Fading Features Found in the Kinematics of the Far-Reaching Milky Way Stellar Halo

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\begin{abstract}
We test the long-term kinematical stability of a Galactic stellar halo model, due to Kafle et al. (2012), who study the kinematics of approximately 5000 blue horizontal branch (BHB) stars in the Sloan Digital Sky Survey (SDSS). The velocity dispersion $\sigma$ and anisotropy parameter $\beta$ of the stars have been determined as functions of Galactocentric radius, over the range $6 < \text{R}_{\odot} < 25$ kpc, and show a strong dip in the anisotropy profile at $\text{R}_{\odot} \sim 17$ kpc. By directly integrating orbits of particles in a 3-D model of the Galactic potential with these characteristics, we show that the $\sigma$ and $\beta$ profiles quickly evolve on a time scale of a few \texttimes{} 10 Myr whereas the density $\rho$ profile remains largely unaffected. We suggest that the feature is therefore transient. The origin of such features in the Galactic halo remains unclear.

\textbf{Key words:} galaxies: individual: Milky Way – Galaxy: halo – Galaxy: kinematics and dynamics – stars: horizontal branch – stars: kinematics and dynamics.
\end{abstract}

1 INTRODUCTION

Studying the Milky Way’s stellar halo is an important route to understanding galaxy formation, as the halo is such an old Galactic component. Intrinsically bright stars with easily measured radial velocities have been the usual means of doing so, with red giants and horizontal branch stars as typical tracers in such studies. Early studies of the stellar halo kinematics date to the 1950s, and focused on halo stars passing through the Solar neighbourhood, but it was not until the 1980s that large ($\gtrsim 100$) samples of halo stars tens of kpc from the Sun began to be collected and analysed (see the reviews by Sandage (1986) and Helmi (2008)).

Milky Way halo BHB stars from $\sim 5$ to 50 kpc have been studied by Sommer-Larsen, Flynn & Christensen (1994). They used about 100 stars to develop a kinematical model of the outer Milky Way halo, with the surprising result that the orbits of stars in the far outer halo ($> 20$ kpc) appear to be much more tangential than radial. Flynn, Sommer-Larsen & Christensen (1996) used simulations of such stars orbiting in the Milky Way potential which showed such a distribution of halo orbits is stable over a Hubble time.

Since then, numerous studies have added to the sample of BHB halo stars (Sommer-Larsen et al. 1997; Sirko et al. 2004; Deason, Belokurov & Evans 2011; Deason et al. 2012) to have very “cold” kinematics – low velocity dispersions of $\approx 50$ – $60$ km s$^{-1}$ in the radial range 100 to 150 kpc. The density falloff in these regions is much steeper than $\propto 1/R$ (e.g. Sandage 1986; Helmi 2008).

Very distant BHB stars have recently been shown by Deason, Belokurov & Evans (2011) and Deason et al. (2012) to have very “cold” kinematics – low velocity dispersions of $\approx 50$ – $60$ km s$^{-1}$ in the radial range 100 to 150 kpc. The density falloff in these regions is much steeper than $\propto 1/R$ (e.g. Sandage 1986; Helmi 2008).

On the other hand, Sirko et al. (2004) have advocated an isothermal outer halo ($\text{R}_{GC} \gtrsim \text{R}_{\odot}$), in which all three components of the velocity dispersion are $\approx 100$ km s$^{-1}$, based on $\approx 1200$ BHB stars from SDSS. Thom et al. (2003) subsequently analysed 530 BHB stars with radial velocities and distances from the Hamburg/ESO survey, finding it difficult to discriminate between the simplest, isothermal kinematic models and anything more complex, and advocating further studies of the inner halo to help resolve the issue.

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than inside 100 kpc, and the dynamical times rather long, so the region is unlikely to be well mixed. Comparison with the kinematical models of the inner region, which implicitly assume the halo is well mixed, are thus difficult.

