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Astrometric observation of the Galactic LPVs with VERA; Miras and OH/IR stars

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Introduction

We present studies of Long Period Variables (LPVs) in out Galaxy based on astrometric VLBI observations of H2O/SiO maser with VERA. The Galactic Miras and OH/IR stars are main targets. For Miras, we present distribution of the Galactic LPVs on Period-Mk plane. We present parallax measurement of an extreme-OH/IR star (Period > 1000 day) obtained with VERA 43GHz observations. Annual parallaxes from VLBI and Gaia DR2 are compared.

Mira variable The LPVs are 1 - 8 Msun AGB stars pulsating with typical period range of 100 - 1000 day. They are on the late stage of their life time, and show high mass loss ratio (10^-7 Msun/yr) before they evolve to planetary nebulae. In figure1, LPVs in the LMC show some period-luminosity relations (PLR), and the PLR is used as distance indicator for Miras in our Galaxy.

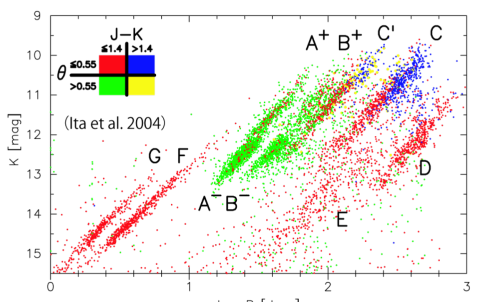


Fig 1: Sequences of variable stars found in LMC. (Ita et al. 2004)

But metallicity is different between the LMC and our Galaxy, it is also important to explore PLR of Miras in MWG. Since 2003, we have been observing dozens of Miras in the Galaxy. The latest Galactic Mira's PLR determined from our study is Mk = −.52 logP+1.09 (±0.14) (Nakagawa et al. 2016). New results will be added here.

OH/IR star There are some OH/IR stars showing quite long period longer than 1000 day (extreme-OH/IR). They are thought to have initial mass of ~4 Msun and ages of ~10^8 yr. Recent studies predict galactic spiral arms bifurcating/merging in time scale of 10^8 yr. So, the extreme-OH/IR stars can become a new probe to survey spiral arms. We started 43GHz VLBI observations of two Extreme-OH/IR stars, OH127.8+0.0 and NSV25875 from Nov. 2017. Since evolutional relation between Miras and OH/IR stars is still an open question, sequential studies of LPVs along wide period axis are also crucial.

- Recent simulation studies of spiral arms
  → "Density wave" vs "Non-steady spiral arms"
- Extreme-OH/IR stars (P > 1000 d)
  → M : ~ 4 Msun (Feast 2008)
  → Age : 10^8 - 10^9 yr
- Extreme-OH/IR star can be good sample to inspect kinematics of stars with ages of 10^8 - 10^9 yr.
  It can offer new data to the study of spiral arms.

	Age	Physics	Target	Model		Obs.
New	~10^6 yr	Spiral arm	SRF, Giants	✔	⇔	✔
⇕	~10^8 yr	Bifurcating/ merging arms	Heavy OH/IR star ?	✔	⇔	No
Old	~10^9 yr	Relaxed system	Mira	✔	⇔	✔

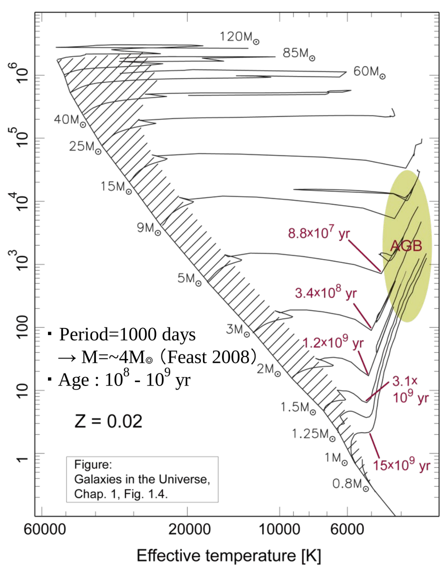


Fig 2: HR diagram.

