

# Annual parallax and galactic orbit of Y Librae (IRAS 15090–0549) Mira variable star—GALORB release

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## Abstract

Using the VLBI Exploration of Radio Astrometry (VERA), we measured the trigonometric parallax of an H<sub>2</sub>O maser source in a variable star of Mira Cet type, Y Lib, to be  $0.855 \pm 0.050$  mas, corresponding to a distance of  $1.17 \pm 0.07$  kpc. From multi-epoch infrared observations with the Kagoshima University 1 m telescope, we derived the mean *J*, *H*, and *K'*-band magnitudes of Y Lib to be  $4.34 \pm 0.22$  mag,  $3.62 \pm 0.18$  mag, and  $3.25 \pm 0.16$  mag, respectively. The pulsation period of Y Lib was obtained to be  $277.2 \pm 13.9$  d. We derived the effective temperature and radius of Y Lib to be  $3100 \pm 125$  K and  $211 \pm 11 R_{\odot}$ , respectively. The peculiar motion of Y Lib  $U_s$  (motion towards the Galactic center),  $V_s$  (motion in the direction of Galactic rotation), and  $W_s$  (motion towards the Galactic North Pole) were obtained to be  $-16 \pm 3$  km s<sup>-1</sup>,  $25 \pm 2$  km s<sup>-1</sup>, and  $13 \pm 3$  km s<sup>-1</sup>, respectively. After validation, we used the new release of the GALactic ORbit simulation package to trace the past 1 Gyr orbit of Y Lib in the Milky Way. Fitting the orbit of Y Lib with the MWPotential2014 Galactic Potential model produced high eccentricity in the direction perpendicular to the Galactic center, but decreasing the Miyamoto–Nagai disk potential contribution in the Milky Way model produced a reasonable result of the Y Lib orbit.

**Key words:** astrometry — masers — stars: AGB and post-AGB — stars: individual (Y Librae)

## 1 Introduction

The importance of the measurement of distances to stars in the Milky Way is enormous. Gaia, Hipparcos (High

Precision PARallax COLlecting Satellite), and very long baseline interferometric (VLBI) arrays have contributed significantly to our current understanding of the Milky

Way through their astrometric measurements towards stars and star-forming regions. Hipparcos produced the parallaxes of more than 100000 stars within a few hundred parsecs from the Sun with median astrometric standard errors of 0.56 mas for stars of magnitude  $<9$  mag (van Leeuwen 2007). Gaia, on the other hand, promises to produce one billion positions, two million proper motions, and parallaxes. Based on the Gaia data release 1 (DR1), the trigonometric parallaxes have a median standard errors of  $\sim 0.32$  mas (random errors). There are also position- and color-dependent systematic errors of about  $\pm 0.3$  mas (Lindgren et al. 2016). While VLBI may not compete with Hipparcos and Gaia in terms of the number of parallaxes it is able to produce, it is by far more accurate than both, with  $\mu$ as accuracy level (Honma et al. 2010; Reid et al. 2009).

Y Lib (IRAS 150904–0549) is an O-rich variable star of Mira Cet type of M5e–M8.2e [reported as M5.5e by Keenan et al. (1974)] with a pulsation period of 275.7 d (Kim et al. 2010). Infrared fluxes of Y Lib (based on IRAS) were obtained to be 11.29 Jy, 5.75 Jy, 0.89 Jy, and 1.0 Jy at 12  $\mu$ m, 25  $\mu$ m, 60  $\mu$ m, and 100  $\mu$ m, respectively. The Gaia G-band magnitude of Y Lib is 6.65 mag (see also Carrasco et al. 2016).<sup>1</sup> Kim et al. (2010) reported the presence of water (H<sub>2</sub>O) and silicon oxide, SiO, ( $\nu = 1$  and  $\nu = 2$ ) masers in Y Lib. The photometric properties of AGB stars exciting SiO masers are reported in Chibueze et al. (2016).

In this paper, we report the accurate trigonometric annual parallax measured with the VLBI Exploration of Radio Astrometry (VERA), its position, peculiar motion, and orbit in the Milky Way.

## 2 Observations and data reduction

### 2.1 VERA observations

We carried out 22-epoch VLBI observations using VERA in dual-beam mode (Kawaguchi et al. 2000) between 2008 February 13 and 2010 December 22, at 22.235080 GHz (the rest frequency of the H<sub>2</sub>O 6<sub>12</sub>–5<sub>23</sub> maser transition). Y Lib and the position reference source J1510–0543 were simultaneously observed with the two-beam system of VERA for phase referencing. Some of the observation epochs were affected by bad weather conditions, evident in the high system temperatures recorded at various stations.

The VERA data correlation was done with the Mitaka FX correlator, adopting the accumulation time of 1 s. The phase tracking center of Y Lib and J1510–0543 were adopted to be  $(\alpha, \delta)_{J2000.0} = (15^{\text{h}}11^{\text{m}}41^{\text{s}}.299, -06^{\circ}00'41''.462)$ , and  $(\alpha, \delta)_{J2000.0} = (15^{\text{h}}10^{\text{m}}53^{\text{s}}.591, -05^{\circ}43'07''.420)$ , respectively. The

spectral resolution of the H<sub>2</sub>O maser was 15.625 kHz, corresponding to a velocity spacing of 0.21 km s<sup>−1</sup>.

The VERA data reduction was carried out using the Astronomical Image Processing System (AIPS) software, developed by the National Radio Astronomy Observatory (NRAO). Standard calibration, phase-referencing, and imaging procedures were used.

Along with the VLBI observations, we also carried out single-dish observations of the H<sub>2</sub>O masers of Y Lib with the VERA-Iriki station. Figure 1 shows the plot of the integrated intensity over time, and clear evidence of a variation in the flux density can be seen in the plot.

Bad observing conditions, non-detection of the phase-reference source, and/or the intrinsic variability of masers (see figure 1) led to the non-detection of the masers in more than half of the observation epochs. Details of the observation epochs in which H<sub>2</sub>O masers were detected are shown in table 1.

### 2.2 Kagoshima 1 m telescope infrared observations

Near-infrared (NIR) observations of Y Lib from 2005 January 30 to 2016 April 22 were carried out using the Kagoshima University 1m telescope. The NIR camera has a 512 × 512 pixel HAWAII array that provides *J* (1.25  $\mu$ m), *H* (1.65  $\mu$ m), and *K'* images (2.15  $\mu$ m), with a field of view of 5'.25 × 5'.25 and a pixel scale of 0''.636 pixel<sup>−1</sup>. The typical seeing size at the Iriki observatory is 1''.5. Each set of observations consisted of five exposures at slightly dithered positions with an exposure time of 1.0 s. Y Lib is saturated on focused images because it is brighter than *K'*  $\sim 6.5$  mag, and we observed such bright sources out of focus. Therefore, no reference star was found in the same field-of-view, and we also observed the standard stars listed in Elias et al. (1982) in the same night.

