PROCEEDINGS OF SCIENCE

Parallax measurements of the Mira-type star UX Cygni with phase-referencing VLBI

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We have measured the annual parallax of the Mira-type star UX Cygni at 0.54 ± 0.06 mas from phase-referencing VLBI observations of its circumstellar water masers with the VLBA. The corresponding distance is $1.85^{+0.25}_{-0.18}$ kpc. This is the first measruement of an annual parallax based on observations of water masers. Some kinds of variable stars, including Mira variables, have period-luminosity relations, and they are used as distance indicators. However, they are relative distance indicators because we do not know the relationships between periods and absolute luminosities. If we can measure the this relationship in Mira variables, it becomes an absolute distance indicator, and we can independently measure the distance of Large Magellanic Cloud (LMC) which is important for the calibration of period-luminosity relations of the other kinds of variable stars. Our result is consistent with the period-luminosity relation of Mira variables in LMC and its distance from present observations.

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1. Introduction

It is known that there are period-luminosity relations in some kinds of variable stars such as Cephids and RR Lyrae, which are the relationship between the variation periods and magnitudes. These relationships are used for distance estimations of near galaxies as “distance ladders” in astronomy. However, the relations between periods and absolute magnitudes are not established well for any types of variables. Thus they are relative distance indicators now. We can esitimate only the ratio of distances by comparing the period-luminosity relations of two groups.

The period-luminosity relation of Miras is studied with Miras in Large Magellanic Cloud. For example, [1] shows the period-luminosity relation of 55 Miras in Large Magellanic Cloud. Especially, the K-band relation has weak dependence with chemical composition of Miras and is potentially useful for determining distances. The distance to Large Magellanic Cloud is not established well, so we can not establish the relation of Miras between variation periods and absolute magnitudes. Therefore, we need to establish it with observations of the distance of galactic Miras.

However, period-luminosity relation of solar-neighborhood Miras is not well established comparing with that of Large Magellanic Cloud. Even with the Hipparcos results, which are the best measurements of parallaxes now, the errors from distance uncertainties are still large for Miras [2, 3, 4]. In [2], 16 Miras are used for period-luminosity relation. Among them, parallax of only 7 Miras satisfy $\varpi/\varepsilon(\varpi) \geq 3.0$ and $\varepsilon(\varpi) < 1.75$ mas (where ϖ is annual parallax, $\varepsilon(\varpi)$ is the error of ϖ) [5, 6]. The accuracy of Hipparcos' parallaxes is not enough to measure the distances to Miras.

Phase-referencing VLBI observes the target source and the phase-referencing source simultaneously or with short intervals (see [7, pp.476–480], [8] and [9]). We can remove the effect of fluctuations of the earth's atmosphere and use VLBI differential phase. We can also get a nearly absolute position reference by choosing a distant source as the phase-referencing source. Therefore phase-referencing observations are useful for detections of weak sources and precise astrometric measurements.

Among them, measurements of annual parallaxes, which are direct distance measurements without assumptions, are often performed for pulsars [10, 11, 12, etc.]. OH maser (1.6 GHz) observations are performed for AGB stars, too [13]. This measurement achieves parallax accuracy about 1 mas. This accuracy is still not enough to measure the distances to Miras because the most of their parallaxes are 1 mas or smaller. However, if we observe water masers at 22 GHz, we can achieve positional accuracies with the order of 0.05 mas in principle [14]. One of this reason is that the synthesized beam width at 22 GHz is about $1/14$ as larget as that at 1.6 GHz. Moreover, water masers are emitted about 100 AU away from Miras, while OH masers are 1000 AU. We can trace steller movements better by water masers than by OH masers.

We selected 5 Miras for this purpose, which have bright water masers and bright reference VLBI sources within 2 degrees with evenly distributed variation periods, and declinations larger than $+10^\circ$, so that they can be observed at high enough elevation for minimizing the airmass correction effect. In this paper, we show the results of UX Cygni, which has the longest period (565 days) of the five. The shape of period-luminosity relation of Miras is different between in Large Magellanic Cloud and in our galaxy in the range of variation period from 400 to 800 days [1, 15, 16]. Thus it is worth while mesuring the distance of a long-period Mira UX Cygni.

In order to check the period-luminosity relation of solar-neighborhood Miras, we have measured the annual parallaxes of water masers in the gas around them with phase-referencing VLBI. This is the first measurements of parallaxes using water masers.

2. Observation and analysis

The positions of 22 GHz water masers around UX Cygni is monitored over a period of the almost 1 year with NRAO VLBA [1] 10 stations. Five-hour-long observations are performed over 4 epochs: 2001 February 22, 2001 October 12, 2001 November 11 and 2002 February 4. The antenna-nodding cycle is 40 seconds, in which UX Cygni is observed about 7 seconds, phase-referencing source is observed about 7 seconds.

