Galactic mass and anisotropy profile with halo K-giant and blue horizontal branch stars from LAMOST/SDSS and Gaia

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Abstract. A major uncertainty in the determination of the mass profile of the Milky Way using stellar kinematics in the halo is the poorly determined anisotropy parameter, \( \beta = 1 - (\sigma_r^2 + \sigma_\theta^2)/(2\sigma_r^2) \), where \( \sigma_r \) is the Galactocentric radial velocity dispersion, and \( \sigma_\theta \) and \( \sigma_\phi \) are the tangential components of the velocity dispersion. We have used a sample of over 24,000 Galactic halo K giant and blue horizontal branch stars from the LAMOST stellar spectroscopic survey and SDSS/SEGUE, combined with proper motions from Gaia Data Release 2, to measure \( \beta(r_{gc}) \) over a wide range of Galactocentric distances from 5 to 80 kpc. Kinematic substructures have been carefully removed to reveal the underlying diffuse stellar halo prior to measuring \( \beta \). We find that orbits are generally radial (\( \beta > 0 \)) and \( \beta \) is constant out to distances of about 40 kpc, with a dependence on metallicity of the stars, such that \( \beta \) declines with lower metallicity. Similar behavior is seen in both the K giant and BHB samples.

Keywords. galaxies: individual (Milky Way) — Galaxy: halo — Galaxy: kinematics and dynamics — Galaxy: stellar content — stars: individual (BHB) — stars: individual (K giants) — stars: kinematics and dynamics

1. Introduction

Our current knowledge of the Milky Way’s total mass is uncertain by a factor of two (see related discussions, e.g. Wang et al. 2015; Eadie & Harris 2016; Eadie & Jurić 2019; Callingham et al. 2019). Via the Jeans equation the mass can be estimated from the density and anisotropy \( \beta \) profile of tracer objects. Measurements of the \( \beta \) profile have eluded our grasp before Gaia due to the lack of large samples of halo stars covering a wide range of distances with both radial velocities and proper motions. We describe here a very large sample of such stars which is part of an ongoing program using LAMOST.
2. Data Sample and Method

We select halo stars from samples of K-giants in LAMOST DR5 (Wu et al. 2011; Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012; Luo et al. 2012; Wu et al. 2014; Luo et al. 2015) and SDSS/SEGUE (Yanny et al. 2009; Ahn et al. 2012) and BHBs from SDSS. We define K giants from LAMOST by $4000 < T_{\text{eff}}/K < 4600$ with $\log g < 3.5$ dex and $4600 < T_{\text{eff}}/K < 5600$ with $\log g < 4$ dex (Liu et al. 2014; Bird et al. 2019). We include K giants from SDSS/SEGUE as selected by Xue et al. (2014). We derive spectroscopic distances using the method presented by Xue et al. (2014). We use the Xue et al. (2011) BHB sample which selects stars based on limits in their color and Balmer line profiles. The distances are photometrically derived as in Xue et al. (2011) and have typical uncertainties of $\sim 10\%$. The large surveys LAMOST and SDSS provide line-of-sight velocities. To these we add proper motions from Gaia DR2 (Gaia Collaboration et al. 2018).

We define Galactocentric spherical coordinates as in Bird et al. (2019). To clean our sample of disk stars, we keep only those with $|Z| > 5$ kpc (all metallicities) and to this add stars with $2 < |Z| < 5$ kpc and $[\text{Fe/H}] < -1$. In total, our stellar halo sample consists of $>15,000$ LAMOST DR5 K giants, $>5,000$ SDSS K giants, and $>4,000$ SDSS BHBs.

3. Results and Discussion

We show the spherical coordinate velocities of our LAMOST halo K-giants in Figure 1. The corresponding results for BHBs will be presented in Bird et al. (2020, in preparation).

The resulting anisotropy profiles and their dependency on metallicity are shown in Figure 2. The key results are

- LAMOST/SDSS + Gaia DR2 yield over 24,000 halo K-giant and BHB stars
- first presentation of 3D velocity profiles for such a large and spatially far-reaching halo star sample
- $\beta$ profile is found to be constant out to distances exceeding $r_{\text{gc}} = 40$ kpc where $\beta \sim 0.4$ to 0.8 depending on the stellar metallicity
- orbits are thus predominantly radial ($\beta > 0$)
- K giants and BHBs both share similar radially dominated stellar orbits and $\beta$ dependence on $[\text{Fe/H}]$.

Our results are in agreement with the recent analyses of Belokurov et al. (2018) and Lancaster et al. (2019) who also use 3D velocities for main sequence and BHB, respectively, halo stars, as seen in Figure 2.

The metallicity dependency of velocity anisotropy $\beta$ has also been seen in observations within 10 kpc by e.g. Chiba & Beers (2000), Carollo et al. (2007, 2010), Hattori et al. (2013), Kafle et al. (2013, 2017), Belokurov et al. (2018), and Lancaster et al. (2019). Simulation studies show that such a feature is likely to be related to the Milky Way’s merger history (e.g. Brook et al. 2003; Amorisco 2017; Loebman et al. 2018; Amorisco 2019; Fattahi et al. 2019).

Fresh evidence of chemo-dynamically different stellar halo components has emerged in combination with Gaia data (e.g. Belokurov et al. 2018; Deason et al. 2018; Koppelman et al. 2018; Helmi et al. 2018; Myeong et al. 2018a,b,c,d, 2019; Bird et al. 2019; Kruĳssen et al. 2019; Lancaster et al. 2019; Mackereth et al. 2019; Matsuno et al. 2019; Simion et al. 2019; Vasiliev 2019), revealing a major contributor to the Milky Way’s
Galactic mass and anisotropy profile

Figure 1. Spherical velocities, \( (V_r, V_\theta, V_\phi) \) in the upper, middle, and lower rows, shown versus Galactocentric distance \( r_{gc} \) for our entire LAMOST halo K giant sample, substructure only sample, and smooth, diffuse halo displayed in the left, middle, and right columns, respectively.

Figure 2. Anisotropy \( \beta(r_{gc}) \) profiles emphasizing the dependency on metallicity for halo K giants, BHBs, and main sequence stars.

dependency of anisotropy and metallicity is likely the recently uncovered large merger remnant, which goes by such names as “Gaia Sausage,” “Gaia-Enceladus,” “Kracken,” and “blob.” Our sample of stars extending to greater distances shows a continuation of the anisotropy-metallicity dependency extending out to 40 kpc.
We are currently working to measure the mass profile of the Milky Way to 80 kpc making use of our greatly improved knowledge of $\beta$ as revealed by this large sample of halo tracers.

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