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Astrometric VLBI Observations of the Galactic LPVs, Miras, and OH/IR stars

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Abstract. Studies of Galactic LPVs based on astrometric VLBI are presented. We use a VLBI array, “VERA”, to measure parallaxes and calibrate the K-band period luminosity relation (PLR) of the Galactic Miras. Since the PLR offers a distance indicator, its calibration is crucial to reveal their spatial distribution. Parallaxes of dozens of LPVs are presented. For the longer period stars, the mass-loss is high and the stars are obscured and recognized as OH/IR stars. We estimated mid-infrared absolute magnitudes of dozens of OH/IR stars and found that they show a loose concentration around −14 mag at λ of 11.6 μm, indicating an existence of PLR for OH/IR stars. Astrometry of OH/IR stars will also help us to study non-steady spiral arms as proposed from the latest simulation study of the galactic dynamics. We will start astrometric VLBI observation of two OH/IR stars NSV25875 and OH127.8+0.0 at 43 GHz with VERA.

Keywords. VLBI, Astrometry, Maser, Mira, OH/IR, AGB.

1. Introduction

Long Period Variables (LPVs) are low- to intermediate-mass ($1 - 8M_\odot$) asymptotic giant branch (AGB) stars that pulsate with a period range of $100 - 1000$ days. They are surrounded by large and extended dust and molecular shells and, in sources with mass-loss rate higher than $\sim 10^{-7} M_\odot \mathrm{yr}^{-1}$, we find maser emission of H_2O, SiO, or OH. The well-known relation between K-magnitude and period of Mira variables, derived from studies of Miras in the LMC (Feast *et al.* 1989), is used as a distance indicator to obtain source distances from their periods and magnitudes. Since there is a metallicity difference between LMC and our Galaxy, it is also important to establish this relation using sources in our Galaxy. Since LPVs are very bright in infrared, we can use them to probe a region where interstellar extinction is strong, such as the direction of the Galactic Center and Galactic plane. Making use of the high performance of the VERA array (Kobayashi *et al.* 2003), which is a Japanese VLBI project dedicated to the Galactic astrometry, we aim to construct the $M_K - \log P$ relation for Galactic LPVs.

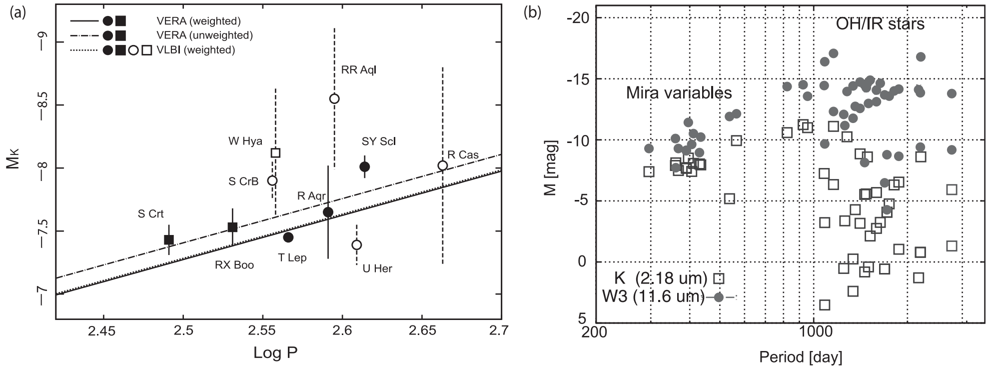

Figure 1. (a) K-band period luminosity relation of the Galactic Mira variables (Nakagawa *et al.* 2014). (b) Same relation for both Miras and OH/IR stars in wider period range. Absolute magnitudes at near(●)- and mid(□)-infrared bands are presented.

2. Period luminosity relation of Galactic LPVs

Mira and semi-regular variables.

In table 1, we show parallaxes of 26 Galactic LPVs whose distances were measured with VLBI observations using VERA and VLBA. Some red giants and semiregular variables are also included. Absolute magnitudes are estimated from their apparent magnitudes and parallax distances. Figure 1(a) shows a PLR derived from some results in table 1. Filled and open symbols indicate results from H_2O and OH maser, respectively. Circles and squares correspond to Mira and semiregular variables. The solid line is an unweighted-least squares fit for an $M_K - \log P$ relation using these results from VERA, $M_K = -3.52 \log P + (1.09 \pm 0.14)$ (Nakagawa *et al.* 2016). New results will be added soon and more accurate calibration can be expected.