Variation period of UX Cygni is 565 days [17]. The average of K-band magnitudes is 1.96 [18, 19]. The phase-referencing source is J2050+3127, whose redshift is $z = 3.18$ [20]. Separation angle between UX Cygni and the phase-referencing source is $1.^{\circ}38$. The synthesized beam width is 0.8 mas in major-axis direction and 0.4 mas in minor-axis direction. Position angle of the major axis of the synthesized beam is 175°.

3. Results

3.1 Water masers around UX Cygni

Figure 1a shows the distributions of maser spots in four epochs. Map origins are at the same positions from the phase-refereincing source J2050+3127. The loop structure to the northeast of the star is consistent with [21].

3.2 Fitting with a parallax and proper motions

Over 4 epochs of the observations, 7 maser spots are detected in all epochs. Figure 1b shows their movements.

By assuming that the movements of maser spots are the sums of linear motions (proper motions) and the parallax motion on the celestial sphere, we fit them with measured right ascensions and declinations of maser spots in each epoch. That is, theoretical equations are follows:

$$\Delta\alpha^{(i)}\cos\delta = \varpi(-\sin\alpha\cos\odot + \cos\varepsilon\cos\alpha\sin\odot) + (\mu_\alpha^{(i)}\cos\delta)t \tag{3.1}$$

$$\Delta\delta^{(i)} = \varpi(\sin\varepsilon\cos\delta\sin\odot - \cos\alpha\sin\delta\cos\odot - \cos\varepsilon\sin\alpha\sin\delta\sin\odot) + \mu_\delta^{(i)}t \tag{3.2}$$

where $(\Delta\alpha^{(i)}, \Delta\delta^{(i)})$ are the displacements of observed positions of i-th maser spot (positions with the parallax and proper motions minus positions without the parallax and proper motions), $(\mu_\alpha^{(i)}, \mu_\delta^{(i)})$ are the linear motions of i-th maser spot (sum of inner motion and the proper motion of UX Cygni itself), t is time, ϖ is annual parallax, (α, δ) are right ascension and declination of source, $\odot$ is ecliptic longitude of the sun, ε is obliquity of the ecliptic [22].

The fitting result is $\varpi = 0.54 \pm 0.06$ mas, $(\langle\mu_\alpha^{(i)}\cos\delta\rangle, \langle\mu_\delta^{(i)}\rangle) = (-6.91, -12.52)$ mas, where $\langle\ \rangle$ denotes the average. The linear motions of maser spots $(\mu_\alpha^{(i)}, \mu_\delta^{(i)})$ are listed in table 1. The

[1] The National Radio Astronomy Observatory is a facility of the Natural Science Foundation operated under cooperative agreement by Associated Universities, Inc.

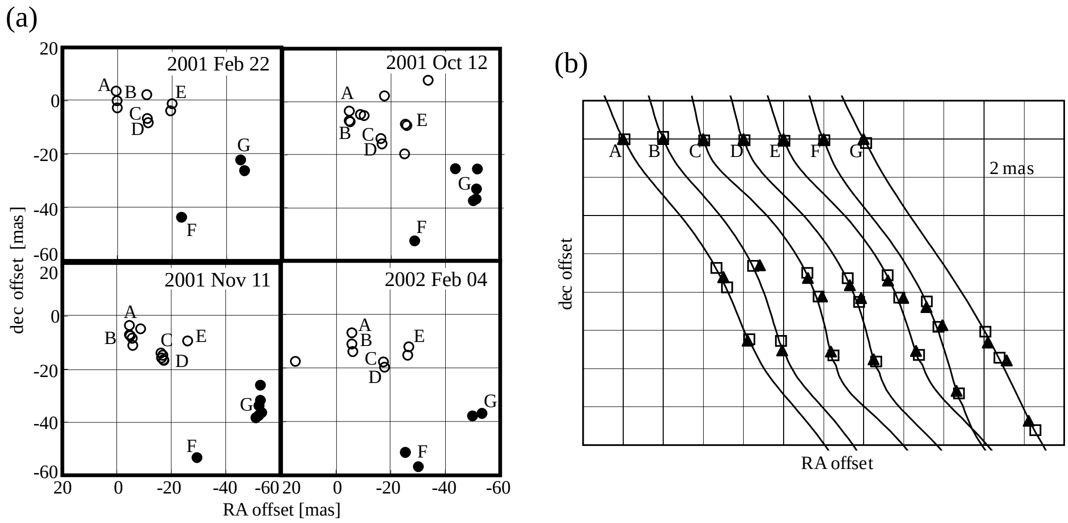

Figure 1: (a) Distribution of maser spots in each observation. Open circles are spots whose radial velocities are negative, and filled circles are positive. The radial velocity of UX Cygni itself is estimated -0.2 km/s [21]. (b) Movements of maser spots and fitting results. Closed triangles show the observed positions, solid lines shows the fitting results. Open squares show the theoretical positions on observed dates. One section is 2 mas. For each maser spot, observed position of the first date is set to the cross point of division.

