Abstract. I review the properties of the Galaxy’s stellar halo, specifically as traced by horizontal branch stars, but with reference to and in comparison with other stellar tracers. I discuss the halo density profile, the variation in horizontal branch morphology with Galactic position, and the kinematics of halo stars in several regions of the Galaxy. I summarize the horizontal branch star findings and place them in the context of a currently popular picture of Galactic halo formation.

1. Introduction

The surviving ancient stars of the Galactic stellar halo (hereafter, “halo”) contain information on the locations, motions, and compositions of the proto-Galactic gas clouds in which they formed. These stars therefore represent our best means of understanding the processes occurring during the formation and early evolution of our Galaxy. They also provide an important consistency check on studies of spiral galaxy formation at high redshift and QSO absorption line systems.

The most visible component of the halo is the globular cluster system (see Harris, this volume). However, the globulars represent only a few percent of the mass of the halo, and are subject to tidal disruption. Therefore, it is not clear whether they provide a truly representative picture of the halo. Furthermore, only \( \sim 150 \) clusters exist, so any statistical arguments based on them have an intrinsic signal-to-noise limit.

Field stars in the halo provide orders of magnitude more objects to study, and are “indestructible” entities. However, it is more difficult to determine distances, metallicities, and ages for individual stars than for clusters of stars.

My goal in this paper is to highlight some of the constraints which halo stars place on our understanding of the formation of the Galactic halo. I discuss specifically horizontal branch (HB) stars, but will link these specific findings with more general ones based on other stellar tracers of the halo.

HB stars are sub-solar mass stars in the helium core burning phase of evolution. Current evolution theory indicates they formed when the universe was <30% of its present age. The HB derives its name from the sequence of stars seen at \( M_V \approx +0.6 \) in the color-magnitude diagrams of globular clusters. HB

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stars with $0.2 < (B - V)_0 < 0.4$ are unstable to radial pulsations, and vary with $V$-band amplitudes of 0.3–1.5 mag and periods of 0.2–0.8 days. They are called RR Lyrae variables (RRL), whereas the stable HB stars redward and blueward of the instability strip are referred to as red and blue HB stars, respectively.

Unfortunately, existing survey techniques limit the range of HB star colors available for study. The red HB stars ($(B - V)_0 > 0.4$) are especially difficult to extract from the overwhelming numbers of disk F- and K-type stars per unit area of the sky. Likewise, for $(B - V)_0 < 0.0$, it becomes difficult to differentiate efficiently between blue HB stars and main sequence A- and B-type stars in the disk. Only for $0.0 < (B - V)_0 < 0.2$ can blue HB stars be separated efficiently on the basis of their lower surface gravities. I will hereafter refer to these stars as BHB stars. RRL are usually detected in variable star surveys by their characteristic light curves. Thus, our knowledge of the halo field HB star population is derived from stars spanning $0.0 < (B - V)_0 < 0.4$ mag, only about half the color extent of the full HB.

2. Structure of the Galactic Halo

Preston, Shectman & Beers (1991, PSB) provide the most extensive look at the distribution of HB stars in the halo. Their Figure 22 shows the distribution of stars, both BHB and RRL, from several deep surveys. The range of coverage of the Galactic halo enables a detailed investigation of the density structure of the halo out to a Galactocentric distance of $R_{GC} \approx 50$ kpc.

Figure 1a shows the density of stars as a function of $R_{GC}$. The PSB BHB stars are shown as crosses. RRL stars come from several sources: the PSB compilation is shown as solid squares, the survey of Hawkins (1984) is shown by stars, the "transit" survey of Wetterer & McGraw (1996) is shown by open squares, and the local ($d < 2$ kpc) counts from Layden (1995) are shown by a triangle. The least-squares fit to the RRL data is shown by the solid line $[\log \rho = 3.00 - 2.80 \log R_{GC}]$, while the fit to the BHB stars is from PSB (slope $= -3.31$).

