# 位置天文観測による<br>ミラ型変光星の周期光度関係の確立


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ミラ型変光星などの長周期変光星は太陽の 1−8 倍の質量を持ち、進化の末期に差し掛かった星である。質量放出が激しく、宇宙の化学組成の理解においても重要な天体である。この種の星には明るさと変光周期の間の比例関係が知られており、これは周期光度関係（Peirod-luminosity relation；PLR）とよばれている。大マゼラン銀河で発見されたこの関係を我々の天の川銀河独自で決めることは絶対等級決定の観点から難しく、この関係の確立を VERA プロジェクトの科学目標の一つとしている。PLR は見かけ等級と変光周期から星の距離を導出するツールとしても重要である。見かけ等級が得られた多くの変光星の年周視差を VERA で計測し、そこから正確な絶対等級 ($M_K$) をわり出して天の川銀河での PLR の確立を目指す。年周視差の検出のためには星の周囲に分布する水メーザーを相対 VLBI により観測する。

VERA を用いたこれまでの観測から、いくつかの天体について 10%より高い精度で距離を決定することができた。例えばミラ型変光星 T Lep の年周視差は 3.06±0.04 mas であり、距離 327±4 pc (Nakagawa et al. 2014) に対応する。星周メーザーの分布や運動も同時に得られている。VERA と VLBA に代表されるこれまでの位置天文 VLBI 観測から、天の川銀河のミラ型変光星に対する PLR は $M_K = -3.51 \log P + 1.37 \pm 0.07$ と得られた。ここで P は変光周期である。

## 1. Astrometry of Mira variables

LMC

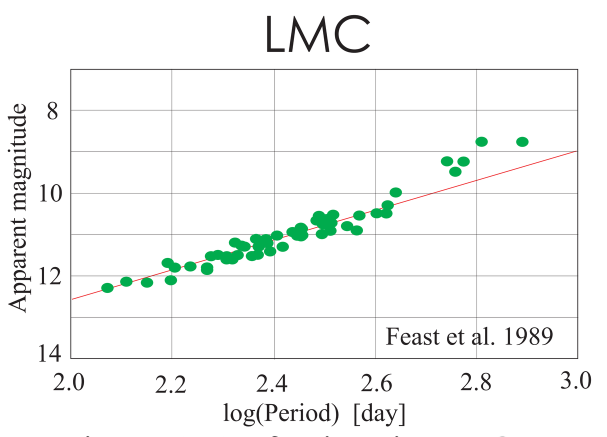


Fig.1. PLR of Miras in LMC, Feast et al. 1989.

Mira variables are pulsating stars with periods of 100 to 1000 days, showing rapid mass loss before ejecting their outer layers as planetary nebula shells. Accurate distance of the sources helps us to understand the nature of the variables.

Although a narrow PL relation for Miras in the Large Magellanic Cloud (LMC) was found (figure 1), the same relation for the Galactic Miras has not been precisely obtained (figures 2,3) because of large errors. Such large errors arise from the ambiguity of absolute magnitudes suffering directly from inaccurate distances to each object.

Milky Way Galaxy

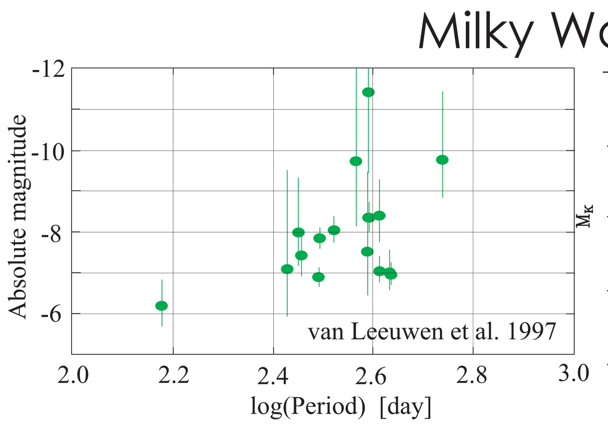


Fig.2. PLR of Galactic Miras, van Leeuwen et al. 1997.

