# ASTROMETRY OF CIRCUMSTELLAR MASERS

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**Abstract** The circumstellar masers around evolved stars offer an interesting possibility to measure stellar parameters through VLBI astrometry. In this paper the application of this technique is discussed, including the accuracy and the uncertainties of the method. The different maser species (OH, $H_2O$, SiO) have slightly different characteristics and applications. This paper does not concern astrometry of maser spots to study the kinematics of the envelope, but concentrates on attempting to measure the motion of the underlying star.

**Keywords:** masers – stars: circumstellar matter – techniques: interferometric – techniques: astrometry

## Introduction

There are a number of scientific justifications for astrometry of stars with circumstellar masers. Historically, the registration of radio single dish and infrared data was so uncertain that proper identification of maser bearing stars was a problem. Most of these problems have been overcome; the accuracy of connected element interferometers is sufficient to make these identifications unambiguously. However, there is still a lot of uncertainty when comparing VLBI data from different experiments. Notably, when maser distributions from different transitions are overlayed, a common origin is usually assumed. Astrometry can be done to do such comparisons properly.

However, the most tantalizing application of astrometry of circumstellar masers is the accurate determination of the motion of the star on the sky. Proper motions of a star anywhere in the Galaxy (10 km/s at 8 kpc corresponds to $\mu = 0.25$ mas/year) can in principle be obtained with VLBI, as can the parallax for such distances ($\pi = 0.125$ mas). A direct distance estimate is important for studying the physics of the mass-losing stars. For many Mira variables Hipparcos measured the distance, but for the most enshrouded stars VLBI offers the best approach. Both the proper motion and distance are inputs for studying the stellar population and Galactic kinematics (Habing, these proceedings).

In addition, detailed astrometric monitoring of evolved stars could reveal information about the existence of binary components, or even planets in these systems. Moreover, by monitoring its position new facts can be learned about maser physics. Are spots persistent, what (turbulent) motions can be measured, is the brightness a function of stellar cycle? Finally it is worth mentioning that the maser astrometry could tie the observational reference frames, in particular in the infrared where these stars are very bright.

Carrying out astrometric monitoring projects with spectral line VLBI is extensive work that requires some special techniques and assumptions. There are a number of technical advancements and initiatives that will make improvements to this field which will make it much more accessible.

## 1. Methods & Techniques

The most straightforward way of doing VLBI astrometry is to use "phase referencing" to a bright and close calibrator in order to overcome the spatial and temporal fluctuations of the ionosphere and/or troposphere. The calibrator is usually an extragalactic source with a fixed and known position, which is sufficiently bright to calibrate the atmospheric and instrumental effects within a fraction of the coherence time. Because the modern VLBI correlators have incorporated the best geodetic models, phase referencing results obtained in this way can be accurate to a few mas. This is already sufficient for a number of applications. In other cases, higher accuracy is required and some adjustments are necessary to improve the model. In such cases one probably needs to return to the "totals" in order to use astrometric/geodetic software. To get accuracies below 1 mas is not trivial; better models of the atmospheric behavior and structure of the reference source are required.

For maser astrometry an additional complication can be that one needs to observe in mixed bandwidth mode, applying a narrow band for the maser detection and simultaneous wide bands for the reference source. Obviously the maser dictates the observing frequency, which rules out some calibration schemes used in continuum and geodetic VLBI.

Ideally the masers should be bright and persistent. The brightness relates to the size of individual maser features, which sets an upper limit to the resolution one can obtain. A fundamental issue remains to link the motion of the maser spot to the stellar properties. One way forward is to assume that the masers are on a linear path with respect to the star (e.g. a constant outflow). In this case the parallax of individual spots equals the parallax of the star, and the average motion may be assumed to be the stellar motion. In other cases one may be able to deduce the position of the star from the distribution of the masers, for example when they form a ring. If we can determine the position of the star, one can in principle measure the motion and the parallax. Note that only when one can consistently determine the stellar position with (much) better than 1 AU accuracy, a useful parallax can be determined. In some cases there is evidence that special maser spots exists that correspond to the stellar continuum amplified by the maser shell. Such spots are then tied very accurately to the stellar position. In other cases one has to worry about the systematic and turbulent motions in the maser shell. In any case, there may be additional motions involved, for example when masers occur in binary stars.

## 2. OH Masers

The OH masers usually originate in large shells at 1000 AU from the mass-losing stars. As the outflow is constant at that point, the maser radiates most effectively radially, from the front and back cones of the shell. Three 18 cm transitions can give reasonably bright maser emission. However, the VLBI spots are usually resolved at 20 mas, sometimes degraded further by angular broadening in the interstellar medium, notably in the direction of the Galactic centre (Van Langevelde et al. 1992).

Although the shells are large, the “amplified stellar image” paradigm makes the OH maser interesting for astrometry. Radio continuum, amplified by the maser results in a spot that is fixed on the stellar position, bright and persistent. The observation that the most blue-shifted spots in two OH transitions coincides is a very good confirmation of this idea (Sivagnanam 1990).

