measured $B = -1.1$ mG, suggesting a dipole magnetic field centred on the star with its axis at position angle $210^\circ \pm 20^\circ$ (the arrow in Fig. 2). Comparison with the kinematics of the OH and H_2O masers (Richards 1997; Murakawa et al. in prep.) suggest this is tilted towards the observer in the South. These observations show that at high resolution the maser shell of VX Sgr has a complicated structure with distinct axial symmetries tentatively aligned with the magnetic field.

A magnetic field with a component along the line of sight of $B = -1$ mG shifts 1667 MHz RHC emission by -0.36 km s^{-1} with respect to LHC emission. We found two Zeeman pairs at 1667 MHz (Fig. 2) indicating a magnetic field of ≥ -1.5 mG. The total shift may be less than a thermal linewidth so more rigorous modelling is required to measure the field strength exactly (Elitzur 1998) but the direction is unambiguous.

The Cook effect (Cook 1966) explains the occurrence of isolated LHC or RHC masers or regions where Stokes V is overwhelmingly of one sign. A dipole magnetic field centred on the star, pointing towards the observer, will have a gradient in the direction of the observer on the far side of the star. The velocity gradient of the stellar wind in this region is in the opposite direction. LHC maser emission in this region is shifted to a more positive velocity, and closer to the star the shift is larger. This produces longer path lengths at the same effective velocity for the amplification of LHC masers. Conversely, such a configuration will enhance RHC masers on the near side of the CSE.

Fig. 2 shows this is the case in the inner regions of the CSE of VX Sgr as V is negative for all OH mainline emission at $V_{\rm LSR} > 18$ km s^{-1} and predominantly positive

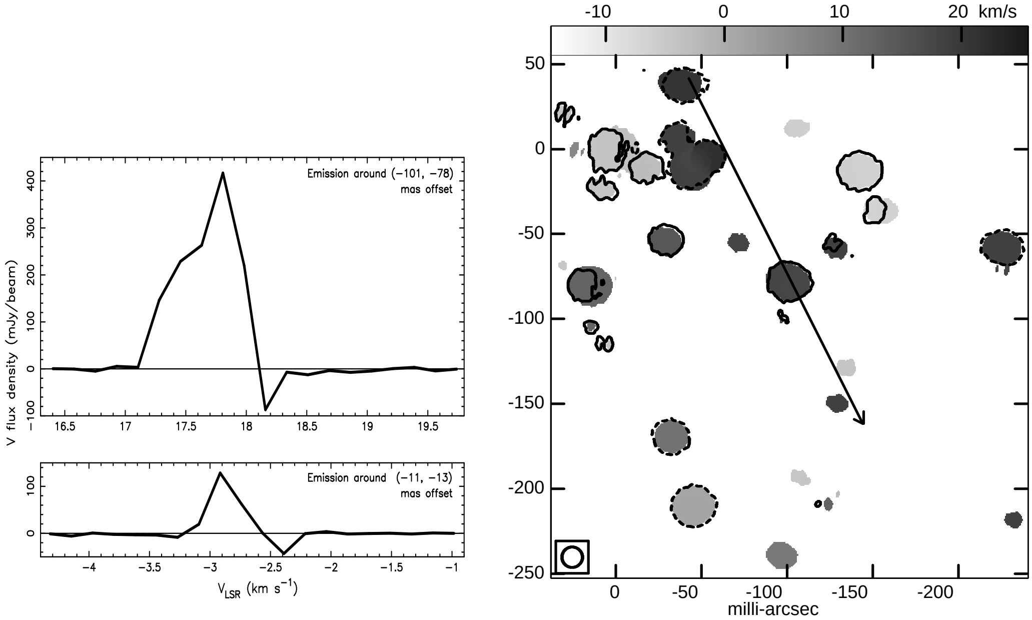

FIGURE 2. VX Sgr 1667 MHz maser emission: *Left* Stokes V velocity profiles for the two Zeeman pairs, at the positions given. *Right* Total intensity maser emission; the grey scale is proportional to the $V_{\rm LSR}$. The dashed contours enclose regions where V/I < –30%; the solid contours show V/I > +30%. (0, 0) is an arbitrary origin, but the stellar position is likely to be in the region of the extreme red- and blue-shifted masers. The arrow shows the proposed magnetic field direction

for $V_{\rm LSR} < 0$ km s^{-1}. If we assume the extreme red- and blue-shifted emission comes from close to the line of sight through VX Sgr, there is a mG magnetic field centred on the star with its axis directed towards the observer.

REFERENCES

BOWERS, P.F., JOHNSTON, K.J., DE VEGT C. 1989 *ApJ* **340**, 479.

CHAPMAN, J.M., COHEN, R.J. 1986 *MNRAS* **202**, 513.

CHAPMAN, J.M., COHEN, R.J., SAIKIA, J.D. 1991 *MNRAS* **249**, 227.

COOK, A.H. 1966 *Nat.* **211**, 503.

ELITZUR, M. 1988 *ApJ* **504**, 390.

GOLDREICH, P., SCOVILLE, N. 1976 *ApJ* **205**, 144.

KIRRANE, T-M. 1986 MSc Thesis, University of Manchester.

LOURIDAS, A. 2000 MSc Thesis, University of Manchester.

MASHEDER, M.R.W. ET AL. 1999 *NewAR* **43** , 563.

MONNIER, J.D., GEBALLE, T.R., DANCHI, W.C. 1998 *ApJ* **502**, 833.

PATAKI, L., KOLENA, J. 1974 *Bull. AAS* **6**, 340.

RICHARDS, A.M.S. 1997 PhD Thesis, University of Manchester.

RICHARDS, A.M.S., YATES, J.A., COHEN, R.J. 1999 *MNRAS* **306**, 954.

SZYMCZAK, M., COHEN, R.J. 1997 *MNRAS* **288**, 945.

SZYMCZAK, M., COHEN, R.J., RICHARDS, A.M.S. 1999 *MNRAS* **304**, 877.

YATES, J.A., COHEN, R.J. 1994 *MNRAS* **270**, 958.