The data reduction and photometry were carried out using the National Optical Astronomy Observatory's Imaging Reduction and Analysis Facility (IRAF) software package. Standard procedures of data reduction were adopted. After subtracting the average dark frame, each image was normalized by a flat-field frame. Subsequently, the sky frame was subtracted from the normalized image. Additional information of the observing technique and data reduction procedure can be found in Kamezaki et al. (2016). Photometry was carried out with the IRAF/APPHOT package. Color correction was made for the Kagoshima system to follow the California Institute of Technology (CIT) system (Elias et al. 1982) using the following equations :

$$(J - H)_{\text{CIT}} = 0.971(J - H)_{\text{Kagoshima}} + 0.173, \quad (1)$$

$$(H - K)_{\text{CIT}} = 1.141(H - K_s)_{\text{Kagoshima}} - 0.227. \quad (2)$$

<sup>1</sup> (<http://gea.esac.esa.int/archive/>).

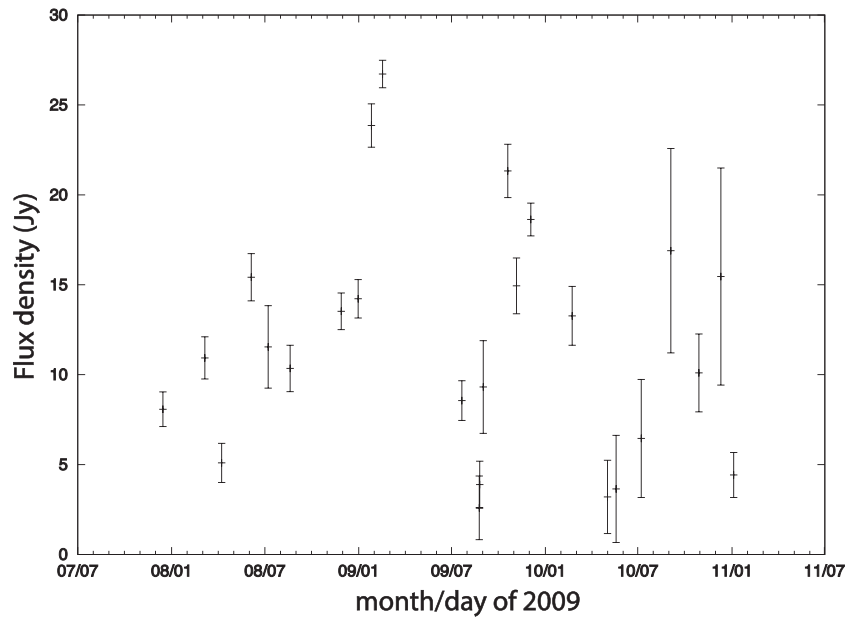


Fig. 1. Time variability of the H<sub>2</sub>O maser integrated intensity during 2009.

**Table 1.** VERA observation epoch with confirmed maser detection.

| Epoch ID | Date              | Year/DOY |
|----------|-------------------|----------|
| 1        | 2009 January 08   | 2009/008 |
| 2        | 2009 February 03  | 2009/034 |
| 3        | 2009 March 10     | 2009/069 |
| 4        | 2009 May 24       | 2009/144 |
| 5        | 2009 September 12 | 2009/255 |
| 6        | 2009 October 11   | 2009/284 |
| 7        | 2009 November 30  | 2009/334 |
| 8        | 2010 January 04   | 2010/004 |

We observed the 30 standard stars from Elias et al. (1982) using the Kagoshima system's *JHK'* band to determine the color correction. We compared the Kagoshima color system to the CIT color system and performed the least-squares fitting to 30 standard stars.

### 3 Results

#### 3.1 Distribution and proper motion of the H<sub>2</sub>O masers

Figure 2 shows the contour image of the phase-reference source (J1510–0543) as detected in our VERA observations. It was detected in eight epochs with peak intensities of 300–500 mJy beam<sup>−1</sup> at noise levels of 0.6–1.0 mJy beam<sup>−1</sup>. The calibrator was compact, showing no extended structures that could impact on the astrometric measurement.

We detected a total of 13 H<sub>2</sub>O maser spots in the phase-referenced maser map. These are grouped into five maser features. Table 2 shows the details ( $V_{\text{LSR}}$ , position and relative proper motion of each maser spot, the epochs at which they are detected, and their group ID) of each of the detected maser spots. Table 3 shows the position and absolute proper motion of the five maser groups.

The H<sub>2</sub>O masers are distributed within a  $16 \times 33$  mas area. The  $V_{\text{LSR}}$  values of the masers range from 12.98 to 16.34 km s<sup>−1</sup>. The computed the mean  $V_{\text{LSR}}$  and the standard deviation (error) of the mean are found to be  $14.40 \pm 1.05$  km s<sup>−1</sup>. The spatial distribution can be described with an ellipse (this interpretation may have been affected by the sensitivity achieved in our data). Figure 3 shows the distribution and the proper motion of the maser spots detected in our observations.

Our single-dish monitoring observations of the H<sub>2</sub>O masers in YLib showed evidence of flux variation over time. Figure 1 shows the time-dependent variation of the integrated intensities of the maser.

#### 3.2 Annual parallax of YLib

We used maser group 1 and fitted a trigonometric function to its parallax motion. Figure 4 shows the positions of the maser spot used for the parallax fitting and absolute proper motion fittings. The positional variations show systematic sinusoidal modulation with a period of one year, caused by the parallax.

