The Milky Way’s Circular Velocity Curve and Its Constraint on the Galactic Mass with RR Lyrae Stars

Iminhaji Ablimit© and Gang Zhao©

Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; iminhaji@nao.cas.cn, gzhao@nao.cas.cn

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Abstract

We present a sample of 1148 ab-type RR Lyrae (RRLab) variables identified from Catalina Surveys Data Release 1, combined with SDSS DR8 and LAMOST DR4 spectral data. We first use a large sample of 860 Galactic halo RRLab stars and derive the circular velocity distributions for the stellar halo. With the precise distances and carefully determined radial velocities (the center-of-mass radial velocities) and by considering the pulsation of the RRLab stars in our sample, we can obtain a reliable and comparable stellar halo circular velocity curve. We follow two different prescriptions for the velocity anisotropy parameter $\beta$ in the Jeans equation to study the circular velocity curve and mass profile. Additionally, we test two different solar peculiar motions in our calculation. The best result we obtained with the adopted solar peculiar motion $1$ of $(U, V, W) = (11.1, 12, 7.2) \text{ km s}^{-1}$ is that the enclosed mass of the Milky Way within 50 kpc is $(3.75 \pm 1.33) \times 10^{11} M_\odot$, based on $\beta = 0$ and the circular velocity $180 \pm 31.92$ (km s$^{-1}$) at 50 kpc. This result is consistent with dynamical model results, and it is also comparable to the results of previous similar works.

Key words: Galaxy: general – Galaxy: halo – Galaxy: kinematics and dynamics – stars: variables: RR Lyrae

1. Introduction

Deriving the rotation curve (RC) and mass distribution of every substructure of the Milky Way would enable us to understand the physical process of galaxy formation. The RC of the Milky Way substructures (i.e., bulge, thin/thick disk and halo) could directly constrain the Galactic mass and could be used to study the local dark matter content (Sofue & Rubin 2001; Bhattacharjee et al. 2013). Many theoretical and observational works have been investigating the RC and Galactic mass, but they are still under debate and remain uncertain (Ibata et al. 1994; Majewski et al. 1996; Weber & de Boer 2010; Nesti & Salucci 2013).

The most reliable method to derive the RC (or circular velocity curve) of the Milky Way is by acquiring three-dimensional velocity information. However, it is hard to measure reliable three-dimensional velocities at larger distances, and only radial velocities are available with current telescopes. In the standard approach, the star tracer population is assumed to be distributed isotropically in the Galaxy, and the Jeans equation (Binney & Tremaine 2008) is adopted for circular velocity at a given radius in the spherical system. The radial velocity dispersion, number density, and velocity anisotropy parameter ($\beta$) of the Jeans equation are important to the circular velocity. Xue et al. (2008) present the circular velocity curve and mass of the Galaxy at $\sim 60$ kpc by using the radial velocity dispersion of 2041 blue horizontal branch (BHB) stars selected from SDSS DR6 and the Jeans equation with two constants of $\beta = 0$ and 0.37. Jeans equation and analytical models of the phase-space distribution function of the tracer population have been adopted for the circular velocity curve and mass estimate of the Milky Way at different distances (Gnedin et al. 2010; Deason et al. 2012; Kafle et al. 2012). Bhattacharjee et al. (2014) consider three different prescriptions of $\beta$, one of them has a radially varying $\beta$ given by $\beta(r) = (1 + r_a^2/r^2)^{-1}$ (see Binney & Tremaine 2008), where $r_a$ is the anisotropy radius. They show the variation of RC within $\sim 200$ kpc with different models. More recently, Huang et al. (2015) use the current direct and indirect measured values of $\beta$ to model the RC out to $\sim 100$ kpc with red clump stars selected from the LAMOST survey and K giants selected from the SDSS/SEGUE survey.