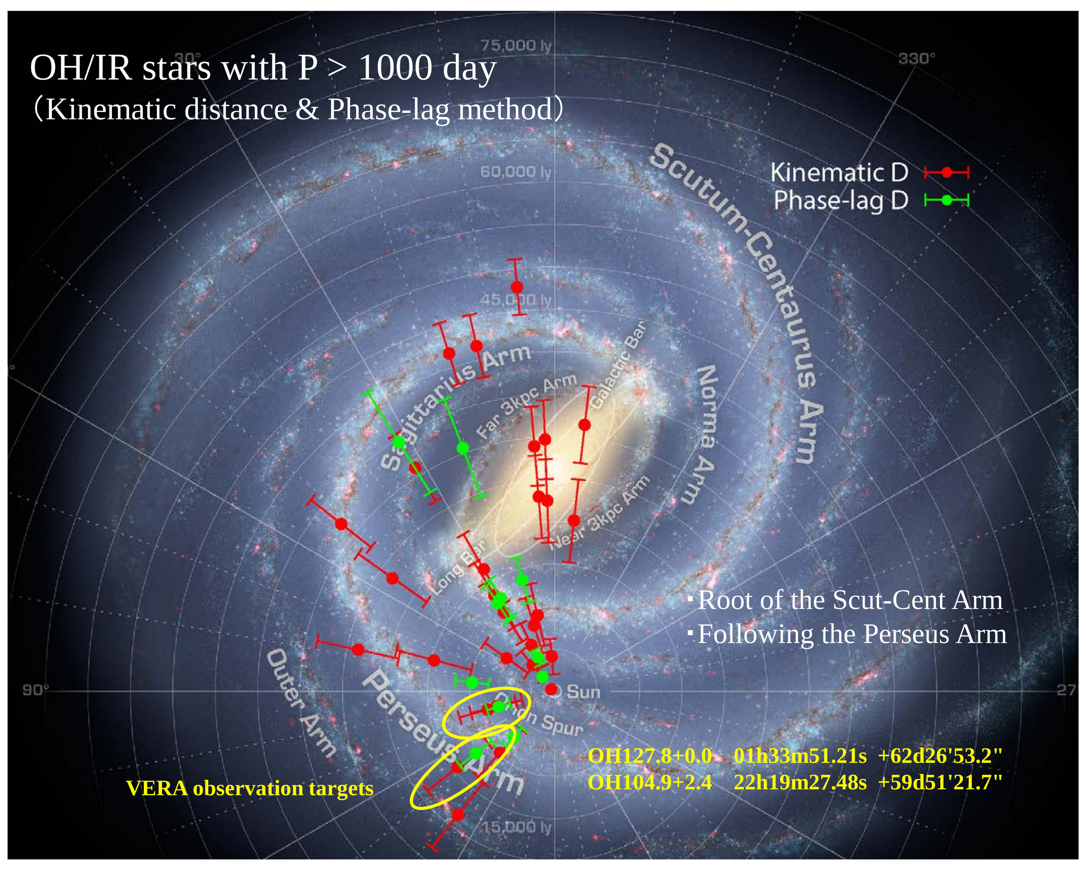
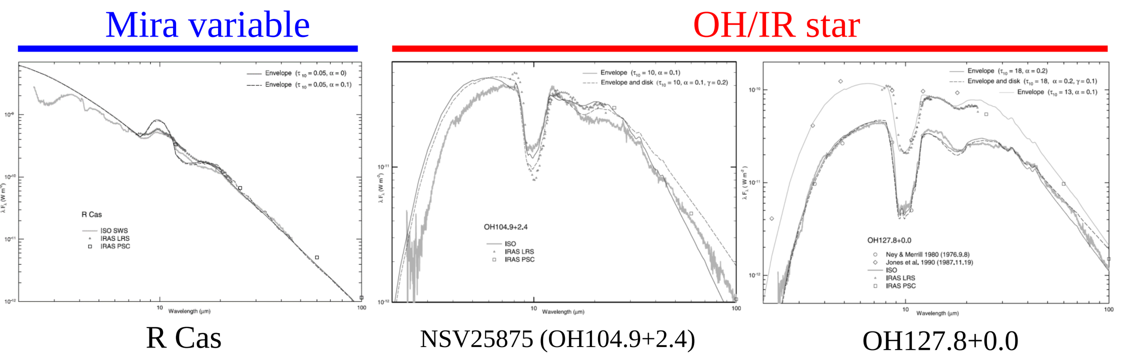


Fig 3: Distribution of extreme-OH/IR stars. Distances are estimated from two methods, Kinematic distance and Phase-lag method. There are some source which seems to trace spiral arms. Two sources are being observed with VERA at 43 GHz.

