# Amplification of the Stellar Image by Circumstellar OH Masers

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Various observations of circumstellar OH masers have confirmed the existence of an amplified stellar image, radiation originating from the stellar radiosphere amplified by a circumstellar OH maser screen. However, some questions regarding the observations of multiple bright maser spots and residual spot motion still remain. Proper motion and parallax of the amplified stellar image of U Herculis have now been measured, for 8 epochs of observations.

## 1. Introduction

In the circumstellar envelopes surrounding AGB stars various different maser species may be found. SiO masers are found closest to the central star, while $H_2O$ masers occur at slightly larger distance (Habing, 1996). In this paper we discuss observations of OH masers which can be detected at the 1665 and 1667 MHz main line and 1612 MHz satellite line transitions. The masers are thought to be located at a distance of $\approx 10^{16}$ cm from the central star, the satellite line situated outside the region with the main line masers. The OH satellite line profile often shows a double peaked spectrum, interpreted as an expanding spherical shell (Reid et al., 1977). This suggestion has been confirmed by VLA (i.e. Bowers et al., 1983) and MERLIN (i.e. Diamond et al., 1985) observations. Since the OH maser process is dominated by radiation travelling radially, emission is mostly seen from the front and rear caps of the shell, as illustrated in Fig. 1. The main source of radiation to be amplified is spontaneous emission originating in the maser shell itself, self-amplification. However, it has been suggested that on the line of sight to the star, radio emission from the star can be amplified (Norris et al. 1984; Van Langevelde & Spaans, 1993).

## 2. Amplified Stellar Image

Continuum emission at cm wavelengths from the star originates from the stellar radiosphere as detected by Reid & Menten (1997). It is thought to extend up to the SiO masering region and can be twice as large as the stellar photosphere. Observations can reveal if radiation from this radio-sphere is amplified by the masing screen in front of it.

### 2.1. *Observational effects of a Background Star*

Amplified radiation from the background star results in a bright compact spot, the stellar image, at the most blue-shifted side of the circumstellar shell. This spot, brighter than other, self-amplified, spots, can then be distinguished by high resolution interferometric observations. Similarly bright red-shifted emission should not be found.

The amplification process works similarly for the different maser transitions, thus the stellar image is expected to occur in both the main line and the satellite line masers. Because the spot is necessarily fixed to the true stellar position, a spatial comparison should find the spots to coincide at the different transitions.

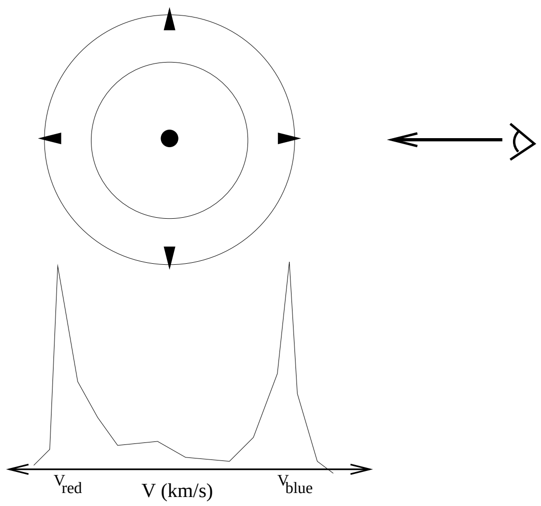


FIGURE 1. OH maser shell with characteristic OH spectrum.

Thirdly, because the line of sight amplification is less sensitive to variations in the masering medium, the stellar image should be persistent throughout multiple epochs of observations.

### 2.2. *Applications*

The stellar image, fixed on the true position of the underlying star, has several interesting applications.

Phase referenced VLBI observations allow for very accurate determination of the radio positions. Comparing the position of the stellar image with optical stellar positions obtained by for instance the Hipparcos satellite, allows for very accurate linking of the optical and radio reference frames.

By tracking the position of the most blue-shifted maser spot over multiple epochs the stellar trajectory can be determined. This enables us to determine proper motion and parallax of stars too faint to be observed optically. Distances to these heavily enshrouded objects are fundamental for studies of stellar evolution.

## 3. Observations

There have been various observations confirming the amplified stellar image theory. The theory was postulated by Norris et al. (1984) whose observations yielded compact features only at the blue-shifted side of the spectrum. Sivagnanam et al. (1990) showed in observations of U Her that the compact, most blue-shifted spot at 1667 MHZ is the brightest maser feature, and that it coincides with the most blue-shifted spot at 1665 MHz.

Recent VLBI phase referencing observations of U Her (Van Langevelde et al. 1999, 2000) have allowed for a comparison between the radio position of the most blue-shifted spot and the Hipparcos optical position with unprecedented accuracy. Fig. 2 shows a zeroth moment map with the stellar radio- and photosphere drawn in. SiO observations give an upper limit to the diameter of the radiosphere of $\approx 20$ mas. As can be seen, the most blue-shifted spot at $-20.6$ km/s and the optical star coincide within the errors.

