Kinematics of RR Lyrae Stars in the Inner and High Halos

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Abstract.
The kinematics of old stellar populations in different regions of the Galaxy place strong constraints on pictures of galaxy formation. Three new surveys which use RR Lyrae variables to trace the old stellar populations are discussed. The first is a local sample, containing stars within $\sim$2.5 kpc of the Sun. The slow prograde rotation and moderate velocity dispersion of this sample are in good agreement with other tracers of the local halo. The second sample was chosen to lie at Galactocentric distances of 3–6 kpc, and to lie more than 2 kpc from the plane. The slow prograde rotation and very high velocity dispersion of this sample contrast strongly with the rotationally supported kinematics of the globular clusters in this region of the Galaxy. The third sample was chosen to lie more than 5 kpc from the plane, at roughly the solar circle. A slight retrograde rotation and a moderate velocity dispersion are observed. These kinematic results are compared with those of other halo tracers, and are interpreted in the context of the current scenarios of halo formation.

1. Introduction

The preceding articles in this volume underscore the importance of kinematic studies to our understanding of the formation of the halo. In particular, the work of Morrison *et al.* (1990) emphasized the importance of studying the rotational kinematics of the Galaxy. Chosing a sample of stars at a distance and direction such that the line of sight to the stars is primarily along the Galactic rotational velocity component of the stars enables us to measure, using radial velocities alone, both the stars' net rotation about the Galaxy and their line-of-sight velocity dispersion. Thus we obtain two important kinematic diagnostics, rather than the line-of-sight velocity dispersion alone that is obtained from a differently-directed sample.

At this point in time, the kinematic properties of the halo within several kpc of the Sun appear to be well known. This industry began with the work of Eggen *et al.* (1962), and culminated in a host of studies over the past decade (e.g.,

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Norris 1986, Sandage & Fouts 1987, Carney *et al.* 1990, Morrison *et al.* 1990, Ryan & Norris 1991, Layden 1995). However, the kinematics in other regions of the Galaxy have not received nearly so much attention. The rotational properties of the halo in different Galactic zones have been particularly neglected.

Several recent studies have indicated that the kinematics may vary considerably with position in the halo. One such study was the work of Zinn (1993, also see this volume), who divided the halo globular cluster sample into two groups based on the horizontal branch (HB) morphology as a function of [Fe/H]. The bluer-HB group had a faster net rotation about the Galaxy and a lower line-of-sight velocity dispersion ($V_{rot} = 70 \pm 22$ km s^{-1} and $\sigma_{los} = 89 \pm 9$ km s^{-1}, respectively) than the redder-HB group. It also had a flattened spatial distribution, and dominated the cluster distribution inside 6 kpc Galactocentric distance (R_{gc}). Zinn suggested that the bluer-HB clusters formed in a dissipative collapse, perhaps similar to that described by Eggen *et al.* (1962), while the redder-HB clusters were accreted from proto-Galactic fragments over the ensuing several Gyrs, following the picture of Searle & Zinn (1978). It would be interesting to know if the field stars participate in this two-halo system. If so, perhaps we can isolate a sample of field stars from the bluer-HB population simply by chosing a sample in the region of the Galaxy where the bluer-HB clusters dominate, i.e., $2 < R_{gc} < 6$ kpc. The vast number of field stars available, relative to the small number of globular clusters, would allow us to refine the kinematic parameters of the dissipated halo component.

A second study showing kinematic differences with position in the halo is that of Majewski (1992). He studied the proper motions of a complete sample of F and G dwarfs toward the North Galactic Pole, and found that the halo stars lying more than 5 kpc above the plane had a retrograde net rotation, $V_{rot} = -55 \pm 16$ km s^{-1}. He noted several other studies which supported his conclusion. More recently, other studies have supported these results. Beers & Sommer-Larsen (1995) used a mixture model to separate a large, literature-derived sample of solar neighborhood objects into thick disk and halo components. The net rotation of the halo group was $V_{rot} = -16 \pm 18$ km s^{-1}. Carney (1994, also this volume) showed that, among the stars in the Carney *et al.* sample which have velocities perpendicular to the plane sufficient to carry them more than 4–5 kpc from the plane, $V_{rot} = -35$ to -50 km s^{-1}. Wilhelm *et al.* (this volume) derived an even larger retrograde rotation using the blue HB stars lying > 4 kpc from the plane. However, this picture is not completely clear, as some local samples of high Z-velocity stars tend to support a prograde rotation. For example, taking stars with $|V_z| > 130$ km s^{-1} from the non-kinematically selected samples of Carney & Latham (1986), Norris (1986), and Layden (1994), we find $V_{rot} = +36 \pm 15$ km s^{-1} for 61 stars. Given our lack of knowledge concerning the mass distribution of the dark matter halo which dominates the gravitational potential far from the plane, it seems safest to study *in situ* samples of high-halo stars. In addition, testing the rotation over a large spatial extent, and using a variety of population tracers, gives us confidence that the rotational signature is a Galaxy-wide phenomenon.