The annual parallax ( $\pi$ ) was obtained to be  $0.855 \pm 0.050$  mas from the combined fitting, corresponding to a

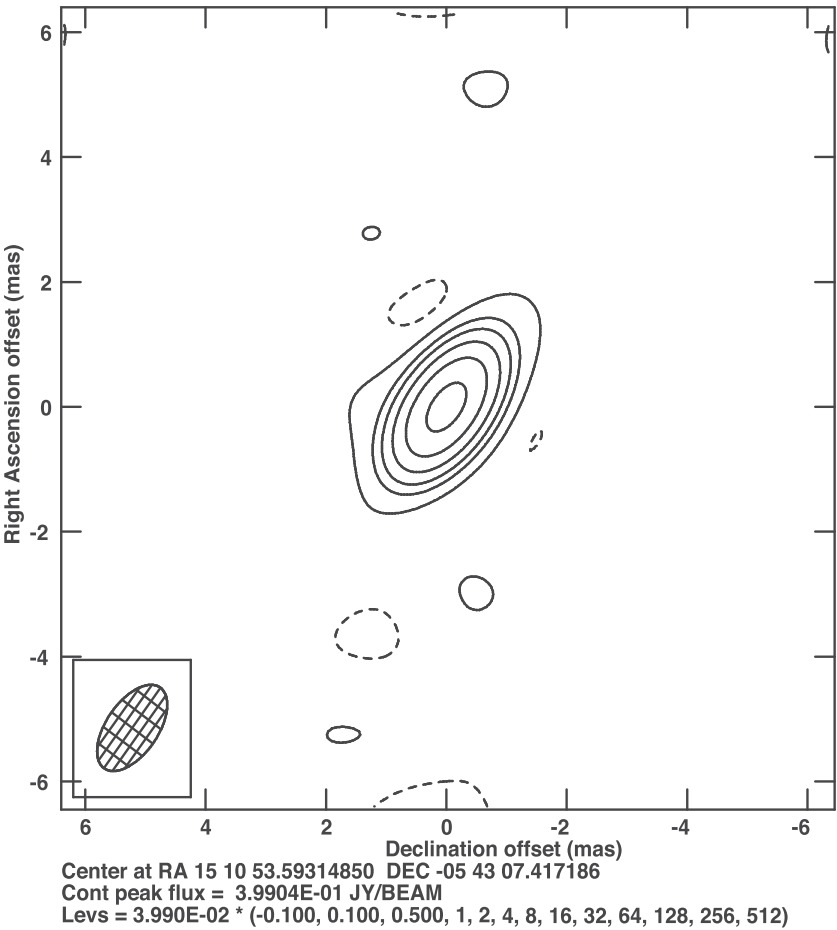


Fig. 2. Continuum image of J1510–0543 detected with VERA on the 2009 March 10 epoch of observations.

Table 2. Parameters of the detected maser spots (positions, relative proper motions, epochs detected, and group ID).

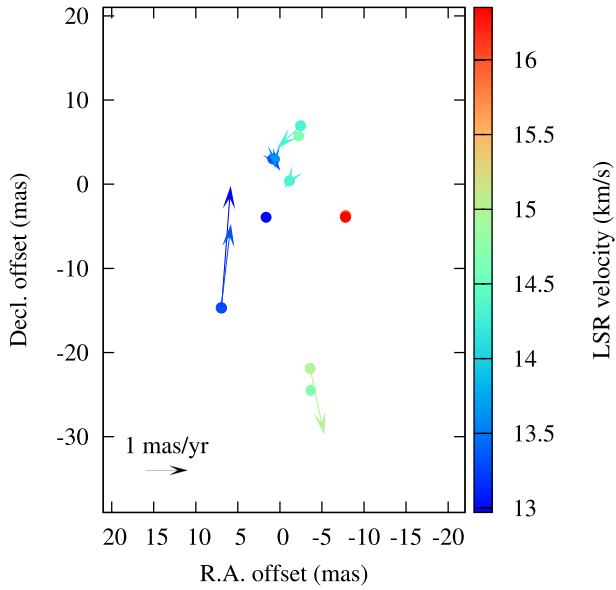
|    | $V_{\text{LSR}}$ (km s <sup>-1</sup> ) | X (mas)        | Y (mas)        | $V_x$ (mas yr <sup>-1</sup> ) | $V_y$ (mas yr <sup>-1</sup> ) | Epoch    | Group ID |
|----|----------------------------------------|----------------|----------------|-------------------------------|-------------------------------|----------|----------|
| 1  | 13.40                                  | 0.842 ± 0.067  | 3.002 ± 0.107  | 0.155 ± 0.103                 | 0.240 ± 0.180                 | 234**78  | 1        |
| 2  | 13.82                                  | 0.634 ± 0.064  | 2.965 ± 0.106  | 0.010 ± 0.092                 | 0.178 ± 0.170                 | 234*678  | 1        |
| 3  | 14.24                                  | -1.129 ± 0.079 | 0.402 ± 0.145  | 0.091 ± 0.142                 | 0.138 ± 0.252                 | 34**78   | 2        |
| 4  | 14.24                                  | -2.448 ± 0.097 | 6.944 ± 0.161  | 0.538 ± 0.824                 | 0.521 ± 1.527                 | 123***** | 3        |
| 5  | 14.66                                  | -2.225 ± 0.108 | 5.737 ± 0.194  | —                             | —                             | *2*****  |          |
| 6  | 15.50                                  | -7.848 ± 0.135 | -3.709 ± 0.222 | —                             | —                             | *2*****  |          |
| 7  | 15.92                                  | -7.769 ± 0.101 | -3.768 ± 0.188 | —                             | —                             | *2*****  |          |
| 8  | 16.34                                  | -7.795 ± 0.106 | -3.923 ± 0.196 | —                             | —                             | *2*****  |          |
| 9  | 14.66                                  | -3.682 ± 0.112 | 24.490 ± 0.204 | —                             | —                             | **3***** |          |
| 10 | 15.08                                  | -3.598 ± 0.116 | 21.903 ± 0.198 | 0.325 ± 1.562                 | 1.529 ± 2.886                 | 23*****  | 4        |
| 11 | 12.98                                  | 6.941 ± 0.116  | 14.699 ± 0.190 | 0.216 ± 1.142                 | 2.853 ± 1.931                 | *****67* | 5        |
| 12 | 13.40                                  | 6.993 ± 0.108  | 14.675 ± 0.187 | 0.227 ± 1.110                 | 1.942 ± 1.916                 | *****67* | 5        |
| 13 | 12.98                                  | 1.643 ± 0.125  | -3.925 ± 0.203 | —                             | —                             | **3***** |          |

distance of  $1.17 \pm 0.07$  kpc. The standard deviations of the post-fit residuals were 0.097 and 0.191 mas in right ascension and declination, respectively. We introduced error floors of 0.097 mas and 0.191 mas in right ascension and declination, respectively, for all of the results of the

position measurements, thus making the reduced  $\chi^2$  to be unity in the least-squares analysis. These error floors can be interpreted as the positional uncertainties in the astrometric observations that may have originated from the difference in the optical path lengths between the target and