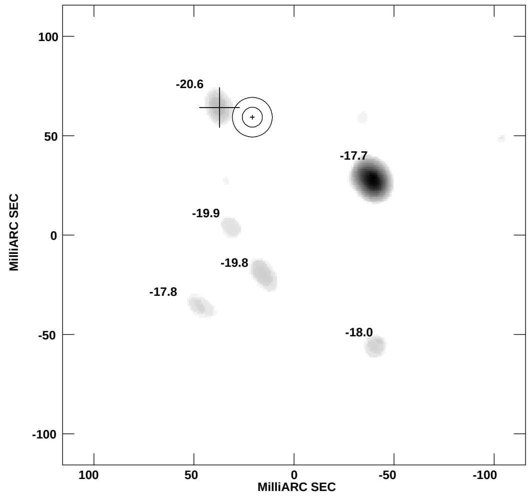


FIGURE 2. Zeroth moment map of the maser spots around U Her. Each spot is labelled with the corresponding velocity. The optical and radio photosphere of the star are drawn (concentric circles) as well as the error bars on optical and radio position. The error bars on the radio position include the uncertainty from extrapolating the fitted proper motion.

However, Fig. 2 also shows an unexpected result: at this observational epoch, the most blue-shifted spot was not the brightest spot. This will be discussed further below.

### 3.1. *Application: Proper Motion & Parallax*

We have used 8 epochs of VLBI phase referenced observations of U Her to determine the proper motion and parallax. The fit to the motion of the most blue-shifted maser spot is shown in Fig.3. The fitted proper motion ($\mu_{\rm VLBI} = -17.11 \pm 0.75, -9.97 \pm 0.63$ mas/yr) is entirely consistent with the Hipparcos proper motion ($\mu_{\rm Hip} = -16.84 \pm 0.82, -9.83 \pm 0.92$ mas/yr) (ESA 1997). A parallax of $\pi_{\rm VLBI} = 6.22 \pm 1.31$ mas is detected, the Hipparcos parallax ($1.64 \pm 1.31$) was inconclusive because of the star being too faint. There are however some residuals remaining in the fit that cannot readily be explained. Earlier results on the first 6 observational epochs of U Her are discussed in Van Langevelde et al. (2000).

## 4. Discussion

The most compelling evidence for the stellar image theory is the comparison between the radio and optical positions of U Her. The U Her stellar image has been tracked over 6 years to determine the stellar trajectory. However, some questions still remain, suggesting that the situation is more complex then previously thought.

In addition to the stellar image we have observed other compact blue-shifted spots, too bright to be self-amplifying. They are found in both the main line transitions where they are coincident. Also, the fit to the motion of U Her leaves some residuals of $\approx 4$ mas which are still unexplained. Possibly U Her is part of a multiple system. This would also explain the occurrence of multiple bright spots, which could be images of possible companions.

There are several ways to address the question of the occurrence of multiple bright spots. Observations of a sample of OH masering stars at 1667 MHz and 1612 MHz have been made to examine the stellar image and the possible occurrence of multiple bright

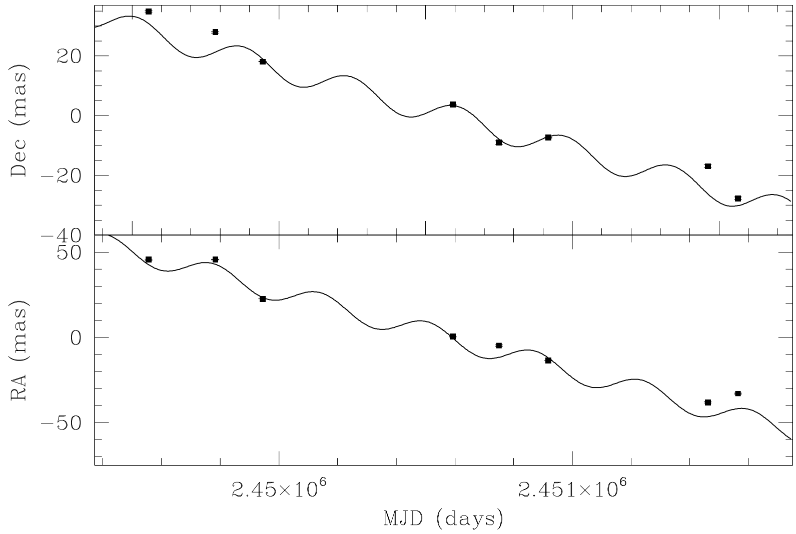


FIGURE 3. The motion of the brightest blue-shifted 1667 MHz maser spot with respect to one of the extra-galactic reference sources.

spots in both transitions. Further study of the movement of the additional bright spots should reveal if those spots are caused by companions. A VLBA project is in progress to determine parallax and proper motion of a sample of stars, in a similar way as done for U Her.

To model the OH maser shell and the amplified stellar image, we have started 3D Monte Carlo simulations. The Monte Carlo method is an expanded form of the one used by Spaans & Van Langevelde (1993). Because it is in 3D, it will allow us to include a background star and density inhomogeneities like platelets or filaments. This enables us to test the possibility of the bright maser spots being caused by density inhomogeneities.

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