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VLBI astrometry for OH/IR stars and Period-Luminosity relation in very long period range

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Abstract. VLBI studies for dust-obscured OH/IR stars using the Japanese VLBI array VERA (VLBI Exploration of Radio Astrometry) are presented. In a late stage of stellar evolution with initial masses of $0.8 - 10M_{\odot}$, they are classified as Asymptotic Giant Branch (AGB) stars. Mira variables, well known for their period luminosity relation (PLR) as distance estimator, are thought to be in the early stage of the AGB phase. With further evolution, they will be recognized as OH/IR stars due to detection of OH masers and infrared excess. Because of extinction by circumstellar dust, parallax measurements of the OH/IR stars in optical bands become difficult. However, VLBI astrometry of H_2O masers around the OH/IR stars are effective to determine their parallaxes. By comparing parallaxes of AGB stars from VLBI and Gaia, advantage of the VLBI astrometry in parallax measurements for OH/IR stars becomes clear. Since some OH/IR stars show quite long pulsation periods ($P \geq 1000$ days), extension of the PLR to longer period range may provide new distance estimator. Based on parallaxes of eight OH/IR stars determined with our VLBI observations, we estimated absolute bolometric magnitudes ($M_{\rm bol}$) using spectral energy distributions (SEDs) fitting. A new period-$M_{\rm bol}$ relation for dust-obscured OH/IR stars applicable to longer period range is indicated.

1. Introduction

1.1. Evolution of AGB stars

Stars with initial mass of 0.8-10 $M_{\odot}$ spend their final stage of evolution as asymptotic giant branch (AGB) stars (e.g., Karakas & Lattanzio 2014). They are surrounded by thick circumstellar dust and frequently present stellar pulsations. The AGB stars exhibit a wide range of pulsation periods, with the shortest periods being around 100 days and occasionally reaching 3000 days (e.g., Habing 1996). The Mira variables, thought to be in the early AGB phase, are well known for their period luminosity relation (PLR) as a distance estimator. Miras are visible in both optical and infrared bands because of relatively thin dust layers. As they evolve, strong absorption by thick circumstellar dust makes them faint and difficult to be detected in optical bands (e.g., Kamizuka et al. 2020). Then, they become brighter in the infrared due to re-radiation from the outer dust layer. At this stage, they represent OH maser, therefore they are recognized as OH/IR stars (e.g., Nyman et al. 1998). Compared to Miras, the OH/IR stars tend to exhibit longer pulsation periods, sometimes exceeding 1000 days. There are not enough samples of parallax for OH/IR stars, and the exploration of PLR for OH/IR stars in the Milky Way Galaxy is also an important concern. To understand physical properties of celestial object, distance is crucial information. If a PLR is confirmed for OH/IR stars, it can serve as a new distance estimator for the groups. In this regard, VLBI astrometry for OH/IR stars is an effective method to explore the PLR and also make a significant contribution for understanding of the evolution from early to late stages in AGB phases.

1.2. Importance of VLBI astrometry

A huge number of astrometric measurements for celestial objects are provided in the Gaia Data Release 3 (DR3) (Gaia Collaboration et al. 2023). For a very large number of Miras, DR3 gives good parallaxes. Since Miras have both Gaia and VLBI parallaxes, they are suitable sources for verifying Gaia and VLBI parallax. Figure 1 shows 41 parallaxes of AGB stars from VLBI ($\Pi_{\rm VLBI}$) and DR2/DR3 ($\Pi_{\rm Gaia\,DR2,DR3}$) on logarithmic scales. For many AGB stars, parallaxes from VLBI and Gaia shows good consistency. However, for two OH/IR stars NSV17351 and OH 231.8+4.2, DR3 parallaxes are smaller and show larger errors compared to those from VLBI.