We take $\beta = 0$ according to the observation, and also adopt the new function from the developed dynamical model of Williams & Evans (2015) for the velocity anisotropy profile in this work (see below sections for more details). We use ab-type RR Lyrae (RRLab) stars (fundamental-mode pulsators) by combining the SDSS DR8 and LAMOST DR4 spectral data to construct the circular velocity curve. RR Lyrae variables (RRLs) are low-metallicity stars that have evolved through the main sequence and He-burning variable stars on the horizontal branch of the color–magnitude diagram. At near-infrared wavelengths, the absolute magnitude deviation could be as low as 0.02 mag for the single one, which means $\sim 1\%$ uncertainty in distance for an individual star (see Beaton et al. 2016 for details). To the whole population, the scatter of absolute magnitudes of Milky Way RRab’s field and globular cluster stars may reach $\sim 0.1$ mag (Dambis et al. 2013, 2014). In comparison to other stars like the BHBs and K giants used in previous studies, RRLab stars are brighter and can be detected at larger distances, and they can also be used as standard candles (for more details of distance uncertainty see below sections) because of the narrow luminosity–metallicity ($M_V - [\text{Fe/H}]$) relation in the visual band and period–luminosity–metallicity relations in the near-infrared wavelengths. RRL stars have been widely accepted as a great tool for determining distances and studying the age, formation, and structure of the Milky Way and local galaxies.

We select a sample of RRL stars that have measured radial velocity and metallicity to investigate the circular velocity curve and mass distribution of the Milky Way. We describe the sample selection of RRLab stars in Section 2. We present the measured circular velocity curve and the gravitational mass of
the Milky Way in Section 3. Section 4 contains our concluding remarks.

2. The Sample Selection

Drake et al. (2013) analyzed 12227 RRLab stars (\~9400 are newly discovered) from the 200 million public light curves in Catalina Surveys Data Release 1. These stars span the largest volume of the Milky Way ever surveyed with RRLs, covering \~20,000 deg$^2$ of the sky (the equatorial coordinates are shown in Figure 1). They show data taken by the Catalina Schmidt Survey (CSS), and the uncertainty in photometry is \~0.03 mag for $V < 16$ mag and rises to 0.1 mag at $V \sim 19.2$ mag (see Figure 3 of Drake et al. 2013). They also identify RRLab stars with both radial velocity and metallicity information by combining Catalina photometry with Sloan Digital Sky Survey (SDSS) spectroscopic Data Release 8 (DR8). Among the SDSS-matched stars, we selected 351 SDSS-matched sample stars that have both velocity and metallicity in our work (in the region of Galactic centric distance $\leq$ 50 kpc).

The Large sky Area Multi-Object fibe Spectroscopic Telescope (LAMOST) is a Chinese national scientific research facility operated by National Astronomical Observatories, Chinese Academy of Sciences (Zhao et al. 2006, 2012). It is a special reflecting Schmidt telescope with 4000 fibers in a field of view of 20 deg$^2$ in the sky. LAMOST has completed its pilot survey, which was launched in 2011 October and ended in 2016 June. LAMOST DR4 has 7,681,185 low-resolution ($R \sim 2000$) spectra in total, and we use these data to cross match with the other CSS RRL stars (without SDSS-matched samples), within an angular distance of 3 arcsec. We find 797 matched RRLab stars, and their metallicities and radial velocities are given in Figure 2. For the LAMOST-matched RRLab stars, we find that the metallicity mean uncertainty is 0.19 dex (average metallicity is $-1.1$ dex) and the mean uncertainty of the radial velocity is 14.93 km s$^{-1}$. Comparing to the mean uncertainty of the metallicity (0.1 dex, average metallicity is $-1.38$ dex) and radial velocity ($<15$ km s$^{-1}$) of the SDSS-matched RRLab stars, the parameters derived by LAMOST observations are reliable. Totally, we have 1148 RRLab star samples that have precise distances and radial velocities to study kinematics and mass of the Milky Way.

RRL stars are widely used for distance determination, and an absolute magnitude–metallicity relation has traditionally been used for distance calculations (Sandage 1981). One popular method that is adopted for the absolute magnitude is given as (Chaboyer 1999; Cacciari & Clementini 2003),

$$M_V = (0.23 \pm 0.04)([\text{Fe}/\text{H}] + 1.5) + (0.59 \pm 0.03),$$

where [Fe/H] is the metallicity of an RR Lyrae star. Considering the uncertainties from the photometric calibration and the variations in metallicity and uncertainty in RRab absolute magnitudes (also see Dambis et al. 2013 for the uncertainty in absolute magnitude), the overall uncertainties are around 0.15 mag. Correspondingly, we derive \~7% uncertainties in distances. For the heliocentric $d$ and Galactocentric distances $R_{GC}$, we use the equations,

