Part IIb. H_2O MASERs

https://doi.org/10.1017/S0074180900222584 Published online by Cambridge University Press

Cosmic MASERs: From Protostars to Blackholes
IAU Symposium, Vol. 206, 2002
V. Migenes and M. J. Reid, eds

The H_2O maser proper motions of RT Vir and VX Sgr

Jeremy Yates

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK.

Anita Richards

JBO, University of Manchester, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, UK.

Malcolm Gray

Department of Physics, UMIST, P.O. Box 88, Manchester, M60 1QD, UK.

Abstract.
We have measured significant proper motions using the water maser clouds in the outflows from RT Vir (6 epochs) and VX Sgr (2 epochs). In both cases proper motions are measured in the bright emission found perpendicular to the OH emission. This strongly suggests latitude dependent mass-loss with the water masers tracing a dense equatorial outflow and the OH emission tracing a less dense polar outflow. In both cases the rotational velocities are < 1 km s^{-1} thus ruling out a strongly rotating circumstellar envelope. This suggests the outflow is not shaped by an orbiting companion. In the case of VX Sgr the proper motions are contained in a wedge perpendicular to the measured magnetic field axis, thus strongly suggesting that the magnetic field is helping to shape the mass outflow.

The proper motion results have thrown up a puzzle. For VX Sgr the material is being radially accelerated and material enters the water maser zone at 4 km s^{-1}. This is consistent with the mass loss model of Bowen (1988). However the RT Vir proper motion results show no such radial acceleration. The masers have already received their acceleration before they reach the water maser zone at 3-AU (our numerical models seem to support the small radius). This was probably done in the pulsation zone. The acceleration mechanism is unclear for this source.

1. Introduction

Mass-loss from long period variable red giants on the AGB phase replenishes the ISM with nucleosynthesis products such as C,N,O and Si in the form of molecules, as both gas and dust. It is by this process that efficient radiative molecules and chemical surface catalysts are placed in the ISM. These products make for more efficient future star formation and hence greatly affects future

https://doi.org/10.1017/S0074180900222584 Published online by Cambridge University Press

evolution of the galactic ISM and stellar populations. A typical AGB star of 1 $M_\odot$ radially pulsates with a period of 300 days. During the early and mid AGB the star loses mass at a rate of $10^{-6}\, M_\odot\, yr^{-1}$ for about 10^5 years. However at the end of the AGB the mass-loss rate increases by 100x and the star becomes an OH-IR star and the envelope does become optically thick at MIR wavelengths. At the end of the AGB the star will have lost up to 90% of its original mass. It will become a white dwarf star surrounded by a nebulae with both an ionised and molecular phase.

The role of dust is crucial in this mass-loss. Radiation pressure on dust is thought to drive the gas outflow via collisions. Proper Motion studies of H_2O masers using MERLIN and the VLA (Yates and Cohen 1994, Richards et al, 1996,1998,1999) show that the gas is accelerated above the escape velocity in the region populated by water masers (3-30 AU). The individual maser clouds can be tracked over time using the method of Doppler Tagging (Elitzur 1995). The overall maser spectrum is composed of many small spectral lineshapes of 0.5-2.0 km s^{-1} FWHM each having their own spatial position on the sky. These are the maser features or clouds. Each feature has its own unique Doppler velocity RA-Dec signature on the sky that is maintained over the lifetime of the feature (see Richards et al. 1996 for an excellent example of this). If the interferometer you use combines both 20-mas angular resolution and short baselines the spatial extent of the unique Doppler velocity RA-Dec signature gives the real spatial extent of the maser feature. This is because one is both able to resolve the maser cloud, but one is able to detect and map the weak extended flux as well; hence giving the real size of the maser cloud.

MERLIN2 has both these characteristics with 90% of the 22GHz maser flux detected. The cloud sizes are therefore a lower limit. To measure the real cloud size all the maser flux must be detected. The VLA and MERLIN together can perform this experiment and proposals have been made for this purpose. MERLIN2 22-GHz observations are making it increasingly clear that outflows from long period variable stars on the AGB contain discrete clumps (Bains 1995; Richards et al. 1996). MERLIN measurements of 22-GHz maser emission towards RT VIR and the red supergiant S Per measured unbeamed maser cloud sizes of 10^{13} and 10^{14} cm respectively. Using these sizes, maser emission models and the CO mass-loss rate the authors were able to estimate that the gas number density in a water maser cloud was 50 times that of ambient. The evidence that maser sites in these outflows represent real concentrations of material, blobs or clumps, and removing the nagging doubts that they were still chance velocity coherent alignments in the molecular outflow, has allowed us to use water masers as appropriate probes of the velocity field in mass outflows from evolved AGB and RSG stars.