Chiavassa et al. (2018) conducted a study using three-dimensional radiative hydrodynamics simulations of convection to explore the impact of convection-related surface structures in AGB stars on their photometric variability, and reported that the position of the photocenter has a temporal excursion of 0.077 − 0.198 au (5 to 11% of the corresponding stellar radius). Since the distances of our VLBI targets are in the order of a hundred pc to a few kpc, the angular size of the excursion can be converted to 0.1 − 1 mas. In addition, AGB strs have time variation of surface brightness distribution which can degrades the accuracy of astrometric measurements on optical images. Therefore, the DR3 parallax of AGB stars can be expected to suffer from this effect. In the late stage of AGB phase, central stars are surrounded by thick dust layers and they become faint in optical bands. An OH/IR star OH127.8+0.0, which is known to have a thick circumstellar dust shell and a high mass loss rate (Kemper et al. 2002) is an example that cannot be found in DR3. OH127.8+0.0 is very bright in the infrared, but faint in the optical bands due to the strong circumstellar extinction by the dust layer. Astrometric VLBI is still a very promising method for parallax measurements of such heavily dust-obscured AGB stars.

2. VLBI observation and astrometric results

We conduct 22 GHz VLBI monitoring observations for H_2O maser with VERA. The VERA array consists of four 20-metre aperture radio telescopes at Mizusawa, Iriki, Ogasawara, and Ishigaki-jima. Using the dual beam system in VERA, the relative position of the target maser spots with respect to the position reference continuum source can be determined with an accuracy of better than 0.1 mas, then the parallax is derived. In our previous observations, main targets were Miras with shorter pulsation periods ($P \leq 400$) (Nakagawa et al. 2018). From 2017, we started observations of OH/IR stars showing longer periods. Potential targets of our current study are shown in Table 1 with their DR3 parallaxes. Relative parallax errors and pulsation periods are also given. Some sources show negative DR3 parallaxes or have relative errors greater than 100 %. So, we can interpret that Table 1 shows difficulty in parallax measurements of dust-obscured OH/IR stars for Gaia. We have also chosen these targets from the perspective of covering a wide range of pulsation periods.

In addition to NSV17351 already published in Nakagawa et al. (2023), some preliminary parallax results are now available and presented in Table 2, however it is difficult to successfully measure all the parallax of potential targets in Table 1. For OH 39.7+1.5, using two maser spots with radial velocities of 34.6 and 8.6 $\mathrm{km\,s^{-1}}$, a preliminary parallax of 0.55±0.03 mas (its corresponding distance is 1.82±0.10 kpc) was obtained. For IRC−30363, using a maser spot with a radial velocity of 9.72 $\mathrm{km\,s^{-1}}$, a parallax of 0.49±0.09 mas (distance of 2.04±0.39 kpc) was obtained. VERA parallaxes of other sources are also presented as preliminary values in Table 2. Although we are curious about many other OH/IR stars in Table 1, they could not be shown in Figure 1 because Gaia and/or VLBI parallaxes of many dust-obscured OH/IR stars are currently not determined.

3. Absolute bolometric magnitude estimation and implication for new PLR

In dust-obscured OH/IR stars, their thick circumstellar dust absorbs emission from the central star, and the warmed dust layer re-radiates at longer wavelengths. A PLR of Miras are usually discussed using absolute magnitudes in infrared K-band (M_{K}). However, in the case of OH/IR stars, the period-M_{K} relation represent large scattering (Nakagawa et al. 2018). So, in this study, we explore a new PLR for OH/IR stars by estimating their absolute bolometric magnitudes M_{bol}.

Table 1. Gaia DR3 parallaxes of our VLBI targets.

