VLBI Measurements of the Parallax & Proper Motion of U Herculis

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Abstract

The OH 1667 maser in the circumstellar shell around the Mira variable U Her has been observed with the VLBA at 6 epochs, spread over 4 years. By using straightforward phase referencing techniques the stellar proper motion can be measured. Preliminary analysis indicates that the parallactic motion is also detected. An important question is whether the maser spots can be assumed to be fixed with respect to the star. The observations show both evidence supporting and contradicting the idea that one maser spot is the amplified stellar image.

Key words:
masers — stars: circumstellar matter — stars: individual (U Her) — stars: AGB and post-AGB — techniques: interferometric — astrometry
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1 Introduction

The Mira variable U Her is a well known circumstellar main line OH maser source, and has been the target of many previous VLBI observations. Because U Her is supposedly relatively close ($\approx$ 300 pc) it should be possible to detect its radio proper motion and parallax (Sivagnanam et al., 1987). This is particularly interesting as U Her is too faint in the optical to have a reliable Hipparcos parallax.

In order to use the maser positions to monitor the trajectory of the star U Her, an assumption has to be made about the motion of the masers with respect to the underlying star. It was expected that in these circumstellar masers the most blue-shifted maser spot corresponds to a special condition, namely maser action in the shell initiated by the radio continuum radiation of the stellar surface. If this is the case, the most blue-shifted peak should be a bright beacon, necessarily fixed on the true stellar position.

2 Observations

VLBA data from six epochs, spread over almost 4 years, has been used to measure the position of the circumstellar masers of U Her. The 1667 MHz OH line was observed with high (0.18 km/s) spectral resolution. Simultaneously 3×4 MHz wide bands were recorded and correlated separately with modest spectral resolution (5.8 km/s). Two nearby extra-galactic, continuum sources were used to calibrate phase, delay and phase rate. The calibrators are both within $3°$ and were observed every $5 - 7$ minutes. The 1665 MHz OH transition, which is usually also observable in these sources, happens to fall in these continuum bands. It can be detected, but with very limited spectral resolution.

The data has been processed in AIPS without any special astrometric software. We rely on the accuracy of the VLBA correlator model and in all cases phase referencing works well, even at this relatively low frequency; in particular no ionospheric model is included (yet). Maser spots appear slightly distorted by the remaining (ionospheric) effects in the data, but contain positional information relative to the positions of the calibrator(s). The spots are also quite resolved; we believe this is intrinsic to the maser. Structure which is more compact than $\lesssim 20$ mas has seldom been detected in circumstellar OH main line masers.

The accuracy of the correlator model can be demonstrated by measuring the separation between the two calibrators. This number is reproducible to 2.5 mas in every epoch (Fig. 1). We take this as an indication of the systematic errors in the observations.

3 Results

On VLBI baselines most of the OH maser emission is resolved out ($\approx 75\%$). Although the U Her 1667 MHz line displays a regular double peaked spectrum in single dish observations, the VLBI emission is limited to blue-shifted emission only. In different epochs 4 - 7 regions of emission can be found, spread

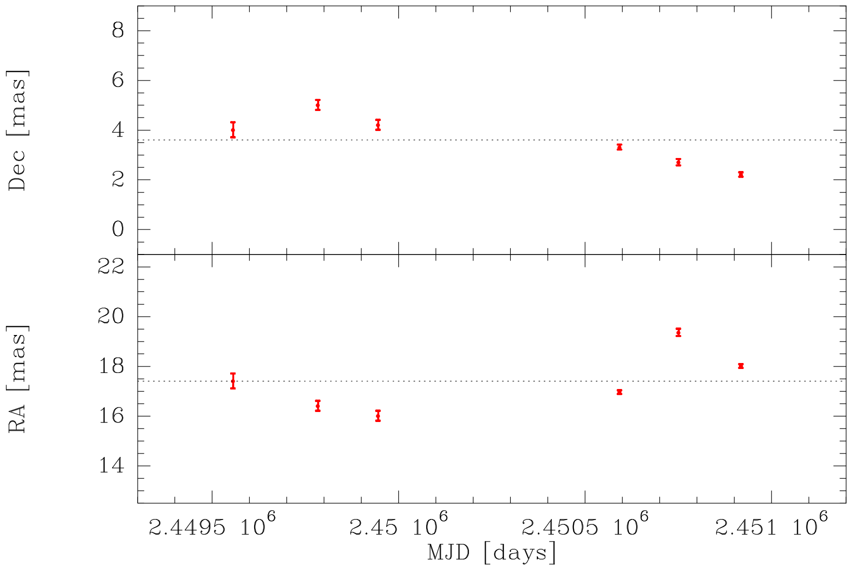

Fig. 1. The residual position of one extra-galactic continuum calibrator with respect to the other. The offsets reflect the uncertainty of the a-priori position information. The small residual scatter shows 2.5 mas accurate positions can be obtained without special measures.