2. Three New Samples

In order to study the kinematics in these interesting regions, we have devised several new samples of stars, designed to measure the rotational kinematics in the inner and high halos. We employ RR Lyrae variable stars to trace the halo populations. RR Lyraes are effective tracers because they are relatively luminous, and can therefore be traced to large distances. They also yield accurate distances, since the range of absolute magnitudes they span is small compared to the M_V range of dwarf or red giant stars. RR Lyraes also yield accurate abundances ($\sigma_{[Fe/H]} < 0.2$ dex) from low resolution spectra using the equivalent widths of the CaII K line and the Balmer lines (the "ΔS" method, Preston 1959). Finally, RR Lyraes have the advantage of being selected by their large amplitude light variations, so are not subject to the kinematic biases suffered when stars are selected from a proper motion catalog.

However, there are selection effects incurred when using RR Lyraes. RR Lyraes only form when some fraction of stars lying on the horizontal branch lie in the instability strip. If all the HB stars lie blueward or redward of the HB (typically due to an extremely metal-poor or metal-rich population, respectively), the population will produce no RR Lyraes, and will not be traced. Nevertheless, any RR Lyraes present should effectively trace the bluer and redder HB stars of the same abundance and approximate age. Furthermore, by using RR Lyraes to trace the stellar components in all three of our samples, we hope to minimize the effect of this selection bias on our conclusions.

2.1. The Local Sample

We begin with a discussion of a solar neighborhood sample of RR Lyraes. Data for the present analysis (the [Fe/H], radial velocity, and distance of each star) where taken from Layden (1994). The kinematics of this sample are described in detail in Layden (1995). There are 302 *ab*-type RR Lyraes in the sample, lying in a roughly spherical volume of radius ~2.5 kpc centered on the Sun.

We compute the kinematics of the sample using the method of Frenk & White (1980). Fig. **??** shows plots of V_s *vs.* cos ψ. V_s is the radial velocity observed from the position of the Sun by a stationary observer not participating in the Galactic rotation. ψ is the angle between the line of sight to a star and the star's rotation vector about the Galaxy. In these plots, the least squares fit provides an estimate of the systemic rotation about the Galactic center, V_{rot}, and the dispersion about this line gives σ_{los}. Clearly, stars with large absolute values of cos ψ have the highest leverage in determining V_{rot}.

Based on the analysis in Layden (1995), we have divided the local sample stars into two groups, a metal-rich group (Fig. 1a) and a metal-poor group (Fig. 1b). In Fig. 1a, we see the fast rotation and low velocity dispersion characteristic of the thick disk. The slow prograde rotation and larger velocity dispersion of the halo are seen in Fig. 1b. The derived kinematic values are listed in Table 1. These values are in excellent agreement with other tracers of the local halo (e.g., Carney & Latham 1986, Norris 1986, Morrison *et al* 1990, Norris & Ryan 1991, Armandroff 1993). Thus, we can with confidence use the local sample as a benchmark with which to compare the kinematics of the inner and high halo samples.

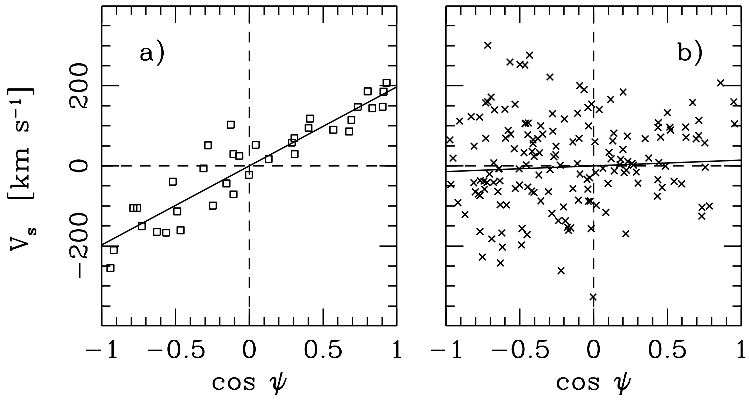

Figure 1. Kinematic solutions for the local sample. (a) stars with [Fe/H] > -1 show the fast rotation and low velocity dispersion of the thick disk. (b) stars with [Fe/H] < -1 show the slow prograde rotation and large dispersion of the halo.