Recently, comparison of a proper motion study of U Her with Hipparcos agreed to 15 mas (van Langevelde et al. 2000), thus confirming that the most blue-shifted and most persistent spot indeed follows the stellar

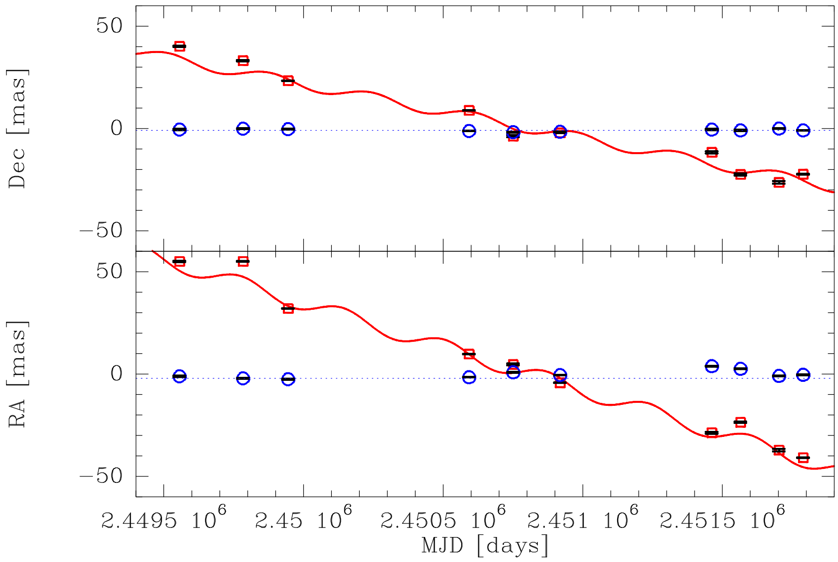


*Figure 1.* Proper motion of the most blue-shifted spot in the 1667 MHz maser of U Her. A motion of $\mu_{\rm vlbi} = -15.57 \pm 0.56, -9.66 \pm 0.61$ mas/yr and a parallax of $\pi_{\rm vlbi} = 3.85 \pm 1.14$ mas are fitted to the data. For comparison the position of a secondary reference source is also displayed.

trajectory in this case. Therefore the maser motion can be used to obtain the parallax and proper motion of the star. U Her was observed 10 times in 6 years on the NRAO VLBA which resulted in the first VLBI parallax of a mass-losing star (Fig 1; Van Langevelde et al. 2000). The motion agrees within the error with the Hipparcos data, from which no reliable parallax could be obtained.

If the amplified stellar image is a general feature in circumstellar OH masers, it will allow astrometric measurements of a large number of stars. However, the modest brightness of OH masers limits the application of this technique to stars closer than 1 kpc.

## 3. $H_2O$ masers

The 22 GHz masers are much brighter than the OH masers in circumstellar shells. Therefore positional accuracies in the order of 50 $\mu$as are in principle achievable. Of course at this high frequency the coherence time is much shorter and phase referencing VLBI at 22 GHz is quite a bit more challenging.

Additional complications arise from the fact that the circumstellar $H_2O$ masers are rather messy. The structures are often ring-like on scales of 100 AU, as expected from tangential amplification. However, large departures have been observed, as well as considerable variability. If the structures are persistent enough one can attempt to track individual maser spots over a year and measure the parallax of the star from these (e.g. Kuruyama et al., these proceedings). If this approach works the water maser observations offer the interesting possibility to measure parallaxes throughout a large fraction of the Galaxy.

There have been claims that in water masers the amplified stellar image can also occur (Marvel 1996, Colomer et al. 2000). To check this we have observed U Her at 22 GHz with MERLIN, which yields a comparable resolution as our previous OH VLBI results. Using the same position calibrators we find, somewhat surprisingly, that the brightest $H_2O$ maser coincides with the optical position and the OH image. Although the MERLIN observations do not resolve individual maser spots observable with VLBI, we take this as a clue that amplification of background radiation may play a role in water masers too (Fig 2; Vlemmings et al. 2002).

## 4. The use of SiO masers

The SiO masers around evolved stars can be even brighter. At 43 GHz the spots sizes allow $10\mu$as accurate positions. At the same time the technical difficulties are considerable. The coherence time is only of the order of a minute and in addition there are fewer suitable extragalactic calibrators.

The masers themselves are located close to the star, within 10 AU. They are bright and abundant. Monitoring of their structure indicates that the masers are showing motions on the time-scale of the variability of the star (Diamond & Kemball 1999). Often these motions are not linear and it will be a challenge to measure a parallax from the combined motions of SiO masers. As the masers are in a ring close to the star, it will be possible to estimate the stellar position from the distribution of SiO masers. The proper motion of the star can be measured this way, even if the individual spots cannot be resolved. Proper motions of individual stars can probably be measured throughout the Galaxy using the 43 GHz transition.