Maser ID	$\mu_\alpha^{(i)} \cos\delta$ mas/yr	$\mu_\delta^{(i)}$ mas/yr	$v_{\rm LSR}$ km/s
A	-6.32 ± 0.29	-10.96 ± 0.28	-2.0
B	-6.09 ± 0.29	-11.61 ± 0.29	-2.4
C	-6.73 ± 0.29	-11.69 ± 0.28	-4.0
D	-6.82 ± 0.29	-12.06 ± 0.28	-3.9
E	-6.92 ± 0.29	-11.70 ± 0.28	-2.9
F	-6.92 ± 0.29	-13.85 ± 0.28	2.2
G	-8.59 ± 0.29	-15.79 ± 0.28	2.8
average	-6.91 ± 0.75	-12.52 ± 1.57	

Table 1: Fitting results of linear motions. Annual parallax $\varpi = 0.54 \pm 0.06$ mas. $v_{\rm LSR}$ is average of radial velocity over time. Maser IDs (A–G) are corresponding to all figures. Errors in average columns are standard deviations of 7 spots.

distance to UX Cygni is $1.85^{+0.25}_{-0.19}$ kpc. We abandon the third-epoch data of maser spot B because its residual is much larger than the others ($\sim$ 1 mas). Hereafter, we assume that the average value is the proper motion of UX Cygni itself. Since we assume the inner motions of maser spots are linear motions, this method is not able to separate inner motions from the proper motion of UX Cygni itself, but is able to separate the parallax from the other motions. Because of the effect of inner motions, $(\mu_\alpha^{(i)}, \mu_\delta^{(i)})$ are different.

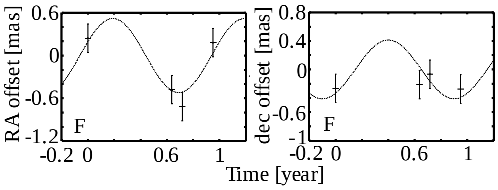

Figure 2: Right ascention or declination versus time plot for maser F. Crosses and error bars are observed data minus fitted linear motions. Dashed curves are the fitted parallax motions.

4. Discussion

4.1 Comparison with the period-luminosity relation in Large Magellanic Cloud

According to [1], the period-luminosity relation in Large Magelanic Cloud shows a bending at 420-day period. From the data written in [1], the period-luminosity relation over 420 days is

$$K = -5.22 \log P + 23.7. \tag{4.1}$$

(Where K is K-band magnitude, P is variation period [day].) If we adopt this relation and we calculate the distance to Large Magellanic Cloud based on our result $\varpi = 0.54 \pm 0.06$ mas and $K = 1.96$, it is $55.1^{+9.0}_{-7.2}$ kpc (distance modulus is $18.71^{+0.33}_{-0.31}$). The error in distance modulus consists of 0.24–0.27 mas from parallax error and 0.19 mas from intrinsic width of the period-luminosiry relation. This value is consistent with 50.1 ± 0.5 kpc by [23]. The period-luminosity relation of galactic OH/IR stars (They are a kind of Miras.) between 400 and 800 days is fainter than other range of periods [15, 16], and the relation of Miras in Large Magellanic Cloud is brighter. This difference of shape of period-luminosity relation affects the central value (55.1 kpc) of our results.

4.2 Three-dimensional position and kinematics of UX Cygni in Our Galaxy

From our result ($\varpi = 0.54 \pm 0.06$ mas) we can calculate the position of UX Cygni in our galaxy. If we assume that the sun lies on galactic plane and $R_0 = 8.5$ kpc, the cylindrical coordinates of UX Cygni are $(R, \theta, z) = (8.20 \pm 0.01 \text{ kpc}, 12.^\circ 4^{+1.^\circ 7}_{-1.^\circ 3}, -0.30^{+0.03}_{-0.04} \text{ kpc})$, where the sun lies at $(R, \theta, z) = (R_0, 0, 0)$ and the origin is at the galactic center.

