Astrometry of the Galactic Miras and LPVs with a Japanese VLBI Array "Vera"

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A relation between pulsation periods and magnitudes (PL-relation) of the Galactic long period variable (LPVs) is studied based on VLBI observations. Calibration of the PL-relation applied to the Galactic LPVs is our scientific aim. From 2004, we have been conducting astrometric VLBI observations towards dozens of Mira and semiregular variables to measure their parallaxes. Current result of our ongoing study is presented. As a future plan, we started a study of mid-infrared PL-relations applied to OH/IR stars with period longer than $\sim$1000 days. We mention a contribution to the study of Galactic kinematics from our research of OH/IR stars.

Keywords: Variable star, VLBI, Astrometry.

1 Introduction

A term "Long period variables (PLVs)" is generally used to indicate luminous cool stars that pulsate with period of about 100 to, in some cases, a few thousand days. They eject their outer layers into interstellar space and have a large influence on a chemical property of astronomical object. Their remarkable periodicity in optical wavelength is also an important characteristic of them. A relation between their pulsation period and magnitude (PL-relation) is recognized as a basic part of distance ladder. Although a narrow PL-relation for LPVs in the Large Magellanic Cloud (LMC) are well confirmed (e. g. [1]), same relations for the Galactic LPVs has not been precisely obtained because of ambiguities of their absolute magnitudes due to distance uncertainties [2]. For a calibration of the PL-relation applied to the Galactic Mira variables, we are conducting astrometric VLBI observations towards Galactic LPVs to obtain accurate distances. As an extension of this study, we are surveying existence of the same kind of relation for variables stars with periods longer than $\sim$1000 days, that has not well been studied yet. The OH/IR stars sometimes represent quite long period ($\geq$1000 days). In this period range, OH/IR stars become dominant among several types of LPVs, so they are targets of our future study.

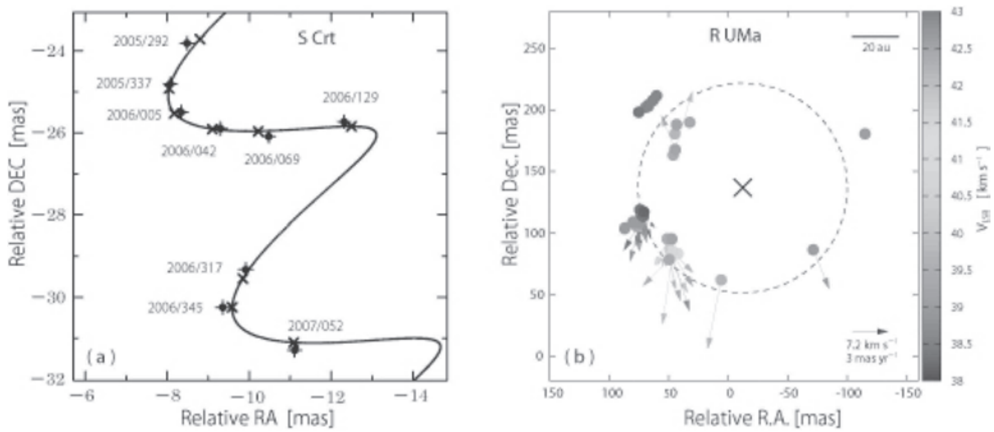

Fig. 1. (a) Trajectory of a maser spot in S Crt on the sky plane [4]. Filled circles and cross symbols indicate observed positions and best-fit model. Linear proper motion of the maser spot was modulated with a parallax oscillation. (b) Circumstellar distribution and motions of H_2O maser in R UMa [2]. A cross symbol indicate an estimated stellar position. A shell radius of 85 mas is shown with a dotted circle

2 VLBI observation and parallax measurement

Intensity of the maser emission usually shows large variability. Like the periodic pulsation at optical wavelength, the maser emission sometimes represents quasi-periodic variability with the same periods as the optical band. To derive the parallax by observing maser emission, it is necessary to find targets accompanied by bright maser emission enough to be detected with VLBI. We are monitoring candidate targets using IRIKI 20 m telescope with nearly one month interval. Based on this single-dish observation, we select targets for VLBI astrometry.