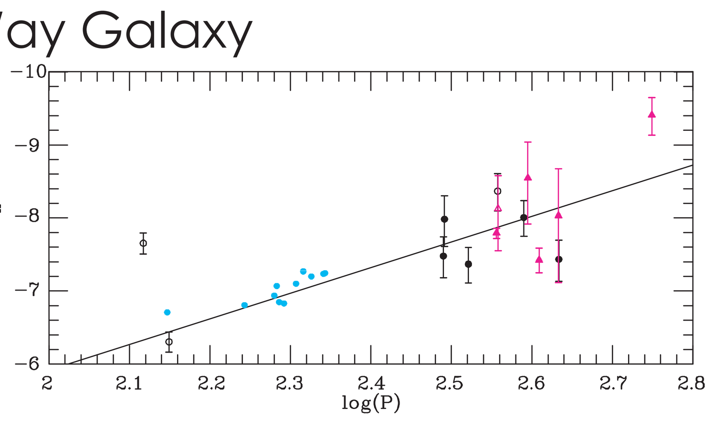


Fig.3. PLR of Galactic Miras, Whitelock et al. 2008.

Using absolute magnitudes derived from accurate distances measured with VERA, we can investigate precise PL relation in the Galaxy. Once we have calibrated the relation based on the absolute magnitudes, we can convert the pulsation period to the distance for many Galactic variables.

## 2. Observation and data reduction

### 2.1 Source selection and single dish monitoring

Water maser emission around Mira variables are so bright and compact thet they are good targets to observe with VLBI as a tracer of their motion.

In table 1, we show a part of our target sources. Long period variables including Miras and semiregular variables are presented. Pulsation periods (P) of these sources are aslo presented. Figure 4 shows a period distribution of ~800 Mira variables in Feast et al. (2000) and our ~80 target sources. Period average of ~80 Miras with water maser emission is 407 day (LogP = 2.61), which is longer than that of 338 day (LogP = 2.53) of the sources in Feast et al. (2000).

To determine a beginning of the series VLBI observations, we monitor >250 long period variables at Iriki station (Shintani et al. 2008). Intensity of ~10 Jy is a threshold of a successful detection in VLBI observation with VERA.

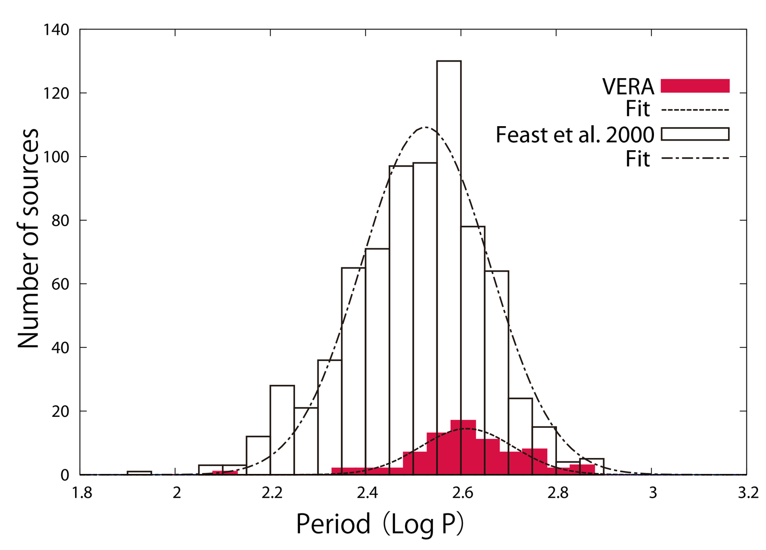


Fig.4. Period distribution of Mira variables in Feast et al. (2000) (white) and our targets (red).