**Table 3.** Maser groups' positions and absolute proper motions.

| Group ID | X (mas)            | Y (mas)             | $V_x$ (mas yr <sup>-1</sup> ) | $V_y$ (mas yr <sup>-1</sup> ) |
|----------|--------------------|---------------------|-------------------------------|-------------------------------|
| 1        | $0.738 \pm 0.093$  | $2.984 \pm 0.151$   | $-10.235 \pm 0.138$           | $-15.229 \pm 0.248$           |
| 2        | $-1.129 \pm 0.079$ | $0.402 \pm 0.145$   | $-10.062 \pm 0.142$           | $-15.158 \pm 0.252$           |
| 3        | $-2.448 \pm 0.097$ | $6.944 \pm 0.161$   | $-9.614 \pm 0.821$            | $-15.541 \pm 1.527$           |
| 4        | $-3.598 \pm 0.116$ | $-21.903 \pm 0.198$ | $-10.478 \pm 1.562$           | $-16.549 \pm 2.886$           |
| 5        | $6.967 \pm 0.158$  | $-14.687 \pm 0.267$ | $-10.374 \pm 1.592$           | $-12.623 \pm 2.720$           |
| Average  | $0.106 \pm 0.251$  | $-5.252 \pm 0.424$  | $-10.153 \pm 2.385$           | $-15.020 \pm 4.264$           |

**Fig. 3.** H<sub>2</sub>O maser distribution and proper motion in YLib. The color code represents the  $V_{\text{LSR}}$  of the maser spots, while the length of the arrows represents the magnitude of the proper motion, and the direction is indicated by the arrows' direction. (Color online)

reference sources, caused by the atmospheric zenith delay residual and/or a variability of the structure of the maser spot (Honma et al. 2007; Hirota et al. 2007).

Hipparcos obtained the parallax, the proper motion in right ascension and declination directions, as  $2.06 \pm 3.43$  mas,  $-5.59 \pm 3.34$  mas yr<sup>-1</sup>, and  $-18.48 \pm 2.35$  mas yr<sup>-1</sup> (van Leeuwen 2007), while our VERA improved measurement puts the values at  $0.855 \pm 0.050$  mas,  $-10.15 \pm 2.39$  mas yr<sup>-1</sup>, and  $-15.02 \pm 4.26$  mas yr<sup>-1</sup>. The disparity in the proper motions reported with the Hipparcos and those from VERA measurements can be attributed to the internal motion of the H<sub>2</sub>O masers used in VLBI astrometry.

### 3.3 Photometry and light curve of YLib

From our infrared observations, we derived the mean  $J$ ,  $H$ ,  $K'$ -band magnitude of YLib to be  $4.34 \pm 0.22$  mag,  $3.62 \pm 0.18$  mag and  $3.25 \pm 0.16$  mag, respectively. The obtained

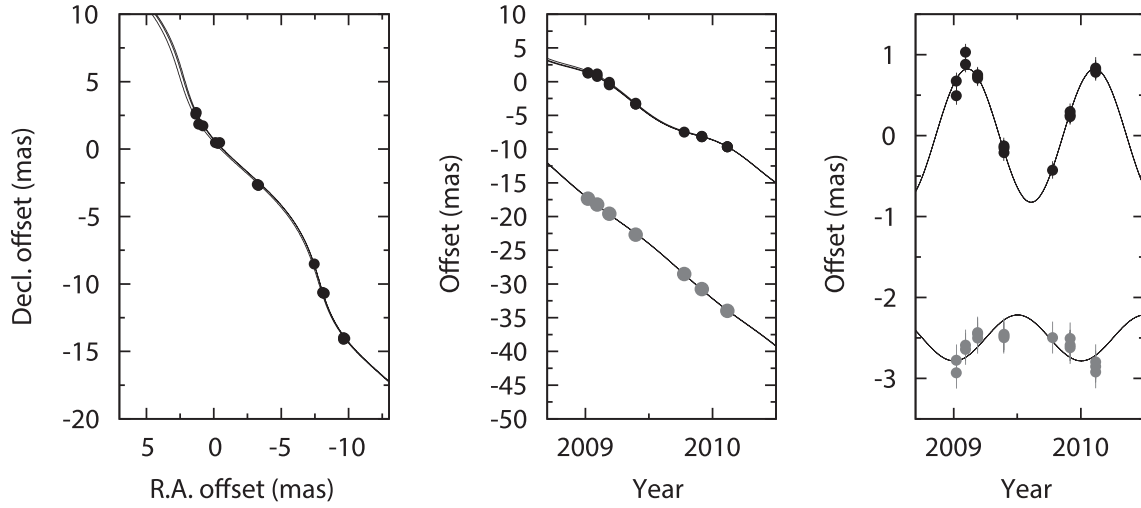
$J$ -,  $H$ -, and  $K'$ -band magnitudes are consistent within the error limits with the values reported in Whitelock et al. (2000). The pulsation period of YLib is  $277.2 \pm 13.9$  d (see figure 6). Our results agree with the YLib periods from the Galactic Catalogue of Variable Stars (GCVS;  $P_{\text{GCVS}} = 275$  d) and Hipparcos ( $P_{\text{Hipparcos}} = 276$  d). Whitelock et al. (2000) reported a  $K$ -band period of 307 d, which is 10% more than the values from GCVS and Hipparcos. This is likely due to the limited number of observations, as they suggested. The least-squares fit method was employed in deriving the period, searching for minimal rms residual within 100 to 1500 d. The gray arrow in the middle panel of figure 6 points to the period of YLib with the least residual. The period of YLib was only derived from the  $K'$ -band light curve. Figure 5 show the  $J$ ,  $H$ , and  $K'$  magnitudes against the Modified Julian Date (MJD) and the best fit of the periodicity, with a line indicating the mean values of the respective bands. Detailed analysis of the  $K'$ -band variability is shown in figure 6.