OH/IR stars with very long periods ($P \gtrsim 1000$ days).

Compared to Mira variables, OH/IR stars tend to show longer pulsation periods, and sometimes it extends 1000 days. We compiled OH/IR stars with such very long periods from literatures (e.g. Engels & Bunzel 2015). Distances of some sources were determined by the "phase-lag method" (Engels *et al.* 2015). For sources with no estimated distances, we derived kinematic distances using their radial velocities. Then, apparent magnitudes were converted to absolute ones and presented in figure. 1(b). The K-band absolute magnitudes of LPVs are presented with open squares. Since OH/IR stars are surrounded by thick circumstellar dust shells, K-band absolute magnitudes become lower. And also we can see scattering of the magnitudes. We think this is due to an anisotropic distribution of the circumstellar dust. At longer wavelengths, re-radiation from the dust shell becomes dominant. To minimize circumstellar extinction, we estimated absolute magnitudes in the mid-infrared band ($\lambda = 11.6\mu$m, W3-band) using data from the Wide-field Infrared Survey Explorer (WISE; http://wise.ssl.berkeley.edu/index.html). Absolute magnitudes in the W3-band of Mira, semiregular, and OH/IR stars are presented with filled circles in figure 1(b). Although it is difficult to find clear relation for OH/IR stars with $P \gtrsim 1000$ days in K-band, it becomes narrower in the W3-band, and some relation can be implied. It is well known that there are deep silicate absorption features at $\lambda \simeq 8 - 18\mu$m, and so a more appropriate waveband should be considered or calibration of the absorption is needed. If the mid-infrared PLR is confirmed, this can be used as a new distance indicator for sources along the Galactic plane or deeply obscured by dust.

Table 1. Parallax of the Galactic LPVs determined with VLBI astrometry.

Source	Type	Parallax [mas]	P [day]	Log$P$	m_K [mag]	M_K [mag]	Maser	Reference (Parallax[1], m_K[2])
RW Lep	SRa	1.62±0.16	150	2.176	0.639	-8.31 ± 0.22	H_2O	kam14, a
S Crt	SRb	2.33±0.13	155	2.190	0.786	-7.38 ± 0.12	H_2O	nak08, a
RX Boo	SRb	7.31±0.5	162	2.210	−1.96	-7.64 ± 0.15	H_2O	kam12, b
T UMa	Mira	0.96±0.15	257	2.410	2.60	-7.49 ± 0.44	H_2O	**in prep.**, a
Y Lib	Mira	1.24±0.13	276	2.441	3.16	-6.37 ± 0.23	H_2O	**in prep.**, a
R UMa	Mira	1.92±0.05	302	2.480	1.19	-7.39 ± 0.06	H_2O	nak16, d
SY Aql	Mira	1.10±0.07	356	2.551	2.36	-7.43 ± 0.14	H_2O	**in prep.**, a
R Cnc	Mira	3.84±0.29	357	2.553	−0.97	-8.05 ± 0.16	H_2O	**in prep.**, a
W Hya	SRa	10.18±2.36	361	2.558	−3.16	-8.12 ± 0.51	OH	vle03, c
S CrB	Mira	2.39±0.17	360	2.556	0.21	-7.90 ± 0.15	OH	vle07, c
T Lep	Mira	3.06±0.04	368	2.566	0.12	-7.45 ± 0.03	H_2O	nak14, c
R Peg	Mira	3.98±0.21	378	2.577	0.45	-6.55 ± 0.11	H_2O	**in prep.**, a
R Hya	Mira	8.96±0.51	380	2.580	-2.51	-7.75 ± 0.12	H_2O	**in prep.**, a
R Aqr	Mira	4.7±0.8	390	2.591	−1.01	-7.65 ± 0.37	SiO	kam10, c
R Aqr	Mira	4.59±0.24	390	2.591	−1.01	-7.70 ± 0.11	SiO	min14, c
RR Aql	Mira	1.58±0.40	396	2.598	0.46	-8.55 ± 0.56	OH	vle07, c
U Her	Mira	3.76±0.27	406	2.609	−0.27	-7.39 ± 0.16	OH	vle07, c
SY Scl	Mira	0.75±0.03	411	2.614	2.55	-8.07 ± 0.09	H_2O	nyu11, b
R Cas	Mira	5.67±1.95	430	2.633	−1.80	-8.03 ± 0.78	OH	vle03, c
U Lyn	Mira	1.27±0.06	434	2.637	1.533	-7.95 ± 0.10	H_2O	kam15, a
OH231.8+4.2	OH/IR	0.55±0.05	551	2.741	···	···	H_2O	**in prep.**
UX Cyg	Mira	0.54±0.06	565	2.752	1.40	-9.94 ± 0.24	H_2O	kur05, a
OZ Gem	Mira	1.00±0.18	598	2.777	3.00	-7.00 ± 0.40	H_2O	**in prep.**, a
S Per	SRc	0.413±0.017	822	2.915	1.33	-10.59 ± 0.09	H_2O	asa10, b
PZ Cas	SRc	0.356±0.026	925	2.966	1.00	-11.24 ± 0.16	H_2O	kus13, b
VY CMa	SRc	0.88±0.08	956	2.980	−0.72	-11.00 ± 0.20	H_2O	cho08, b
NML Cyg	···	0.62±0.047	1280	3.107	0.791	-10.25 ± 0.16	H_2O	zha12, a