More recently, Kafle et al. (2012) have used ≈ 5000 BHB halo stars found in the SDSS/Sloan Extension for Galactic Understanding and Exploration (SEGUE) to analyse the kinematics of the Galactic stellar halo. Working from photometric distance estimates and radial velocity measurements for each star, they performed a maximum likelihood analysis to determine the velocity dispersion $\sigma$ and anisotropy $\beta$ profile, where $\beta$ is defined by Binney & Tremaine (2008) in spherical coordinates using radial $\sigma_r$ and tangential $(\sigma_\theta, \sigma_\phi)$ velocity dispersions such that

$$\beta = 1 - \frac{\sigma^2_\theta + \sigma^2_\phi}{2\sigma^2_r}. \quad (1)$$

Kafle et al. (2012) found a previously unseen feature, most prominent in the $\beta$ profile measured out to a Galactocentric radius of $R_{GC} \approx 25$ kpc, which shows a rapid decline at $R_{GC} = 13$ kpc, reaching a minimum at $R_{GC} = 17$ kpc, followed by a sharp rise within just a few kpc (Fig. 1). This feature has been confirmed in a very recent study of the halo with an even larger sample of stars by King et al. (2015).

Given that the feature is so narrow and deep, but is made up of stars in an otherwise “hot” (i.e. high velocity dispersion) Galactic halo, we were motivated by the question of whether such a feature could be long-term stable or simply transient.

We have tested this by setting up simulations of the stars in the Milky Way potential, and determined the model’s stability over the order of a Hubble time, finding that it is transient, and dissolves away in just a few tens of Myr.

In Sec. 2 we describe our choice of potential to use for our simulations (Flynn, Sommer-Larsen & Christensen (1996)), updating it to be consistent with the remarkable new constraints on the Galactic potential by Bovy & Rix (2013). In Sec. 3 we describe our simulations testing stability over time of the stellar halo density distribution $\rho$, the velocity dispersion $\sigma$, and anisotropy $\beta$ profiles, motivated as such by the analysis of Kafle et al. (2012). We discuss our results and draw conclusions in Sec. 4.

### 2 GALACTIC POTENTIAL MODEL

We used a Milky Way potential model similar to that of Flynn, Sommer-Larsen & Christensen (1996). The potential consisted of the sum of three components, namely the the potential due to the dark halo, a central component, and the disc. The dark halo potential was spherical with mass of order $10^{12}M_\odot$ within 100 kpc. The central potential was modeled by the sum of a spherical bulge/stellar-halo and a spherical inner core potential. The disc potential itself consisted of three Miyamoto-Nagai potentials (Miyamoto & Nagai 1973). In this model, the disc has a scalelength of $R_D = 2.2$ kpc, to be consistent with the measurements of Bovy & Rix (2013) from the kinematics of over 16,000 G-type dwarfs in the SDSS/SEGUE survey distributed between Galactocentric radii of $5 < R_{GC}/kpc < 12$.

Our Galactic potential model parameters are listed in Table 1.

![Figure 1. Anisotropy $\beta$ profile as a function of Galactocentric radius, $R_{GC}$, showing $\beta$ as calculated from the input Kafle et al. (2012) radial and tangential velocity dispersions, $\sigma_r$ and $\sigma_t$.](image)

| Component                      | Parameter | Value | Unit  |
|-------------------------------|-----------|-------|-------|
| Dark Halo                     | $r_H$     | 15.0  | kpc   |
|                               | $V_{HI}$  | $\sim 10^{12}$ | $M_\odot$ |
|                               | $M(R_{GC} \leq 100 \text{ kpc})$ | $220$ | km s$^{-1}$ |
| Bulge/Stellar Halo            | $r_{C1}$  | 2.70  | kpc   |
|                               | $M_{C1}$  | 3.0   | $10^6 M_\odot$ |
| Central Comp.                 | $r_{C2}$  | 0.42  | kpc   |
|                               | $M_{C2}$  | 16    | $10^5 M_\odot$ |
| Disc                          | $b$       | 0.3   | kpc   |
|                               | $r_{D1}$  | 5.81  | kpc   |
|                               | $M_{D1}$  | 106   | $10^7 M_\odot$ |
|                               | $r_{D2}$  | 17.43 | kpc   |
|                               | $M_{D2}$  | -45.8 | $10^7 M_\odot$ |
|                               | $M_{D3}$  | 34.86 | kpc   |
|                               | $M_{D4}$  | 5.24  | $10^5 M_\odot$ |