$$d = 10^{(V - M_V + 5)/5} \text{kpc},$$

where $\langle V \rangle$ average magnitudes were corrected for interstellar medium extinction using Schlegel et al. (1998) reddening maps, and

$$R_{GC} = (R_\odot - d \cos b \cos l)^2 + d^2 \cos^2 b \sin^2 l$$

$$+ d^2 \sin^2 b \text{ kpc},$$

where $R_\odot$, $l$, and $b$ are the distance from the Sun to the Galactic center (8.33 kpc in this work, see Gillessen et al. 2009), Galactic longitude, and latitude of the stars, respectively.

3. Results and Discussion

Our sample of 1148 RRLab stars contains 288 thick disk stars with $1 < |z| < 4$ kpc, and also 860 halo stars with $|z| > 4$ kpc (see Figure 3).

One of the important issues is deriving a dependable radial velocity (the center-of-mass radial velocity) of the RRL stars. RRL stars are well known to exhibit significant variation in radial velocity measurements because of their pulsation (e.g., Liu 1991). Sesar (2012) recently noted differences between velocities measured using hydrogen and metallic lines as references and derived relationships for correcting these. They found that the combination of three Balmer lines would lead to uncertainties of a few km s$^{-1}$. Drake et al. (2013) combined the relationships given by Sesar (2012) to produce an appropriate correction for the SDSS measurements. Thus, we have the velocity in Galactic standard of rest frame with corrected radial velocities of 350 SDSS-matched halo RRLab stars within 50 kpc directly from Drake et al. (2013). LAMOST observes every star three times continuously for a 30-minute exposure each time, and some objects are observed multiple times in the different observational periods. (We have 145 multi-observed stars in our sample, and we average all data of the multi-observed stars for their stellar parameters.) In addition, LAMOST derives the radial velocity by averaging the velocities from the metallic lines: Balmer H$\alpha$, H$\beta$, and H$\gamma$ lines. To accurately correct for velocity variation, we need to know how the radial velocities were measured and the observed phase of the star. Using an average time of LAMOST observations, the period and ephemeris of the RRLab, we obtain the phase of observations for each star and keep the phase between 0.1 and 0.95 because of the uncertain velocity correction from that region (see Sesar 2012). The correction method based on combinations of Balmer and metallic lines.
with combined relationships of Sesar (2012) used in Drake et al. (2013) is adopted in this work as well. The distribution of the original radial velocity and the redetermined radial velocity by the proper correction is given in Figure 4 (right panel). We find that the correction for the pulsation velocities improves the velocity data quality with a mean uncertainty of 14.43 km s$^{-1}$. Our mean uncertainty has good agreement with the uncertainties of Sesar (2012), 13 km s$^{-1}$, and Drake et al. (2013), 14.3 km s$^{-1}$. We agreed with the conclusion that the metallicity dispersion measurement is not affected by the pulsation (Drake et al. 2013), and the distribution of metallicities of halo tracers in our sample is shown in the left panel of Figure 4. Therefore, we have reliable radial velocities of 510 stellar halo tracers with acceptable uncertainties from the analysis of 1302 LAMOST spectra for further calculations.

To transform the heliocentric radial velocities ($V_{h}$) of the stars to the fundamental standard of rest (FSR), we adopt the following equation by using the solar peculiar motion 1 of ($U$, $V$, $W$) = (11.1, 12, 7.2) km s$^{-1}$ (SM1, Binney & Dehnen 2010), which are defined in a right-handed Galactic system with $U$ pointing toward the Galactic center, $V$ in the direction of rotation, and $W$ toward the north Galactic pole. We adopt the solar peculiar motion 2 of ($U$, $V$, $W$) = (11.1, 18, 7.2) km s$^{-1}$ (SM2 has the only change in $V$, see Reid et al. 2014 and Rastorguev et al. 2017) for comparison. We take a recent value of 235 ± 7 km s$^{-1}$ for the local standard of rest ($V_{lSR}$, Reid et al. 2014 and Rastorguev et al. 2017) in the equation below,

$$V_{FRS} = V_{h} + U \cos b \cos l + (V + V_{lSR}) \cos b \sin l + W \sin b.$$  

(4)

The calculation results are given in Figure 5. From the figure, it can be seen that the change of $V$ in the solar peculiar motion slightly affects the distribution of $V_{FRS}$.