## 4 Discussion

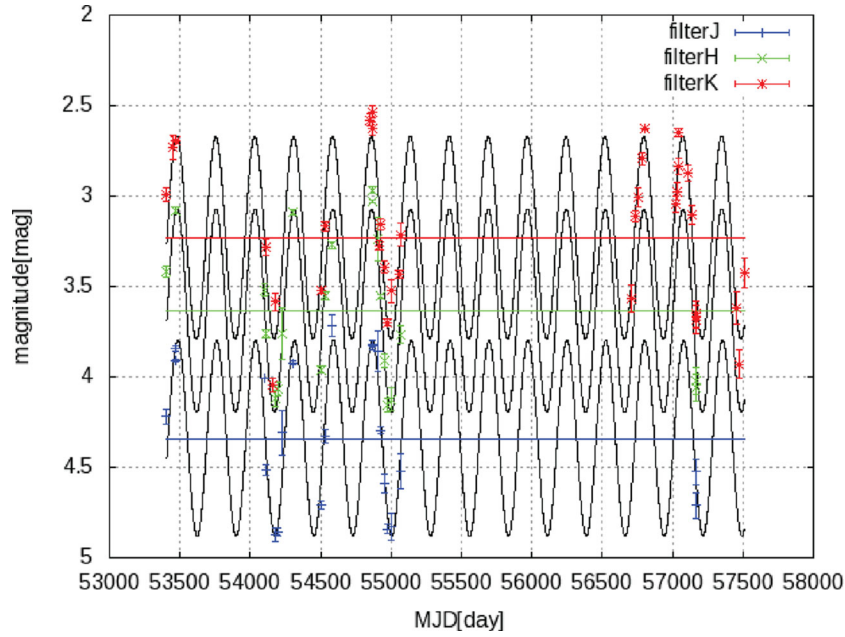
### 4.1 Photometric properties of YLib

Exploring the physical/photometric properties of YLib, we have derived its absolute bolometric magnitude ( $M_{\text{bol}}$ ), luminosity ( $L_{\text{YLib}}$ ), effective temperature ( $T_{\text{eff}}$ ), and the radius ( $R_{\text{YLib}}$ ). Pojmanski and Maciejewski (2004) reported the  $V$ -magnitude value of YLib as  $9.21 \pm 5.53$  mag, which is the maximum light value. In this paper, we have used the average values ( $11.15 \pm 3.22$  mag) derived from the GCVS (Samus' et al. 2017) photometric data. It is important to note that we have used Carpenter et al.'s (2001)<sup>2</sup> transformation equations to transform from the CIT to the South African Astronomical Observatory (SAAO) system to correspond with the system used in Bessell, Castelli, and Plez (1998). Feast, Whitelock, and Carter (1990) showed the intrinsic color range of Mira variables to be  $0.3 < H - K < 0.6 \sim 0.7$  (our  $H - K$  was 0.38), which can be adopted for periods up to 400 d. Using a

<sup>2</sup> Updated website ([http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6\\_4b.html](http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html)).



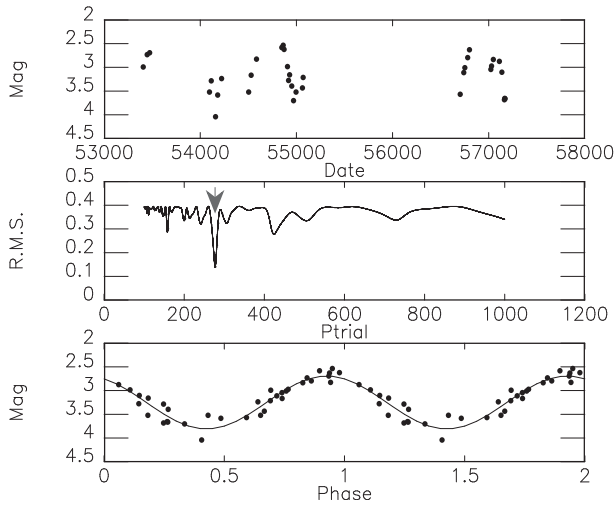
**Fig. 4.** Left: Maser group 1 position on the sky and the modeled maser motion (solid curve). Middle: Maser feature position in RA (black circle) and declination (gray circle) offsets against the epoch of observation. Right: Same as middle panel but a linear proper motion is subtracted.



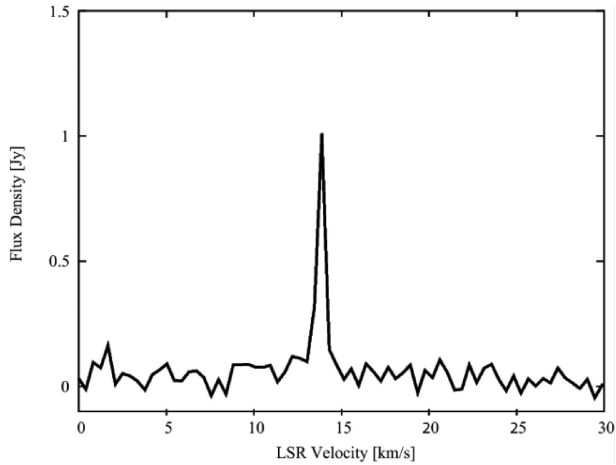
**Fig. 5.** Fitting of the YLib period from our infrared observations. The blue, green, and red data points represent  $J$ ,  $H$ ,  $K'$  magnitude measurements from our NIR observations, while the blue, green, and red horizontal lines represent the mean  $J$ ,  $H$ , and  $K'$  magnitudes. (Color online)

period of 270 d, we derive an excess  $E(H - K)$  value of 0.04. This value falls within the observational error and thus shows no need for reddening correction. Our  $K'$  magnitude ( $3.25 \pm 0.16$  mag) corresponds to a  $K_{\text{SAAO}}$  of  $3.24 \pm 0.19$  mag. First, we derived the  $V - K$  values, and used them to estimate the  $T_{\text{eff}}$  and  $BC_K$  (bolometric correction) from effective temperature versus  $(V - K)$  and  $BC_K$  versus  $(V - K)$  diagrams shown in Bessell, Castelli, and Plez (1998), respectively. With an average  $V$ -band magnitude of YLib obtained from GCVS and the  $K$ -band magnitude from our NIR observations, we got  $(V - K = 11.15 - 3.24) 7.91$  mag. Based on Bessell, Castelli, and

Plez (1998), the  $T_{\text{eff}}$  and  $BC_K$  of YLib will correspond to  $3100 \pm 125$  K and  $2.92 \pm 0.05$ , respectively. The bolometric magnitude ( $m_{\text{bol}}$ ) of YLib can be computed from  $BC_K$  using  $m_{\text{bol}} = BC_K + m_K$ ; we obtained  $m_{\text{bol}}$  to be  $6.16 \pm 0.20$  mag. The absolute bolometric magnitude ( $M_{\text{bol}}$ ) of YLib can be computed from  $BC_K$  using  $M_{\text{bol}} = m_{\text{bol}} - 5 \log_{10}(D/10)$ , where  $D$  is distance; we obtained  $M_{\text{bol}}$  to be  $-4.18 \pm 0.21$  mag. To derive the radius of YLib, we used  $M_{\text{bol}} = 4.74 - 2.5 \log[T_{\text{eff}}^4 R^2 / (T_{\text{eff}\odot}^4 R_{\odot}^2)]$  from Bessell, Castelli, and Plez (1998), and obtained the radius of YLib to be  $\sim 211 \pm 11 R_{\odot}$ . Using equation (7) of Whitelock and Feast (2000), we estimated the radius of YLib from its



**Fig. 6.** YLib K-band magnitude measurement. Top: YLib K-band light curve. Middle: Root-mean-square (rms) deviation from the data point of each period. The gray arrow shows the period with the least deviation. Bottom: Plot of the K-band magnitude against the phase.