over $\approx$ 200 mas. The most blue-shifted maser spot can be identified in all epochs, however it does not seem to be more compact than the others. Most of the other spots can be tracked over many epochs as well.

In at least one of the epochs a 1665 MHz maser coincides spatially with the most blue-shifted 1667 spot.

The positions of several maser spots can thus be measured in every observation, although the image quality differs substantially between epochs. Not only is the quality of the data dependent on ionospheric conditions (solar cycle, day and night), but also on the variability of U Her. For our astrometric purposes, the images have been processed without using any self-calibration and are obtained in a 2 kHz wide channel (Fig. 2).

3.1 Proper Motion and Parallax

The proper motion detected in right ascension and declination, $\mu_{\rm VLBI} = -17.4$, -10.9 mas/yr, agrees well with the result on U Her by Hipparcos: $\mu_{\rm Hip} = -16.84 \pm 0.82, -9.83 \pm 0.92$ mas/yr. The Hipparcos data are inconclusive with respect to the parallax for U Her ($\Pi_{\rm Hip} = 1.64 \pm 1.31$ mas). Fig. 3 shows a fit to the observed motion of the same maser spot. Included is a parallax of 5.3 mas.

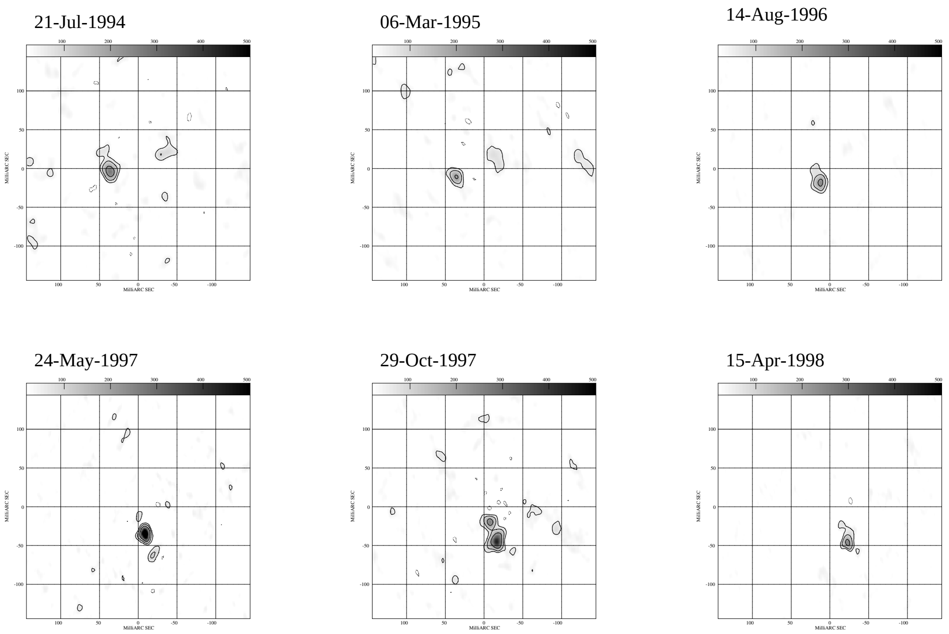

Fig. 2. Most blue shifted feature at -20.6 km/s mapped at six epochs. The coordinate grid has a 50 mas spacing. The proper motion is clearly observed.

Although we have not completed the numerical analysis we are convinced that the data is represented better with a model including a significant parallax.

The errors displayed in Figs. 1 and 3 are the formal uncertainties in fitting Gaussian profiles to the maser spot in order to obtain the position. These errors are typically ≈ 1.0 mas in each coordinate. In addition it is known that there are errors associated with the phase connection. From the calibrator pairs these are estimated to be ≈ 2.5 mas. This effect can be expected to give correlated residuals for different spots at a certain epoch, as can be observed in some cases.