### 3.1. The Circular Velocity Curve by the Halo Tracers

The sample has 860 halo tracers of the distance up to $R_{GC} \sim 50$ kpc. We take a simple and widely used method to derive the circular velocity $V_{C}$ by applying the velocity dispersion $\sigma_{c}$ of tracers and the spherical Jeans equation (Binney & Tremaine 2008),

$$V_{C}^2 = -\sigma_{c}^2 \left( \frac{d \ln \nu}{d \ln r} + \frac{d \ln \sigma_{c}^2}{d \ln r} + 2\beta \right),$$  

(5)

where $\sigma_{c}$, $\nu$, and $\beta$ are the Galactocentric radial velocity dispersion, number density of tracer population, and velocity anisotropy parameter, respectively. A number of studies follow a broken power-law distribution $\nu \propto r^{-\alpha}$ and a shallow slope of $\alpha \sim 2$–3 up to a break radius $r_{b} \sim 16$–27 kpc and a steeper slope of $\alpha \sim 3.8$–5 out of $r_{b}$ (Bell et al. 2008; Watkins et al. 2009; Sesar et al. 2013; Faccioli et al. 2014). According to the number density of RRL given by Watkins et al. (2009), we adopt $\alpha = 2.4$ for the inner halo ($r \leq 25$ kpc) and $\alpha = 4.5$ for the outer halo ($r > 25$ kpc). We address $\sigma_{c}$ and $\beta$ below.

Before obtaining the Galactocentric radial velocity dispersion $\sigma_{c}$ in the first step we divide all stars into several bins and calculate $\sigma_{FRS}$ in each bin by averaging; the first bin is to
10 kpc, and beyond 10 kpc we use 5 kpc to make a bin. We take $\Delta \sigma_{\text{FRS}} = (\sqrt{1/[2(N - 1)]}) \sigma_{\text{FRS}}$ for the uncertainty of $\sigma_{\text{FRS}}$ in each bin, where $N$ is the number of members in tracer population in the bin. In the first bin, for $<10$ kpc, we have 128 stars. There are 274, 176, 119, 76, 28, 24, 19, and 16 stars in the bins representing 10–15, 15–20, 20–25, 25–30, 30–35, 35–40, 40–45, and 45–50 kpc, respectively. In the second step, we derive the Galactocentric radial velocity dispersion $\sigma_r$ at the Galactocentric distance $r$ for each bin by using $\sigma_{\text{FRS}}$ and the relation (Battaglia et al. 2005),

$$\sigma_r = \frac{\sigma_{\text{FRS}}}{\sqrt{1 - \beta H(r)}},$$

(6)

where

$$H(r) = \frac{r^2 + r_s^2}{4r^2} - \frac{(r^2 - R_s^2)^2}{8r^3R_s} \ln \frac{r + R_s}{r - R_s},$$

(7)

The velocity anisotropy parameter $\beta$ is described as,

$$\beta(r) = 1 - \frac{\sigma^2_r}{2\sigma^2_t},$$

(8)

where $\sigma_r$ is the transverse velocity dispersion. Because of a lack of the proper motions for tracers, $\beta$ is usually taken to be a constant or taken from the modulated relations as discussed in Section 1. Deason et al. (2013) show that the halo is isotropic $\beta = 0.0^{+0.2}_{-0.4}$ at $r = 26 \pm 6$ kpc. Kafle et al. (2014) find $\beta = 0.4 \pm 0.2$ beyond 50 kpc. For the $\beta$, we adopt two different scenarios; one is regarding it as a constant $\beta = 0$ out to 50 kpc, and the other is following a new relation between $\beta$ and Galactocentric distance $r$ given by Williams & Evans (2015), as,

$$\beta(r) = \beta_0 + \frac{(\beta_1 - \beta_0)r}{r + r_0},$$

(9)