SED of Mira and OH/IR star Miras and OH/IR star often represent H2O, SiO, and OH masers, and they are good target of VLBI astrometric observation. Because of heavy dust and molecular shell around its central star, infrared emission is prominent in OH/IR stars. Since the Galactic LPVs with longer period tend to be fainter in visible band, VLBI astrometry play a promising and complementary role even in Gaia era.

Mira variable OH/IR star



R Cas NSV25875 (OH104.9+2.4) OH127.8+0.0

name	Period	U	B	V	R	I	J	H	K	F12	F25	F60	F100
	[day]	[mag]	[mag]	[mag]	[mag]	[mag]	[mag]	[mag]	[mag]	[Jy]	[Jy]	[Jy]	[Jy]
OH127.8+0.0	1380/ 1994	-	-	-	-	-	16.7	11.2	7.1	289	456	194	50.2
NSV25875	1535	-	-	-	-	-	16.4	10.7	6.9	123	229	90.7	35.0

Fig 4: SED of OH/IR stars and Miras

Observation : Single-dish and VLBI

- Single-dish monitoring at VERA IRIKI 20m telescope, to grasp variability of target.
- Freq: 22 GHz (H2O), and 43GHz (SiO)

Fig5: VERA IRIKI station

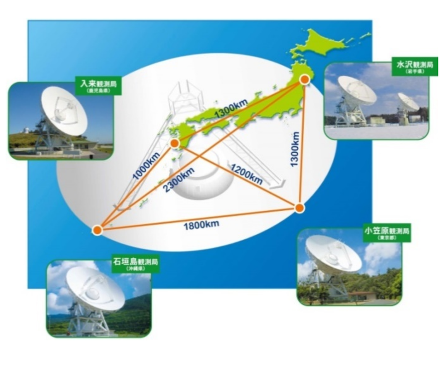


Fig 6: VERA array

- Astrometric VLBI with VERA
- Freq: 22 GHz (H2O), and 43GHz (SiO)
- Duration: 1-2 yr with 1month interval
- Technique: Phase referencing

Results: Single dish monitoring at 43 GHz (SiO maser)

Results of single-dish monitoring of two extreme-OH/IR stars OH127.8+0.0 and NSV25875 are shown in figure 7. We want to confirm availability of SiO maser variation to derive pulsation period of the extreme-OH/IR stars. Using these monitoring results, we determine start date of monitoring VLBI observations with VERA.

We selected samples of extreme-OH/IR stars from,
(1) Database of Circumstellar Masers[*], and
(2) Nançay 1612MHz monitoring of OH/IR star[**].

[*] http://www.hs.uni-hamburg.de/~st2b102/maserdb/
[**] http://www.hs.uni-hamburg.de/DE/Ins/Per/Engels/engels/nrt_monitoring/index.html