Table1: Target Sources

| Name | P | LogP | Type |
|---|---|---|---|
| SY Scl | 415 | 2.62 | Mira |
| WX Psc | 660 | 2.82 | Mira |
| RU Ari | 354 | 2.55 | SR |
| T Lep | 368 | 2.57 | Mira |
| BW Cam | --- | --- | Mira |
| RW Lep | 150 | 2.18 | SR |
| BX Cam | 454 | 2.66 | Mira |
| U Ori | 368 | 2.57 | Mira |
| AP Lyn | 450 | 2.65 | Mira |
| U Lyn | 434 | 2.64 | Mira |
| GX Mon | 527 | 2.72 | Mira |
| Z Pup | 509 | 2.71 | Mira |
| QX Pup | --- | --- | Mira |
| R Cnc | 362 | 2.56 | Mira |
| X Hya | 301 | 2.48 | Mira |
| R UMa | 302 | 2.48 | Mira |
| S Crt | 155 | 2.19 | SR |
| VX UMa | 215 | 2.33 | Mira |
| T UMa | 257 | 2.41 | Mira |
| RS Vir | 354 | 2.55 | Mira |
| FV Boo | 340 | 2.53 | SR |
| W Hya | 361 | 2.56 | Mira |
| RX Boo | 278 | 2.44 | SR |
| Y Lib | 276 | 2.44 | Mira |
| S CrB | 360 | 2.56 | Mira |
| SW Lib | 292 | 2.47 | Mira |
| FS Lib | 415 | 2.62 | Mira |
| IRC+10374 | --- | --- | Mira |
| IRC-20540 | 510 | 2.71 | Mira |
| SY Aql | 356 | 2.55 | Mira |
| SV Peg | 145 | 2.16 | SR |
| R Aqr | 390 | 2.59 | Mira |

### 2.2 VLBI observation

VERA is a Japanese VLBI project dedicated for the Galactic astrometry. We observe QSOs adjacent to the maser sources as a position reference, and this simultaneous observation towards two sources can be realized by a dual-beam system equipped to the VERA antennas. We conduct 22 GHz multi epoch VLBI observations during 1 - 2 years with a typical interval of one month.

In the data reduction, we use AIPS. Image of maser emission detected in phase-referenced map is fitted with 2-dimensional Gaussian model to determine its position and flux density. Motion of the maser obtained from sequential VLBI observations is considered as a combination of its linear proper motion and parallactic motion. We numerically deduce the parallax and linear proper motion.

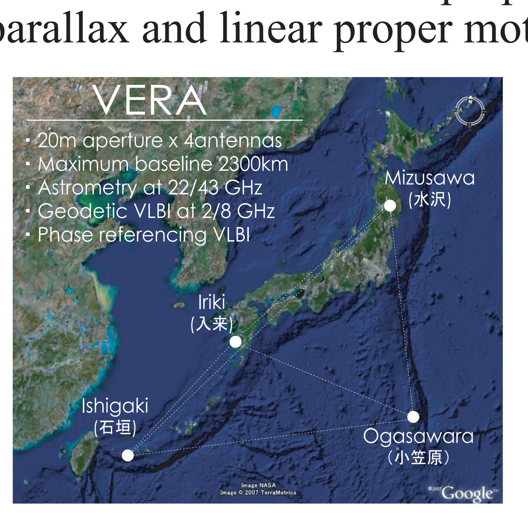


Fig.5. VERA array.

System parameters of observations for Mira variables.

- Array : VERA 20m antenna × 4 stations
- Frequency : 22GHz (rest freq. 22.235080 GHz)
- Band width for maser : 16 MHz
- Velocity resolution for maser : 0.42 km/s
- Band width for reference QSO : 240 MHz
- Recording rate : 1024 Mbps.
- Separation angle of maser and QSO : 0.3 - 2.2 °
- Reduction software : AIPS software package (NRAO)
- Technique : Phase referencing mapping

## 3. Recent result and discussion of T Lep

### 3.1 Parallax measurement

Among the water maser spots around T Lep detected in radial velocity ($V_{LSR}$) range of −32 to −23 km/s, $V_{LSR}$ = −29.73 km/s was continuously bright during our VLBI monitoring period. The annual parallax was estimated to be 3.06±0.04 mas, corresponding to a distance of 327±4 pc. Figure 6 shows parallactic motions in R.A. and Dec.