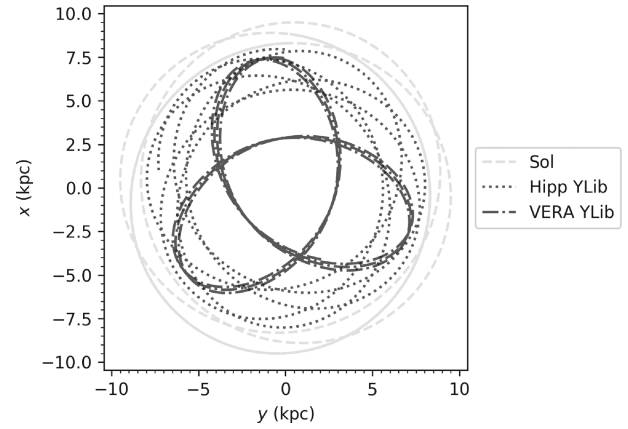


**Fig. 7.** Cross-power spectrum of H<sub>2</sub>O maser emission of YLib observed with the Iriki-Mizusawa baseline of VERA.

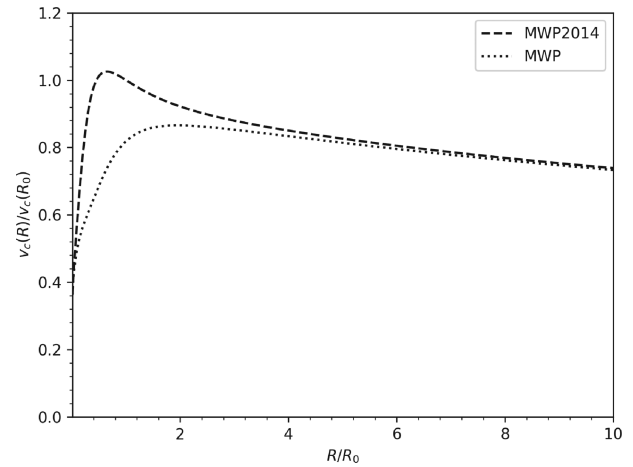
period (derived from our data) to be  $\sim 396 \pm 15 R_{\odot}$ . The discrepancy in the derived radii based on Bessell, Castelli, and Plez (1998) and Whitelock and Feast (2000) may be because the  $V - K$  vs.  $T_{\text{eff}}$  and  $V - K$  vs.  $BC$  relations of Bessel et al. (1998) were for normal giants, so these values could be different from those for AGB stars. We speculate that the radius derived from Whitelock and Feast (2000) might be more reliable because of its dependence on the more accurately derived period.

## 5 The orbit of Y Lib in the Milky Way: GALORB (GALactic ORBit simulation)

The velocities and positions of sources within the Galaxy are fully described by astrometric motion measurements. If a full set of these motion parameters are available for



**Fig. 8.** Simulated orbit as seen from above showing the X and Y components representing the radial velocity relative to the Galactic center and the Galactic rotational velocity, respectively. Overlaid are simulated orbits using Hipparcos and VERA astrometric observations, showing the greatest difference to the simulated in-plane motions.



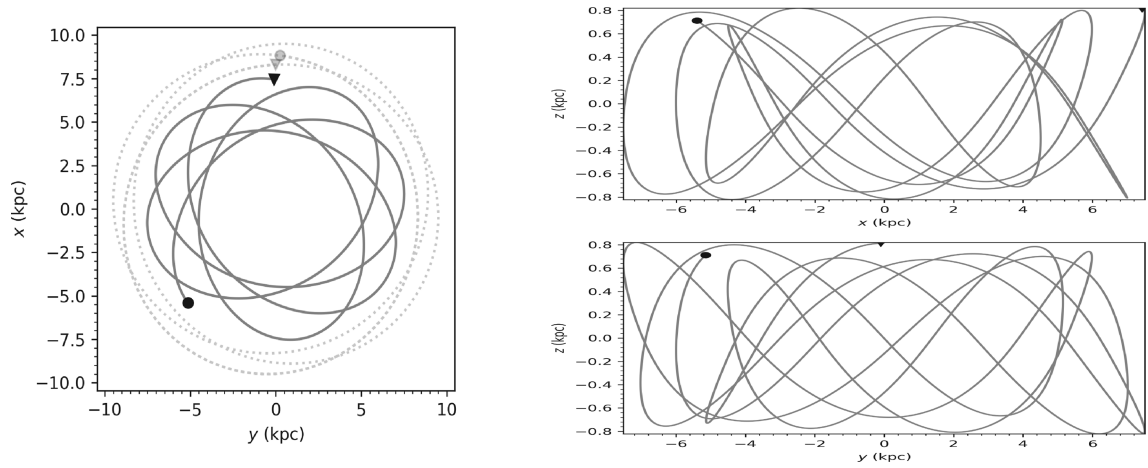
**Fig. 9.** Relaxing the values for the Miyamoto-Nagai disk potential contribution to the MWPotential2014 model created a potential model, MWP, that could visually reproduce the orbits simulated using the Hipparcos values.

a source, the anticipated orbit of that source around the Galactic center can be simulated.

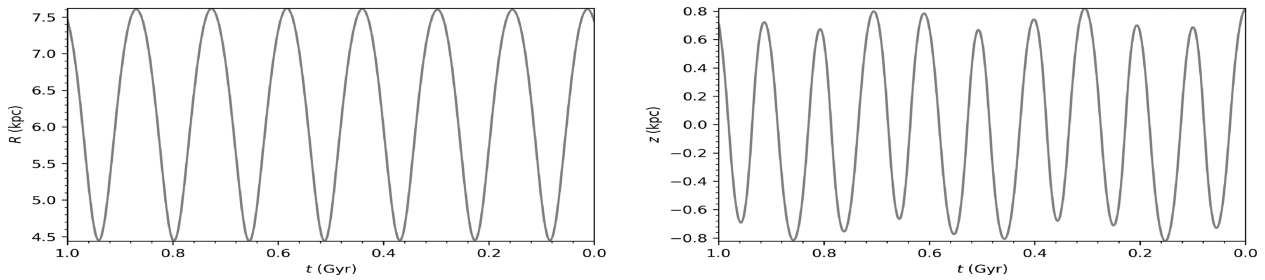
Orbit simulation of stellar motion can be useful during analysis and this functionality is conveniently available in the GalPy (Bovy 2015) Python package. GalPy also provides various numerical integration techniques required for simulation as well as a number of Galactic potential models.