where $\beta_0 = 0.05$, $\beta_1 = 0.82$, and $r_0 = 18.2$ kpc. By the relation, we get $\beta$ changing from $\sim 0.32$ to $\sim 0.67$ at the distance from 10 to 50 kpc. The calculated Galactocentric radial velocity dispersion with $\beta = 0$ and two SM are given in Figure 6. There are $\sim 2$ km s$^{-1}$ discrepancy between $\sigma_r$ at 50 kpc calculated with SM1 and SM2. From the figure, we can see that the Galactocentric radial velocity dispersion profile clearly declines in the range of $10 < r < 25$ kpc; the profile is slightly changed in the range $25 < r < 50$ kpc. Xue et al. (2008) fit an exponential function to their SDSS DR6 sample, which is a linear approximation that gives $\sigma_r \approx 111 - 0.31r$. Gnedin et al. (2010) find a relation $\sigma_r \approx 120 - 0.22r$ in the range $25 < r < 80$ kpc. Their linear profile is less steep than Battaglia et al. (2005), $\sigma_r \approx 132 - 0.6r$. Compared to them, we get a different linear fit function in the range $25 < r \leq 50$ kpc with SM1 and $\beta = 0$: $\sigma_r \approx 112 - 0.6r$; the uncertainty of the profile fit is dominated by the unclear parameters $\beta$ and $\alpha$. In order to express the profile better, we apply a power-law fit and find $\sigma_r \propto r^{-0.38}$ with the solar
peculiar motion 1 (the red dotted line in the Figure 6) & \( \sigma \propto r^{-0.37} \) with the solar peculiar motion 2 (the black solid line in the Figure 6). The changes in the solar basic data (U, V, W, and \( V_{lsr} \)) can affect the velocity distributions and final results (also see Bhattacharjee et al. 2014).

Finally, we can derive the circular velocity curve from the Jeans equation with values of \( \nu \) and \( \sigma_r \), and evaluate \( \beta \) in two different ways for the halo tracers. The results with the solar peculiar motion 1 (hereafter results with SM1 are shown) are presented in Figure 7. This figure shows that the circular velocity and its uncertainty have higher values with a constant \( \beta = 0 \) than the varying \( \beta \) of Williams & Evans (2015). \( \beta \) changes from 0.32 to 0.67 based on the relation given by Williams & Evans (2015). This value is much higher than the isotropic one. We have 156.87 ± 28.26 km s\(^{-1}\) with varying \( \beta \) and 180.0 ± 31.92 km s\(^{-1}\) with \( \beta = 0 \) at \( R_{GC} = 50 \) kpc. Drake et al. (2013) discussed that the CSS RRLab stars are located across the Sagittarius stream. We have a clear increase in the circular velocity distribution around 40 kpc, which is probably caused by the stream effect. We give the two best simulated RCs based on the results of the Jeans equation with two different assumptions of \( \beta \). In comparison to previous works, our two different circular velocity curves have a similar gentle declination and comparable circular velocity curve with moderate uncertainty. The isotropic one seems more reasonable than the varying \( \beta \) within 50 kpc. It can be determined that the circular velocity and its uncertainty depend on the adopted values of parameters like \( \nu \) and \( \beta \) in the Jeans equation. We also need to measure all three-dimensional velocity information and study the Galaxy with a non-spherical method. Newly developed telescopes can enable us to achieve that purpose in the future.

### 3.2. Mass Estimate

The total mass and mass profile of the Milky Way affect the Milky Way’s composition, structure, dynamical properties, and formation history. The circular velocity of the objects can be described by the relation between the equality of the centripetal and gravitational force, as

\[
\frac{mV_C^2}{r} = \frac{m}{r} \frac{d\Phi}{dr} = \frac{GmM(r)}{r^2}
\]

where \( m \) and \( \Phi \) are the mass of the object and the gravitational potential that satisfies the Poisson equation, respectively. Therefore, the following equation is simply derived,

\[
\frac{mV_C^2}{r} = \frac{GmM(r)}{r^2}
\]

where \( M(r) \) is the enclosed total mass within \( r \).