Masers therefore do make excellent probes of the mass loss mechanism from AGB and RSG stars. We have begun a program to use 22-GHz water masers to monitor the motion of individual maser clouds in the outflows of RT Vir, VX Sgr, NML Cyg, VY Cma, S Per, W Hya, R Crt, U Ori and IK Tau. These observations will yield information on the density distribution, velocity structure and cloud distribution in the mass outflows from these stars. We will test simple radial acceleration models using the proper motion data. In this paper

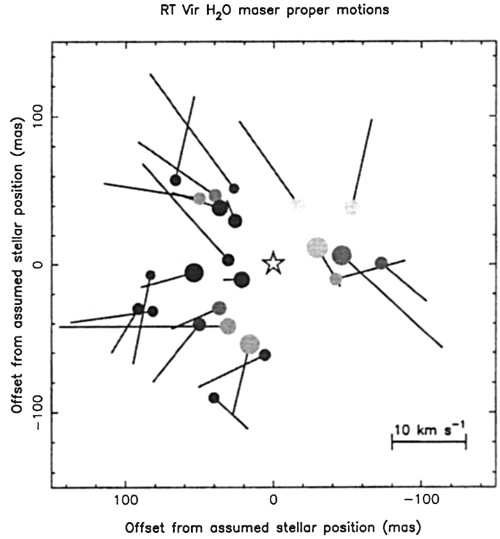


Figure 1. The H_2O maser proper motions at 6 epochs observed towards the semi-regular variable AGB star RT Vir over 10 weeks between April and June 1996. The proper motions are represented by heavy lines and are 10x their actual length. The maser features are represented by shaded circles; the darker, the more red-shifted they are.

we present our first 2 results for the Semi-regular variable star RT Vir and the red supergiant VX Sgr.

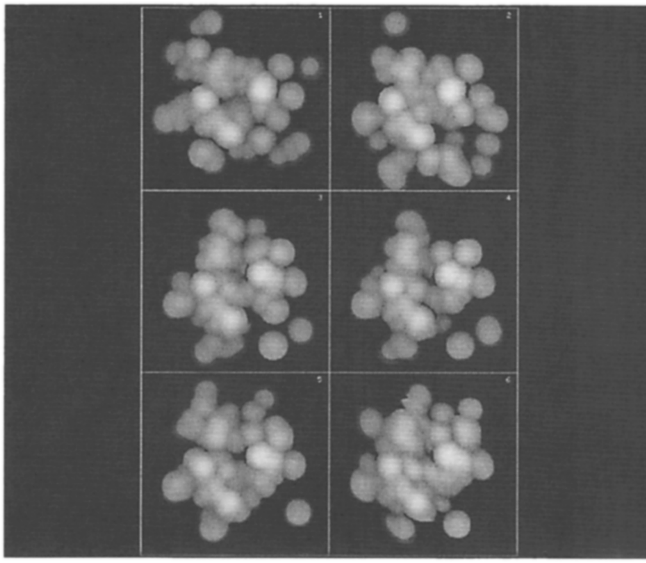
2. RT Vir

The semi-regular variable star RT Vir has a mass of 1.5 M⊙ and mass-loss rate of $3 \times 10^{-6}\,M_\odot\,yr^{-1}$. The Hipparcos distance is 140 pc. Yates and Cohen (1994) used MERLIN1 data (50-mas angular resolution) to show the 22-GHz H_2O maser emission was aligned E-W, with the blue-shifted emission offset to the W and the red-shifted emission offset to the East. The total velocity extent of the emission was 24 km s^{-1}, suggesting an expansion velocity of 12 km s^{-1} in the H_2O maser zone which had radial extent of 50-mas. Yates and Cohen suggested RT Vir was a strong candidate for a bipolar or rotating outflow.

The 22-GHz H_2O maser emission towards RT Vir was observed at 6 epochs over 10 weeks from April to June 1996 by the UK MERLIN2. The beam size was 12 mas and the velocity resolution was 0.2 km s^{-1}. Typical rms sensitivity per channel was 30-mJy. The MERLIN2 observations showed that the brightness distribution varied markedly over 10 weeks. The emission was spread over a region 140 mas (19 AU) in radius. The average inner radius of emission was 33 mas, 4.6 AU. The ability of MERLIN2 to detect structure on all spatial scales allowed us to measure the unbeamed sizes of the maser features. These turn out to be discrete dense clouds with a density contrast of 50:1 over the ambient medium, with sizes ranging from 2 to 16 mas. The typical cloud size is 10 mas.

https://doi.org/10.1017/S0074180900222584 Published online by Cambridge University Press

Figure 2. The H_2O maser cloud distribution at 6 epochs observed towards the semi-regular variable AGB star RT Vir over 10 weeks between April and June 1996. The cloud sizes are still convolved with the CLEAN beam of 12-mas.