Since GalPy interfaces natively with the AstroPy (Astropy Collaboration 2013) Python package, the two packages were wrapped into the GALORB (GALactic ORBit simulation) Python tool to provide a user friendly command line interface for orbit simulations.<sup>3</sup> GALORB utilizes AstroPy to represent celestial targets and for coordinate conversion. After establishing the implementation

<sup>3</sup> ([https://bitbucket.org/r\\_et\\_d/galorb/wiki](https://bitbucket.org/r_et_d/galorb/wiki)).



**Fig. 10.** Left: Face-on view of the Galactic orbit of Y Lib over the last 1 Gyr. The grey line indicates the orbit of Y Lib, while the dotted line displays the solar orbit. Right: X-Z and Y-Z edge-on views of the orbit. The dot and triangle markers indicate the positions 1 Gyr ago and at present, respectively.



**Fig. 11.** Left: Y Lib variation of radial distance from the Galactic center from the simulation time. Right: Y Lib variation of distance from the Galactic center over the simulation time.

against published results (see the Appendix), GALORB was applied to the VERA observations of Y Lib.

Hipparcos (Wenger et al. 2000) provides the following optical astrometry values for proper motions:  $(\mu_x, \mu_y) = (-5.59 \pm 3.34, -18.48 \pm 2.35) \text{ mas yr}^{-1}$ , radial velocity,  $V_r = -7.00 \pm 3.4 \text{ km s}^{-1}$  and parallax,  $\tau = 2.06 \text{ mas}$ . VERA observations update these values of motions to  $(\mu_x, \mu_y) = (-10.153 \pm 2.385, -15.020 \pm 4.264) \text{ mas yr}^{-1}$ , radial velocity  $14.40 \pm 1.05 \text{ km s}^{-1}$  with respect to LSR (see subsection 3.1 and figure 7) and parallax  $0.855 \pm 0.05 \text{ mas}$ . There are no GAIA DR2 data available for Y Lib. Thus, orbit simulation is carried out using Hipparcos and VERA measurements only.

What makes the Y Lib measurements interesting is the significant difference between Hipparcos and VERA motion measurements. Applying the distance from the Sun to the Galactic center,  $R_0 = 8 \text{ kpc}$ , and the circular velocity at the solar circle,  $V_0 = 217.4 \text{ km s}^{-1}$ . Hipparcos data results in a peculiar motion of  $(U_s, V_s, W_s) = (5.28, -39.59, -20.69) \text{ km s}^{-1}$  for Y Lib, while applying the VERA measurements gives  $(U_s, V_s, W_s) = (4.86, -99.44, -14.03) \text{ km s}^{-1}$  with a large rotational component.

For orbit simulation, GalPy (Bovy 2015) recommends using the `MWPotential2014` Milky Way-like potential. This potential model includes a realistic bulge model and fitted dynamical constraints on the Milky Way. (Bovy 2015). When applied to VERA and Hipparcos measurements for Y Lib, the simulated orbit from the VERA measurements are highly eccentric in the direction perpendicular to the Galactic center (figure 8). This is to be expected given the large rotational velocity,  $V_s$ .

To relax the eccentricity in the VERA orbital direction, one of two adjustments can be applied: The first is to increase the parallax distance and move the masers closer, such as per the Hipparcos parallax. Given that the VERA parallax measurement has a higher probability of being closer to the actual distance, this adjustment is not favoured. The second adjustment is to decrease the Miyamoto–Nagai disk potential contribution in the Milky Way model (figure 9).

Implementing the relaxed potential model, we obtain similar graphs shown in figure 10, integrating for 1 Gyr. Figure 11 illustrates the time variation of radial distance and directional distance from the Galactic plane.

It is impossible to draw realistic conclusions from a single data point. The large deviation of the results obtained using the VERA measurements compared to the Hipparcos data indicates that the next logical step is to investigate the current Milky Way potential model implemented in GalPy further. Since VERA measurements compare well with values published by Gaia, updated measurements for the Mira variables listed in Feast and Whitelock (2000) could be obtained by combining data from both archives. These values can then be used in combination with the simulation tools developed to obtain an updated potential model for the Milky Way.

## 6 Conclusions and summary

We have successfully measured the trigonometric parallax of Y Lib with VERA, pinning the value at  $0.855 \pm 0.050$  mas, which is equivalent to the distance of  $1.17 \pm 0.07$  kpc. Using our multi-epoch NIR observations of Y Lib with the Kagoshima University 1 m telescope, we derived the pulsation period of Y Lib to be  $277.2 \pm 13.9$  d (long-period Mira variable). Other properties of Y Lib derived from our work includes the effective temperature ( $3100 \pm 125$  K) and the radius ( $211 \pm 11 R_{\odot}$ ).

This paper also serves as the first release of the GALORB simulation package. We have tested and validated it with the SY Scl results of Nyu et al. (2011). We have also compared the results using both Hipparcos and VERA measurements (see figure 12 in the Appendix).

## Acknowledgment

We acknowledge all VERA staff members and students who have helped with the array operation and with the data correlation. In

