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THE CASE FOR THE DUAL HALO OF THE MILKY WAY

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ABSTRACT

Carollo et al. have recently resolved the stellar population of the Milky Way halo into at least two distinct components, an inner halo and an outer halo. This result has been criticized by Schönrich et al., who claim that the retrograde signature associated with the outer halo is due to the adoption of faulty distances. We refute this claim, and demonstrate that the Schönrich et al. photometric distances are themselves flawed because *they adopted an incorrect main-sequence absolute magnitude relationship from the work of Ivezić et al.* When compared to the recommended relation from Ivezić et al., which is tied to a Milky Way globular cluster distance scale and accounts for age and metallicity effects, the relation adopted by Schönrich et al. yields up to 18% shorter distances for stars near the main-sequence turnoff (TO). Use of the correct relationship yields agreement between the distances assigned by Carollo et al. and Ivezić et al. for low-metallicity dwarfs to within 6%–10%. Schönrich et al. also point out that intermediate-gravity stars ($3.5 \leqslant \log g < 4.0$) with colors redder than the TO region are likely misclassified, with which we concur. We implement a new procedure to reassign luminosity classifications for the TO stars that require it. New derivations of the rotational behavior demonstrate that the retrograde signature and high velocity dispersion of the outer-halo population remain. We summarize additional lines of evidence for a dual halo, including a test of the retrograde signature based on proper motions alone, and conclude that the preponderance of evidence strongly rejects the single-halo interpretation.

Key words: Galaxy: evolution – Galaxy: formation – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure – surveys

Online-only material: color figures

1. INTRODUCTION

The nature of the stellar halo of the Milky Way has been debated for many decades. Among the questions that have been asked: Is the halo a monolithic structure, well described by a simple Gaussian velocity ellipsoid? If so, is it in zero net rotation, and does that rotational character apply to all of its constituent stars? Do the stars in the halo comprise a single stellar population, with similar ages and drawn from a common metallicity distribution function (MDF)? Can the spatial distribution of the halo stars be adequately described by a single density law (power law or otherwise)? Due to the difficulty of teasing out the properties of such a low-density component (as compared, e.g., to the bulge and disk systems), the basic data required to address these and other questions have only recently begun to arrive. Not surprisingly, multiple interpretations have emerged.

Massive new data sets from, e.g., SkyMapper (Keller et al. 2007), *Gaia* (Perryman et al. 2001), and eventually, the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008b), will provide definitive answers to the above questions and, of course, raise new ones. However, it is critical to address these issues with presently available data, so that the most meaningful probes of future data sets can be developed.

The two largest spectroscopic data sets available today for examination of the stellar populations of the Milky Way are the RAdial Velocity Experiment (RAVE; Steinmetz et al. 2006; Zwitter et al. 2008; Siebert et al. 2011) and the Sloan Digital Sky Survey (SDSS; York et al. 2000), in particular the subsurvey Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009). The SEGUE-2 subsurvey (C. M. Rockosi et al. 2012, in preparation) has recently been publicly released as part of SDSS DR8 (Aihara et al. 2011), and will add to this bounty of information. For now, we concentrate on the information available from the previous public release from SDSS DR7 (Abazajian et al. 2009), and in particular address the criticisms raised by Schönrich et al. (2010, hereafter S10) of the previous work of Carollo et al. (2007, hereafter C07) and Carollo et al. (2010, hereafter C10).

Note that S10 is the version of the Schönrich et al. manuscript that appeared as arXiv:1012.0842v1. In their published paper (Schönrich et al. 2011, hereafter S11), these authors chose to respond to the submitted version of the present paper, which appeared as arXiv:1104.2513v1. Due to the potential confusion over the issues raised in the two versions of the Schönrich et al. drafts, we have confined our analysis below to the version that appeared as S10; in the Appendix we briefly consider the issues raised by S11.