The clumpiness of the wind is clearly observed in Figure 2. Some clouds can be seen to move (by eye) between epochs. The cloud brightness decreasing with with increasing radius, there is a clear brightening with time of the cloud - this could be a weak shock passing through. These clouds were used as proper motion markers and were used to measure the velocity field in the inner 100 mas of the circumstellar envelope around RT Vir. 11 maser clouds were detected at all 6 epochs and a further 7 also had proper motions accurate to $> 2\sigma$. The proper motions and positions of the maser clouds are shown in Figure 1. The lines are a least-squares fit to the maser positions; however there is actually possibly some systematic curvature as well as scatter.

The average proper motion corresponds to an expansion velocity of 12 km s^{-1}, which agrees with that deduced from the maser spectrum. The proper motion velocities of the clouds are anticorrelated with their Doppler velocities, which is expected for an outflow. The proper motions show a strong radial expansion component and the expansion velocity is **not** dependent on position angle. However the brightest masers are found along a WNW-ESE axis. The tangential components are randomly directed and the extreme red- and blue-shifted maser clouds show detectable proper motions. The upper limit on the rotation velocity is 0.2 km s^{-1}, hence rotation is negligible 7-14 AU from the star.

3. VX Sgr

VX Sgr is a red supergiant in the vicinity of the Sgr OB1 cluster at a distance of 1.7 kpc, although Loup et al. (1993) suggest it is at a distance of 400-

pc. This would make VX Sgr an AGB star and not a red supergiant. The proper motion measurements should be consistent with the velocity extent of the 22-GHz water maser spectrum. Thus the proper motion data will suggest which distance measurement is more appropriate for VX Sgr and confirm its status as either a red supergiant or AGB star. The spectral type of VX Sgr varies between M4e-Ia to M9.5 and it has well defined luminosity period of 732 days (Kukarkin et al. 1970). The period-luminosity suggests a mass of 10 $M_{\odot}$. The star is undergoing mass-loss at $2.0 \times 10^{-5}\, M_{\odot}\, yr^{-1}$ based upon an average of CO (Nercessian et al. 1989, A&A, 210, 225) and IR (Danchi et al, 1994) observations. The stellar temperature ranges between 2400-3300 K (Lockwood and Wing 1982) and optical and IR data suggest a stellar radius of 13-mas at minimum and 9-mas at maximum (Danchi et al. 1994). The stellar velocity estimated from OH 1612-MHz observations is 5.3 ± 0.4 km s^{-1}. Chapman and Cohen (1986) using MERLIN1 data showed that the22-GHz H_2O masers position-velocity distribution is consistent with them being located in an accelerating thick-shell region with a mean radius of 3×10^{13} m and a mean expansion velocity of 9 km s^{-1}. Both Chapman and Cohen (1986) and Bowers et al. (1993) show the H_2O maser distribution to be 300-mas E-W and 100-200 mas N-S.

The 22 GHz maser emission from VX Sgr was observed at 2 epochs in 1994 and 1999 by MERLIN2. At both epochs the brightness distribution comprises a bright WNW-ESE wedge 300 mas E-W and 150 mas N-S (See Figure 3) This contains the extreme red and blue-shifted emission and the bright emission at intermediate Doppler velocities. In this wedge the bright blue-shifted emission is found to the N and W and the red-shifted emission is found to the S and E. The wedge is parallel to the major axis of the OH 1612 MHz emission and perpendicular to the magnetic field axis (Szymczak and Cohen 1997). This wedge is contained within an ellipse of emission that is 450 mas N-S and 300 mas E-W. This contains dimmer emission at velocities close to V_*.

The maser emission at 1994 and 1999 were assigned to 92 and 96 features respectively. Forty-three maser clouds could be matched using the Doppler tagging technique suggesting 43 could survived between 1994 and 1999. The matched clouds were all in the wedge region. The proper motions between each pair of matched features are shown in Figure 4 (1994-1999). The squares show the 1994 features and the circles the 1999 features. The average values of the proper motion ΔXY, the radial change in position wrt the estimated stellar position Δradius and the tangential change in position wrt to the estimated stellar position $\Delta\theta$ are 10.7, 6.8 and -0.65 mas respectively.