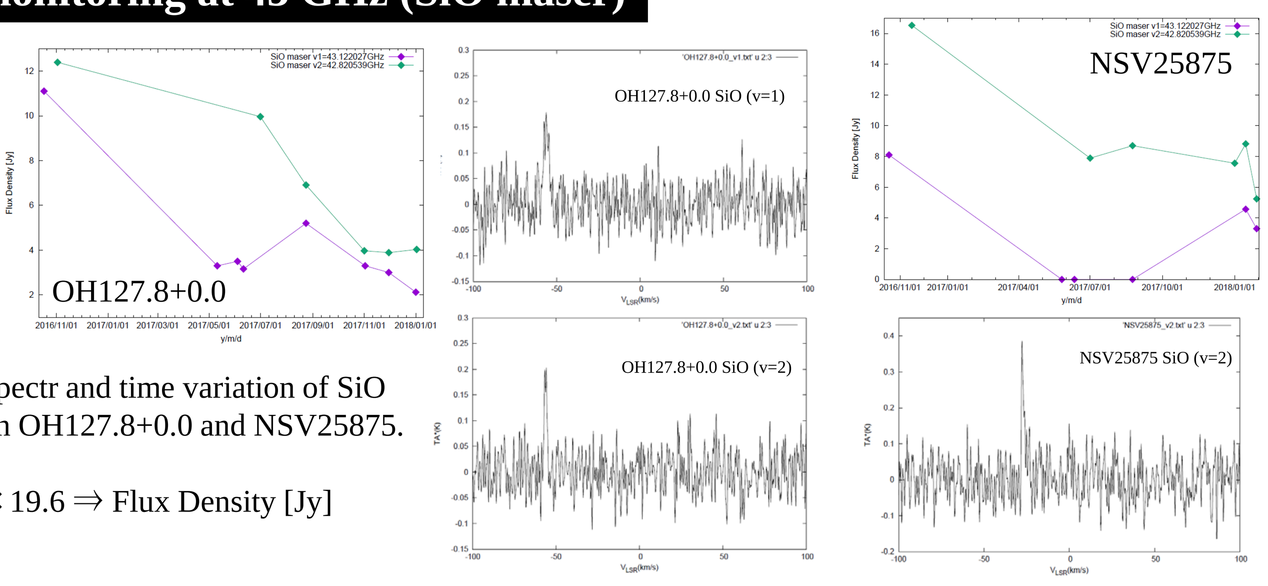


Fig 7:Spectr and time variation of SiO maser in OH127.8+0.0 and NSV25875.

Ta[K] × 19.6 ⇒ Flux Density [Jy]

Results: Astrometry of Galactic LPVs with VLBI method

Table 1 shows all parallaxes measured with astrometric VLBI (VERA and VLBA). Gaia DR2 parallaxes are also presented. Some semiregulars, red giants, and OH/IR stars are also included. The K-band absolute magnitudes (MK) errors are based on their VLBI distance errors. Figure 8 shows MK - log P diagram. Filled and open circles indicate Miras and other types of variables. We find consistency of PLRs between LMC and our Galaxy, but some stars show fainter magnitudes than expected from the PLR previously obtained. Though the discrepancy should carefully be investigated, this can possibly indicate different properties of Miras in the LMC and our Galaxy.