### 3.2 Properties of the source

We revealed distribution of the maser spots around T Lep together with their internal kinematics (Figure 7). Color image at the map center is obtained from VLTI infrared interferometer (le Bouquin et al. 2009). Angular radii of a photosphere (2.9 mas) and a molecular layer (7.5 mas) in le Bouquin et al. (2009) can be converted to linear sizes of 0.95 AU (=204 Rsun) and 2.45 AU (=527 Rsun), respectively. From a consideration of the proper motion in Galacto-centric coordinate, we obtained peculiar motion of T Lep to be 69.9 km/s. Direction of this peculiar motion projected on sky plane is also shown.

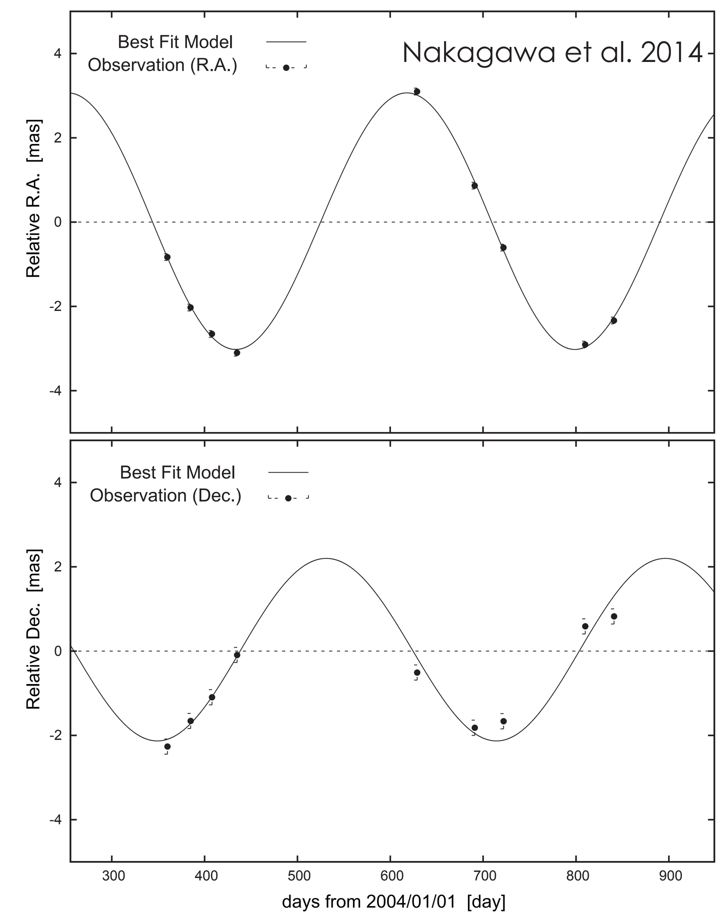


Fig.6. Oscillation of the maser spot at $V_{LSR}$ = -29.73 km/s in T Lep. Filled circles represent the maser position obtained by phase-referencing analysis. Solid lines indicate the best fit model of the parallactic oscillation.