The parameters have been set such that the rotation curve, i.e. circular velocity as a function of Galactocentric radius, is flat out to $R_{GC} = 500 \text{ kpc}$ – i.e. the outer limit of our modeled halo (although we only analyse the stars within 100 kpc). We adopted the same parameters used by Kafle et al. (2012), namely the Galactocentric position of the Sun at $R_\odot = 8.5$ kpc and the velocity of the local standard of rest as $v_{LSR} = 220$ km s$^{-1}$.

### 3 NUMERICAL METHODS AND SIMULATIONS

We tested for stability over time of the Galactic stellar halo density distribution $\rho$, velocity dispersion $\sigma$, and anisotropy $\beta$ profiles, setting them up to initially match the observations of Kafle et al. (2012). We ran simulations for 10 Gyr using $2.24 \times 10^5$ particles in the Milky Way potential model, and determined the stability over the order of a Hubble time, finding that it is transient, and dissolves away in just a few tens of Myr.
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Recently found drop in stellar density as it would have negligible effects on the stability of the system at much smaller radii near 17 kpc.

The initial velocity dispersions profiles are shown in the upper panel of Fig. 4. Our simulations are of tracer stars in a fixed Galactic potential and the stars did not interact. The stellar orbits were integrated using a Runge-Kutta scheme control (Press, Flannery & Teukolsky 1986) with a 0.01 Gyr (adaptive) stepsize over a period of 10 Gyr, and the density $\rho$, velocity dispersion $\sigma$, and anisotropy $\beta$ profiles of the particles as functions of $R_{\text{GC}}$ were determined at 2 Gyr intervals. We found that the $\rho$ profile was stable over the 10 Gyr simulation, as seen in Fig. 2 when comparing the negligible changes between the initial (red crosses) and final (blue circles) profiles. Unlike the stable $\rho$ profile, the initial $Kafle$ et al. (2012) $\sigma$ profiles as seen in the top panel of Fig. 3 quickly relaxed to a new state, appearing in the lower panel of Fig. 3 which was stable over the remaining simulation time. Fig. 3 shows that the initial profile was quickly changed within the first 0.02 Gyr (top right panel of Fig. 3). By 0.1 Gyr (lower right panel of Fig. 3), relaxation had occurred and the new $\sigma$ profiles were stable over the remaining 8 Gyr. Similarly, the initial feature in $\beta$ disappeared and the profile remained stable during the rest of the simulation. In addition, we tested variations in the initial conditions which were consistent with the boundaries set by the error bars of the $Kafle$ et al. (2012) determinations of sigma versus $R_{\text{GC}}$. In each test, the results remained similar, showing the outcome is not dependent on one unique choice of initial conditions. We experimented by initially exaggerating the feature to see if the stars would settle upon the actual model. We began the simulation with a larger dip in the $\sigma_t$ profile, starting at a value of 50 km s$^{-1}$ within the first 10 kpc instead of 90 km s$^{-1}$. All other conditions remained the same as our previous simulations. We found that the $\sigma$ profiles flattened and the anomalous feature dissolved away. We ran the simulations with the same conditions as previously described, but with a model potential with a perfectly flat rotation curve, very similar to the one determined in $Kafle$ et al. (2012). The results were the same as the other tests. Thus we concluded the Milky Way’s $\sigma$ and $\beta$ profiles are in a transient phase, and the observed features at 17 kpc will smooth away within a few ten million years.