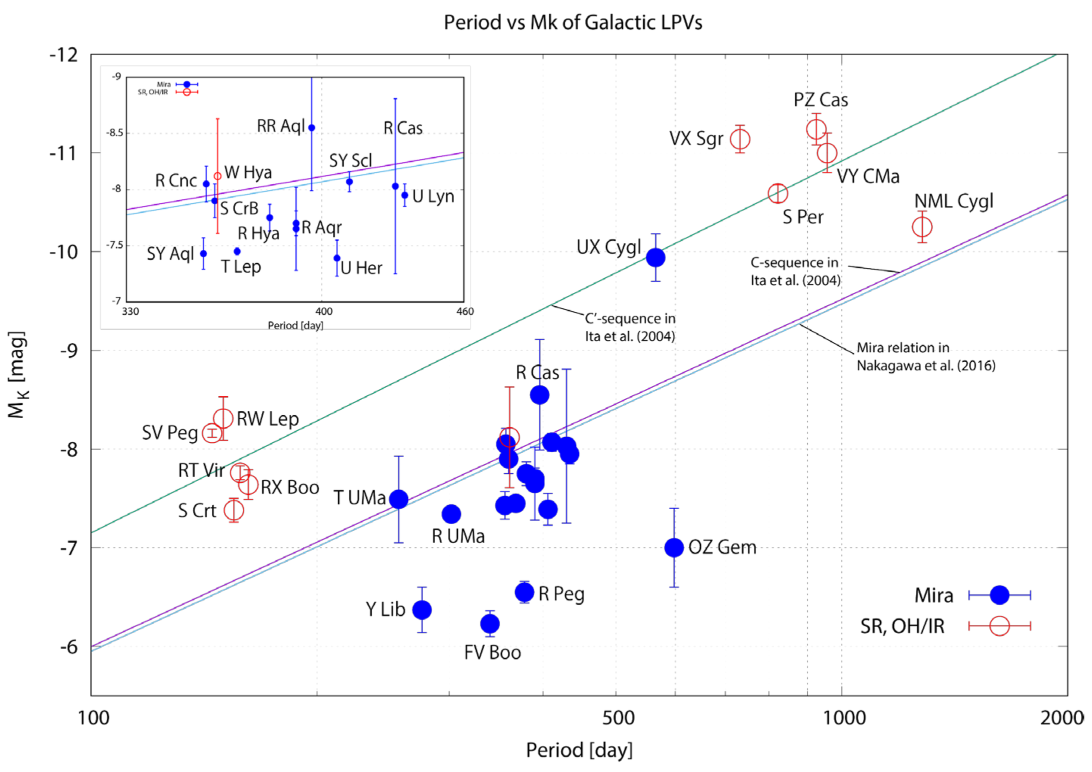


Fig 8: Absolute K-band magnitude (Mk) of Galactic LPVs obtained from apparent magnitude (mk) and VLBI parallaxes. Three solid lines show sequences in literatures. Filled and open circles are results of Mira and other type of variables.

Table 1: Results of astrometric observation from VLBI and Gaia DR2

Source	Type	Π_{VLBI} [mas]	Π_{Gaia} [mas]	P [day]	Log$P$	m_K [mag]	M_K [mag]	Maser	Ref. † (Π_{VLBI}, m_K)
SY Scl	Mira	0.75±0.03	0.68±0.23	411	2.614	2.55	−8.07 ± 0.09	H_2O	nyu11,b
WX Psc	OH/IR	5.3^b	···	660	2.820	2.22	−4.16	OH	oro17,a
S Per	SRc	0.413±0.017	0.22±0.12	822	2.915	1.33	−10.59 ± 0.09	H_2O	asa10,b
OH138.0+7.2	OH/IR	0.52±0.09	···	1410	3.149	8.548	−2.87 ± 0.38	OH	oro17,a
T Lep	Mira	3.06±0.04	2.96±0.19	368	2.566	0.12	−7.45 ± 0.03	H_2O	nak14,c
RW Lep	SRa	1.62±0.16	2.35±0.13	150	2.176	0.639	−8.31 ± 0.22	H_2O	kam14,a
U Lyn	Mira	1.27±0.06	0.58±0.22	434	2.637	1.533	−7.95 ± 0.10	H_2O	kam16a,a
VY CMa	SRc	0.88±0.08	−5.92±0.83	956	2.980	−0.72	−11.00 ± 0.20	H_2O	cho08,b
OZ Gem	Mira	1.00±0.18	−0.96±0.46	598	2.777	3.00	−7.00 ± 0.40	H_2O	iaus336,a
OH231.8+4.2	OH/IR	0.55±0.05	0.10±0.18	548	2.739	6.546	−4.53 ± 0.11	H_2O	iaus336,a
R Cnc	Mira	3.84±0.29	4.43±0.55	357	2.553	−0.97	−8.05 ± 0.16	H_2O	iaus336,a
R UMa	Mira	1.97±0.05	2.04±0.20	302	2.480	1.19	−7.34 ± 0.06	H_2O	nak16,d
S Crt	SRb	2.33±0.13	2.65±0.15	155	2.190	0.786	−7.38 ± 0.12	H_2O	nak08,a
T UMa	Mira	0.96±0.15	0.75±0.10	257	2.410	2.60	−7.49 ± 0.44	H_2O	iaus336,a
RT Vir	SRb	4.417±0.134	2.05±0.29	158	2.199	−0.97	−7.76 ± 0.07	H_2O	zha17,a
R Hya	Mira	8.96±0.51	4.47±0.89	380	2.580	−2.51	−7.75 ± 0.12	H_2O	iaus336,a
W Hya	SRa	10.18±2.36	6.09±0.82	361	2.558	−3.16	−8.12 ± 0.51	OH	vle03,c
RX Boo	SRb	7.31±0.50	7.83±0.30	162	2.210	−1.96	−7.64 ± 0.15	H_2O	kam12,b
VF Boo	Mira	0.97±0.06	0.57±0.18	340	2.531	3.84	−6.23 ± 0.13	H_2O	kam16b,a
Y Lib	Mira	1.24±0.13	···	276	2.441	3.16	−6.37 ± 0.23	H_2O	iaus336,a
S CrB	Mira	2.39±0.17	2.32±0.29	360	2.556	0.21	−7.90 ± 0.15	OH	vle07,c
U Her	Mira	3.76±0.27	1.75±0.15	406	2.609	−0.27	−7.39 ± 0.16	OH	vle07,c
VX Sgr	SRc	0.64±0.04	0.79±0.23	732	2.865	−0.17	−11.14 ± 0.14	H_2O	xu18,a
RR Aql	Mira	1.58±0.40	3.15±0.30	396	2.598	0.46	−8.55 ± 0.56	OH	vle07,c
SY Aql	Mira	1.10±0.07	3.43±0.21	356	2.551	2.36	−7.43 ± 0.14	H_2O	iaus336,a
NML Cyg	SRc	0.62±0.047	1.53±0.57	1280	3.107	0.791	−10.25 ± 0.16	H_2O	zha12,a
UX Cyg	Mira	0.54±0.06	0.18±0.17	565	2.752	1.40	−9.94 ± 0.24	H_2O	kur05,a
SV Peg	SRb	3.00±0.06	1.12±0.28	145	2.161	−0.55	−8.16 ± 0.04	H_2O	sud18,a
NSV25875	OH/IR	0.38±0.13	···	1748	3.243	6.857	−5.24 ± 0.77	SiO	···,a
IRAS22480+6002	SRc	0.400±0.025	0.48±0.08	···	···	2.78	−9.21 ± 0.14	H_2O	ima12,a
R Peg	Mira	3.98±0.21	2.83±0.25	378	2.577	0.45	−6.55 ± 0.11	H_2O	iasu336,a
R Aqr	Mira	4.7±0.8	3.12±0.28	390	2.591	−1.01	−7.65 ± 0.37	SiO	kam10,c
R Aqr	Mira	4.59±0.24	3.12±0.28	390	2.591	−1.01	−7.70 ± 0.11	SiO	min14,c
PZ Cas	SRc	0.356±0.026	0.42±0.08	925	2.966	1.00	−11.24 ± 0.16	H_2O	kus13,b
R Cas	Mira	5.67±1.95	5.34±0.24	430	2.633	−1.80	−8.03 ± 0.78	OH	vle03,c