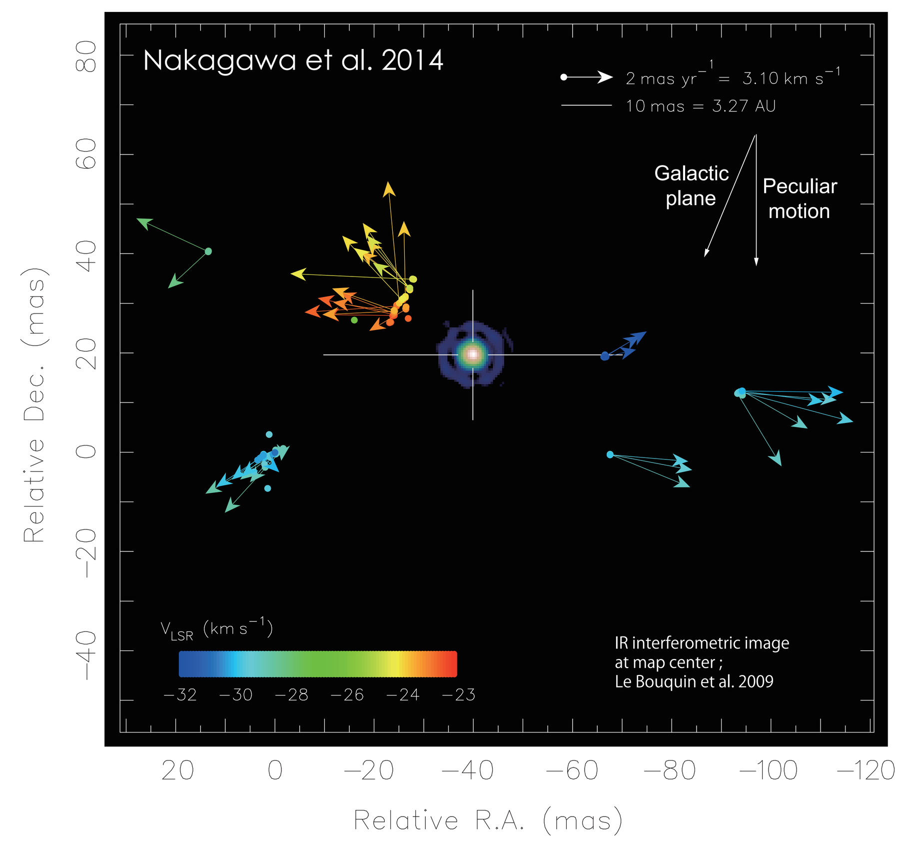


Fig.7. Water maser distribution in T Lep. Superposition of VLTI infrared interferometric image and water maser distribution obtained with VERA. Color image at the center is an image obtained with VLTI (le Bouquin et al. 2009). Water masers observed with VERA are distributed at outer area of this figure. Colors of filled circles indicate their VLSR. Color of the central star is unrelated to the color index of the maser.

### 3.3 Period luminosity relation

Table 2 shows parallaxes of variables stars measured with astrometric VLBI (VERA and VLBA). Errors in absolute magnitudes are attributed to the parallax errors. Based on these VLBI results, we obtained a period luminosity relation of the Galactic Mira variables as (red line in Figure 8),

$$M_K = -3.51 \log P + 1.37 \pm 0.07.$$

Un-weighted least squares fitting was adopted in this fitting. We solved for the zero point of 1.37 ± 0.07. The slope of -3.51 (Whitelock et al. 2008) was fixed. Various fitting results are also presented in the same figure.

Table2: Results from VLBI astrometry

| | Source | Type | Parallax† [mas] | P [day] | LogP | $m_K$‡ [mag] | $M_K$ [mag] |
|---|---|---|---|---|---|---|---|
| VERA | T Lep | Mira | 3.06±0.04(a) | 368 | 2.566 | 0.12 (h) | -7.45±0.03 |
| | S Crt | SR | 2.33±0.13(b) | 310* | 2.190 | 0.73 (i) | -7.43±0.12 |
| | R Aqr | Mira | 4.7 ±0.8 (c) | 390 | 2.591 | -1.01(h) | -7.65±0.37 |
| | SY Scl | Mira | 0.75±0.03(d) | 411 | 2.614 | 2.61 (j) | -8.01±0.09 |
| | RX Boo | SR | 7.31±0.5 (e) | 340 | 2.531 | -1.85(k) | -7.53±0.15 |
| VLBA | S CrB | Mira | 2.39±0.17(f) | 360 | 2.556 | 0.21(h) | -7.90±0.15 |
| | U Her | Mira | 3.76±0.27(f) | 406 | 2.609 | -0.27(h) | -7.39±0.16 |
| | RR Aql | Mira | 1.58±0.40(f) | 394 | 2.595 | 0.46(h) | -8.55±0.56 |
| | W Hya | SR | 10.18±2.36(g) | 361 | 2.558 | -3.16(h) | -8.12±0.51 |
| | R Cas | Mira | 5.67±1.95(g) | 460 | 2.663 | -1.79 (l) | -8.02±0.78 |