2.2. The Inner Halo Sample

In selecting stars for the Inner Halo sample, we chose *ab*-type RR Lyraes from the General Catalog of Variable Stars (Kholopov 1985; GCVS4) such that their Galactic coordinates, photographic magnitudes and Burstein & Heiles (1982) reddenings would place them in the region $3 < R_{gc} < 6$ kpc, $|Z| > 2$ kpc (where Z is the distance perpendicular to the plane), and so that their values of $|\cos\,\psi|$ > 0.7.

We obtained V-band CCD photometry of the stars using the CTIO 0.9-m telescope. Light curves and intensity-mean magnitudes were derived from these data. Distances were computed using the intensity-mean magnitudes, the reddenings of Burstein & Heiles (1982), and the Carney, Storm & Jones (1992) prescription for the absolute RR Lyrae magnitude.

Spectra were obtained using the CTIO 4.0-m telescope. The 2Å spectra yielded radial velocities and equivalent widths of the CaII K line, and the Hδ and Hγ lines. The equivalent widths were used to compute [Fe/H] for each star, using the methods described in Layden (1994). Observations of standard RR Lyrae stars at the signal-to-noise of the program stars indicates that the abundances are accurate to 0.2 dex. The observed radial velocities were corrected for atmospheric pulsations using the new photometric ephemerides. Observations of the standard RR Lyraes showed that the final radial velocities were accurate to 15 km s^{-1}.

A goal of this project is to see if the inner halo RR Lyrae stars share the cooler kinematic signature exhibited by the bluer-HB clusters. It is therefore critical to eliminate all thick disk stars from the sample. Layden (1994) showed that the number of local thick disk RR Lyraes above $|Z| \approx 2$ kpc is small. Thus our $|Z| > 2$ kpc requirement will eliminate many thick disk interlopers. Layden (1995) showed that there are few "metal-weak thick-disk" RR Lyraes on $-1.3 <$ [Fe/H] < -1.0, and that they appear non-existent below [Fe/H] $=$ -1.3. Thus we expect very few indeed in our higher-Z inner halo sample. Plots of radial velocity *vs.* [Fe/H] for the local and inner halo samples show the same

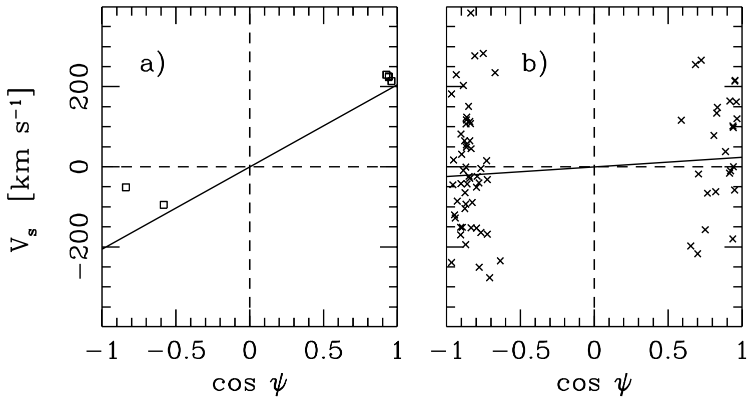

Figure 2. Kinematic solutions for the inner halo sample. (a) stars with [Fe/H] > -1.1 show the kinematic signature of the thick disk, and can be eliminated from the sample. (b) stars with [Fe/H] < -1.1 give a slow prograde rotation, like that of the local halo, and very large velocity dispersion.

pattern: a low velocity dispersion among the metal-rich stars giving way to the high velocity dispersion of the halo at lower abundances. For the inner halo, the transition occurs at [Fe/H] $= -1.1$.

In doing the Frenk & White (1980) kinematic solutions, we divided the inner halo sample at [Fe/H] $= -1.1$. Fig. ??a shows the solution for the metal-rich group. Again, we see the fast rotation and low velocity dispersion of the thick disk (see Table 1). On this basis, we can safely ignore these stars in the discussion of the inner halo. Fig. 2b presents the solution for the metal-poor group. There is only a slow prograde rotation, and the velocity dispersion is very large (see Table 1). The kinematic signature of the inner halo field RR Lyraes does not match that of the globular clusters in this region.