Carollo et al. (2007) performed a kinematic analysis (within a local volume) for a large sample of calibration stars from SDSS DR5 (Adelman-McCarthy et al. 2007), and argued for the existence of at least a two-component halo. In their view the Galactic halo comprises two broadly overlapping structural components, an inner halo and an outer halo. Note that these labels are not merely descriptors for the regions studied, but rather are labels for two individual stellar populations. These components exhibit different spatial-density profiles, stellar orbits, and stellar metallicities. It was found that the inner-halo component dominates the population of halo stars found at distances up to 10–15 kpc from the Galactic center, while the outer-halo component dominates in the region beyond 15–20 kpc. The inner halo was shown to comprise a population of stars exhibiting a flattened spatial-density distribution, with an inferred axial ratio on the order of ∼0.6. According to C07, inner-halo stars possess generally high orbital eccentricities, and exhibit a small (or zero) net prograde rotation around the center of the Galaxy. The MDF of the inner halo peaks at $[\mathrm{Fe/H}] = -1.6$, with tails extending to higher and lower metallicities. By comparison, the outer halo comprises stars that exhibit a more spherical spatial-density distribution, with an axial ratio ∼0.9. Outer-halo stars possess a wide range of orbital eccentricities, exhibit a clear retrograde net rotation, and are drawn from an MDF that peaks at $[\mathrm{Fe/H}] = -2.2$, a factor of four lower than that of the inner-halo population.

Carollo et al. (2010) used an expanded sample of calibration stars available from SDSS DR7, which included the SEGUE sample, to refine and extend the results of C07. They derived velocity ellipsoids for the inner- and outer-halo components of the Galaxy, as well as for the canonical thick-disk and the proposed metal-weak thick-disk populations. The C10 paper also considered the fractions of each component required to understand the nature of the observed kinematic behavior of the stellar populations of the Galaxy as a function of distance from the Galactic plane. Spatial-density profiles for the inner- and outer-halo populations were inferred from a Jeans theorem analysis. The full set of calibration stars (including those outside the local volume) was used to test for the expected changes in the observed stellar MDF with distance above the Galactic plane in situ, due to the changing contributions from the underlying stellar populations.

Derivation of sufficiently accurate distances is a crucial required step in carrying out kinematic analyses that make use of full space motions, as these involve distances, combined with radial velocities and proper motions, in order to assemble the local velocity components of a sample. It is these distances that have been called into question by S10. In the present paper, we show that many of their objections arise from *their incorrect adoption* of a main-sequence absolute magnitude relationship from Ivezić et al. (2008a, hereafter I08) that *does not apply* for metal-poor halo stars near the main-sequence turnoff (MSTO), and which leads to assignments of stellar distances that strongly disagree (a shorter scale by 10%–18%) with those derived using the correct relationship recommended by I08. A legitimate criticism by S10 relates to the luminosity classifications for stars of intermediate gravity (as assigned spectroscopically) used by C07 and C10, which we demonstrate below is easily corrected. We then consider a new kinematic analysis of likely outer-halo stars from C10, and demonstrate that their original claim that the halo of the Milky Way requires at least a two-component model (with the outer-halo component in net retrograde rotation and possessing a large velocity dispersion) remains intact.

This paper is outlined as follows. In Section 2, we summarize the procedures used by C07 and C10 to derive absolute magnitudes and distance estimates for their stars, which were based on those described by Beers et al. (2000). A technique for the reassignment of (some of the) luminosity classifications for TO stars in the original C10 sample is then developed and applied. In Section 3, we compare with absolute magnitudes and distances derived by the approaches of I08 and D. An et al. 2012 (in preparation, hereafter A12) for stars spectroscopically classified as likely dwarfs based on their derived surface gravities, as well as with those claimed by S10. We demonstrate concordance between the distances for low-metallicity dwarf stars obtained by C10, I08, and A12, and the apparent discordance of all three of these techniques with the results of S10. In Section 4, we reanalyze the kinematics of likely outer-halo stars from the C10 dwarf sample, as well as from the full sample, including stars of dwarf, TO, and subgiant/giant luminosity classifications, and compare to the results obtained from adoption of the I08, A12, and S10 distances. Additional tests for the presence of a kinematically and/or chemically distinct outer halo in the C10 sample are discussed in Section 5. Section 6 presents a summary of further evidence in favor of a dual-halo model for the Milky Way, based on other data sets from SDSS and elsewhere. Our conclusions are given in Section 7. In the Appendix, we consider the issues raised by S11 (the published version of S10).

