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Letter to the Editor

# Astrometry of the stellar image of U Her amplified by the circumstellar 22 GHz water masers

W. H. T. Vlemmings[1], H. J. van Langevelde[2], and P. J. Diamond[3]

[1] Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands
[2] Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, The Netherlands
[3] Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire, SK11 9DL, England, UK

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**Abstract.** The 22 GHz $H_2O$ masers in the circumstellar envelope of the Mira variable star U Her have been observed with MERLIN using a phase referencing technique to determine accurate astrometric positions. The positions were compared with the optical positions obtained with the Hipparcos satellite to an accuracy of 18 mas. The absolute radio position of the brightest $H_2O$ maser spot is found to match the optical position, indicating that this spot is the stellar image amplified by the maser screen in front of it. The occurrence of an amplified image in the 22 GHz maser can be used to accurately determine the positions of the $H_2O$ with respect to the star as well as with respect to the SiO and OH masers. Our observations seem to indicate that the star is not in the centre of the distribution of maser spots, which has been interpreted as a ring.

**Key words.** masers – stars: circumstellar matter – stars: individual: U Her – stars: AGB and post-AGB – techniques: interferometric – astrometry

## 1. Introduction

The circumstellar envelopes (CSEs) around late-type stars contain several maser species that are excellent probes of the dynamics of the outflowing material. Astrometric observations are an important tool to study the locations and motions of the circumstellar masers with respect to the central star. This understanding is essential to reach the main goal of maser astrometry, which is to determine the distances to heavily enshrouded stars, that are too faint for their parallax to be determined directly.

### 1.1. Circumstellar $H_2O$ masers

Interferometric observations of the 22 GHz $H_2O$ masers in the CSEs of Mira-variable stars with MERLIN, the VLA and Very Long Baseline Interferometry (VLBI) indicate that the $H_2O$ masers are found up to a few hundred AU from the star (e.g. Lane et al. 1987). This is generally inside the OH maser shell, which is located at up to several 1000 AU. The $H_2O$ masers often show an a-spherical distribution, and the size of the maser region is thought to increase with mass-loss rate (Cooke & Elitzur 1985). The maser is expected to be pumped due to collisions (Neufeld & Melnick 1991). The 22 GHz maser can then be easily excited in the inner parts of the CSE at temperatures of 400 to 1000 K and $H_2$ number densities of $10^9$ cm$^{-3}$. In this region the outflow is still being accelerated. Therefore, as shown by Rosen et al. (1978) the velocity coherent paths through the masing medium are of approximately equal length in both the radial direction as well as the direction tangential to the star, and thus the $H_2O$ maser beaming is expected to be both radial and tangential. The radial beaming results in the maser occurring in front of the star, tangential beaming would display a ring within a narrow velocity range close to the stellar velocity (e.g. Reid & Menten 1990).

$H_2O$ masers are significantly more variable than their OH cousins. They exhibit strong variability in intensity, which seems to indicate that the masers are at least partially unsaturated, since an unsaturated maser is strongly influenced by changes in the local conditions. An analysis of the $H_2O$ maser line-widths and line-shapes also indicates that the masers are not completely saturated (e.g. Vlemmings et al. 2002).

Whereas semi-regular stars are observed to have $H_2O$ maser spectra that can change shape rapidly, Mira-variable stars typically show no large profile changes over several years. However, the individual features can still show significant changes in intensity (Engels et al. 1988).

### 1.2. Amplified stellar image

Interferometric observations of OH masers have revealed that the most compact features were only found at the blue-shifted

*Send offprint requests to*: W. H. T. Vlemmings,
e-mail: `vlemming@strw.leidenuniv.nl`

side of the spectrum (Norris et al. 1984). It was argued that this was due to amplification of the continuum maser emission from the underlying star by the maser screen in front of it. This is called the *Amplified Stellar Image Theory*. Amplification of the stellar emission results in a high brightness maser spot at the most blue-shifted side of the OH maser spectrum. This spot should coincide at the different OH maser transitions, and is expected to be persistent over a long period of time. Several observations have confirmed this hypothesis (e.g. Sivagnanam et al. 1990).