Source	Π_{DR3}/[mas]	Err./[%]	P/[day]
OH 127.8−0.0	n/a[†]	n/a	1994
OH 141.7+3.5	n/a	n/a	1750
RAFGL 5201	−0.131 ± 0.253	−194	600
NSV 17351	0.088 ± 0.147	166	1122
RAFGL 1686	1.053 ± 0.359	34	500
V697 Her	1.029 ± 0.129	13	497
IRC +10322	0.553 ± 0.183	33	570
V1018 Sco	n/a	n/a	n/a
NSV 23099	0.209 ± 0.102	49	431
OH 358.16+0.49	n/a	n/a	1507
OH 358.23+0.11	−0.061 ± 0.190	−313	704
OH 358.667−0.044	0.207 ± 0.142	69	300
IRAS 17411−3154	−0.122 ± 0.553	−452	n/a
OH 000.658−0.073	n/a	n/a	n/a
IRAS 18039−1903	n/a	n/a	n/a
OH 9.097−0.392	0.261 ± 0.232	89	634
IRC −30363	0.241 ± 0.130	54	720
IRAS 18176−1848	2.404 ± 0.618	26	n/a
OH 26.5+0.6	n/a	n/a	1589
OH 26.2−0.6	n/a	n/a	1330
OH 39.7+1.5	n/a	n/a	1260
OH 42.3−0.1	n/a	n/a	1650
OH 44.8−2.3	0.918 ± 0.631	69	n/a
OH 51.8−0.1	n/a	n/a	1270
RAFGL 2445	−1.548 ± 0.369	−24	n/a
IRC +10451	0.818 ± 0.196	24	730
OH 83.4−0.9	0.836 ± 0.556	66	1428
CU Cep	0.231 ± 0.057	25	700
NSV 25875	n/a	n/a	1535
NSV 14347	0.643 ± 0.071	11	366

[†] Parallaxes are not available in DR3.

Using observed flux densities in various wavelengths and parallax distances from our VLBI observations, we tried to estimate M_{bol} of the target OH/IR stars. For acquisition of multiwavelength data, we referred Pan-STARRS, Gaia DR3, 2MASS, WISE, MSX, IRAS, and AKARI databases. The SED model calculations were performed using the radiative transfer code DUSTY (V4) (Ivezic & Elitzur 1997) to take into account the effects of scattering, absorption, and re-radiation by circumstellar dust in AGB stars, and an optimal SED model was selected that is consistent with multi-wavelength observations. DUSTY(V4) is a software that produces a SED model by giving the following five main parameters; T^* [K]: surface temperature of the central star, r_{in} [cm]: in-