The final fit, however, leaves residuals of $3.5 - 5.0$ mas in each coordinate. This problem can also be seen by studying the distances between individual spots over the 4 years (not shown). Indeed the mutual separations of the maser spots seem to vary over a range of $\lesssim 4$ mas during the 4 years. This effect can be partly attributed to turbulent motion in the masering shell. A 1 km/s turbulent motion, as needed to explain line widths of the masers, corresponds to 0.7 mas/yr at a distance of 300 pc.

3.2 Amplified stellar image

One motivation to attempt the detection of the U Her motion by means of the OH maser, was the theoretical prediction that on the line of sight to the star the maser will amplify radio photons from the stellar surface (Norris et al.,

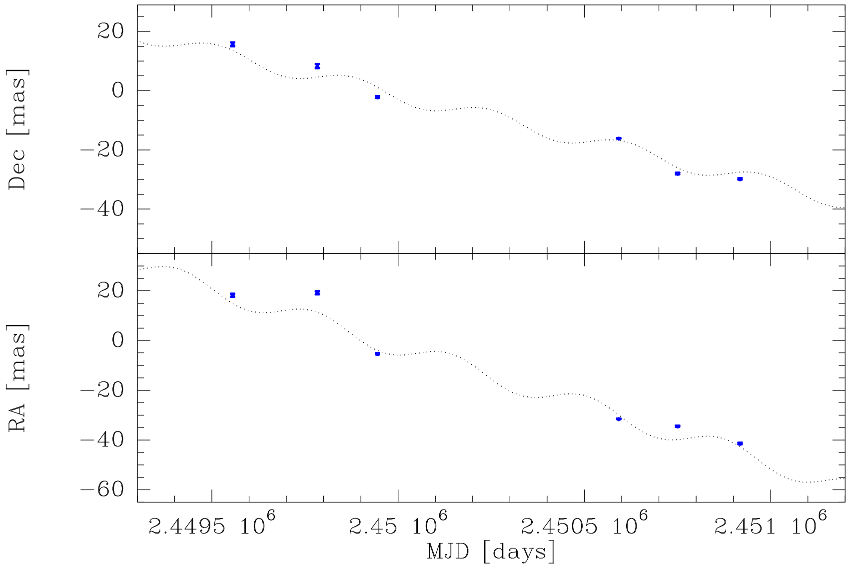

Fig. 3. The motion of the brightest blue-shifted 1667 MHz masers spot with respect to one of the extragalactic reference sources.

1984; Van Langevelde & Spaans, 1993). In a spherically symmetric shell with a constant outflowing velocity this would result in a special condition for the most blue-shifted part of the spectrum. That maser spot would be favoured over other parts of the shell in the sense that it is amplifying a background source, rather than amplifying spontaneous emission. This would result in a spot with more maser beaming, and hence brighter, more compact emission. That spot would be fixed to the stellar photosphere (which could be as large as ≈ 10 mas for U Her) and probably be persistent over the years. It would also be observable at different transitions. It could still vary in flux with stellar cycle, through changing pumping conditions.

Some of the current results seem to confirm this idea. For instance, it is clear that the brightest and most compact features are from the blue side of the shell, although it is not clear why there would be many compact blue-shifted VLBI spots and not a single red-shifted one. Furthermore, our wide-band data confirms the observation by Sivagnanam et al. (1990) that the most blue-shifted 1667 MHz spot matches one of the 1665 MHz spots exactly. This spot at -20.6 km/s also seems to be the most persistent in the monitoring campaign.

However, the most blue-shifted spot is not always the brightest or most compact; other spots are dominant at different epochs. Finally, the motion of a single stellar body can not adequately describe the motion of the maser spot. The residuals in the proper motion could be interpreted as turbulent motion.

This interpretation is inconsistent with the amplified stellar image theory, because it predicts that the most blue-shifted image should exactly follow the stellar trajectory. Another tempting possibility is that U Her does not follow a simple trajectory because it is a multiple stellar system. This could also give rise to residuals of a few mas.

4 Conclusions

We have shown that it is straightforward to do relative astrometry to ≤ 3 mas accuracy with the VLBA.

Some of the 1667 MHz OH features in U Her can be traced over 4 years.

The proper motion derived from VLBI observations for U Her is consistent with Hipparcos results in the optical. Inclusion of the stellar parallax in the motion of the maser spots appears to fit the data better.

The evidence in favour of the "amplified stellar image" theory is weak. Either it would require a binary (or multiple components) or we are simply observing maser motion due to turbulence in the shell.

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