PoS PROCEEDINGS OF SCIENCE

Maser misto: overlap in circumstellar envelopes

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MERLIN and global VLBI observations show that, in three out of four red supergiants, the OH mainline masers exist at similar distances from the star as do the water masers. This is unlikely to be solely a projection effect, although there are some signs of latitude dependence. It seems probable that at least some of the OH emission comes from the less dense gas surrounding the water maser clouds. The smaller OH shells around Miras and other AGB stars are harder to image at high enough resolution and tend to be resolved-out by VLBI, but we have obtained enough MERLIN and/or EVN data for a handful of objects to show a similar, but less pronounced effect. This leads to several questions: What produces the OH so close to the star? The OH masers are not closely co-spatial with water masers, but even so, how can their very different propagation requirements be satisfied? We also consider the further investigations which will be possible with e-MERLIN and the next generation of VLBI, such as whether the same clump of gas may progressively support SiO, water and OH masers, as it flows away from the star in the stellar wind.

This paper is dedicated to the memory of Jim Cohen, who contributed so much to the study of this field in general and these sources in particular.

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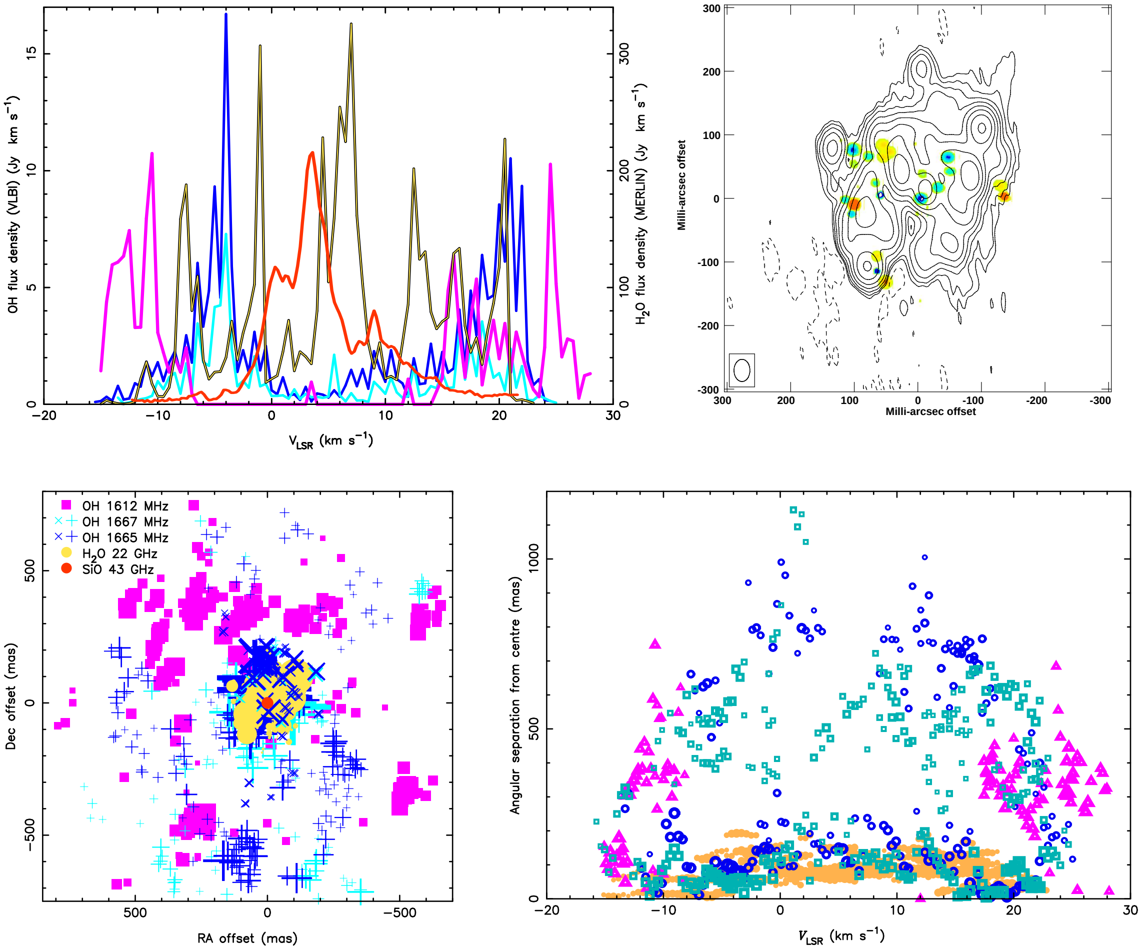

Figure 1: Distribution of masers around VX Sgr. The spectra (top left), and the component positions (lower plots) show the species colour coded as in the position plot. H_2O [8] and OH 1612-MHz [15] data are from MERLIN; OH mainline data are from MERLIN and VLBI. The SiO spectrum is from [4]. The contoured image at top right shows integrated H_2O maser emission overlaying a first moment map of the VLBI OH mainline masers, colour representing velocity.

