# VLBI Observations of OH stars : S Persei

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**Abstract**

The masers in three stars, S Per, OH53.6-0.2 and VXSgr, were observed in the main lines of OH at $\lambda$18 cm in March 1997 with a VLBI array consisting of 6 EVN antennas and 3 in the USA. Both S Per and VX Sgr were detected on transatlantic baselines, showing that at least some of the maser spots are very compact with sizes less than around 2 mas. The observations confirm that in S Per there is main line OH emission close to star at a similar distance ($\approx$ 100 AU) as the $H_2O$ shell. The most blue-shifted emission comes from the centre of the object suggesting radial amplification of the maser radiation, whilst most of the remainder comes from a thick shell, some 100 AU from the star. This contrasts with the 1612 MHz OH emission that comes from an outer shell some 1000 AU from the star. Estimates of the magnetic fields in the shell from Zeeman pairs in S Per show fields of a few hundred nT.

*Key words:* radio lines: stars, stars: AGB and post-AGB, circumstellar matter, individual (S Persei)
*PACS:* 97.10.Fy, 97.10.Me, 97.20.Pm

[1] MRWM & MDG acknowledge the support of the European Commissions TMR programme, "Access to Large-Scale Facilities" under contract No. ERBFMGECT950012.

## 1 Introduction

Masers due to various species of molecule often arise in the circumstellar envelopes of evolved AGB and RSG stars. Each type of maser requires a different set of conditions to operate, so the masers form at differing distances from the central star, giving rise to the so-called "onion" standard model. Although this model may be inadequate in a number of ways, it nevertheless provides a useful framework. In this model the central highly-luminous evolved star is losing mass from its extended atmosphere. In a shell around 2 to 4 stellar radii molecules start to form, in particular SiO, which can form masers in this relatively warm and dense region. These are therefore observed close to the star and at velocities around the stellar velocity. Further out the refractory materials condense out to form dust grains. The dominant force on these grains is the pressure from the stellar radiation, so they are accelerated outwards. In this process they entrain the molecules of the gas, giving rise to an accelerating wind. The drift velocity between the dust and the gas is smallest in the densest regions.

Outside the dust formation shell, $H_2O$ is formed and its masers at 22GHz are commonly observed. In the accelerating wind, the longest paths with small velocity gradients lie tangentially to the shell and this is where $H_2O$ masers are often seen with modest velocities relative to the star; however higher velocity $H_2O$ masers are also seen. Finally, much further away (around 100 stellar radii) from the star, the wind has a constant velocity and the $H_2O$ is dissociated by interstellar UV to form OH. Here strong OH masers at 1612 MHz are often observed with a characteristic double peaked spectrum corresponding to the front and back of the shell. The typical outflow velocities as measured by the separation of these peaks is between 5 and 20 $\mathrm{km\,s^{-1}}$.

Main line OH masers at 1665 and 1667 MHz are also often observed in these objects, but they do not fit well with this onion model and are the subject of the present contribution. Results from the present VLBI observations confirm the impression from the lower resolution MERLIN results (Richards et al., 1998) that in S Per at least, they arise not in the outer OH shell but from that usually associated with $H_2O$ masers.

## 2 The VLBI Observations

### *2.1 What we can learn from VLBI of OH/IR Stars*

(1) In order to understand the structure of the object, the most important measurements are those of the positions of the various maser features. These may be then combined with velocity information to model the geometry and kinematics of the emitting region. In particular the features can be fitted to an expanding shell model as part of the onion model described in the introduction.

(2) Any features in the two hands of circular polarisation which are aligned in position can be used to measure the magnetic field using the Zeeman effect. A field along the line of sight shifts the frequencies of the two components of polarisation in opposite directions so that it can be estimated by the apparent velocity difference.

(3) Very small angular diameters are characteristic of OH masers. Their spot sizes can be measured if there are baselines in the VLBI array of more than about 5000 km. Assembling the maser components into features in three dimensions ($\alpha, \delta$,vel) can give useful information about the masing clouds.

### *2.2 The VLBI setup*

The observations were made in March 1997, using nine telescopes, of which six were in Europe (Effelsberg, Jodrell, Medicina, Onsala, Torun, Westerbork) and three in USA (Green Bank, Hancock, St Croix).

This experiment was one of the first in Europe to use the MkIV recording system. This allowed easy scheduling and enhanced sensitivity with 2-bit sampling at twice the Nyquist rate using four 500 kHz bands. Each band corresponds to one OH line in one polarisation. The VLBA correlator divided each band into 512 spectral channels, giving a resolution of 0.17 km/s.