Following the work of Kinman (1965), PSB show that the sequence of points for a particular field which passes through the inner halo indicates that the
isodensity contours in this region must be flattened towards the plane. The connected set of points in Figure 1a shows that the points nearest the Sun (and hence the Galactic plane; upper end of “hook”) are overdense compared to more distant points (farther from the plane).

To correct this, PSB adopt a density model in which the ellipsoid axis ratio \(c/a\) decreases from a central value of 0.5 to 1.0 (spherical) at 20 kpc. Figure 1b shows this model applied to the data from Figure 1a. The “hook” has now collapsed on itself, and the scatter about the best fit is reduced, indicating that this model more accurately fits the density distribution of halo HB stars than a simple spherical distribution. The least-squares fit to the RRL data in Figure 1b is \[\log \rho = 3.72 - 3.33 \log a\], where \(a\) is the semi-major axis of the ellipsoidal isodensity contours. The fit to the BHB stars from PSB has a slope of –3.57.

It is impressive that a simple model can fit so nicely the run of HB star densities over 50 kpc in \(R_{GC}\) and a factor of 10^6 in density. Furthermore, the lack of a density enhancement inside \(R_{GC} \approx 2\) kpc supports the claim by Minniti (1996) that the RR Lyrae stars in this region belong to the inner halo, not the bulge. The Figure 1 results are in general agreement with the halo density distribution as traced by the globular clusters \(\rho \propto R^{-3.5}\), Zinn (1985).

It should also be noted that in their study of HB star densities, Kinman et al. (1994) interpreted data similar to that shown in Figure 1 as evidence for a two-component halo; a spherical component which dominates at large distances from the Galactic plane, and a flattened component which dominates near the Sun. The density resolution of the available surveys is not sufficient to distinguish clearly between these two possibilities. Clearly, additional RRL density studies of the inner halo are needed to confirm the presence of the “hook” and to establish and quantify the nature of the density variations.

3. Horizontal Branch Morphology

The HB morphology (color distribution of stars along the HB) of a stellar population at a given abundance tends to be bluer for older populations, and redder for younger ones. Estimates of the HB morphology of the halo field at different positions in the Galaxy can thus give insights into the relative epochs and durations of halo star formation in these regions. However, exact knowledge is hampered by (1) the possible influence of additional parameters (e.g., He abundance, stellar rotation, etc.; see Lee et al. 1994) on HB morphology, and (2) the limited color range over which the HB can be sampled (see Sec. 1).

Figure 1 provides a hint that the field HB morphology may change as a function of position in the Galaxy. The fits to the BHB stars have a steeper slope than for the RRL stars (albeit with large uncertainty), suggesting that the inner halo has a higher relative density of BHB stars, i.e. a bluer HB morphology.

In a more intensive study of HB stars in several of these fields, Kinman et al. (1994) found that the number ratio of BHB to RRL stars was >1 near the Galactic plane, but ≈1 at distances >5 kpc from the plane. Since the metallicity in the two regions was the same, they suggested that the bluer HB morphology of the flattened component of their two-component halo indicated that it was older than the spherical component.
However, the relative counting incompleteness between the BHB and RRL surveys in these fields clouds the issue. Using BHB stars alone, PSB showed that the color distribution of BHB stars in their narrow color window shifts dramatically with direction in the Galaxy (see their Fig. 1). Toward the inner Galaxy (angles \( A = 10–45^\circ \) from the Galactic center), the color distribution is strongly peaked to the blue side of the BHB color window, while at \( 45 < A < 90^\circ \) and \( A > 90^\circ \) the distribution becomes progressively redder and broader. The \([\text{Fe}/\text{H}]\) gradient in the halo is small, and in the sense of lower \([\text{Fe}/\text{H}]\) at larger \( R_{GC} \) (e.g., Zinn 1985). The expected change in HB morphology due to this gradient would be for bluer HBs at larger \( R_{GC} \), the opposite of what is observed. If age is indeed the dominant “second parameter” controlling HB morphology (e.g., Chaboyer et al. 1996), the inner halo must be older than the outer halo to overcome the effects of the \([\text{Fe}/\text{H}]\) gradient. Calibrating their color shift with observed globular cluster ages and horizontal branch theory, PBS estimated that the age of the halo decreases outward by \(~2\) Gyr over the \( 2 < R_{GC} < 12 \) kpc range of their observations. They also suggested that the broader color range in the outer halo may indicate that it formed over a more extended period than the inner halo.