A very suitable target for stellar astrometry by SiO masers are the Galactic center stars. In this region there is an abundance of maser stars

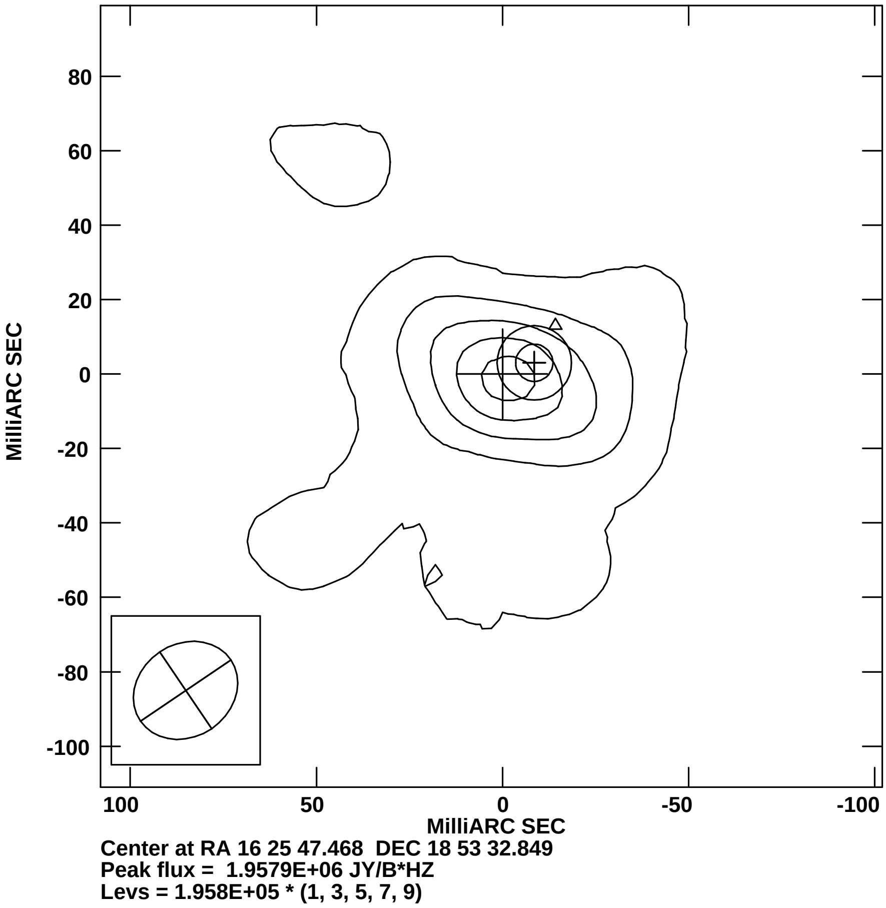


*Figure 2.* The location of the U Her $H_2O$ masers with respect to the stellar positions determined from the Hipparcos observations, as determined from phase referencing to an extragalactic calibrator. The star is denoted by two circles indicating the star itself and the stellar radio photo-sphere. The error bars on the maser feature are the errors due to the positional fitting. The errors on the stellar position 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 secondary calibrator.

close together (Sjouwerman, these proceedings). In addition, SgrA* is a suitable calibrator; it is bright at short wavelengths and, as it is is the location of a massive black hole, it is stationary. In fact, an important results from circumstellar maser astrometry is the tie between the IR and radio positions in the Galactic centre. By locking the positions of the IR sources to the radio maser counterparts, it can be shown that the motion of stars in the Galactic centre is consistent with motion around a massive black hole located at the position of SgrA* (Menten et al. 1997; Eckart et al. 2002).

Several groups have explored the possibility to start monitoring SiO masers in the Galactic centre region with VLBI (Sjouwerman et al. 1998; Deguchi, these proceedings; Imai, these proceedings; Reid, private communication). The basic goal is to add two more components to the measurement of kinematics in this dynamically interesting region (Winnberg, these proceedings).

## 5. Future

There are many planned improvements of ordinary VLBI that will facilitate more astrometry of circumstellar masers. Several modern, big telescopes are under construction that will observe at high frequencies, necessary for $H_2O$ and SiO masers. Disk-based recording systems will improve the reliability and productivity of VLBI, and will be especially advantageous for time consuming astrometric monitoring. In addition there are several indications that the atmospheric modeling can be improved considerably. Other improvements of the geodetic models are important too, for example accurate telescope positions.

However, the future for astrometry of masers clearly lies in instrumental setups that overcome the temporal variability of the atmosphere at high frequencies. Some of this can be done with "cluster–cluster" VLBI, but the dedicated VERA project provides a far more ambitious approach that will soon produce interesting results (Kobayashi & Sasao, these proceedings).

A number of studies are required to establish new techniques for astrometry of circumstellar masers. Careful analysis of errors and consistency checks will be necessary to determine how to use the masers optimally to determine the underlying stellar motions. But in potential this method enables the measurement of proper motions and distances of mass-losing stars throughout the Galaxy. This will progress the study of stellar evolution as well as our knowledge of the structure of the Galaxy.

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