We can thus present the mass profile estimate for the Milky Way by using the equation,

\[
M(r) = \frac{V_C^2r}{G}.
\]

The crucial issue in this equation is how to derive the circular velocity \( V_C \), because proper motion measurements are incomplete and the mass estimate model with line-of-sight velocity measurements depends on several uncertain parameters. We adopt one of the two different ways to estimate the mass of the Milky Way, which only uses the line-of-sight velocity measurements. There have been many works computing the mass profile by using the fitting model with different tracer populations, producing the estimated mass profile within 50 kpc. Kochanek (1996) estimated a mass of the Galaxy within 50 kpc of \((4.9 \pm 1.1) \times 10^{11} M_\odot \) by using the satellites of the Galaxy and the Jaffe potential model. Wilkinson & Evans (1999) used 27 globular clusters and satellite galaxies with a Bayesian likelihood method and a spherical halo mass model to give the mass of \( M(50\text{kpc}) = (5.4_{-3.5}^{+1.0}) \times 10^{11} M_\odot \), and a similar method used by Sakamoto et al. (2003) with the sample of 11 satellite galaxies, 137 globular clusters, and 413 field horizontal branch stars, and they found the mass of \( M(50\text{kpc}) = 1.8_{-0.7}^{+1.1} \times 10^{11} M_\odot \). Later, Smith et al. (2007) considered three models based on a sample of high-velocity stars from the RAVE survey, and the results from their three models were \((4.04_{-1.13}^{+1.04}) \times 10^{11} M_\odot \), \((3.87_{-0.56}^{+0.64}) \times 10^{11} M_\odot \), and \((3.58_{-0.17}^{+0.15}) \times 10^{11} M_\odot \) within 50 kpc. Interestingly, the results of Smith et al. (2007) perfectly match our result based on \( \beta = 0 \). Recently, Deason et al. (2012) found \( M(50\text{kpc}) = 4.0 \times 10^{11} M_\odot \) from about 4000 blue horizontal
et al. 2012. The result from the results of D12, G10, and W99 at 50 kpc, we slightly move the positions (r) of D12, G10, and W99.

branch stars with the same method as Xue et al. (2008) and that of this paper.

We obtain $(3.75 \pm 1.33) \times 10^{11} M_\odot$ and $(2.85 \pm 1.03) \times 10^{11} M_\odot$ by deriving $180.0 \pm 31.92$ km s\(^{-1}\) based on the Jeans equation with $\beta = 0$ and 156.87 $\pm$ 28.26 km s\(^{-1}\) with varying $\beta$ within 50 kpc, respectively. Williams & Evans (2015) develop a new dynamical model to study the circular velocity curve and the mass profile as a function of distance. They show the maximum likelihood mass profiles with Galactocentric distance and find the mass of $4.5 \times 10^{11} M_\odot$ at 50 kpc. Our result based on the relation of $\beta$ with distance found by Williams & Evans (2015) is lower than the results of Williams & Evans (2015) and some of the other works mentioned above. However, our result including the error with $\beta = 0$ and the solar peculiar motion 1 has a good fit with the results of the model and previous works. We plot this result in Figure 8 by marking it with the red word “A17.” As we can see in the figure, our result covers the results of the model and previous works.

4. Concluding Remarks

We study the kinematics of 1148 RRLab stars to derive the circular velocity curve and mass profile of the Milky Way. We obtain the radial velocity dispersion out to 50 kpc by using measured radial velocity and metallicity profiles of 860 CSS RRLab halo stars from SDSS DR8 and LAMOST DR4. The spectral parameters of RRLab in this work show that results from the two survey projects are comparable. We consider the influence of the pulsation of RRLab stars on the radial velocity, and the velocity uncertainty is reduced in a reasonable way. By measuring the precise Galactocentric distance ($\sim$7%) and the velocity dispersion, we adopt the parameter of the RRLab star number density from a comprehensive study and take two different anisotropy profiles to model the circular velocity curve and constrain the mass of the Milky Way. Two sets of $V$ continue to be considered in the calculation, and it is worth noting that the entirety of the basic solar data has an influence on the results. We derive our best result of $M(50 \text{ kpc}) = (3.75 \pm 1.33) \times 10^{11} M_\odot$ by obtaining $180.0 \pm 31.92$ km s\(^{-1}\) based on the Jeans equation with $\beta = 0$ and the solar peculiar motion 1 (SM1). We find a lower mass of $M(50 \text{ kpc}) = (2.85 \pm 1.03) \times 10^{11} M_\odot$ with the circular velocity of 156.87 $\pm$ 28.26 km s\(^{-1}\). We adopt SM1 and a new function of $\beta$ with distance given by a new developed dynamical model (Williams & Evans 2015). More recently, Bobylev et al. (2017) studied the halo with different Galactic gravitational potential models such as a spherical logarithmic Binney potential, a Plummer sphere, and a Hernquist potential. The resulting Galactic masses within 50 kpc based on the three models are $(4.09 \pm 0.2) \times 10^{11} M_\odot$, $(4.17 \pm 0.34) \times 10^{11} M_\odot$ and $(4.17 \pm 0.32) \times 10^{11} M_\odot$, respectively (see Bobylev et al. 2017). In conclusion, it is always very useful to see and compare the results of different objects (or and different approaches) to the problem, and our result is in good agreement with results from theoretical and observational studies.