According to the amplified stellar image theory, the compact, most blue-shifted, spot is necessarily fixed to the stellar position. Therefore, high resolution astrometric observations of this spot can be used to determine the stellar trajectory. This hypothesis has been tested for the Mira-variable star U Her by van Langevelde et al. (2002, hereafter vL00). The *absolute* positions of the OH maser spots were determined with respect to the radio-reference frame using extra-galactic phase reference sources. The positions were compared with the optical Hipparcos positions with unprecedented accuracy. It was shown that the most blue-shifted spot was indeed located in front of the stellar radio-photosphere. The size of this spot was found to be ≈20 mas, which is comparable with the expected size of the radio-photosphere, which is thought to be twice the size of the star, as proposed by Reid & Menten (1997).

Although the $H_2O$ masers generally show a great number of spots over an area of several hundred mas, it has been argued that in some cases one of the $H_2O$ maser spots corresponds to the stellar image (Reid & Menten 1990; Marvel 1996; Colomer et al. 2000). However, because the distribution of the $H_2O$ masers is considerably less spherical than that of the OH masers, it is not straightforward to assume that the stellar image underlies the most blue-shifted spot. Also, because the maser brightness depends strongly on local effects such as density or pumping inhomogeneities, several bright spots can be observed and an $H_2O$ maser stellar image could be less conspicuous or persistent than the OH stellar image.

Here we present phase referencing observations of the $H_2O$ masers around U Her used to determine accurate maser spot positions. These have been compared with the Hipparcos optical position and the positions obtained for the OH masers in vL00.

## 2. Observations

MERLIN was used to determine the positions of the $H_2O$ masers in the CSE of U Her with respect to 3 extragalactic reference sources. From the observations, which were performed on May 20 2001, we were able to determine accurate astrometric positions. The observations required a total of 8 hours on the target source and the calibrator and reference sources. As a result the beam size was $\approx 30 \times 25$ mas.

One of the main problems of using the phase referencing method to determine accurate positions at 22 GHz is the lack of bright reference sources at that frequency. For this project 3 reference sources were selected from the VLBI calibrator catalog (Beasley et al. 2002). These were J1628+214 (now J1630+231, ≈80 mJy, at 2.8° from U Her), J1635+1831 (≈50 mJy, at 2.4°) and J1619+2247 (≈200 mJy, at 4.2°). They were selected to have a flat spectrum, making it possible to detect them at 22 GHz with a 2 min integration time. Our phase reference observation cycle consisted of 2 min per reference source and 4 min on the target source. The $H_2O$ masers were observed in a 4 MHz band with 128 spectral channels, providing a velocity resolution of 0.42 km s$^{-1}$. The continuum reference sources were observed in a 16 MHz band with 16 channel, giving a 13.5 km s$^{-1}$ resolution. In the 2 min integration time on the reference source we typically reached a $SNR \approx 5$.

Reference source J1628+214 was also used in vL00 to determine the positions of the 1667 MHz OH masers around U Her. We can thus determine the positions of the $H_2O$ masers with respect to the OH masers. The positional accuracy of the reference sources with respect to the radio reference frame is ≈3 mas. However, as the positions were determined at 2.4 and 8.4 GHz the position at the different frequencies can be different at the sub-milliarcsecond level, as shown in e.g. Fey et al. (1997).

After initial flux calibration with the MERLIN software, the data were processed in AIPS. Because the reference sources at 22 GHz are weak, we performed both a normal and a reverse phase referencing scheme. In the reverse scheme, we were able to determine accurate positions of both J1619+2247 and J1628+214 with respect to the brightest $H_2O$ maser feature of U Her. As a consistency check, we managed to get a good phase connection from J1628+214, the closest reference source, to the U Her $H_2O$ masers with the normal phase referencing scheme. J1635+1831 was too faint for us to obtain a good phase connection.

The accuracy of the phase referencing model depends on the MERLIN correlator model. The two largest uncertainties in the model are the telescope positions (accurate to ∼5 cm) and tropospheric effects. Under normal circumstances these combine to produce an error in absolute position measurements of up to ∼10 mas for a target-reference source separation of ∼3° (e.g. Kovalevsky et al. 1997).