Suntzeff et al. (1991) interpreted similar data, concerning the \([\text{Fe}/\text{H}]\) distribution of halo RRL stars with \( R_{GC} \), as evidence that the inner regions of the galaxy are older than the outer regions.

4. Kinematics

4.1. Local HB Stars

The kinematic properties of HB stars within several kpc of the Sun have recently been the topic of several studies involving large numbers of stars, and are correspondingly well-determined. The RRL sample of Layden (1995) contains 130 stars with \([\text{Fe}/\text{H}] < -1.3\) (the low metallicity cut isolates the halo from contaminating thick disk stars). Figure 2a shows the Frenk & White (1980) analysis of this data (i.e., based on radial velocities alone; the slope of the least-squares fit in this plane gives the net rotation of the population about the Galactic center, \( V_{\text{rot}} \), and the dispersion around the fit gives the line-of-sight velocity dispersion, \( \sigma_{\text{los}} \)). Layden obtained \( V_{\text{rot}} = 18 \pm 13 \) km s\(^{-1}\) and \( \sigma_{\text{los}} = 116 \pm 7 \) km s\(^{-1}\).

Meanwhile, Wilhelm et al. (1996) recently reported progress on a large sample of BHB stars, a subset of which defines the kinematics of the local BHB population. Their Figure 2 shows the Frenk & White (1980) analysis of their data. They obtained \( V_{\text{rot}} = 40 \pm 17 \) km s\(^{-1}\) and \( \sigma_{\text{los}} = 103 \pm 5 \) km s\(^{-1}\) for 199 BHB stars with \([\text{Fe}/\text{H}] < -1.6\) (their data indicated an even lower metallicity cut to isolate the halo) and \(|Z| < 4\) kpc from the Galactic plane.

Both samples show the slow prograde rotation and large velocity dispersion typical of the halo, as traced by globular clusters (Armandroff 1989), field subdwarfs (Ryan & Norris 1991, Carney et al. 1996), and field red giants (Morrison 1990). Thus the local HB star kinematics are in good agreement with other tracers of the stellar halo.

Velocity dispersions in the three cardinal Galactic directions have been determined for the RRL sample using proper motions and radial velocities to get the space motions of each star (Layden 1995): \((\sigma_{\rho}, \sigma_{\phi}, \sigma_z) = (166 \pm 14, 109 \pm\)
9.95 ± 5) km s\(^{-1}\). Again, these agree well with the velocity ellipsoids of other halo tracer stars.

The variation of kinematics with abundance in the halo has long been used as a diagnostic of the processes which formed the halo. Eggen et al. (1962) described a formation scenario in which kinematics were correlated with abundance, i.e., chemical enrichment took place concurrently with the dynamical transition from spherical halo to flattened disk. The other extreme was promoted by Searle & Zinn (1978), who suggested that the halo formed via the accretion of individual “fragments”. Each fragment underwent chemical evolution in isolation from the other fragments, and later reached dynamical equilibrium with the forming Galaxy. Correlations between kinematics and abundance were erased in the resulting halo.

The local HB stars provide a useful check on this point. Layden (1995) and Beers & Sommer-Larsen (1995) have divided their samples into small \([\text{Fe/H}]\) bins and computed \(V_{\text{rot}}\) and \(\sigma_{\text{los}}\) for each bin. For both RRL and BHB stars, the run of these kinematic indicators with \([\text{Fe/H}]\) appears to be flat for abundances below the suspected thick disk cut-off. Thus they support the idea that the halo stars (near the Sun) formed in proto-Galactic fragments which were later accreted by the forming Galaxy. The larger samples of field subdwarfs (e.g., Ryan & Norris 1991, Carney et al. 1996) show this effect even more clearly. Norris (1994) discusses the possibility that a kinematically cooler, dissipatively formed component might “hide” within the hot velocity dispersions of the accreted component.