† Reference of VLBI parallax : (nyu11)Nyu et al. 2011, (oro17)Orosz et al. 2017, (asa10)Asaki et al. 2010, (nak14)Nakagawa et al. 2014, (kam14)Kamezaki et al. 2014, (kam16a)Kamezaki et al. 2016a, (cho08)Choi et al. 2008, (iaus336)nakagawa, IAU Symposium 336 , (nak16)Nakagawa et al. 2016, (nak08)Nakagawa et al. 2008, (zha17)Zhang et al. 2017, (vle03)Vlemmings et al. 2003, (kam12)Kamezaki et al. 2012, (kam16b)Kamezaki et al. 2016b, (vle07)Vlemmings & van Langevelde 2007, (xu18)Xu et al. 2018, (zha12)Zhang et al. 2012, (kur05)Kurayama et al. 2005, (sud18)Sudo et al. , (ima12)Imai et al. 2012, (kam10)Kamohara et al. 2010, (min14)Min et al. 2014, (kus13)Kusuno et al. 2013. 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.

Results: Astrometry of SiO maser in NSV25875 and H2O maser in OH231.8+4.2

Figure 9 is the latest results of a phase referencing VLBI observation with VERA. A target source "NSV25875" is one of the extreme-OH/IR stars. We can compare the VLBI parallax with distance estimations from "Phase-lag method" and "Kinematic distance".

- Phase referencing analysis ⇒ Annual parallax
- NSV25875 and J2231+5922
- Pulsation period =1748 day (Engels et al. 2015)
- Annual parallax = 0.38±0.13 mas
  ⇒ Distance = 2.60±0.85 kpc
- μ_RA = −0.97±0.55 mas/yr
- μ_DEC = −1.06±0.31 mas/yr

Method	Distance [kpc]
VERA parallax	2.60±0.85
Phase-lag method	2.1±0.42
Kinematic distance	2.50±1.18