About 37 of the ΔXY proper motions listed are significant at the 3σ level and 5 are significant at the 2σ level. Two out of 43 Δradius motions are negative and are above the 3σ uncertainty level. Tewnty-Seven out of 43 ΔA motions are positive and are above the 3σ uncertainty level. About 12 of 43 $\Delta\theta$ measurements are non-zero and are above the 3σ uncertainty level, however close inspection of the proper motion vectors and the value of the average $\Delta\theta$ shows there is no systematic rotation in this outflow. These results indicate a radial velocity field in the water maser shell around VX Sgr. The value of $\Delta\theta$ is the same size as the positional error and from these data we can place an upper limit of 0.7 mas (1 km s^{-1}) on the rotational velocity in the water maser region. Assuming a distance

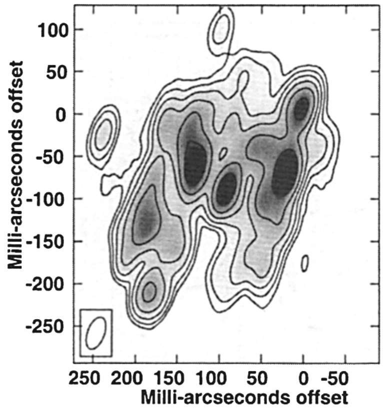


Figure 3. A grayscale and contour map of the 1999 VX Sgr 22-GHz H_2O maser emission integrated over all channels. The contours are 1, 2, 4, 8, 16, 32, 64, 128 and 256 times the lowest level of 0.1 Jy beam^{-1}. The grayscale covers the range 0 to 20 Jy beam^{-1}. A restoring beam of 40x20 mas^2 with position angle of -20^o was used.

of 1700 pc and a time baseline of 5 years the mean angular displacement and radial velocity become 17.6 and 11.2 km s^{-1}. The average values of the maser proper motions are within the velocity range of the measured spectrum $\pm$ 20 km s^{-1} This suggests that 1700 pc is a suitable distance to assume for VX Sgr.

Figure 4 clearly shows all the matched individual maser clouds undergoing significant proper motions. The proper motions are evenly distributed E-W of the common centre of expansion. The proper motions are confined to the bright E-W emission described in Section 3 and not to the low brightness low velocity halo described in Section 3. These are broadly spread into regions at positions angles of 50-190 degrees and 230-10 degrees respectively. There is a clear axis of position angle 210 degrees that shows few proper motion pairs and the water maser emission is fainter along this axis. The measured ΔXY, Δradius and $\Delta\theta$ values for each matched pair are plotted against the radial distance r_{94} at 1994 from the common estimated stellar position. These are presented in Figure 5. An error weighted least squares fit was performed on each set of data and is shown by a dashed line on each plot. The fit to the ΔXY-r_{94} data produced a fit of the form $\Delta XY = 0.051 \pm 0.018 r_{94} + 6.52 \pm 1.61$ mas with a correlation coefficient of 0.40,,$\Delta radius = 0.064 \pm 0.028 r_{94} + 1.68 \pm 2.46$ mas with a correlation coefficient of 0.34. There was no significant correlation between $\Delta\theta$ and r_{94}.

There is a correlation at the 99% level that suggests the radial velocity increases with distance from the star. This supports the dust driven mass-loss hypothesis. The radial component of the proper motion is related to the projected radial distance from the star by $v_{tang} = 0.11 r_{feat} \pm 0.05 + 2.4 \pm 4.6$ km s^{-1} (assuming a distance of 1700 pc). The fit suggests the VX Sgr water masers enter the H_2O maser region with a velocity of 4 km s^{-1}.

The distribution of the maser emission and the proper motion analysis suggest that the WNW-ESE wedge contains material that is expanding in a thick disk. This thick disk is also inclined to the sky plane such that blue-shifted

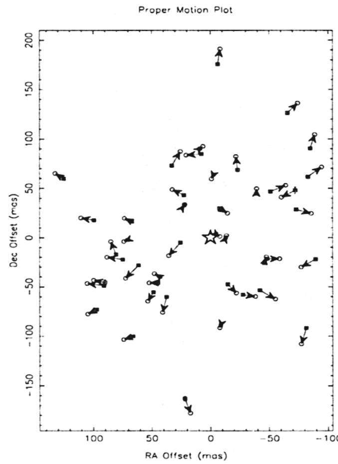


Figure 4. Changes in the positions of matched pairs of 22-GHz H_2O maser features in the CSE of VX Sgr between 1994 and 1999. The squares show the 1994 positions and the circles show the 1999 positions. The arrows show the displacement and direction of the proper motion between 1985 and 1994. The common centre of expansion position is at (0,0) and is shown as a star symbol. The error bars are usually smaller than the symbols used to show the 1994 and 1999 positions.

emission predominates in the N and W and red-shifted emission predominates in the S and E. This ellipsoidal shape in the brightness emission is probably due to latitude dependent mass-loss caused by the N-S magnetic field geometry of the star, which allows easier mass-loss from the equator of the star. This allows a denser wind to develop and hence brighter collisionally excited H_2O maser emission. The N-S ellipse of dim low Doppler velocity emission is probably from a less dense polar wind; the axis of this emission is close to the magnetic field axis.