## 3. Results

At the time of our observations the spectrum of the 22 GHz $H_2O$ masers around U Her did not show significant structure, as only a few features were detected. The averaged cross power spectrum is shown in an inlay in Fig. 1. We find that the shape of the spectrum is similar to previous observations, performed with MERLIN, the Very Large Array (VLA) and with the 100-m radio telescope in Effelsberg (Baines et al. in preparation; Yates & Cohen 1994; Colomer et al. 2000; Engels et al. 1988). In our spectrum we find that the strongest feature is located at −15.7 km s$^{-1}$, and this is the feature which was used to determine the phase solutions. The stellar velocity of U Her is $-14.5 \pm 0.5$ km s$^{-1}$, which was determined from OH and SiO maser observations (Chapman et al. 1994). As the U Her $H_2O$ maser emission is located between −13 and −20 km s$^{-1}$, the strongest feature is not the most blue-shifted feature.

After phase referencing and determining the position of J1628+214 with respect to the brightest $H_2O$ maser feature of U Her, we find that the position of J1628+214 is shifted

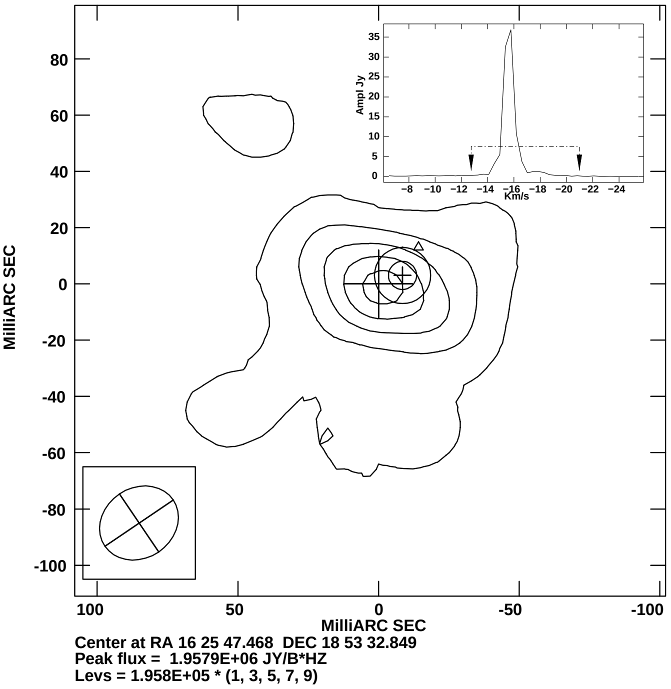


**Fig. 1.** The location of the U Her $H_2O$ masers with respect to the stellar positions determined from the Hipparcos observations, as determined from phase referencing to J1628+214. The star is denoted by two circles indicating the star itself and the stellar radio photo-sphere. The large cross indicates the position of the $H_2O$ maser, the error bars are due to the positional fitting. The errors on the stellar position (small cross) are due to the link to the radio-reference frame and due to the errors in the proper motion used to transpose the optical position. The triangle denotes the stellar position when using the phase referencing results on the J1619+2247 reference source. The inlay is the averaged cross-power spectrum of the $H_2O$ maser emission. The masers were mapped over the velocity range indicated in the spectrum.

by +83 mas in right ascension and +15 mas in declination with respect to the positions in vL00 ($(\alpha,\delta)_{2000} = 16^h30^m11\overset{s}{.}23117$, $+21°31'34\overset{''}{.}3144$). A similar process for J1619+2247 results in a position shift of +76 mas in right ascension and +25 mas in declination with respect to the position in the VLBA calibrator list. As a consistency check we have also determined the position shift of the brightest maser spot after phase referencing with respect to J1628+214. We find that the maser spot is shifted −83 and −11 mas in right ascension and declination respectively with respect to the a priori assumed target coordinates.

The formal uncertainty in fitting a Gaussian profile to the reference source or maser spot is a fraction of the beam width, and depends on the $SNR$ of the image. For the reference sources the formal position errors are of the order of 5 mas in each coordinate, for the U Her maser spot the errors are ≈1 mas. The best phase connection was made when phase referencing J1628+214 to the brightest maser spot, so we assume that the positions as determined with J1628+214 are the most reliable. The actual phase referencing errors can be estimated from the difference between the position of the brightest maser spot with respect to the two reference sources. From this, we conclude that our positions are accurate to within 10 mas, which is in agreement with the estimated errors due to the correlator model that are described above. For the brightest $H_2O$ maser spot around U Her we then find a position of $(\alpha,\delta)_{2000}$ = $16^h25^m47\overset{s}{.}468, +18°53'32\overset{''}{.}849$ at the time of our observations.