2. PROCEDURES USED FOR ABSOLUTE MAGNITUDE AND DISTANCE ESTIMATES

2.1. As Employed by C07 and C10

The analyses of C07 and C10 made use of distance estimates for various luminosity classes as assigned by the software pipeline employed by SDSS/SEGUE to estimate stellar atmospheric parameters based on low-resolution ($R \sim 2000$) spectroscopy and *ugriz* photometry. The SEGUE Stellar Parameter Pipeline (SSPP) assigns distances for stars under the following assumed luminosity classes—D: dwarf, TO: main-sequence turnoff, SG/G: subgiant and giant, FHB: field horizontal-branch, and AGB: asymptotic giant branch.[14] Details of the development, calibration, and validation of the SSPP can be found in Lee et al. (2008a, 2008b), Allende Prieto et al. (2008), and Smolinski et al. (2011), to which we refer the interested reader.

The SSPP obtains estimates of stellar effective temperatures, T_{eff}, with errors of determination on the order of 150 K. The surface gravity estimates returned by the SSPP are accurate, for stars other than the coolest giants, to on the order of 0.25 dex. Metallicity estimates for stars in the temperature range $4500\ \mathrm{K} < T_{\mathrm{eff}} < 7000\ \mathrm{K}$ are accurate to on the order of 0.2 dex.

The SSPP distance estimates for various luminosity classes are based on a set of absolute magnitude relationships (using

[14] The FHB and AGB classes do not pertain to the sample of calibration stars used by C07 and C10, and so are not discussed further here.

absorption and reddening-corrected Johnson V magnitudes and $B-V$ colors) calibrated to Galactic globular and open clusters, as described by Beers et al. (2000; their Table 2). As demonstrated in Beers et al. (2000), photometric distances estimated for their sample are in good agreement with distances derived from accurate *Hipparcos* parallaxes. Even when confined to TO stars alone (with well-examined assignment of stars into the TO class provided from previous work), the photometric distances using the Beers et al. formulae are consistent with *Hipparcos* distances.

The samples used by C07 and C10 were selected from the calibration stars of SDSS/SEGUE, which cover an apparent magnitude range of $15.5 < g_0 < 18.5$. In those analyses, confinement to a local sample with distances less than 4 kpc from the Sun corresponds to a g-band absolute magnitude fainter than $M_g = 2.5$, i.e., the local sample is dominated by D and TO stars. This is in contrast to the sample considered by Beers et al. (2000), which is dominated by SG/G stars.

Since the Beers et al. (2000) approach makes use of a non-SDSS photometric system, it is also necessary to employ a color transformation from the SDSS system. Zhao & Newberg (2006) derived a transformation obtained by making matches of SDSS stars with available Johnson magnitudes and colors from the HK survey of Beers and colleagues (Beers et al. 1985, 1992), as well as additional photometry of the HK sample stars obtained over the past decade (see, e.g., Beers et al. 2007, and references therein). They obtained

$$V = g - 0.561\,(g-r) - 0.004$$
$$B - V = 0.916\,(g-r) + 0.187.$$

Stars from the HK survey were used in order to specifically include stars with [Fe/H] < -1.0, which pertain to most halo stars, although the results did not differ drastically from those of Fukugita et al. (1996) that were based primarily on higher abundance stars. The color range of the matching stars sets the region of applicability of the above transformation, which is $-0.5 < g - r < 1.0$. The choice of distance estimates based on a non-SDSS photometric system was one of necessity at the time the SSPP was put into operation, as there were no suitably calibrated fiducials based on SDSS photometry of Galactic clusters available, and the isochrones that had been developed were rather primitive. These limitations no longer apply, and future versions of the SSPP will employ alternative distance estimates based on improvements that have become available in the past year.

It should be noted that the SSPP, by design, does not identify a preferred distance estimate, leaving the choice of the appropriate luminosity classification to the user's discretion. This choice is due, in part, to the fact that the estimation of surface gravity by the SSPP has evolved with time, and may continue to do so in the future. Hence, as many users will rely, at least at some level, on $\log g$ estimates for making distance estimates based on luminosity classifications from available spectroscopic information, no "approved" distance estimate is supplied by the SSPP.