4. Conclusions

We have measured significant proper motions using the water maser clouds in the outflows from RT Vir and VX Sgr. In both cases proper motions are measured in the bright emission found perpendicular to the OH emission. This strongly suggests latitide dependent mass-loss with the water masers tracing a dense equatorial outflow and the OH emission tracing a less dense polar outflow. In both cases the rotational velocities are < 1 km s^{-1} thus ruling out a strongly rotating circumstellar envelope. This suggests the outflow is not shaped by an orbiting companion. In the case of VX Sgr the proper motions are contained in a wedge perpendicular to the measured magnetic field axis, thus strongly suggesting that the magnetic field is helping to shape the mass outflow.

The proper motion results have thrown up a puzzle. For VX Sgr the material is being radially accelerated and material enters the water maser zone at 4 km s^{-1}. This is consistent with the successful model for mass loss of Bowen

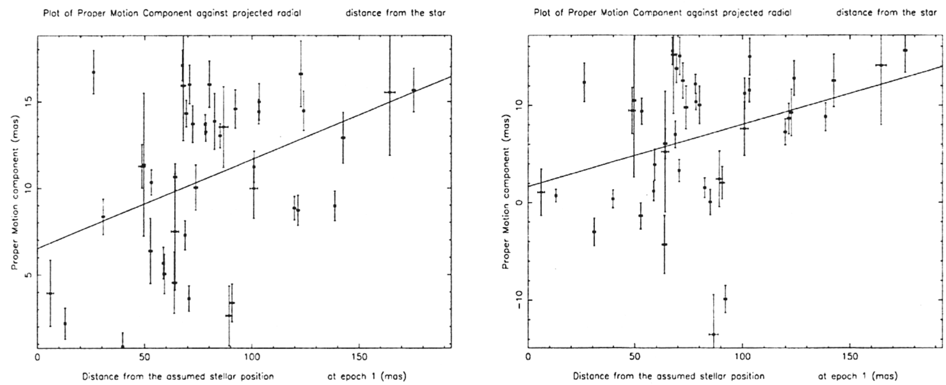


Figure 5. *Left*: The increase in angular separation ΔXY of 22-GHz H_2O maser features in the CSE of VX Sgr between 1994 and 1999 is shown as a function of the 1994 radial position. *Right*: The correlation between the change in radial position Δradius of the maser features between 1994 and 1999 and the 1994 radial position.

(1988) that shows that stellar pulsations levitate the atmosphere, allowing dust to condense. The dust is then accelerated away from the star by stellar radiation pressure and transfers this outward momentum to gas molecules via collisions. However the RT Vir proper motion results show no such radial acceleration. The masers have already received their acceleration before they reach the water maser zone. This was probably done in the pulsation zone. The acceleration mechanism is unclear for this source.

References

Bains, I., 1995, MSc Thesis, Manchester University.

Bowen, G., 1988, ApJ, 329, 299.

Bowers, P.F., Claussen, M.J., Johnston, K.J., MNRAS, 1993, AJ, 105, 284.

Chapman, J.M. & Cohen, R.J., 1986, MNRAS, 220, 513.

Danchi, Bester, Degiacomi, Greenhill, Townes, 1994, AJ, 107, 1469.

Elitzur, 1995 in RMAASC on Circumstellar Disks, Outflows and Star Formation, ed. Cozumel, 85.

Lockwood, G.W., Wing, R.F., 1982, MNRAS, 198, 385.

Loup, C., Forveille, T., Omont, A., Paul, J.F., 1993, A&AS, 99, 291.

Richards, A.M.S., Yates, J.A., Cohen, R.J., 1996, MNRAS, 282, 655.

Richards, A.M.S., Yates, J.A., Cohen, R.J., 1998, MNRAS, 299, 319.

Richards, A.M.S., Yates, J.A., Cohen, R.J., 1999, MNRAS, 306, 954.

Szymczak, M, Cohen, R.J., 1997, MNRAS, 288, 945.

Yates, J.A. & Cohen, R.J., 1994, MNRAS, 270, 958.

Yates, J.A., Gray, M.D., Field, D., 1997, MNRAS, 285, 303.