We have been conducting monitoring VLBI observations using "VERA" with typical duration of 1.5–2 yr and interval of $\sim$1 month for each source. The VERA array consists of four antennas with 20 m aperture located in Japan [3]. Using a dual beam system installed in VERA antennas, we simultaneously observe a QSO adjacent to the target maser and this gives absolute position of the maser spot. We observe the H_2O maser emission at 22.235 GHz, yielding a synthesized beam size of $\sim$1 mas. Detected images are fitted to two-dimensional Gaussian model to determine their position and flux densities. By tracing the positions during 1–2 years, we can solve a parallax. Fig. 1 (a) is a typical result of our measurement showing a serpentine motion of maser spot on the sky plane. This motion is obtained as a combination of linear proper motion and parallactic oscillation. We can also obtain internal motions of circumstellar masers at a rest frame fixed to the central star. Fig. 1 (b) is an example of the internal motions of maser spots in a Mira variable R UMa [2]. This map revealed 72 maser spots distributed in an $\sim$110 au area around the expected stellar position.

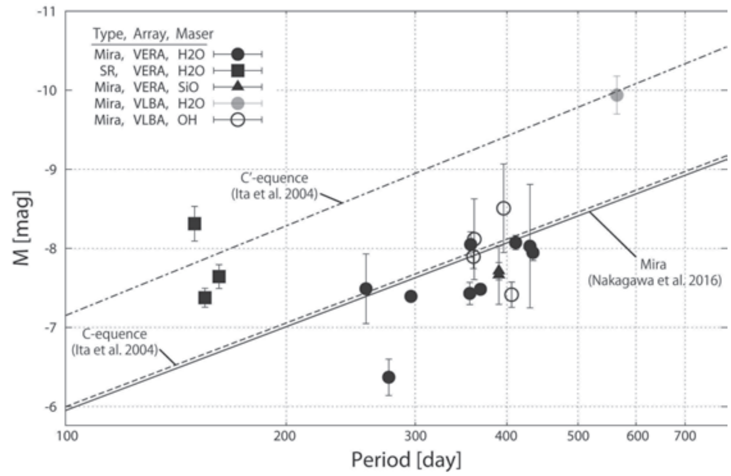

Fig. 2. The K-band absolute magnitudes $(M_K) - \log P$ diagram of the Galactic LPVs in table 1. Solid line shows the relation $M_K = -3.52 \log P + (1.09 \pm 0.14)$. The labels C, C', and corresponding dashed-lines indicate sequences found for LPVs in the LMC [5]

3 Current results: PL-relation of the Galactic Mira and semiregular variables

Large progress of astrometric VLBI technique in the last decade made it possible to measure parallaxes of dozens of LPVs. Table 1 shows parallaxes of the Galactic LPVs whose distances were measured with VLBI observations using VLBA and VERA. In addition to Mira, some red giants and semiregular variables are also included. Absolute magnitude errors are based on their distance errors. The same table is already published [2], and detail references of each value can be confirmed in the literature.

Using these values and additional preliminary results from our ongoing study, we consider PL-relation of the Galactic LPVs. Fig. 2 shows an absolute magnitudes distribution of LPVs in table 1 on $M_K - \log P$ plane. Results from VERA observation towards Mira and semiregular variables are presented with filled symbols. Difference of its shape indicate species of the maser emission. Gray and open circles indicate results from VLBA observations using H_2O and OH maser, respectively. Solid line shows an unweighted-least squares fitting result of $M_K - \log P$ relation applied to the Galactic Mira variables, $M_K = -3.52 \log P + (1.09 \pm 0.14)$ [2]. The labels C, C', and corresponding dashed-lines indicate sequences found for LPVs in the LMC [5]. Distance modulus of 18.49 is assumed to calibrate absolute magnitudes of source in the LMC. Now we can find that two PL-relations for Mira variables in the Galaxy and LMC is consistent with error range. More results from VERA observations will soon be added, and zero point of the PL-relation will be solved with better accuracy.