Notes: [1] References of the parallax are as follows : (kam14) Kamezaki *et al.* 2014, (nak08) Nakagawa *et al.* 2008, (kam12) Kamezaki *et al.* 2012, (nak16) Nakagawa *et al.* 2016, (vle03) Vlemmings *et al.* 2003, (vle07) Vlemmings & van Langevelde 2007, (nak14) Nakagawa *et al.* 2014, (kam10) Kamohara *et al.* 2010, (min14) Min *et al.* 2014, (nyu11) Nyu *et al.* 2011, (kam15) Kamezaki *et al.* 2015, (kur05) Kurayama *et al.* 2005, (asa10) Asaki *et al.* 2010, (kus13) Kusuno *et al.* 2013, (cho08) Choi *et al.* 2008, and (zha12) Zhang *et al.* 2012.
[2] References of the apparent magnitudes (m_K) are as follows : (a) The IRSA 2MASS All-Sky Point Source Catalog (Cutri *et al.* 2003), (b) Catalogue of Stellar Photometry in Johnson's 11-color system (Ducati(2002)), (c) Photometry by (Whitelock & Feast 2000), and (d) Photometry using Kagoshima 1m telescope.

Table 2. Correspondence table of model and observation in galactic dynamics.

Age	Physics	Target	Model		Observation
$\sim 10^6$ yr	Spiral arm	SFR, Giants	✓	↔	✓
$\sim 10^8$ yr	Bifurcating/merging arm	Heavy OH/IR star ?	✓	↔	No
$\sim 10^9$ yr	Relaxed system	Mira	✓	↔	✓

3. Astrometry for heavy OH/IR stars for galactic dynamics

The OH/IR stars showing longer periods are thought to have larger mass, i.e. variable stars with $P \simeq 1000$ days have initial masses of $\simeq 4.0 M_\odot$ (Feast *et al.* 1989). Their ages are thought to be on the order of 10^8 yr. The latest study of galactic spiral arms based on three-dimensional N-body simulations supports a picture of non-steady spiral arms (e.g. Baba *et al.* 2013). As a characteristic behavior, it is predicted that spiral arms bifurcate or merge on a time scale of 10^8 yr. Now, we can find that this time scale is similar to the age of OH/IR stars with very long periods ($P \gtrsim 1000$ days). From recent VLBI