1. The traditional 'Onion' model for circumstellar envelopes

Stars more than about 8 times the mass of the Sun live fast and go out in a blaze of glory as a supernova. It is less well known that even before then, these stars contribute up to half of all the dust and a large proportion of light elements which enrich the interstellar medium and hence the next generation of star formation. Red supergiants (RSG) typically lose half their mass over a few hundred thousand years. Lower-mass Asymptotic Giant Branch (AGB) stars have lower mass loss rates but are more than two orders of magnitude more numerous and are a similarly important source of silicate dust. The stars lose mass through a combination of pulsation and radiation pressure on dust. They have no detectable rotation and the simplest "onion" model [9] places spherical SiO, H_2O and OH maser shells at increasing distances from the star. Typical stellar radii ($R_\star$) are around 1 AU for AGB stars and 10 times greater for RSG. SiO masers at 43 and 86 GHz are found from 2–5 $R_\star$, by which distance dust formation is more or less complete, the temperature has dropped to about 1000 K and H_2O maser emission at 22 GHz appears. The outermost maser species is OH 1612-MHz emission, at between 50 and a few 100 $R_\star$. The various masers occur in order of decreasing excitation temperature and it was thought that the OH masers form where H_2O is dissociated by external interstellar UV.

The spectra shown in Fig. 1 show that expansion velocity increases as expected for species found further from the star. This demonstrates acceleration continues out to many hundreds of AU from VX Sgr, first noted by [2] and also seen in other RSG ([11]; [12]; [13]; [8]).

2. Red supergiant deviants

Figure 1 shows that the OH mainline masers are found at intermediate distances between the H_2O and OH 1612-MHz masers. The total extent of the VX Sgr H_2O maser shell is a few hundred mas, just a few times the MERLIN beam at the OH frequencies. The positions of bright masers can be found with greater precision by component fitting, but global VLBI plus EVN observations of VX Sgr and S Per [7] were needed to confirm that the mainline masers are indeed interleaved between the outer H_2O maser clouds. The slightly nearer, larger RSG, VY CMa and NML Cyg, are better resolved by MERLIN alone. The OH mainline masers overlap the H_2O masers in 3 out of the 4 RSG (Richards et al. 1999; Murakawa et al. 2003). The exception, NML Cyg, may be approaching a later stage of evolution with signs that the mass loss rate has changed [6] and is becoming bipolar [11].

There are three possible scenarios: that the H_2O and OH mainline masers co-propagate; that they are found at similar radii but different latitudes or azimuthal angles, or that they are interleaved on a smaller scale. The first option is highly unlikely, since H_2O maser amplification takes place under hotter, denser conditions (typically T 500–1200 K; $5 \times 10^{14} < n < 5 \times 10^{15}$ m^{-3}) than those needed to invert the OH mainline transition. Despite several searches, no excited OH masers are detected (apart from in NML Cyg, [16]), so the OH gas must be at $T \leq 500$ K and $n \leq 10^{14}$ m^{-3}. The second possibility is hard to rule out completely but current observations support the third option, described in detail in [13] and [8].

Evidence for the concentration of H_2O masers in dense clouds is illustrated in Fig. 1 lower right, which shows a sharp cut-off to the inner edge of the H_2O maser shell (in yellow). The inner rim is defined by the number density at which the masers are collisionally quenched, $n_q \approx 5 \times 10^{15}$ m^{-3} [5]. However, if the entire maser shell had this density, the mass loss rate of the star would have to be up to ~ 100 times higher than is indicated by measurements from other species such as CO or dust. MERLIN directly resolves the H_2O clouds, which are, on average, 10–20 AU in size around RSG. Up to 100 clouds are found between about 5–50 $R_\star$ with a volume filling factor of $\leq 1\%$. This implies that they are about 50–100 times denser than the surrounding gas, which in turn would thus be of a suitable density to support OH mainline masers.