Table 1

VLBI parallaxes of the Galactic LPVs

Source	Parallax, mas	P, day	m_K, mag	M_K, mag	Maser
RW Lep	1.62 ± 0.16	150	0.639	-8.31 ± 0.22	H_2O
S Crt	2.33 ± 0.13	155	0.786	-7.38 ± 0.12	H_2O
RX Boo	7.31 ± 0.5	162	-1.96	-7.64 ± 0.15	H_2O
T UMa†	0.96 ± 0.15	257	2.60	-7.49 ± 0.44	H_2O
Y Lib†	1.24 ± 0.13	276	3.16	-6.37 ± 0.23	H_2O
R UMa	1.97 ± 0.05	302	1.19	-7.34 ± 0.06	H_2O
FV Boo	0.97 ± 0.06	340	3.836	-6.23 ± 0.13	H_2O
SY Aql†	1.10 ± 0.07	356	2.36	-7.43 ± 0.14	H_2O
R Cnc†	3.84 ± 0.29	357	-0.97	-8.05 ± 0.16	H_2O
W Hya	10.18 ± 2.36	361	-3.16	-8.12 ± 0.51	OH
S CrB	2.39 ± 0.17	360	0.21	-7.90 ± 0.15	OH
T Lep	3.06 ± 0.04	368	0.12	-7.45 ± 0.03	H_2O
R Aqr	4.7 ± 0.8	390	-1.01	-7.65 ± 0.37	SiO
R Aqr	4.59 ± 0.24	390	-1.01	-7.70 ± 0.11	SiO
RR Aql	1.58 ± 0.40	396	0.46	-8.55 ± 0.56	OH
U Her	3.76 ± 0.27	406	-0.27	-7.39 ± 0.16	OH
SY Scl	0.75 ± 0.03	411	2.55	-8.07 ± 0.09	H_2O
R Cas	5.67 ± 1.95	430	-1.80	-8.03 ± 0.78	OH
U Lyn	1.27 ± 0.06	434	1.533	-7.95 ± 0.10	H_2O
QX Pup†	0.55 ± 0.05	551	—	—	H_2O
UX Cyg	0.54 ± 0.06	565	1.40	-9.94 ± 0.24	H_2O
S Per	0.413 ± 0.017	822	1.33	-10.59 ± 0.09	H_2O
PZ Cas	0.356 ± 0.026	925	1.00	-11.24 ± 0.16	H_2O
VY CMa	0.88 ± 0.08	956	-0.72	-11.00 ± 0.20	H_2O
NML Cyg	0.62 ± 0.047	1280	0.791	-10.25 ± 0.16	H_2O

† Preliminary results.

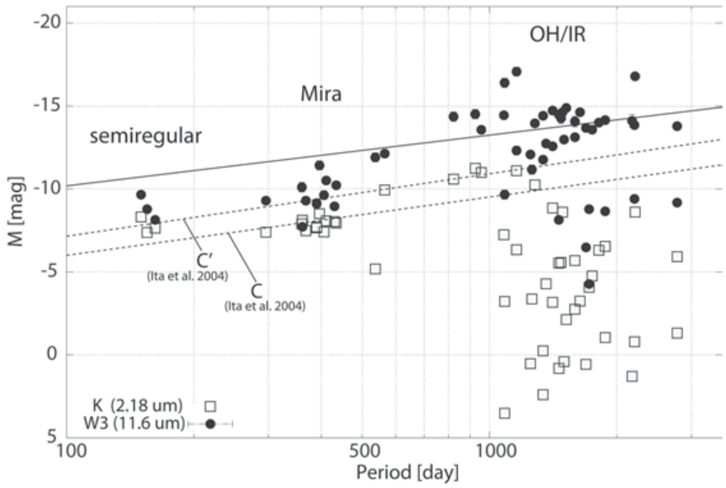

Fig. 3. From 100 to 3500 days wide period range PL-diagram of the Galactic LPVs in K-band (□) and mid-infrared band (•). The WISE data at a wavelength of $11.6\ \mu$m (W3) are used as mid-infrared measurements. At the W3-band, we see a clustering of OH/IR stars around -13 mag, and we regard it as important to explore the possibility of new distance estimator of this kind of sources. Solid line is a tentative mid-infrared PL-relation of OH/IR stars