Using our proper motion value $(\mu_\alpha \cos\delta, \mu_\delta) = (-6.91 \pm 0.75, -12.52 \pm 1.57)$ mas/yr, we can estimate three-dimensional velocity of UX Cygni in our galaxy. The three-dimensional velocity of UX Cygni is $(V_R, V_\theta, V_z) = (-81.6^{+14.0}_{-15.3}, 204.0^{+3.6}_{-3.4}, -12.1^{+10.2}_{-10.3})$ km/s. These are calculated by assuming $R_0 = 8.5$ kpc, $\Theta_0 = 220$ km/s and standard solar motion. We use the converting matrix from equatorial coordinates to galactic coordinates [24] in order to convert the proper motion in equatorial coordinates to that in galactic coordinates. We used the average of maser spots (-1.46 ± 2.60 km/s) for the radial velocity. Errors are estimated by root sum square of each error (ϖ, $\langle \mu_\alpha^{(i)} \rangle$, $\langle \mu_\delta^{(i)} \rangle$ and radial velocity).

5. Conclusion

We observed water masers around a Mira UX Cygni with phase-referencing VLBI observations by using extragalactic source as a phase-referencing source. We obtain the parallax $\varpi =$

0.54 ± 0.06 mas. Combining the period-luminosity relation in the Large Magellanic Cloud, it shows a slightly larger value of the distance to Large Magellanic Cloud, but it is affected the displacement of the period-luminosity relation. We can get the three-dimensional position and motion in our galaxy from the parallax and the proper motion.

References

[1] Feast, M. W., Glass, I. S., Whitelock, P. A., and Catchpole, R. M. 1989, MNRAS, 241, 375

[2] van Leeuwen, F., Feast, M. W., Whitelock, P. A., and Yudin, B. 1997, MNRAS, 287, 955

[3] Whitelock, P. and Feast, M. 2000, MNRAS, 319, 759

[4] Knapp, G. R., Pourbaix, D., Platais, I. and Jorissen, A. 2003, A&A, 403, 993

[5] Willson, L. A. 2000, ARA&A, 38, 573

[6] Wallerstein, G. and Knapp, G. R. 1998, ARA&A, 36, 369

[7] Thompson, A. R., Moran, J. M. and Swenson, G. R., Jr. 2001, Interferometry and Synthesis in Radio Astronomy (2nd ed.; New York; Wiley)

[8] Alef, W. 1989, in Very Long Baseline Interferometry Techniques and Applications, ed. M. Felli and R. E. Spencer (NATO ASI Ser. C, 283; Dordrecht; Kluwer), 261

[9] Beasley, A. J. and Conway, J. E. 1995, in ASP Conf. Ser. 82, Very Long Baseline Interferometry and the VLBA, ed. J. A. Zensus, P. J. Diamond and P. J. Napier (San Francisco; ASP), 327

[10] Chatterjee, S., Cordes, J. M., Vlemmings, W. H. T., Arzoumanian, Z., Goss, W. M. and Lazio, T. J. W. 2004, ApJ, 604, 339

[11] Dodson, R., Legge, D., Reynolds, J. E. and McCulloch, P. M. 2003, ApJ, 596, 1137

[12] Brisken, W. F., Benson, J. M., Goss, W. M. and Thorsett, S. E. 2002, ApJ, 571, 906

[13] Vlemmings, W. H. T., van Langevelde, H. J., Diamond, P. J., Habig, H. J. and Schilizzi, R. T. 2003, A&A, 407, 213

[14] van Langevelde, H. J. and Vlammings, W. H. T. 2003, in Mass-Losing Pulsating Stars and Their Circumstellar Matter, ed. Y. Nakada, M. Honma and M. Seki (Dordrecht: Kluwer), 381

[15] Whitelock, P., Feast, M. and Catchpole, R. 1991, MNRAS, 248, 276

[16] van Langevelde, H. J., van der Heiden, R. and van Schooneveld, C. 1990, A&A, 239, 193

[17] Samus, N. N. et al. 2003, Astron. Lett., 29, 468

[18] Feast, M. W. and Whitelock, P. A. 2000, MNRAS, 317, 460

[19] Gezari, D. Y., Pitts, P. S. and Schmitz, M. 1999, Catalog of Infrared Observations (5th ed.; Strasbourg; CDS)

[20] Fey, A. L., Boboltz, D. A., Gaume, R. A., Eubanks, T. M. and Johnston, K. J. 2001, AJ, 121, 1741

[21] Bowers, P. F. and Johnston, K. J. 1994, ApJS, 92, 189

[22] Green R. M. 1985, Spherical Astronomy (Cambridge; Cambridge Univ. Press)

[23] Alves, D. R. 2004, New A Rev., 48, 659

[24] Murray, C. A. 1989, A&A, 218, 325