3. New results for AGB stars

MERLIN observations demonstrate the clumpy nature of H_2O masers around AGB stars also, in clouds about one tenth the size of those around the RSG [1]. The maser regions can only be resolved in detail around stars within a few hundred pc. At such distances the entire OH shell is

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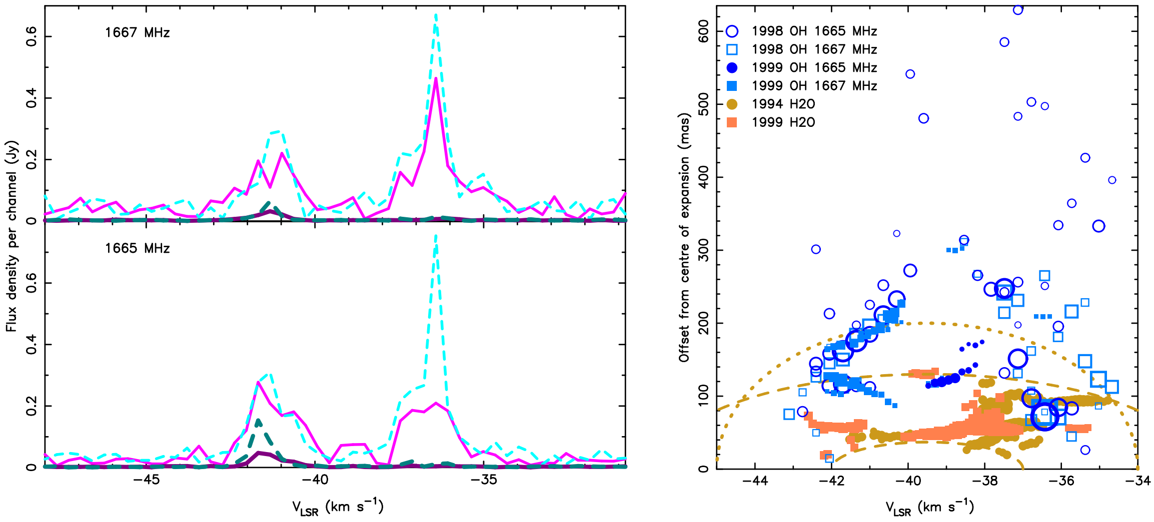

Figure 2: The paler lines on the left show 1998 MERLIN spectra of OH mainline masers from U Ori; the darker lines show contemporaneous EVN data, in LCP (dashed, blue) and RCP (continuous, purple). The right-hand plot shows the angular positions with respect to velocity for the combined MERLIN+EVN OH mainline maser components (1998) and EVN-only (1999) compared with the H_2O masers.

only slightly larger than the MERLIN beam, but VLBI alone resolves out extended emission. We obtained EVN data for 8 objects, including the 4 covered in [1], IK Tau, RT Vir, U Her and U Ori, with contemporaneous MERLIN data for U Ori in 1998.

The U Ori spectra in Fig. 2 shows that the EVN only detected a small fraction of the total OH emission (whilst MERLIN detects about half of the flux seen at arcsec resolution). The flux density on the longest MERLIN baselines was similar to that on the shortest EVN baselines (of similar length) and we combined the data to produce image cubes with a resolution of 50 mas. The MERLIN OH data were phase-referenced, as were a later epoch of H_2O observations, giving a combined astrometric uncertainty of ~ 50 mas, plus uncertainties in proper motions. The species and epochs were aligned by assuming that the masers emanate from spherical shells with the same centre of expansion. The OH mainline masers appear to overlap the H_2O maser shell in the right-hand plot in Fig. 2 but we consider the alternatives.

The H_2O maser shell around U Ori is poorly filled and asymmetric. The maser distribution varied considerably and the angle of elongation changed from NNE-SSW in 1994 to E-W in 1999, although the brightest emission was at a similar distance from the star, albeit in a different direction (unrelated to the change in angle of elongation). This suggests that masing from individual clouds lasts < 5 yr, but there is no reason not to adopt a spherical envelope for the H_2O masers. The sound-crossing time for a 1-AU cloud is 1.6 yr, and proper motion studies in U Ori and other AGB stars suggests that clouds can be tracked for up to 18 months but not longer. Our OH and 1999 H_2O observations were made within 1 yr. The OH mainline masers have occupied a shell of similar extent for at least a decade [3]. Overall, variability or changes in the extent of the maser shells between observations are not likely to have produced spurious results.