Table 1. RR Lyrae Kinematics.

Sample	V_{rot}	σ_{los}	N_{stars}	Comments
Local, [Fe/H] > -1	197 ± 14	46 ± 6	35	thick disk
Local, [Fe/H] < -1	14 ± 17	113 ± 6	165	halo
Inner, [Fe/H] > -1.1	205 ± 29	60 ± 18	6	thick disk
Inner, [Fe/H] < -1.1	24 ± 19	146 ± 12	78	halo
Inner, [Fe/H] < -1.1	29 ± 22	156 ± 13	70	trimmed a lá MFF
High	-27 ± 23	116 ± 11	59	all stars
High	-23 ± 26	126 ± 13	53	trimmed a lá MFF

We note that the large velocity dispersion can not be the result of errors in our observed radial velocities. To inflate the local value of $\sigma_{los} = 113$ km s^{-1} to 146 km s^{-1} would require typical errors of over 90 km s^{-1}. The good agreement of the low signal-to-noise standard RR Lyrae velocities with their literature velocities, and inter-correlations of the 8–12 radial velocity standard stars observed per run, indicate that the typical errors are only 15 km s^{-1}. Use of the outlier trimming procedure developed by Morrison *et al.* (1990) does not change the kinematic results either (Table 1). Thus we conclude that the large inner halo velocity dispersion is real.

Is there a way to subdivide the inner halo sample to look for the globular cluster signature? Most of the inner halo globulars with [Fe/H] < -1.1 have $|Z| < 2.5$ kpc. If we do a solution for the RR Lyraes in this zone, we find a slightly faster rotational velocity, but the dispersion remains large (see Table 2).

Table 2. Subdividing the Inner Halo Sample.

Sample	V_{rot}	σ_{los}	N_{obj}
IHGC,[a] [Fe/H] < -1.1	59 ± 50	102 ± 18	16
IHRR,[b] [Fe/H] < -1.1	24 ± 19	146 ± 12	78
IHGC, [Fe/H] < -1.1, $\|Z\| < 2.5$	78 ± 45	95 ± 19	13
IHRR, [Fe/H] < -1.1, $\|Z\| < 2.5$	48 ± 29	147 ± 18	34
IHGC, $-1.7 <$ [Fe/H] < -1.1	43 ± 43	81 ± 16	12
IHRR, $-1.7 <$ [Fe/H] < -1.1	37 ± 21	133 ± 13	56
IHGC, $-1.7 <$ [Fe/H] < -1.1, $\|Z\| < 2.5$	68 ± 33	59 ± 14	9
IHRR, $-1.7 <$ [Fe/H] < -1.1, $\|Z\| < 2.5$	57 ± 31	145 ± 19	29
IHRR, $-1.4 <$ [Fe/H] < -1.1	50 ± 32	136 ± 19	25

[a]All globular clusters with $2 < r < 6$ kpc and $|Z| < 7$ kpc, irrespective of HB morphology.

[b]The inner halo RR Lyrae sample discussed herein.

Most of the inner halo globular clusters have $-1.7 <$ [Fe/H] < -1.1. If we restrict our RR Lyrae solutions to this abundance range, we again find a slightly elevated rotation, and a large velocity dispersion (Table 2). Combining these cuts still fails to reduce the size of the velocity dispersion, and the error bars have grown due to the dwindled sample size. Finally, a solution for RR Lyraes on $-1.4 <$ [Fe/H] < -1.1, the region where the bluer-HB population might make the most RR Lyraes (see Fig. 1 of Zinn 1993), still shows the large velocity dispersion (Table 2).

Interestingly, the large velocity dispersion we consistently find is close to that found by Zinn (1993) for the redder-HB clusters, $\sigma_{los} = 149 \pm 24$ km s^{-1}. Could it be that the inner halo RR Lyraes trace the redder-HB population instead of the bluer-HB population? If so, we must explain why the inner halo field contains redder-HB stars, while the clusters do not.