To compare this position to the stellar position of U Her we have extrapolated the optical position found by the Hipparcos satellite at J1991.25 to our epoch of observation. We have used the proper motion and parallax determined by monitoring the position of the most blue-shifted OH maser spot, which was shown to be the stellar image. The first fit was performed in vL00 for 6 epochs of observations, a fit including additional epochs was presented in Vlemmings et al. (2000). As described in vL00, the OH maser proper motion is entirely consistent with the Hipparcos proper motion. The error in the transposed position is dominated by the error in proper motion. At our epoch of observation this error is ≈6 mas in each coordinate. Combined with the errors on the parallax and our position errors, we have been able to compare the radio and optical position with ≈18 mas accuracy. Figure 1 shows a map of the $H_2O$ maser features, covering the velocity range indicated in the spectrum, including the position of the star. Circles indicate the size of the star and the radio-photosphere. The size of the radio-photosphere can be estimated from SiO maser observations by Diamond et al. (1994). Their observations provide an upper limit of ≈20 mas if, as proposed by Reid & Menten (1997), the radio-photosphere extends to the edge of the SiO masing region. The triangle denotes the stellar position as determined when using the maser positions with J1635+1831 as the reference source.

Although the size of the brightest $H_2O$ maser spot (≈50 mas) is larger than the expected size of the stellar radio-photosphere, most likely due to the blending of several weaker maser features, the position of peak intensity matches the predicted location of the star within the errors. This indicates that the $H_2O$ maser spot also coincides with the most blue-shifted OH maser spot which has been shown to be the amplified stellar image. Thus, also the brightest $H_2O$ maser spot seems to be emission from the stellar radio-photosphere amplified by the maser medium at the line of sight.

## 4. Discussion

The observations of an amplified stellar image in the $H_2O$ masers of U Her indicate that at least for the brightest spot at this epoch the maser beaming is radial. Reid & Menten (1997) have detected 22 GHz continuum emission from a small sample of Mira stars, finding the typical stellar brightness temperature to be $T_* = 1600$ K. Compared to their estimate of the maser excitation temperature (≈10 K), this is strong enough to influence the $H_2O$ maser medium and produce a stellar image, as the increased seed radiation from the star will cause the radial maser beam to be brighter. Since the $H_2O$ masers are found to be mostly unsaturated, slight changes in density, pumping and velocity structure have a strong effect on the maser and the relative strength of the maser features and the amplified stellar image may be less dominant than the OH, as is demonstrated by the detection by Reid & Menten (1990) of an $H_2O$ maser feature at the stellar position of W Hya which was several orders of magnitude weaker than the strong feature observed here.

The $H_2O$ masers around U Her have been observed before with MERLIN, the VLA and the VLBA. VLA observations by Colomer et al. (2000), and MERLIN observations by Bains et al. (in preparation) show an incomplete ring structure with a scale of 150−200 mas. The brightest maser spot seen in our MERLIN observations corresponds in velocity with the masers on the edge of the ring structure. So somewhat surprisingly, our astrometric results indicate that the star is not in the center of this ring.

The maser spots detected with high resolution VLBA observations do not show any indication of circular structure (Vlemmings et al. 2002). They have a linear extent of ≈60−70 mas and they most likely correspond to the brightest VLA and MERLIN features.

## 5. Conclusions

Our observations have shown that the circumstellar $H_2O$ maser can amplify the stellar image and produce a strong stellar image, a phenomenon previously detected at the OH maser transitions. Although this effect is not necessarily strong in all $H_2O$ masers, it can be very valuable for astrometric purposes. Accurate astrometry of the stellar image can be used to determine the location of the various maser species in the CSE with respect to each other and the star. Simultaneous, high resolution observations significantly improve our understanding of the kinematics in the CSEs. Using the stellar image in $H_2O$ masers, it will also be possible to determine the stellar trajectory and distance with a higher accuracy than with OH masers. However, because of the high variability of $H_2O$ masers additional monitoring will have to be performed to show if the stellar image is persistent enough for a long term monitoring campaign.

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