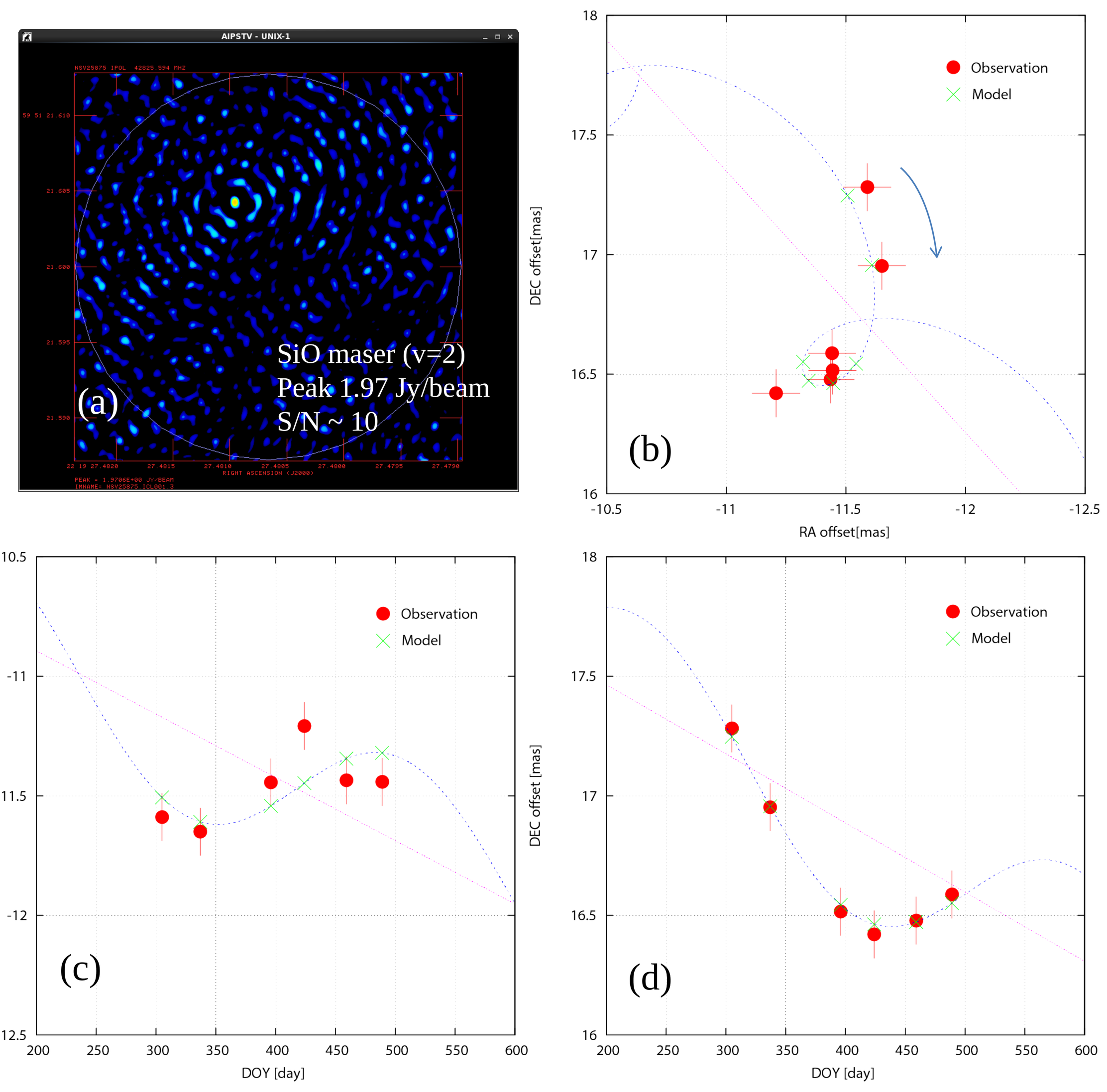


Fig 9: (a)43GHz SiO v=2 maser spot of an OH/IR star NSV25875 on 1 Nov 2017. (b)Sky plane motion of the maser spot from 1 Nov., 2017 to 4 May, 2108. (c)RA motion of the spot. Horizontal axis is days from 1 Jan., 2017. (d)DEC motion.

We also conduct 22GHzVLBI astrometric observations. It can reveal internal motions of masers around central star. Figure10 shows distribution of H2O maser in OH231.8+4.2 obtained with VERA. Fitting with 3D-cone model gives opening angle of ~58±1 degree.