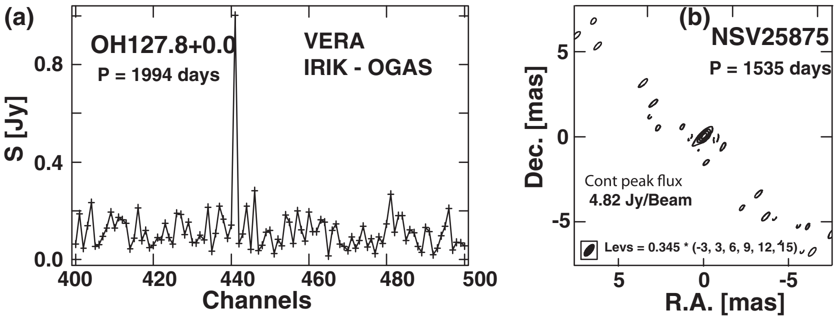

Figure 2. (a) SiO maser cross correlated spectrum of OH127.8+0.0 detected at Iriki-Ogasawara baseline of VERA. (b) Self-calibrated map of SiO maser in NSV25875.

observations, astrometric results of many SFRs and Mira variables are obtained. But the ages of the sources are in the order of 10^6 yr and 10^9 yr, respectively. So, observations of sources with various ages are needed to fully understand the mechanism of spiral arm formation, and OH/IR stars can become a good probe to compensate the time scale gap in these studies (Table 2). Astrometric VLBI is a promising method to determine three-dimensional positions and motions of the OH/IR stars. We selected several OH/IR stars with $P \gtrsim 1000$ days and detected two sources of 43 GHz SiO maser emission using VERA. Phase-referencing VLBI monitoring for two pairs, "OH127.8+0.0 & J0128+6306" and "NSV25875 & J2231+5922" have just started in Oct. 2017. Figure 2(a) and (b) show results of a test VLBI observation prior to the monitoring VLBI. Parallax measurements of the two sources will also be used for the PLR study proposed in the previous section.

References

Asaki, Y., Deguchi, S., Imai, H., *et al.* 2010, *APJ*, 721, 267
Baba, J., Saitoh, T. R., & Wada, K. 2013, *APJ*, 763, 46
Choi, Y. K., Hirota, T., Honma, M., *et al.* 2008, *PASJ*, 60, 1007
Cutri, R. M., Skrutskie, M. F., van Dyk, S., *et al.* 2003, VizieR Online Data Catalog, 2246,
Engels, D. & Bunzel, F. 2015, *A&A*, 582, A68
Engels, D., Etoka, S., Gérard, E., & Richards, A. 2015, Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time, 497, 473
Feast, M. W., Glass, I. S., Whitelock, P. A., & Catchpole, R. M. 1989, *mnras*, 241, 375
Kamezaki, T., Nakagawa, A., Omodaka, T., *et al.* 2012, *PASJ*, 64, 7
Kamezaki, T., Kurayama, T., Nakagawa, A., *et al.* 2014, *PASJ*, 118
Kamezaki, T., Nakagawa, A., Omodaka, T., *et al.* 2015, *PASJ*, 208
Kamohara, R., Bujarrabal, V., Honma, M., *et al.* 2010, *A&A*, 510, A69
Kobayashi, H., *et al.* 2003, ASP Conference Series, 306, 48P
Kurayama, T., Sasao, T., & Kobayashi, H. 2005, *APJ*, 627, L49
Kusuno, K., Asaki, Y., Imai, H., & Oyama, T. 2013, *APJ*, 774, 107
Min, C., Matsumoto, N., Kim, M. K., *et al.* 2014, *PASJ*, 66, 38
Nakagawa, A., Tsushima, M., Ando, K., *et al.* 2008, *PASJ*, 60, 1013
Nakagawa, A., Omodaka, T., Handa, T., *et al.* 2014, *PASJ*, 66, 101
Nakagawa, A., Kurayama, T., Matsui, M., *et al.* 2016,*PASJ*, 68, 78
Nyu, D., Nakagawa, A., Matsui, M., *et al.* 2011, *PASJ*, 63, 63
Vlemmings, W. H. T., van Langevelde, H. J., Diamond, P. J., Habing, H. J., & Schilizzi, R. T. 2003, *A&A*, 407, 213
Vlemmings, W. H. T. & van Langevelde, H. J. 2007, *A&A*, 472, 547
Whitelock, P. & Feast, M. 2000, *MNRAS*, 319, 759
Zhang, B., Reid, M. J., Menten, K. M., Zheng, X. W., & Brunthaler, A. 2012, *A&A*, 544, AA42