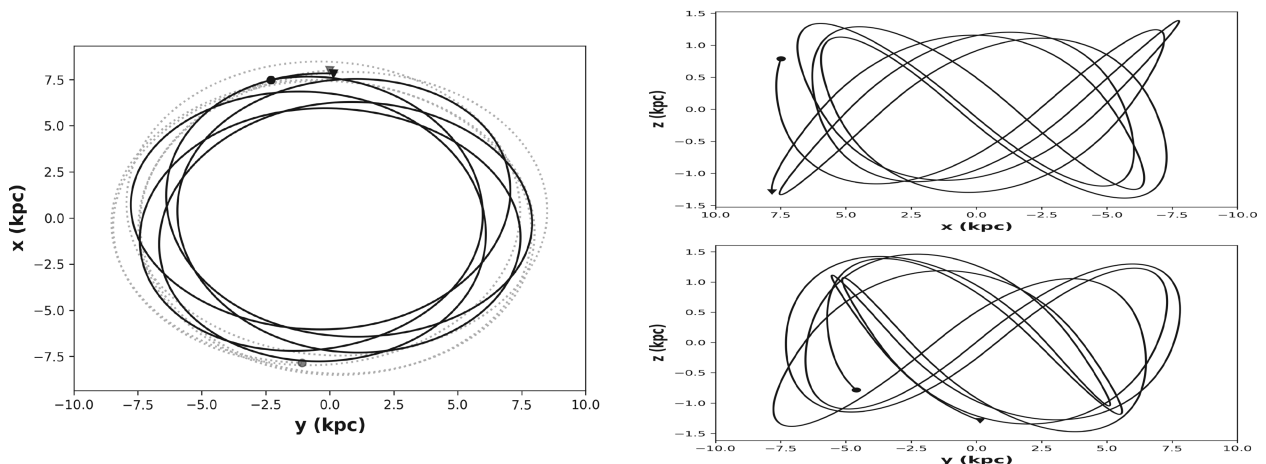
this research, we have used and acknowledge with appreciation, the data from the American Association of Variable Star Observers (AAVSO) International Database, based on observations submitted to the AAVSO by variable star observers worldwide.

## Appendix

Nyu et al. (2011) has shown how VLBI observations of masers associated with Mira variables can be used to obtain more accurate distance measurements compared to optical astrometry from Hipparcos. The reason for this is that the optical luminosity of high mass-loss sources can be affected by the circumstellar envelopes.

In this paper, updated motion measurements from VERA astrometry observations of SY Scl,  $(\alpha, \delta)_{J2000.0} = (00^h07^m36^s.25, -25^{\circ}29'40''.03)$ , as well as a group of H<sub>2</sub>O masers around the Mira variable, gave a new parallax of  $0.75 \pm 0.03$  mas and proper motion  $(\mu_x, \mu_y) = (6.41 \pm 0.04, -6.90 \pm 0.12)$  mas yr<sup>-1</sup> (Nyu et al. 2011). These values compare well to Gaia values  $\pi = 0.6751 \pm 0.2272$  mas and  $(\mu_x, \mu_y) = (6.111 \pm 0.326, -7.475 \pm 0.290)$  mas yr<sup>-1</sup> (Wenger et al. 2000). Unfortunately, Hipparcos does not have any optical astrometry measurements for SY Scl; values were obtained from the all-sky catalogue of solar-type dwarfs (Zacharias et al. 2013)  $(\mu_x, \mu_y) = (4.6, -7.8)$  mas yr<sup>-1</sup>. These comparative proper motion values confirm the assertion that if optical astrometry observation of the Mira variable is not available, the average motion of the masers associated with the star can be used to approximate the stellar motion (Nyu et al. 2011).

As a natural extension, the motion measurements were used to simulate an anticipated galactic orbit of the observed stars, using numerical integration methods. The Nyu et al. (2011) paper provides great detail of all



**Fig. 12.** Orbit of SY Scl for the last 1 Gyr. The black lines show the predicted orbit for SY Scl, while the light gray lines on the left-hand graph indicate the equivalent orbit simulated for the Sun. Left to right is the face-on, X-Z and Y-Z edge-on views of the simulated orbit. The dot and triangle markers indicate the estimated position 1 Gyr ago and the known position at present, respectively.

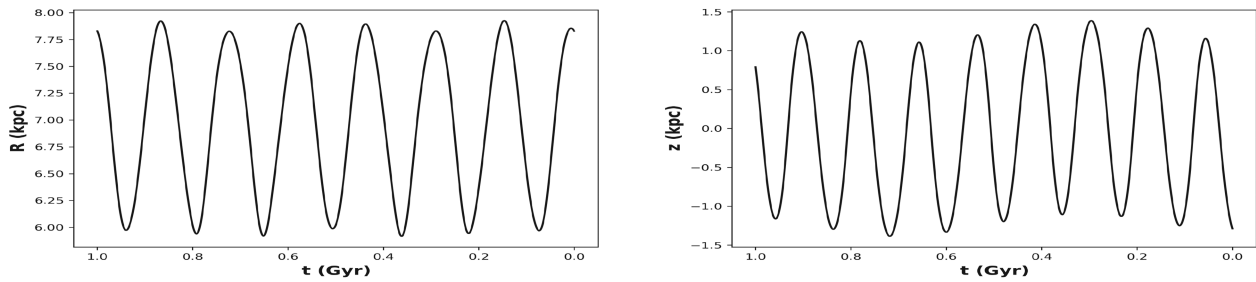


Fig. 13. Left: Variation in time over the simulation period for SY Scl with radial distance variance. Right: Variation of distance from the Galactic center.

calculations converting Heliocentric measurements to motion coordinates relative to LSR, as well as clear graphs of the resulting orbit simulations, using Runge–Kutta integration over a period of 1 Gyr.

Since we implemented the methodology presented in Nyu et al. (2011), we used their results obtained from SY Scl to validate our implementation. Given a radial velocity of  $22 \text{ km s}^{-1}$  and systemic proper motion  $(\mu_x, \mu_y) = (5.57 \pm 0.04, -7.32 \pm 0.12) \text{ mas yr}^{-1}$ , motion coordinates and orbit vectors obtained with GALORB were compared to the published values. For calculation verification, the distance from the Galactic center to the Sun,  $R_0 = 8 \text{ kpc}$ , and a circular velocity at the solar circle,  $V_0 = 217.4 \text{ km s}^{-1}$ , were adopted providing output for Galactic motion and velocities  $(\mu_l, \mu_b) = (-6.02, -6.95) \text{ mas yr}^{-1}$  and  $(v_l, v_b) = (-38.05, -43.95) \text{ km s}^{-1}$ , respectively. From these follows the peculiar motion of  $(U_s, V_s, W_s) = (-5.28, -54.02, -33.72) \text{ km s}^{-1}$ , where  $U$  is the motion towards the Galactic center,  $V$  is the motion in the direction of Galactic rotation, and  $W$  is the motion towards the Galactic north pole. We also have position and space motion  $(X, Y, Z) = (7.83, 0.15, -1.29) \text{ kpc}$  and  $(V_R, V_\theta, V_Z) = (-1.53, 178.74, -26.00) \text{ km s}^{-1}$  for orbit simulations shown in figures 12 and 13.<sup>4</sup>

<sup>4</sup> Details of the simulations can be found at ([https://bitbucket.org/r\\_et\\_d/galorb/wiki](https://bitbucket.org/r_et_d/galorb/wiki)).

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