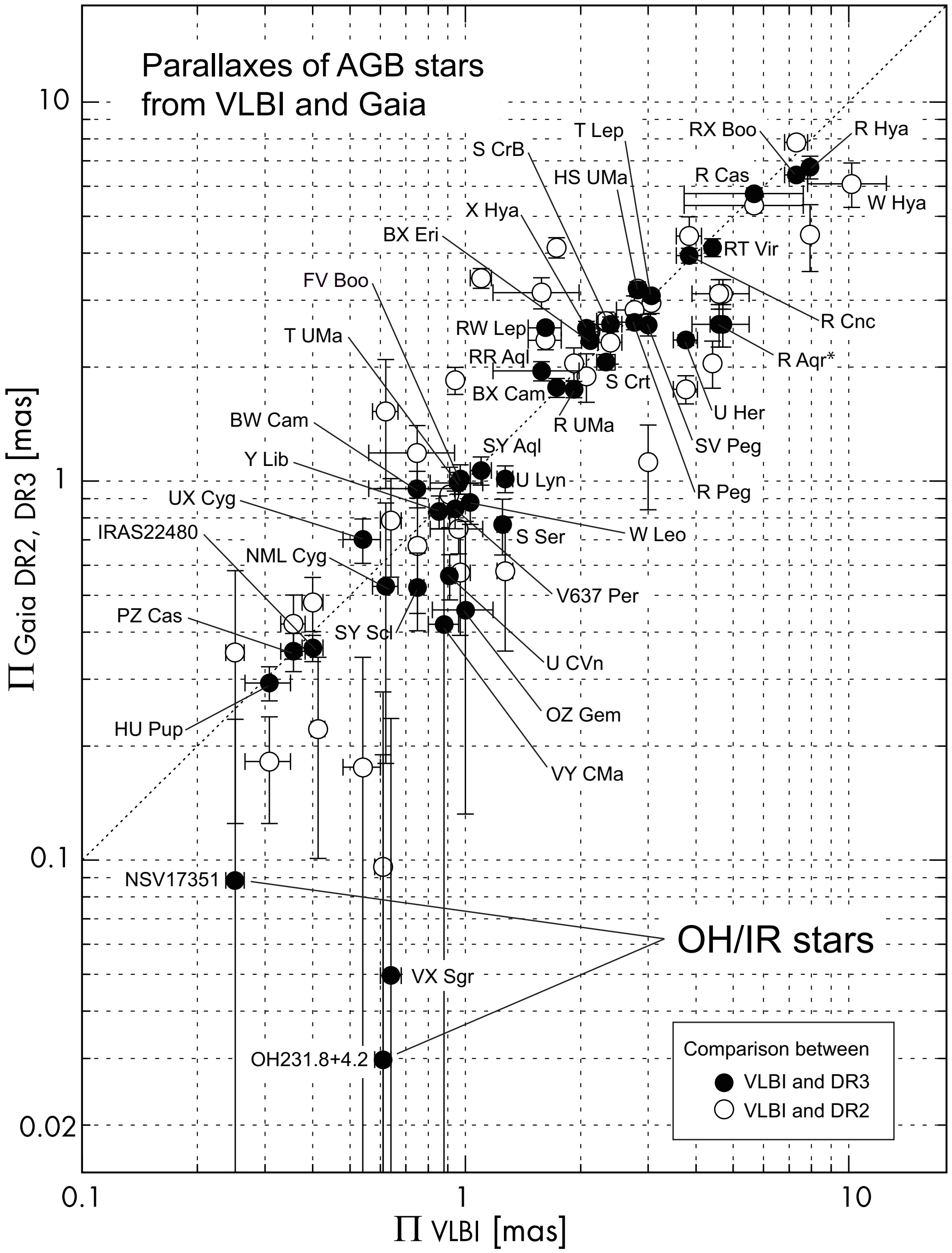

Fig. 1. Parallaxes of 41 pulsating AGB stars obtained from VLBI (horizontal axis) and Gaia DR2/DR3 (vertical axis) on a logarithmic scale. Open (filled) circles correspond to the comparison between the VLBI and DR2 (VLBI and DR3). For two OH/IR stars, errors in horizontal axis (VLBI) are much smaller than those in horizontal axis (DR3).

ner radius of the circumstellar dust shell, $r_{\rm out}$ [cm]: outer radius of the circumstellar dust shell, τ_{10}: optical depth at the wavelength of 10 μm, and $L\,[L_\odot]$: luminosity of the central star. In our calcurations, we fixed the following three parameters; T^* to 3000 K, $r_{\rm in}$ to 4.2×10^{14} cm, and $r_{\rm out}$ to $10^4 \times r_{\rm in}$, by referring to previous studies by Gauger et al. (1999) and Andriantsaralaza et al. (2022). Then we solved for the remaining two parameters of τ_{10} and L by applying various trial values with increments of 0.1 for τ_{10} and $10^3\,L_\odot$ for L. Finally, the SED model (τ_{10} and L) with the smallest discrepancy from the observed multi-wavelength flux densities was adopted as solutions for the calculation. For the two sources of OH 39.7+1.5 and IRAS 17411$-$3154, the best-fitted luminosities were estimated to be 24000$\pm$2500 $L_\odot$ and 6000$\pm$1800 $L_\odot$, respectively (Table 2). The best-fitted values of τ_{10} were also obtained and presented in the same table. Using these luminosities, we calculated absolute bolometric magnitude $M_{\rm bol}$ of each OH/IR star by assuming $M_{\rm bol\odot} = 4.74$ and presented in the last column in Table 2.