4 SUMMARY AND CONCLUSIONS

We tested the kinematic model of the Galactic halo proposed by $Kafle$ et al. (2012), by directly integrating particles in the $Flynn$, Sommers-Larsen & Christensen (1996) 3-D model of the Galactic potential, under the assumption of an initial Gaussian velocity distribution. We found that the particles relaxed quite quickly from the initial profiles observed by $Kafle$ et al. (2012). The features at 17 kpc, most prominently seen in the anisotropy $\beta$ profile as the steep decline reaching minimum at $R_{\text{GC}} = 17$ kpc and the sharp rise within a few kpc, dissolved after 0.02 Gyr. We propose that this feature in the Milky Way’s velocity dispersion $\sigma$ and anisotropy $\beta$ profiles is in a transient phase, and will flatten within a few ten million years.

Observational studies have shown that stellar inhomogeneities as described in Sec. 2. The stellar velocities were initially! randomly drawn from Gaussian distributions and set up in a spherical non-rotating configuration. The density profile (Fig. 2) followed the double power law assumed by $Kafle$ et al. (2012), as observed by Watkins et al. (2009) and Deason, Belokurov & Evans (2011) where $\rho \propto R_{\text{GC}}^{-\alpha}$ with $\alpha = 2.4$ at $R_{\text{GC}} \leq 27$ kpc and $\alpha = 4.5$ at $R_{\text{GC}} > 27$ kpc (red crosses with red fit line). The profile is plotted at 0 and 10 Gyr (blue circles), showing the stability of $\alpha$ as we see negligible change between the initial and final states. The break radius at which the two power laws meet is $R_{\text{GC}} \approx 27$ kpc, or log($R_{\text{GC}}$) $\approx 1.43$ kpc.

![Figure 2](image1.png)

**Figure 2.** Radial density $\rho$ profile of simulated halo stars. The initial density at 0 Gyr is the broken power law assumed by $Kafle$ et al. (2012) (as observed by Watkins et al. (2009) and Deason, Belokurov & Evans (2011), where $\rho \propto R_{\text{GC}}^{-\alpha}$ and $\alpha = 2.4$ at $R_{\text{GC}} \leq 27$ kpc and $\alpha = 4.5$ at $R_{\text{GC}} > 27$ kpc (red crosses with red fit line). The profile is plotted at 0 and 10 Gyr (blue circles), showing the stability of $\alpha$ as we see negligible change between the initial and final states. The break radius at which the two power laws meet is $R_{\text{GC}} \approx 27$ kpc, or log($R_{\text{GC}}$) $\approx 1.43$ kpc.

![Figure 3](image2.png)

**Figure 3.** Upper panel displays the initial velocity dispersion $\sigma$ profile from $Kafle$ et al. (2012). Radial and tangential velocity dispersions, $\sigma_r$ (blue crosses) and $\sigma_t$ (red asterisks) (km s$^{-1}$), respectively, are plotted as a function of distance from the galactic centre, $R_{\text{GC}}$ (kpc). The lower panel shows the $\sigma$ profiles after 2 Gyr. The initial turnover features at $R_{\text{GC}} \approx 17$ kpc in the model halo disappear within 0.02 Gyr and the new $\sigma$ profiles remain stable in the simulations.
Figure 4. Similar to Fig. 3 but shown over the first 0.1 Gyr in the simulation. Radial and tangential velocity dispersions, $\sigma_r$ (blue crosses) and $\sigma_t$ (red asterisks) (km s$^{-1}$), are plotted as a function of distance from the Galactic centre, $R_{GC}$ (kpc). The $\sigma$ profiles are plotted every 0.02 Gyr as indicated in the top left corner of each panel. The model input $\sigma$ profiles, as observed by Kafle et al. (2012), are plotted in each panel as the orange line ($\sigma_r$) and the green dashed line ($\sigma_t$). The $\sigma_r$ and $\sigma_t$ profiles change within the first 0.02 Gyr (top right panel). After 0.1 Gyr, the profiles have relaxed (lower right panel) and change negligibly over the remainder of the simulation.
In order to find what causes the features in the Galactic kinematic profiles as interpreted by Kafle et al. (2012), we plan to set up a complete library of dynamically stable halos in the adopted Milky Way potential. The library will be particularly useful to compare with the large amounts of new data anticipated from surveys such as Gaia and LAMOST.

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