For the purpose of the analyses carried out by C07 and C10, the following spectroscopically assigned surface gravity intervals from the SSPP were used in the assignment of luminosity classifications.

1. D: $\log g \geqslant 4.0$.
2. TO: $3.5 \leqslant \log g < 4.0$.
3. SG/G: $\log g < 3.5$.

Estimates of $\log g$ carry errors, and one has to be concerned about the possible effects on any resulting analyses based on their adoption. For the present, this is best assessed by consideration of inferences based on samples of individual luminosity classes relative to the sample as a whole, which we discuss below.

Note that the above prescription for assignment of luminosity class does not take into account the "known" evolutionary stage of a given star, as might be inferred from the location of a star in a color–magnitude diagram (CMD) expected to pertain to objects of a given age and metallicity. This uncertainty is of particular concern for stars assigned to the TO class, since an alternative assignment to the D or SG/G class could result in potentially large discrepancies in the adopted distance. This "defect" (actually a choice, given that such knowledge is at best only partially constrained with present data, and in any case relies on assumptions regarding the underlying stellar population one adopts) is one of the criticisms of the C07 and C10 work levied by S10. However, it can be readily addressed, as described below.

As part of their analysis, I08 compared absolute magnitude estimates obtained by the Beers et al. (2000) procedures with those used in their own analysis (which only applied to dwarfs). Pointing at the bottom left panel of their Figure 21, which examined the main-sequence comparisons of Galactic clusters between the two studies, I08 concluded that "... the median offset of implied M_r evaluated in small bins of $u-g$ and $g-r$ color is -0.07 mag, with an rms of 0.06 mag." This satisfying level of agreement provided additional reason to have faith in the distances for the majority of stars in the C10 sample upon which their kinematic analysis was based. This agreement remains intact, as shown below.

2.2. A Refined Prescription for Luminosity Class Assignments

As pointed out above, refinements in luminosity class assignment require assumptions about the ages and age distributions of the population(s) to which they will be applied. For the present discussion, which turns on the nature of the stars associated by C07 and C10 with the inner- and outer-halo populations, it is reasonable to adopt a uniformly old age, with the unavoidable caveat that not all stars of these populations may strictly adhere to this assumption.

We proceed as follows.

First, a set of theoretical $\log g$ versus $T_{\rm eff}$ diagrams is obtained, based on the Y^2 isochrones (Demarque et al. 2004), for a population with age set to 12 Gyr, metallicities in the range $-3.0 \leqslant$ [Fe/H] $\leqslant 0.0$, and with [α/Fe] set to 0.0 for solar metallicity, [α/Fe] $= +0.3$ for [Fe/H] $\leqslant -1.0$, and using a linear scaling between [Fe/H] $= 0$ and [Fe/H] $= -1.0$. We then obtain the effective temperatures at the position of the MSTO for each model, $T_{\rm MSTO}$, and assign a "critical temperature," $T_{\rm crit}$, to be 250 K cooler than $T_{\rm MSTO}$. The offset of 250 K was chosen since, in the region of the MSTO, this roughly corresponds to the 2σ accuracy of the estimated temperature from the SSPP, and provides a reasonable location for the base of the subgiant branch for isochrones of old, low-metallicity populations. Our purpose is to define a criterion such that a reassignment of luminosity classes can be considered for stars of intermediate gravity ($3.5 \leqslant \log g < 4.0$) that are cooler than $T_{\rm crit}$.

A second-order polynomial is then fit to the positions of the $T_{\rm MSTO}$ values for each model:

$$T_{\rm MSTO} = 5572 - 519.3\,[{\rm Fe/H}] - 44.3\,[{\rm Fe/H}]^2. \quad (1)$$

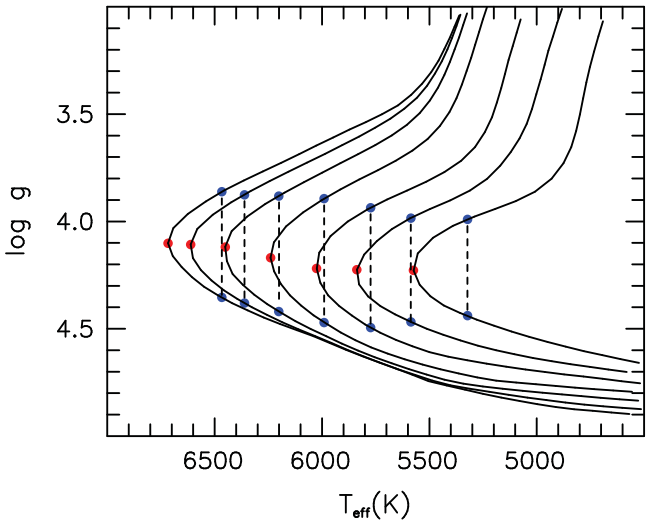

Figure 1. Theoretical surface gravity ($\log g$) vs. $T_{\rm eff}$ diagram based on the Y^2 isochrones (Demarque et al. 2004), under the assumption of a uniform age of 12 Gyr. From left to right in the figure, the isochrones cover the range of metallicities $-3.0 < [{\rm Fe/H}] < 0.0$, in steps of 0.5 dex. The $[\alpha/{\rm Fe}]$ ratios are set to 0.0 for solar metallicity, $[\alpha/{\rm Fe}] = +0.3$ for $[{\rm Fe/H}] \leqslant -1.0$, and are linearly scaling between $[{\rm Fe/H}] = 0$ and $[{\rm Fe/H}] = -1.0$. The red dots mark the position of the MSTO, while the blue dots correspond to temperatures 250 K cooler than the MSTO, referred to as $T_{\rm crit}$. The vertical dashed lines connect the multi-valued positions on the isochrones at a given $T_{\rm eff}$. Stars with estimated gravities in the range $3.5 \leqslant \log g < 4.0$, which were classified as TO by C07 and C10, are reassigned to either D or SG/G classes if their metallicities and $T_{\rm eff}$ place them to the right side of these divisions, or remain classified as TO if their metallicities and $T_{\rm eff}$ place them to the left of these divisions. See the text for additional details.

The critical temperature is then simply set to $T_{\rm crit} = T_{\rm MSTO} - 250$ K. This process is illustrated in Figure 1. The critical temperature is used in order to separate intermediate-gravity stars classified as TO by C07 and C10 into either bona-fide TO stars (those with $T_{\rm eff} \geqslant T_{\rm crit}$) or into the D or SG/G classes (those with $T_{\rm eff} < T_{\rm crit}$) according to their surface gravity estimates, as summarized in Table 1. Note that stars with original luminosity classifications D and SG/G are not changed by this procedure.

The luminosity class reassignment procedure described above affects a total of 4514 of the original 16,920 accepted stars in the C10 sample (26%). The upper left panel of Figure 2 shows the CMD for the original assignments of C10, while the upper right panel is that obtained after the revised assignments have been applied to this same sample. The gray dots are stars with $[{\rm Fe/H}] > -2.0$, while the red dots are stars with $[{\rm Fe/H}] < -2.0$.[15] As can be appreciated from comparison of these two panels, stars that formerly fell into regions of the CMD that might be considered astrophysically unlikely for an old, metal-poor population have primarily moved into either the D or SG regions. The lower panels of Figure 2 contrast the absolute magnitudes of the revised and original C10 classifications (lower left) and the corresponding derived distances (lower right).

Inspection of the upper left panel of Figure 2 clearly shows the presence of the "spurious" TO stars in the original C10 sample, most easily seen among the $[{\rm Fe/H}] < -2.0$ stars as the plume extending from roughly $M_r = 3.7$ to $M_r = 4.7$, over the color range $0.25 < g - i < 0.6$. Comparison with the upper right panel of this figure shows that most of these stars (51%) are reassigned to D status, with only some 10% being reassigned to SG/G status (the remaining stars, 39%, retain their original luminosity classification of TO). At low metallicity, $[{\rm Fe/H}] < -2.0$, the fraction of reassigned TO stars to D status is 85%, while those reassigned to SG/G status comprise 14%, and only a small fraction retain their TO classification. At higher metallicities, $[{\rm Fe/H}] > -2.0$, 44% of the TO stars are reassigned to D status, and only a small fraction are reassigned to SG/G status. The remaining stars, 56%, retain their original luminosity classification of TO.