### 4.2. The High Halo

The kinematic properties of stars lying at large distances from the Galactic plane have recently provided tantalizing clues about the structure and formation of the halo (e.g., Majewski 1992). Samples of HB stars in this region of the Galaxy are now becoming available for kinematic study.

Wilhelm et al. (1996) reported initial results for BHB stars with \([\text{Fe/H}] < -1.6\) and \(|Z| > 4\) kpc. Their Figure 2 shows the Frenk & White (1980) analysis for 90 such stars: \(V_{\text{rot}} = -93 \pm 36\) km s\(^{-1}\) and \(\sigma_{\text{los}} = 116 \pm 9\) km s\(^{-1}\). Preliminary results for RRL stars (Layden 1996) show a qualitatively similar,
though less extreme, result: \( V_{\text{rot}} = -27 \pm 23 \, \text{km s}^{-1} \) and \( \sigma_{\text{los}} = 116 \pm 11 \, \text{km s}^{-1} \) for 59 stars (see Figure 2b). Note that though the number of stars is smaller in the Layden work, their distribution in the \((\cos \psi, V_z)\) plane is better-suited to determining \( V_{\text{rot}} \).

In both samples, the net rotation of the halo appears to be retrograde. Though surprising, this result is in agreement with the field subdwarf work of Majewski (1992) and Carney et al. (1996). These \( V_{\text{rot}} \) values assume a local circular velocity of \( V_{\text{LSR}} = 220 \, \text{km s}^{-1} \). If \( V_{\text{LSR}} = 250 \, \text{km s}^{-1} \), the RRL rotation becomes approximately zero, though the other surveys still indicate a marginally retrograde high halo. In either case, it is clear that the rotation of the high halo is slower than that of the halo near the Sun by 50–100 km s\(^{-1}\). This is consistent with the concept of a two-component halo, one of which is flattened toward the plane and which possesses higher angular momentum. This idea will be pursued in the Conclusions section.

Another intriguing revelation concerning the high halo comes from Kinman et al. (1996), who studied the radial velocities of RRL and BHB stars far from the plane in the direction of the North Galactic Pole. They found that among a group of 24 stars in one field with \( 4 < |Z| < 11 \, \text{kpc} \), the mean radial velocity was \( -59 \pm 16 \, \text{km s}^{-1} \). In a nearby field, the 16 stars in the same distance range had a mean radial velocity of \( -34 \pm 27 \, \text{km s}^{-1} \). They interpreted this as evidence for kinematic substructure in the halo, perhaps the streaming motions associated with a long-dissolved proto-Galactic fragment of the type envisioned by Searle & Zinn (1978). Majewski et al. (1996) found very similar vertical velocities for their NGP subdwarfs, and noted kinematic clumping in the radial and tangential velocities as well. However, the velocity dispersions found by both studies are large, a quality difficult to understand in the context of long-lived star streams. Perhaps instead the flow represents a transitory “wake” induced in the stellar halo by the tidal action of the Magellanic Clouds or the Sagittarius dwarf (see M. Weinberg, this volume).

4.3. The Outer Halo

The kinematics of stars in the outer halo \((R_{\text{GC}} > 10 \, \text{kpc})\) provide further clues to the formation of the halo. Sommer-Larsen et al. (1997) present radial velocity data for 679 BHB stars in four directions within the Galaxy. They binned the stars by distance in each field and estimated the radial velocity dispersion of the stars in each bin out to mean distances of \( d \approx 20 \, \text{kpc} \).

Since the velocity ellipsoid near the Sun is radially anisotropic (Sec. 4.1), some variation in \( \sigma_{\text{los}} \) is expected as the contribution of the different Galactic velocity components \((\rho, \phi, z)\) changes with distance along each line of sight. However, at large \( d \), all the lines of sight mainly measure the Galacto-radial \((\rho)\) velocity component, and their observed values of \( \sigma_{\text{los}} = 100–110 \, \text{km s}^{-1} \) are significantly smaller than the adopted local value of \( \sigma_{\rho} = 140 \, \text{km s}^{-1} \).