One possible scenario involves the bluer-HB forming first, and in so doing, sweeping clear the inner 6 kpc of the halo. The bluer-HB clusters are highly concentrated to this region, as shown by Zinn (this volume). The redder-HB clusters and field stars would then be accreted over the course of several Gyrs from material falling from much larger Galactocentric radii. Thus, only objects near their perihelia, a brief segment of the orbit, would populate the inner halo. Only one redder-HB cluster, NGC 6584, lies in this zone at present. However, clusters make up only 1–2% of the mass of the halo at large, so a respectably large number of redder-HB population field stars might presently exist in the inner halo. In addition, if the orbits of the redder-HB clusters are characterized by radial infall to a larger extent than the somewhat rotationally supported clusters of the dissipative bluer-HB, then any redder-HB clusters which formed near the $R_{gc} = 6$ kpc cutoff would penetrate further into the center of the Galaxy, and face preferential tidal destruction relative to the bluer-HB clusters.

In addition, its is likely that the selection biases discussed at the beginning of Sec. 2 play a role. Using basic globular cluster data from Harris (1994), and Zinn's (1993) redder/bluer-HB division, we have created histograms of the number of RR Lyraes observed, and of cluster luminosity, as functions of abundance, for both the redder-HB cluster subgroup and the bluer-HB subgroup. Dividing the RR Lyrae number curve by the cluster luminosity curve, we get a curve of RR Lyrae production efficiency as a function of abundance for each subgroup. We find that the redder-HB population produces 2.5 times as many RR Lyraes as the bluer-HB per unit cluster luminosity.

Given these three factors, (1) the large mass of the field stars relative to halo stars, (2) preferential destruction of redder-HB clusters in the inner halo, and (3) higher RR Lyrae production efficiencies among redder-HB clusters, it is possible to see why we observe the signature of the kinematically hotter, accreted, redder-HB population in the inner halo.

2.3. The High Halo Sample

When selecting stars for this sample, we again chose *ab*-type RR Lyraes from the GCVS4 such that they would lie in the desired region of the Galaxy, in this case, $|Z| > 5$ kpc, $6 < r < 10$ kpc (where r is R_{gc} projected onto the plane), and so that their values of $|\cos \psi|$ would be as large as possible.

We again obtained V-band CCD photometry of the stars and produced light curves, and obtained 2–4 Å spectra at the KPNO and CTIO 4.0-m telescopes. Mean magnitudes and radial velocities have been obtained from these data, but the abundance determinations are still in progress. However, Majewski (1992) and others have shown that the contribution of the thick disk at $|Z| > 5$ kpc is negligible, so we feel justified in proceeding without making a cut in [Fe/H] to eliminate metal-rich thick disk stars.

Fig. **??** shows the Frenk & White (1980) solution for the 59 high halo RR Lyraes. The rotation appears to be retrograde, though it is formally only ~1.5-

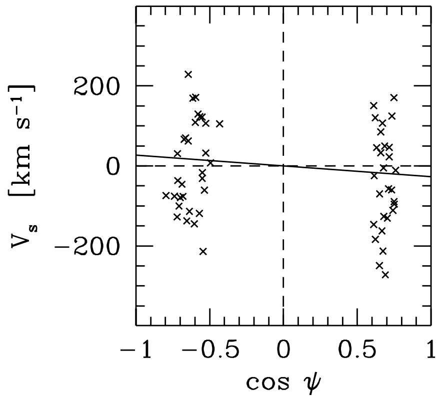

Figure 3. Kinematic solution for the high halo sample. A slow retrograde rotation is seen. The velocity dispersion is similar to that of the local halo.

σ different from the solution for the local RR Lyraes (see Table 1). Note that the eventual removal of any thick disk stars in our sample will only serve to make the kinematics more retrograde. The velocity dispersion is about that expected from the V and W velocity components of the local sample, $\sigma_{los} \approx (V^2/2 + W^2/2)^{1/2} = (112^2/2 + 99^2/2)^{1/2} = 106$ km s^{-1} (Layden 1995), and is somewhat larger than the V velocity dispersion found by Majewski (1992), 80–100 km s^{-1}.

Since this solution could be sensitive to the outliers shown in Fig. 3, we have run solutions employing the $\pm 5\%$ trimming procedure described by Morrison *et al.* (1990). The results are unchanged (see Table 1). The values also remain unchanged if we consider only the 41 stars with $|Z| > 5.5$ kpc.

Though the rotational result differs from the local RR Lyraes by only 1.5-σ, the fact that our result agrees so well with the results of Beers & Sommer-Larsen (1995), Carney (this volume), and to a less extreme extent with those of Majewski (1992) and Wilhelm *et al.* (this volume), we think it is clear that the high halo does in fact have a net retrograde rotation. We also note that, since our sample contains stars from all four quadrants ($l \approx 90$, $b \approx \pm 45$ and $l \approx 270$, $b \approx \pm 45$, at $\langle d_{\odot} \rangle \approx 10$ kpc), we are sampling over four distinct regions of the Galaxy. Thus our result reflects a more global representation of the rotation of the high halo than the pencil beam survey of Majewski (1992), and should not be as sensitive to local moving groups (see Majewski's paper in this volume).