Table 1
Luminosity Class Refinements for Main-sequence Turnoff Stars

Former Class	$T_{\rm eff}$ Range	Gravity Interval	New Class
TO	$\geqslant T_{\rm crit}$	$3.75 \leqslant \log g < 4.00$	TO
TO	$\geqslant T_{\rm crit}$	$3.50 \leqslant \log g < 3.75$	TO
TO	$< T_{\rm crit}$	$3.75 \leqslant \log g < 4.00$	D
TO	$< T_{\rm crit}$	$3.50 \leqslant \log g < 3.75$	SG/G

The lower left panel of Figure 2 shows the difference in the assigned M_r absolute magnitudes that arises when one compares the revised C10 estimates with those of C10. For the TO stars that were reclassified as D stars, and with $[{\rm Fe/H}] > -2.0$, the revised C10 determinations are fainter by a median offset of 0.08 mag (rms 0.36 mag) for $0.4 < g - i < 0.8$, while the median offset of the revised C10 absolute magnitudes is 0.30 mag (rms 0.24 mag) fainter for bluer stars in the range $g - i < 0.4$. For the TO stars that were reclassified as SG/G stars, and with $[{\rm Fe/H}] > -2.0$, the revised C10 determinations are brighter by a median offset of 0.48 mag (rms 0.31 mag) for $0.4 < g - i < 0.8$, while the median offset of revised C10 absolute magnitudes is 0.44 mag (rms 0.22 mag) brighter for bluer stars in the range $g - i < 0.4$.

For the TO stars that were reclassified as D stars, and with $[{\rm Fe/H}] < -2.0$, the revised C10 determinations are fainter by a median offset of 0.97 mag (rms 0.43 mag) for $0.4 < g - i < 0.8$, while the median offset of revised C10 absolute magnitudes is 0.60 mag (rms 0.25 mag) fainter for bluer stars in the range $g - i < 0.4$. For the TO stars that were reclassified as SG/G stars, and with $[{\rm Fe/H}] < -2.0$, the revised C10 determinations are brighter by a median offset of 1.07 mag (rms 0.42 mag) for $0.4 < g - i < 0.8$, while the median offset of revised C10 absolute magnitudes is 0.63 mag (rms 0.24 mag) brighter for bluer stars in the range $g - i < 0.4$.

The lower right panel of Figure 2 shows the fractional difference in the derived distances between the revised C10 and C10 scales. For TO stars that were reclassified as D stars, and with $[{\rm Fe/H}] > -2.0$ and $0.4 < g - i < 0.8$, the median offset of the revised C10 distances with respect to the C10 distances is 26% (rms 9%). In the bluer range, $g - i < 0.4$, the offset increases to about 19% (rms 6%). Both revisions are in the direction that the revised C10 scale is shorter than the original C10 scale for the reclassified TO $\rightarrow$ D stars. For TO stars that were reclassified as SG/G stars, and with $[{\rm Fe/H}] > -2.0$ and $0.4 < g - i < 0.8$, the median offset of the revised C10 distances with respect to the C10 distances is 33% (rms 16%). In the bluer range, $g - i < 0.4$, the offset decreases to about 25% (rms 11%). Both revisions are in the direction that the revised C10 scale is longer than the original C10 scale for the reclassified TO $\rightarrow$ SG/G stars.

For TO stars that were reclassified as D stars, and with $[{\rm Fe/H}] < -2.0$ and $0.4 < g - i < 0.8$, the median offset of the revised C10 distances with respect to the C10 distances is 36% (rms 14%). In the bluer range, $g - i < 0.4$, the offset

[15] We have made use of the corrected metallicity, $[{\rm Fe/H}]_C$, as described by C10, here and throughout the rest of this paper, for the quoted metallicities.