### *2.3 Data reduction*

As usual, AIPS software was used to process the data. The fringe rates, delays, and the bandpasses were calibrated using continuum sources in the standard way. To map the spectral line emission, a reference feature was selected for each band and one of these (1667 RCP in S Per) was chosen to be the overall spatial origin of the experiment. Its FRING solution was applied to all the

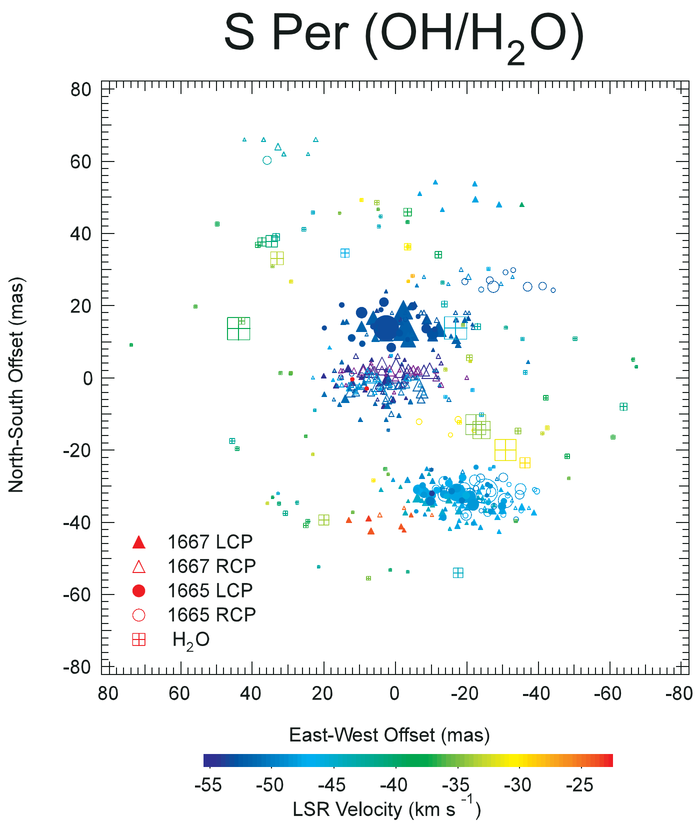


Fig. 1. OH main line maser features in S Persei mapped with strongly tapered long baselines and located with Clumpfind. For comparison the positions of $H_2O$ masers found with MERLIN are shown (Richards et al., 1998).

bands and maps of the reference features made. These were used as the input models for FRING on these references, thus ensuring proper registration of the four maps. Self-calibration solutions were then found for these offset references and used to make four $\alpha$–$\delta$–vel datacubes.

The datacubes were searched for maser features by two methods: (i) The AIPS task SAD (Search And Destroy) was used to fit 2-D spatial gaussians to the emission in each spectral plane. Thresholds were kept low and SAD's rejection features disabled to avoid missing any interesting emission. There is of course then the danger of allowing noise peaks and other spurious effects into the data. We therefore used a program called HAPPY to filter the data from SAD and assemble them into features. In particular, the filter demands that there be emission in 3 consecutive spectral channels. (ii) Clumpfind (Williams et al., 1994), an IDL program designed to analyse 3-D clumps in molecular clouds, was applied to each cube. In this program, clumps or features are assembled by testing the emission in each pixel to see if it should be associated with neighbouring pixels. It has the advantage that it makes no assumptions about the shape of the features in either space or velocity.

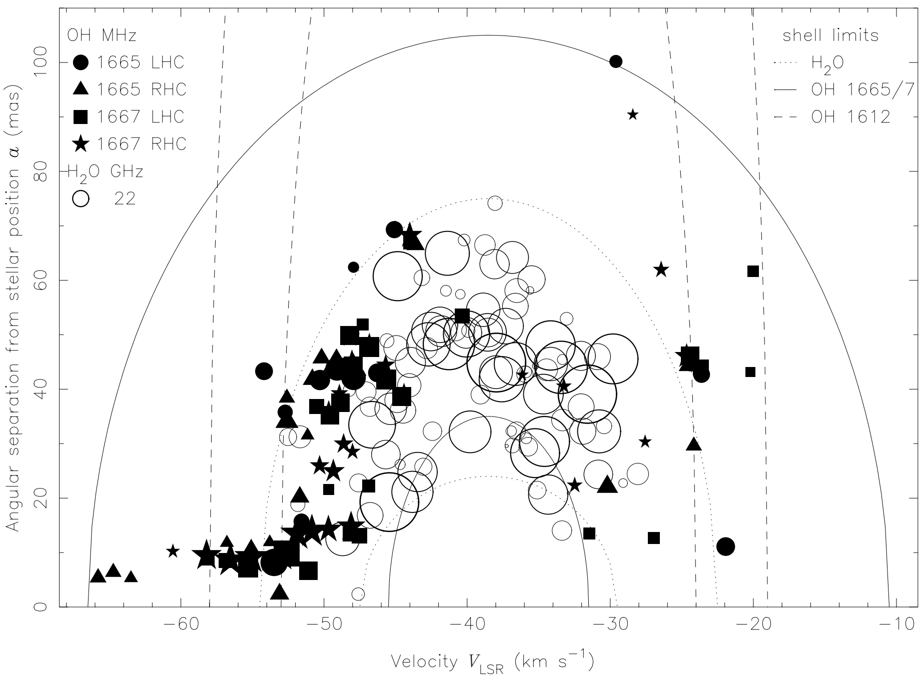


Fig. 2. The angular offsets of OH main line maser features in S Persei plotted versus radial velocity. For comparison the $H_2O$ masers found with MERLIN are shown together with the velocity limits of a fit to an expanding shell for MERLIN observations of the 1612 MHz OH emission.