3. Conclusions

From our studies of RR Lyrae variables, which sample 3 distinct regions of the Galaxy, we conclude the following:

• The kinematics of the local sample thick disk and halo populations are in excellent agreement with the kinematic results of other tracers of these populations. They thus form an important standard of reference for interpreting, in a differential sense, the kinematics of the other two RR Lyrae samples.

• The kinematics of the inner halo sample are characterized by a slow prograde rotation, similar to that of the local sample, and a very large velocity dispersion. This is unlike the faster rotation and much smaller velocity dispersion seen among the bluer-HB globular clusters in this region.
• Using cuts in $|Z|$ and in [Fe/H], we were *not* able to isolate a subsample of inner halo stars that exhibited the cooler kinematic signature of the bluer-HB globular clusters. The inner halo RR Lyraes appear to trace the redder-HB halo population.
• We sketched a picture of the formation and structure of the two halos which may explain this discrepancy. It emphasizes the relative masses of the cluster and field star systems, their likely orbits, the possible destruction of redder-HB clusters in the inner halo, and the relative RR Lyrae formation efficiencies of the redder-HB and bluer-HB halos.
• The kinematics of the high halo sample show a slow retrograde rotation, and a velocity dispersion similar to that of the local halo RR Lyraes. The RR Lyrae data thus support the findings of several other studies; the high halo appears to have a net retrograde rotation.
• The high halo kinematics were derived from stars lying in four well-separated regions of the Galaxy, so they should reflect the global rotation of the high halo rather than a localized stream.

Perhaps the simplest interpretation (Layden 1993, Majewski 1993) of this and other recent studies is that the redder-HB halo dominates at high-$|Z|$, giving the retrograde rotation seen by Majewski (1992), the current high halo RR Lyrae sample, and others. Near the Sun, there exists a superposition of the two components, so the fast-rotating bluer-HB and the retrograde-rotating redder-HB blend together to give the slow prograde rotations observed locally. In the inner halo, the bluer-HB clusters dominate, so we might expect to see similarly cool kinematics among the field stars. Or the inner halo might be a mixture of redder- and bluer-HB stars, perhaps with different relative contributions from those found near the Sun.

The kinematics of the RR Lyraes studied herein appear to be in good agreement with this picture, with one minor exception. In Sec. 2.2 we associated the large velocity dispersion of the inner halo RR Lyraes with the large velocity dispersion of the redder-HB clusters (Zinn 1993). Yet the inner halo RR Lyraes appear to have a slow prograde rotation suggestive of a mixture of the two halo components, rather than the retrograde rotation of the high halo samples, which presumably trace the redder-HB clusters. Statistically, there is a 3.4-σ difference between the rotation velocity of the inner halo RR Lyraes and the mean of the rotation results from four studies which find a retrograde high-halo.

Perhaps this difference has to do with the natural run of velocity dispersions in the Galactic gravitational potential. However, the model of Sommer-Larsen, Flynn, & Christensen (1994) suggests otherwise. Our high halo result, for stars at $\langle d_\odot \rangle \approx 11$ kpc, fits their σ_{los} curve for $(l, b) = (270, -45)$, but our large inner halo dispersion is in clear disagreement with a special curve kindly computed by J. Sommer-Larsen for $(l, b) = (35, -20)$, which gives $\sigma_{los} \approx 100$ km s^{-1} at $\langle d_\odot \rangle \approx 8$ kpc.

We conclude with the reflection that the three surveys discussed here, together with the recent surveys of others, provide exciting constraints on the variation of kinematics with position in the halo. However, they do not appear to give completely consistent results in the larger picture. Additional, larger samples of field stars may help to reconcile the differences noted above. In particular, a study of blue HB field stars at $R_{gc} \approx 4$ kpc may turn up the cool kinematic signature of the bluer-HB clusters, and thus reassure us that the redder/bluer-HB dichotomy extends to the field stars. Similarly, a study of the rotational kinematics of RR Lyraes at $R_{gc} \approx 2$ kpc currently in progress by Layden, Morrison & Harding may further clarify the place of RR Lyrae stars within the above picture.

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