4 Future prospect: OH/IR stars as a new candidate of Galactic disk tracer

OH/IR stars show longer pulsation periods and thought to have larger mass than Mira and semiregular variables, i. e. stars with $P \simeq 1000$ day has initial mass of $M \simeq 4.0 M_{\odot}$ [6]. We compiled OH/IR stars with known periods and distances from literature [7]. Using the distances, apparent magnitudes were converted to absolute ones.

In Fig. 3, we presented the K-band absolute magnitudes of LPVs with open squares. Since the OH/IR stars are deeply enshrouded in thick circumstellar dust shell, K-band absolute magnitudes become lower and scattered. In longer wavelength, such as mid-infrared band, re-radiation from dust shell becomes dominant. To avoid circumstellar extinction, we tried to estimate absolute magnitudes in mid-infrared band using data from the Wide-field Infrared Survey Explorer (WISE)*. In particular, here we present our preliminary study using the WISE measurements at a wavelength of $\lambda = 11.6\ \mu$m (W3-band). Absolute magnitudes in W3-band of Mira, semiregular, and OH/IR stars are presented with filled circles in Fig. 3. Thought it is difficult to find clear relation for OH/IR stars ($P \gtrsim 1000$ days) in K-band, it become narrower in W3-band and some relation can be implied. We fitted the W3-band data of OH/IR stars in 1000 to 3000 days range with a linear function, and obtained a relation of $M_{W3} = -3.1(\pm 2.6) \log P - 4.1(\pm 8.1)$, which is a very prelim-

*http://wise.ssl.berkeley.edu/index.html inary attempt and presented with a solid line in Fig. 3. Sequences C and C' for K-band PL-relation of Mira variables are also presented with dashed-lines.

If the relation for OH/IR stars is well calibrated, the OH/IR stars can become a new disk tracer in addition to star forming region and red supergiants generally considered in recent studies of Galactic kinematics. Stellar evolution study tells us that ages of stars with mass of $M \simeq 4.0 M_{\odot}$ is around $10^8 - 10^9$ yr. Samples with various ages are needed for the study of the Galactic kinematics. Our future plan is to calibrate this mid-infrared PL-relation of OH/IR stars based on VLBI astrometry. The VLBI method using OH/SiO/H_2O masers is a promising technique, and Gaia[†] or JASMINE[‡] can also contribute from optical astrometry.

References

1. *Wood P. R., et al.* MACHO observations of LMC red giants: Mira and semi-regular pulsators, and contact and semi-detached binaries // IAU Symposium 191. — 1999. — P. 151.
2. *Nakagawa A., et al.* Parallax of a Mira variable R Ursae Majoris studied with astrometric VLBI // PASJ. 2016. — Vol. 68. — P. 78.
3. *Kobayashi H., et al.* VERA Project // ASP Conference Series. — 2003. — Vol. 306. — P. 48.
4. *Nakagawa A., et al.* VLBI Astrometry of AGB Variables with VERA — A Semiregular Variable S Crateris // PASJ. — 2008. — Vol. 60. — P. 1013.
5. *Ita Y., et al.* Variable stars in the Magellanic Clouds: results from OGLE and SIRIUS // MNRAS. — 2004. — Vol. 347. — P. 720.
6. *Feast M. W.* The Ages, Masses, Evolution and Kinematics of Mira Variables // asrp.proc. — 2009. — P. 48.
7. *Engels D., et al.* Phase-lag Distances of OH Masing AGB Stars // ASPC. — 2015. — Vol. 497. — P. 473.

[†] http://sci.esa.int/gaia/
[‡] http://www.jasmine-galaxy.org/index-en.html