To further investigate this effect, they chose a formulation for the run of \( \sigma_{\rho} \) with \( R_{\text{GC}} \) with four adjustable parameters. They used the Jeans equation to relate the tangential velocity dispersion \( \sigma_t(R_{\text{GC}}) \) to \( \sigma_{\rho}(R_{\text{GC}}) \), thus enabling the computation of \( \sigma_{\text{los}} \) as a function of distance along any line of sight. Fitting this model (via the four parameters in \( \sigma_{\rho}(R_{\text{GC}}) \)) to their BHB star data (see their Figure 2), they found that the nature of the halo velocity ellipsoid changes
dramatically outside the solar circle. The radial velocity dispersion drops and the tangential dispersion increases (see their Figure 1), reaching the asymptotic (large $d$) values of 89 and 137 km s$^{-1}$, respectively.

They note that if the halo formed through a monolithic collapse of a proto-Galactic cloud, one might expect the outer reaches to be characterized by infall, i.e., radially anisotropic motions. They suggest that their observed tangentially anisotropic velocity ellipsoid is more easily reconciled with fragment accretion pictures.

A possible complication to the arguments of Sommer-Larsen et al. (1997) is the observed velocities of RRL stars in the inner halo by Layden (1996). Though preliminary, those results suggest that the tangential velocity dispersion at $R_{GC} = 3–6$ kpc is quite large, $\sim 150$ km s$^{-1}$, in stark contrast to the low value of $\sigma_t = 95$ km s$^{-1}$ predicted by the Sommer-Larsen et al. model. It is possible that the modeler’s assumed potential field is oversimplified, especially in the flattened inner halo.

5. Conclusions

In summary, HB star observations provide the following insights into the structure and formation of the Galactic halo. (1) The RRL density distribution indicates that either the halo becomes increasingly flattened at smaller $R_{GC}$, or that a two-component halo exists with the flatter component increasingly dominant at smaller $R_{GC}$. (2) The HB morphology of the halo becomes redder, and perhaps broader, with increasing $R_{GC}$; if interpreted as an age effect, the outer halo is several Gyr younger, in the mean, than the inner halo, and may have formed over a longer period of time. (3) Evidence exists that at least a part of the halo at $R_{GC} \geq R_\odot$ formed via accretion of proto-Galactic fragments: (a) lack of a kinematics-metallicity correlation in local HB star samples, (b) slower/retrograde rotation of the high halo, (c) possible presence of star streams in the high halo, and (d) transition from radially to tangentially anisotropic velocity dispersions in the outer halo. (4) The RRL density distribution and the difference between the rotation rates of the local and high halo samples both support the notion of a two-component halo.

These HB star observations fit into the larger picture of Galactic halo formation outlined by Zinn (1993, 1996) and expanded upon by Norris (1994) and Carney et al. (1996). Specifically, two distinct halo components exist, which were created through different mechanisms. One component, variously known as the “old”, “flattened”, or “proto-disk” component, has a significant prograde rotation, a flattened spatial distribution, and a relatively blue HB morphology. It may possess a metallicity gradient, and appears to dominate at $R_{GC} \leq R_\odot$ and near the Plane. Its properties suggest formation through a fairly ordered process of collapse and spin-up, not unlike that described by Eggen et al. (1962). The other component, referred to as “younger”, “spherical”, or “accreted”, has a retrograde net rotation, a spherical spatial distribution, and shows no evidence of a metallicity gradient. Organized streaming motions may be found among the stars in this component, relics of the small galaxies that were accreted during its formation. Cluster ages and HB morphologies suggest that it formed over a period of many Gyr, and is on average several Gyr younger than the other halo.
component (e.g., Chaboyer et al. 1996). These properties are all signposts of the fragment accretion picture of Searle & Zinn (1978). These two halo components have very similar metallicity distributions, and are difficult to separate in local stellar samples. Thus, the current halo formation picture may be regarded, at least in a first approximation, as a fusion of the classical ideas of Eggen et al. (1962) and Searle & Zinn (1978).

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