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References

Battaglia, G., Helmi, A., Morrison, H., et al. 2005, MNRAS, 364, 433 (erratum 370, 1055 [2006])
Beaton, R. L., Freedman, W. L., Madore, B. F., et al. 2016, ApJ, 832, 210
Bell, E. F., Zucker, D. B., Belokurov, V., et al. 2008, ApJ, 680, 29
Bhattacharjee, P., Chaudhury, S., & Kundu, S. 2014, ApJ, 785, 63
Bhattacharjee, P., Chaudhury, S., Kundu, S., & Majumdar, S. 2013, PrvD, 87, 083525
Binney, J., & Tremaine, S. 2008, Galactic Dynamics (2nd ed.; Princeton, NJ: Princeton Univ. Press)
Binney, J. J., & Dehnen, W. 2010, MNRAS, 403, 1829
Bobylev, V. B., Bajkova, A. T., & Gromov, A. O. 2017, AstLr, 43, 241
Cacciari, C., & Clementini, G. 2003, in Stellar Candles for the Extragalactic Distance Scale, Vol. 635, ed. D. Allain & W. Gieren (Berlin: Springer), 105
Chaboyer, B. 1999, in Post-Hipparcos Cosmic Candles, Vol. 237, ed. A. Heck & F. Caputo (Dordrecht: Kluwer), 111
Dambis, A. K., Berdnikov, L. N., Kniazev, A. Y., et al. 2013, MNRAS, 435, 3206
Dambis, A. K., Rastorguev, A. S., & Zabolotskikh, M. V. 2014, MNRAS, 439, 3765
Deason, A. J., Belokurov, V., Evans, N. W., & An, J. 2012, MNRAS, 424, L44
Deason, A. J., Van der Marel, R. P., Guhathakurta, P., Sohn, S. T., & Brown, T. M. 2013, ApJ, 766, 24
Drake, A. J., Catelan, M., Djorgovski, S. G., et al. 2013, ApJ, 763, 32
Faccioli, L., Smith, M. C., Yuan, H.-B., et al. 2014, ApJ, 788, 105
Faccioli, L., Smith, M. C., Yuan, H.-B., et al. 2014, ApJ, 788, 105
Gillessen, S., Eisenhauer, F., Trippe, S., et al. 2009, ApJ, 692, 1075
Gnedin, O. Y., Brown, W. R., Geller, M. J., & Kenyon, S. J. 2010, ApJL, 720, L108

Figure 8. Mass profile of the Milky Way. Our result with $\beta \equiv 0$ is marked by the red “A17.” The black line is from the maximum likelihood mass profiles of Williams & Evans (2015). Other studies of the Milky Way cumulative mass distribution with error bars are plotted: K12 (Kafle et al. 2012), D12 (Deason et al. 2012), G14, W99 (Wilkinson & Evans 1999), X08 (Xue et al. 2008), G10 (Gnedin et al. 2010), and W10 (Watkins et al. 2010). To clearly distinguish our result from the results of D12, G10, and W99 at 50 kpc, we slightly move the positions (r) of D12, G10, and W99.

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ORCID iDs

Iminhaji Ablimit @ https://orcid.org/0000-0001-7003-4220
Gang Zhao @ https://orcid.org/0000-0002-8980-945X