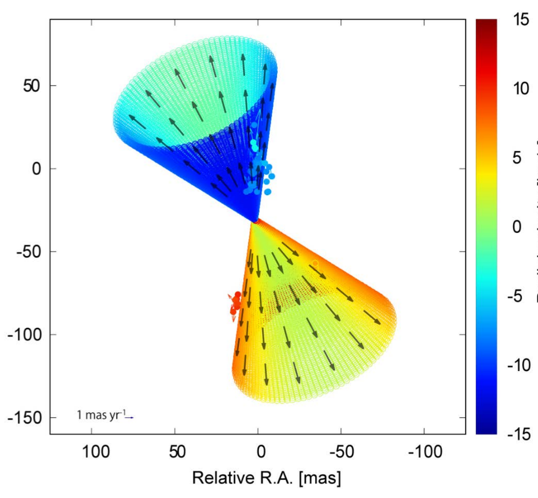


Fig 10: Angular distribution and internal motions of H2O masers in a PPN "OH231.8+4.2", with a 3D-cone model. (Ooyama et al. in prep.)

Annual parallax of Galactic LPVs from VLBI and Gaia DR2

On 25 April 2018, parallaxes of more than 1.3 × 10^9 sources were released in Gaia DR2. Since large part of VLBI parallaxes are determined for star forming regions deeply obscured by heavy dust and molecular cloud, it is difficult to find counterpart of the VLBI targets in the Gaia DR2. On the other hand, LPVs can easily be identified in the Gaia DR2. They are good samples for comparison of parallax from VLBI and Gaia. In table 1, parallax from Gaia DR2 is also given. We introduce a residual parameter

$$\text{Residual} = \frac{\Pi_{VLBI} - \Pi_{Gaia}}{\sqrt{\sigma^2_{\Pi_{VLBI}} + \sigma^2_{\Pi_{Gaia}}}}$$

to evaluate difference between VLBI and Gaia. $\Pi_{VLBI(Gaia)}$ and $\sigma_{VLBI(Gaia)}$ are parallax and its formal error obtained from VLBI (Gaia).

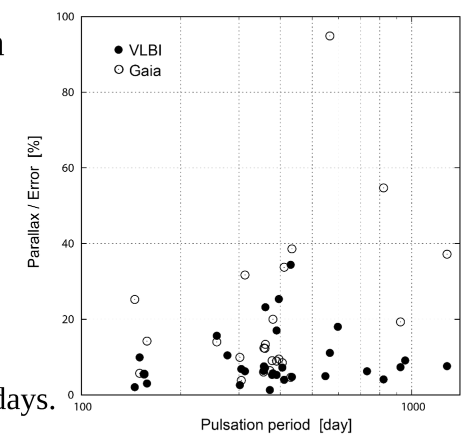


Fig 11: Pulsation period vs parallax errors from VLBI (●) and Gaia (○). Pulsation period range 100 to 1400 days.

Fig 12: Annual parallaxes determined from VLBI (horizontal axis) and Gaia (vertical axis) in logarithmic scale.

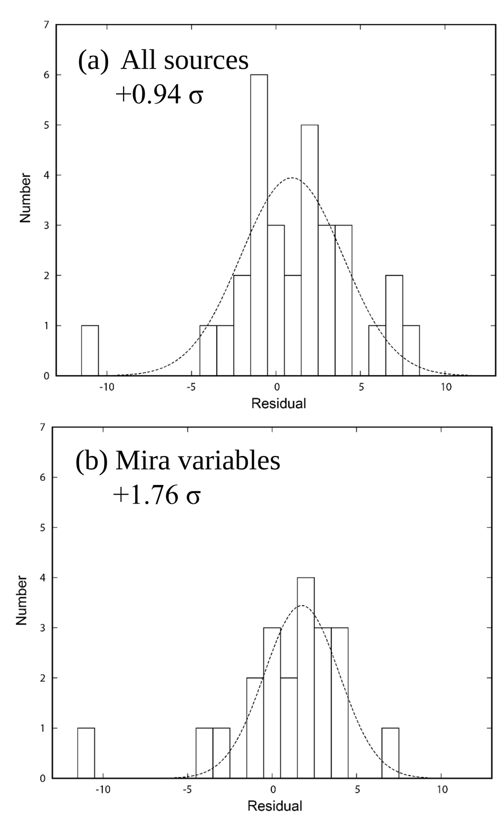


Fig 13:Histogram of the residual. Gaia and fitted Gaussian function. (a)Histogram for all sources (Mira, SR, OH/IR). (b)Histogram for Mira variables.