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

Sarah A. Bird[1], Xiang-Xiang Xue[1], Chao Liu[1], Juntai Shen[2,3,4] Chris Flynn[5] and Chengqun Yang[1,4]

[1]Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Beijing 100012, China
emails: sarahbird@nao.cas.cn, xuexx@nao.cas.cn, liuchao@nao.cas.cn

[2]Department of Astronomy, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
email: jtshen@sjtu.edu.cn

[3]Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China

[4]College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, China

[5]Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Post Office Box 218, Hawthorn, VIC 3122, Australia
email: cflynn@swin.edu.au

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, $\beta = 1 - (\sigma_\theta^2 + \sigma_\phi^2)/(2\sigma_r^2)$, where σ_r is the Galactocentric radial velocity dispersion, and σ_θ and σ_ϕ 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 $\beta(r_{\rm gc})$ over a wide range of Galactocentric distances $r_{\rm gc}$ from 5 to 80 kpc. Kinematic substructures have been carefully removed to reveal the underlying diffuse stellar halo prior to measuring β. We find that orbits are generally radial ($\beta > 0$) and β is constant out to distances of about 40 kpc, with a dependence on metallicity of the stars, such that β 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 β profile of tracer objects. Measurements of the β 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 $4000 < T_{\rm eff}/{\rm K} < 4600$ with $\log g < 3.5$ dex and $4600 < T_{\rm eff}/{\rm K} < 5600$ 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 $[{\rm Fe/H}] < -1$. In total, our stellar halo sample consists of >15,000 LAMOST DR5 K giants, >5,000 SDSS K giants, and >4,000 SDSS BHBs.

We use the method of Xue *et al.* (2020, in preparation) to remove kinematic substructure. Substructure is identified in integral-of-motion space E, L_X, L_Y, L_Z using a friends-of-friends algorithm. We determine orbital parameters $e, a, (l_{\rm orbit}, b_{orbit}), l_{\rm apo}$. Stream-members share similar orbits. We flag these as substructure and remove them to define a smooth, diffuse halo sample. The sample is further cleaned keeping only stars of $E < 0$ (km s^{-1})^2. Our smooth halo sample consists of 15,280 K giants and 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
- **β profile is found to be constant** out to distances exceeding $r_{\rm gc} = 40$ 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 **β dependence on [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 β 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

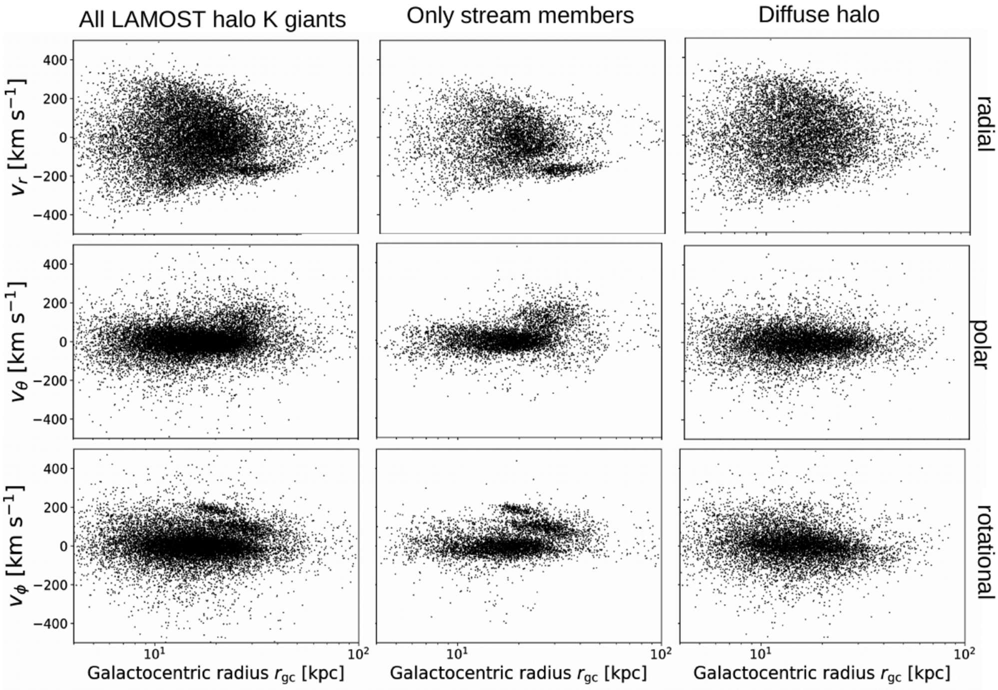

Figure 1. Spherical velocities, (V_r, V_θ, V_ϕ) in the upper, middle, and lower rows, shown versus Galactocentric distance r_{gc} for our entire LAMOST halo K giant sample, substructure only sample, and smooth, diffuse halo displayed in the left, middle, and right columns, respectively.

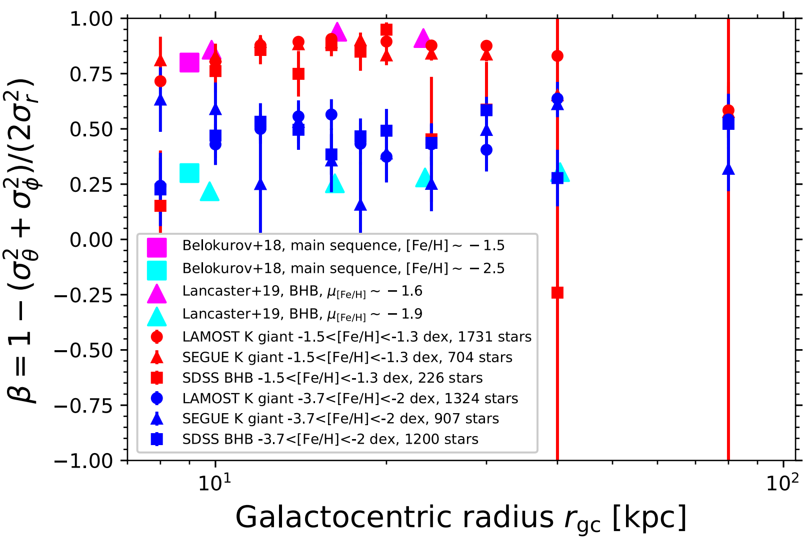

Figure 2. Anisotropy $\beta(r_{gc})$ profiles emphasizing the dependency on metallicity for halo K giants, BHBs, and main sequence stars.

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.

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We are currently working to measure the mass profile of the Milky Way to 80 kpc making use of our greatly improved knowledge of β as revealed by this large sample of halo tracers.

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