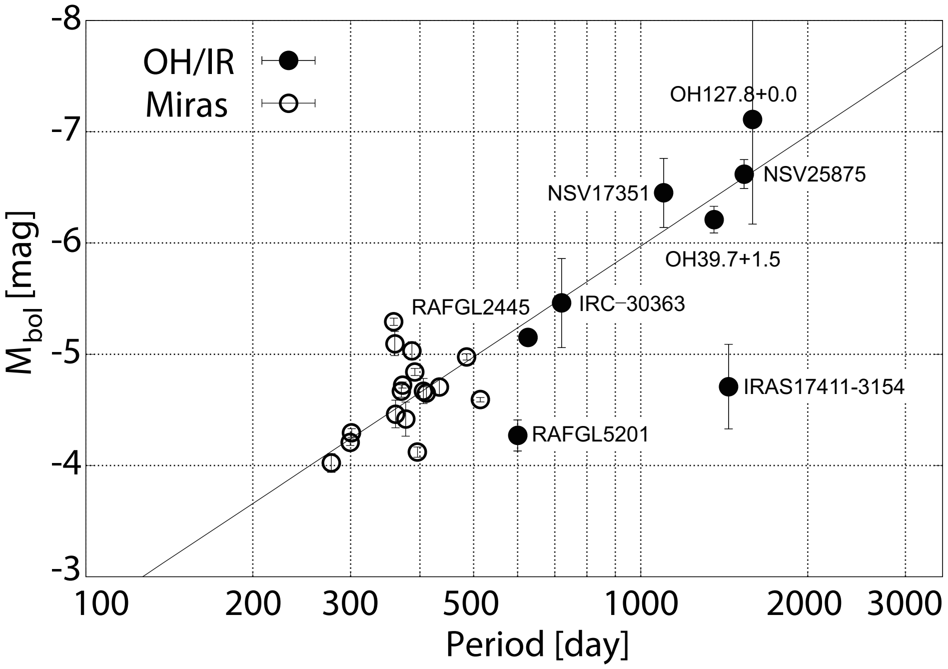

Fig. 2. Absolute bolometric magnitudes of the Galactic AGB stars estimated from VLBI parallaxes. The OH/IR stars (filled circles) with their names are derived from our study. Miras (open circles) and a solid line of the period-$M_{\rm bol}$ relation of $M_{\rm bol} = (-3.31 \pm 0.24)[\log P - 2.5] + (-4.317 \pm 0.060)$ are reported in Andriantsaralaza et al.(2022).

In Figure 2, the eight objects whose $M_{\rm bol}$ were estimated based on our parallax distances are presented with filled circles. Error bars of the $M_{\rm bol}$ are based on parallax errors in our measurements. Using 17 $M_{\rm bol}$ values for Miras with shorter periods reported in Andriantsaralaza et al. (2022), we put them on the figure with open circles. The solid line represents the period-$M_{\rm bol}$ relation for Miras by Andriantsaralaza et al. (2022). We can see that the eight OH/IR stars are in good agreement with an extension of the PLR to longer period range, suggesting the existence of a relation that can be applied to a wide range of pulsation periods. IRAS 17411−3154 is about 2 mag fainter than that expected from the relation. At our current stage of data reduction for IRAS 17411−3154, an accuracy of the VLBI parallax is still poor (see Table 2). For further improvement of the period-$M_{\rm bol}$ relation, it is important to increase the number of OH/IR stars and improve the accuracies of parallax measurements.

Table 2. VERA parallaxes and luminosities of OH/IR stars.

Source	$\Pi_{\rm VERA}$/[mas]	$L/[L_\odot]$	$\sigma L/[L_\odot]$	τ_{10}	$M_{\rm bol}$
OH 127.8−0.0	0.22 ± 0.08	55000	29000	9.1	−7.11
RAFGL 5201	0.61 ± 0.04	4000	500	2.1	−4.27
NSV 17351†	0.25 ± 0.04	30000	8300	1.7	−6.45
IRAS17411−3154	1.21 ± 0.21	6000	1800	8.2	−4.71
IRC −30363	0.49 ± 0.09	12000	3700	1.3	−5.46
OH 39.7+1.5	0.55 ± 0.03	24000	2500	7.1	−6.21
RAFGL 2445	0.64 ± 0.01	9000	300	3.1	−5.15
NSV 25875	0.33 ± 0.02	35000	4000	10.4	−6.62

† Parallax is 0.247±0.035 mas in Nakagawa et al. (2023).

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