## 3 Results on S Per

### *3.1 Mapping*

The cubes were mapped in several ways. With natural weighting and no tapering the beam was 2.5×7.0 mas. The four cubes, 1667 LCP, 1667 RCP, 1665 LCP and 1665 RCP, had peaks fluxes of 5.2 Jy, 5.7 Jy, 2.2 Jy and 1.6 Jy respectively. All had an rms noise around 5 mJy/beam in one spectral channel.

Fig. 1[2] shows the positions of the OH main line features mapped with the long baselines strongly tapered. The cubes were searched with Clumpfind to locate the features. The positions of 22 GHz $H_2O$ masers measured with MERLIN (Richards et al., 1998) are also shown for comparison. The registration between the four OH maps is due to measurement and is secure to within about 1 mas; that between the OH and $H_2O$ maps is inferred from fits to expanding shells and is therefore less secure. Fig. 2 shows the distances from the star of both the main-line OH from the present VLBI observations and $H_2O$ from MERLIN

[2] A larger colour version is available by application to mike.masheder@bristol.ac.uk

plotted versus their velocities. The position of the star itself is found from the fits to the shells.

It is clear from these observations that the main line OH masers appear to come from rather close to the star, at distances similar to those where the $H_2O$ masers are found, in contrast to the 1612 MHz OH masers associated with the outer parts of the envelope. However, it is noticeable that these OH and $H_2O$ masers appear to avoid each other in both position and velocity.

Some of the features in the cluster around the (0,0) position in Fig. 1 are strongly blue-shifted and have apparent expansion velocities greater than the blue-shifted 1612 MHz OH emission at $-55$ km s$^{-1}$ (see Fig. 2). It is thus dubbed "Fast OH" and evidently presents a challenge to an onion model with a monotonically accelerating wind.

### *3.2 Magnetic Fields*

Matching LCP and RCP features were identified on zeroth moment maps of the data cubes shown in Fig. 1. Their spectra were then extracted with ISPEC and compared. The velocity shifts were found to be small with the largest secure measurement being 0.7 mG. The weakness of the fields is compatible with the observed spherical appearance of S Per.

### *3.3 Maser Spot Sizes*

These have been investigated by two methods. The visibility versus UV-distance of twelve bright maser components shows that they are all unresolved on all baselines to a limit of about 2 mas. Gaussian fitting in the image plane suggests that the spots are somewhat resolved, but with a similar limit. Series of several maser components in adjacent velocity channels have positions within a few mas. In many cases the components with the greatest angular separation within the series are also at the greatest velocity separation, typically 1–2 km s$^{-1}$. This suggests that the emission comes from discrete masing clouds with an unbeamed angular diameter of about 4–10 mas.

We have also observed that there are many features in the spectra of VX Sgr which are bright on the long baselines, confirming the observations of Chapman et al (1996). Our observations of OH53.6 show that its 1667 MHz emission is well resolved, whilst that at 1665 MHz is only partially resolved.

## 4 The Wind in S Per

The present observations and those of Richards et al. (1998) are not explained well by the standard onion model in two respects: (a) the presence of OH main line masers near the $H_2O$ masers and (b) the blue-shifts of the fast OH, which are greater than that of the 1612 MHz masers in the outer shell.

In an attempt to account for these phenomena we propose a modification to the onion model, in which the wind is clumpy. For a more detailed and quantitative account refer to Richards et al. (1998). In the inner region, the $H_2O$ masers are formed in dense clumps immersed in more tenuous gas where the OH emission arises. The OH may be formed by photodissociation both by interstellar UV that can penetrate between the $H_2O$ clouds and by UV from the star. Because the lower density gas is less well coupled to the streaming dust, the velocity gradient is smaller, thus favouring radially beamed OH masers.

Further out where the overall densities are lower, it is in the clumps that the OH masers can form. These clumps are still relatively tightly coupled to the flow of dust so can acquire a large outflow velocity. These masers therefore appear as the fast OH.

1612 MHz OH masers require long paths through relatively tenuous gas, so they appear radially beamed in the free-flowing wind in the outer regions of the envelope. The reduced density leads to an increased drift velocity ($\sim$6 $\mathrm{km\,s^{-1}}$) so that this maser emission may be seen at a lower velocity than the fast OH.

## References

Chapman, J.M., Reynolds, J., Wilson, W., et al., 1996, in : King, A.E. (ed), Proceedings of 4th Asia-Pacific Workshop, Australia Telescope National Facility.

Richards, A.M.S., Yates, J.A., & Cohen R.J., 1998, MNRAS, submitted.

Williams, J.P., de Geus, E.J., & Blitz, L., 1994, ApJ, 428, 693.