The second possibility is that the OH distribution has a different latitudinal or angular dependence, for example occurring in polar regions whilst the H_2O is equatorial. MERLIN has made

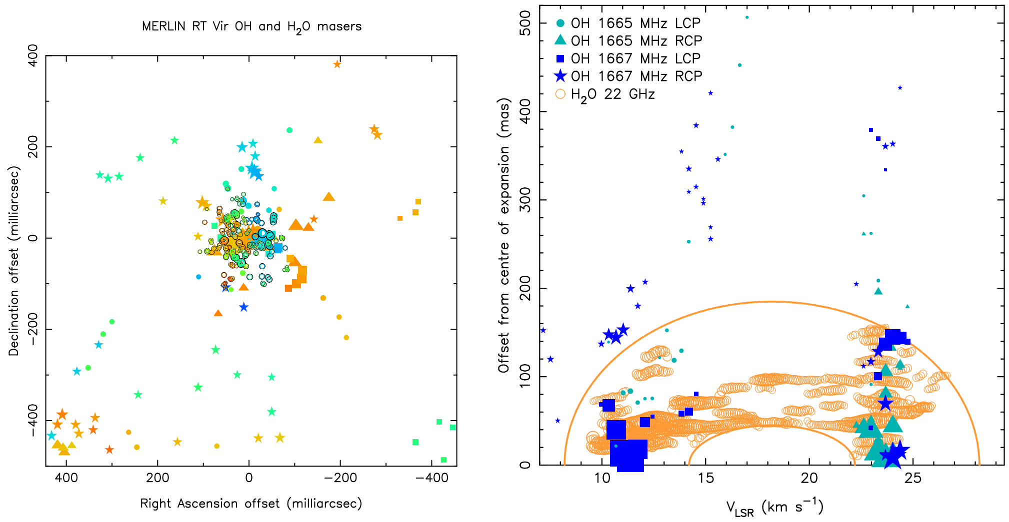

Figure 3: The positions of OH mainline masers and H_2O masers (outlined in black) around RT Vir are shown on the left. The plot on the right shows the angular positions with respect to velocity, colour coded according to the key.

22-GHz multiple epoch observations of all the stars in our sample; averaging over time shows that the H_2O maser shells are filled at all position angles (as discussed above for U Ori). However, there are persistent preferred directions; for example the H_2O masers around VX Sgr are fainter (although still present) in the direction of the magnetic axis [8]. In these AGB stars, the OH mainline masers have expansion velocities which often barely exceed that of the H_2O masers and their velocity profiles suggest that the OH is undergoing less acceleration, since the extreme blue- and red-shifted front and back caps are usually brighter than emission from around the stellar velocity. This is seen in RT Vir, shown in Fig. 3. If emission at close to the stellar velocity (from regions more extended in the plane of the sky) is too faint to be seen, this makes it harder to rule out projection effects producing the overlap. The stronger acceleration of H_2O masers is consistent with their origins in denser clumps, since the wind is driven by radiation pressure on dust and momentum is more effectively transferred to the gas in denser regions with a higher collision rate.

To date, W Hya and IK Tau have also been investigated; no overlap is seen in W Hya whilst a single inner clump at 1667 MHz is detected in IK Tau. The latter is the only AGB star in the sample with well-resolved OH 1612-MHz emission; this is found at much greater angular separations than the H_2O, as is the case in all the RSG.

4. Implications for the study of mass loss from evolved stars

The apparent interleaving of OH mainline masers in between H_2O maser clouds is evidence for clumpy mass loss from AGB and RSG stars, supporting the contention that the clouds are defined by being denser than their surroundings (rather than just by accidents of turbulence). The size of the clouds scales with the size of the parent star, suggesting that they are produced by stellar processes such as convection cells, rather than by local events such as cooling runaways further out in the wind. OH in the inner CSE could be produced by dissociation of H_2O by UV from the stellar chromosphere, or by the propagation of shocks from the stellar pulsations (probably more significant in RSG and AGB stars, respectively) or might be present throughout the wind, since OH has been observed in IR lines from the outer photosphere.

We hope to follow up investigations as part of the e-MERLIN RAGBBBBAGSS (Radio, AGB, B, Be & Binary Advanced Giant Star Studies) legacy proposal, which will simultaneously observe stellar 22-GHz continuum and H_2O masers and track clumps through the various maser shells, starting with VLBA SiO observations. The e-MERLIN results will also confirm (or otherwise) the position of the star at the centre of expansion (hitherto only seen for a very few objects, [10]) while the ability to use much fainter phase reference sources will ensure that all maser species can be securely aligned. The new correlator will allow all ground-state OH transitions to be observed simultaneously, without having to compromise between velocity extent and resolution. Such flexibility will also make it much more straightforward to combine e-MERLIN and EVN spectral line data, required to obtain the resolution and sensitivity needed for OH. This will enable us to constrain models for the physical conditions and contrasts producing OH mainline masing gas surrounding H_2O clumps, as well as to investigate the evolution of the wind and to measure distances using the phase-lag method.

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