[†] Reference of the parallax; (a)Nakagawa et al 2014, (b)Nakagawa et al 2008, (c)Kamohara et al 2010, (d)Nyu et la 2011, (e)Kamezaki et al 2012, (f)Vlemmings & van Langevelde 2007, and (g)Vlemmings et al. 2003.
[‡] Reference of the m_K; (h)Whitelock et al. 2000 (Fourier mean magnitude), (i)Jura & Kleinmann 1992, (j)Whitelock et al. 1994, (k)Glass & van Leeuwen 2007, and (l)Feast & Whitelock 2000.
[*] For the period of S~Crt, we use 310~days, which is the double of its first overtone period of 155~day.

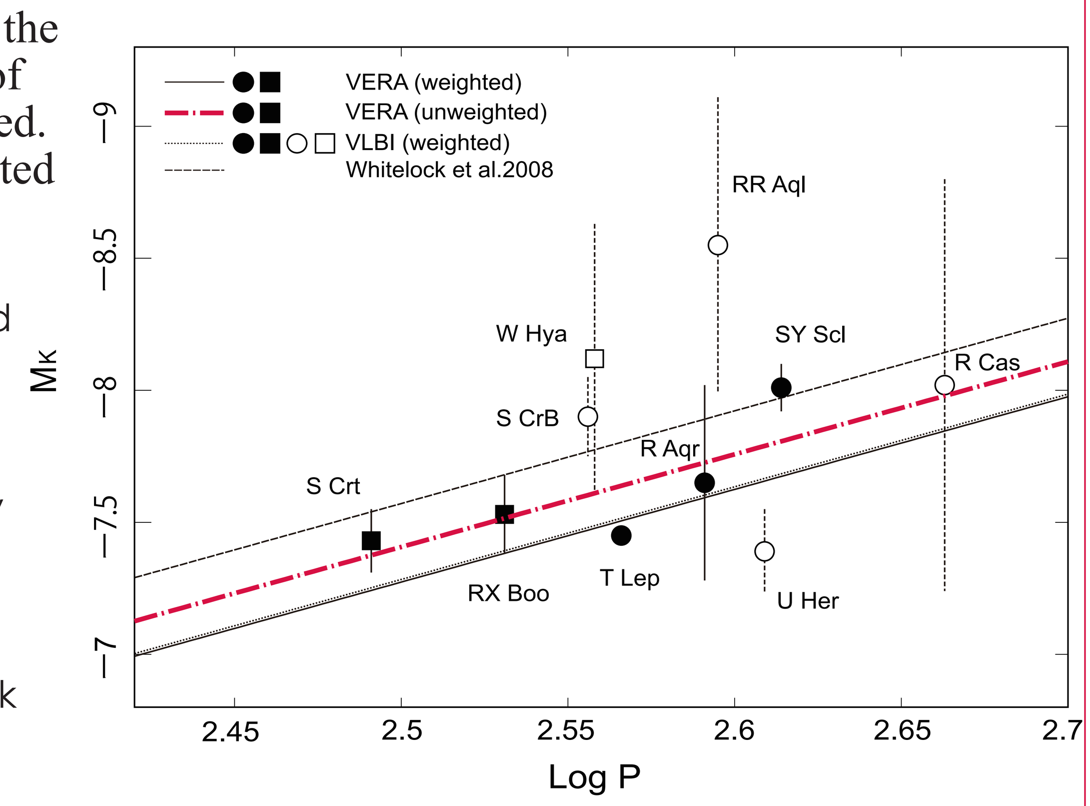


Fig.8. Period luminosity relation derived from astrometric VLBI. Filled symbols represent absolute magnitudes MK that derived from VERA observations. Open symbols represent those from other VLBI observations conducted by Vlemmings et al. (2003) and Vlemmings & van Langevelde (2007). Square symbols are used to denote semiregular variables. Dashed line shows a relation reported by Whitelock etal. (2008).

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