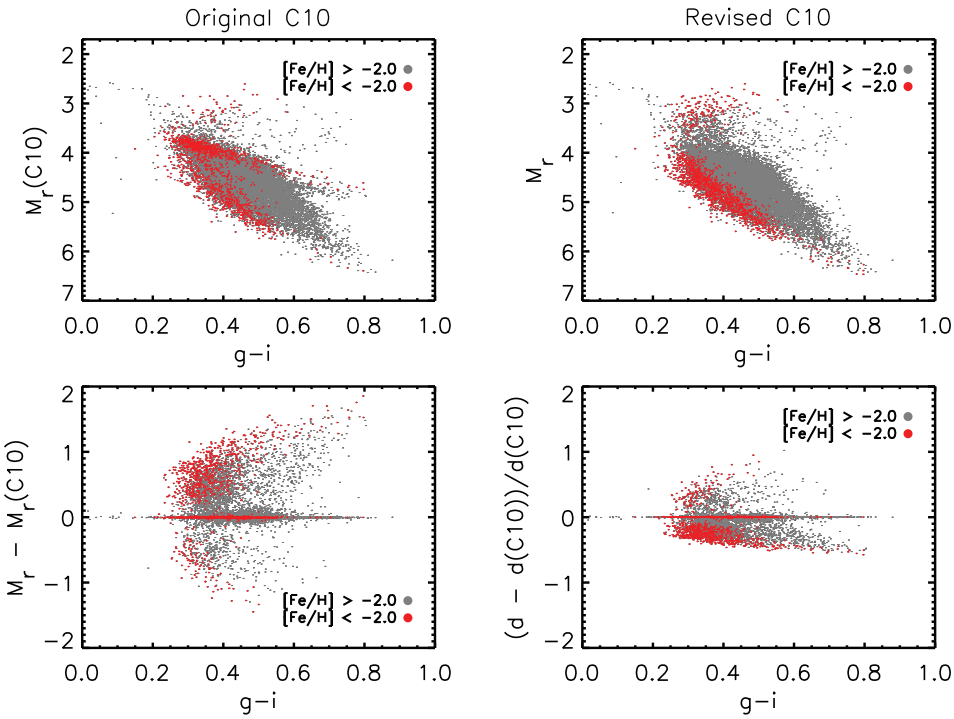

Figure 2. Upper left: M_r, $g-i$ CMD for the C10 sample, using the original luminosity classifications. Upper right: M_r, $g-i$ CMD for the C10 sample, using the revised luminosity classifications, as described in the text. The stars with [Fe/H] > -2.0 are shown as gray dots, while those with [Fe/H] < -2.0 are shown as red dots. Lower left: difference between the M_r absolute magnitudes for the revised luminosity classifications and the original C10 classifications, as a function of $g-i$. Lower right: fractional change in derived distances for the revised luminosity classifications vs. the original C10 classifications, as a function of $g-i$.

decreases to about 24% (rms 9%). Both revisions are in the direction that the revised C10 scale is shorter than the original C10 scale for the reclassified TO → D stars. For TO stars that were reclassified as SG/G stars, and with [Fe/H] < -2.0 and $0.4 < g-i < 0.8$, the median offset of the revised C10 distances with respect to the C10 distances is 65% (rms 26%). In the bluer range, $g-i < 0.4$, the offset decreases to about 34% (rms 14%). Both revisions are in the direction that the revised C10 scale is longer than the original C10 scale for the reclassified TO → SG/G stars.

It is worth considering that our reclassification procedure *assumes* that many of the stars with spectroscopically assigned surface gravities in the range $3.75 \leqslant \log g < 4.0$ (those significantly cooler than an inferred old-population MSTO) are indeed metal-poor dwarfs with slightly misestimated $\log g$. This is certainly a conservative assumption, and errs on the side of decreasing distances for actual TO or SG/G stars to the much smaller values that would be derived if they are in fact main-sequence dwarfs. These fine adjustments require further study and verification by high-resolution spectroscopic follow-up of a sample of such stars, at a variety of metallicities and temperatures.

Note that for construction of Figures 2–8, and for the distance-scale comparisons we carry out below, it is useful to consider samples that explore the same local volumes. For simplicity, and for consistency with C07 and C10, we have selected stars with revised C10 distance estimates that satisfy 7 kpc $< R <$ 10 kpc and $d <$ 4 kpc as our basis sample.

2.3. Comparison Between Revised C10 and S10

The essence of the S10 complaint is that the distance scale utilized by C07 and C10 is too "long," i.e., that we have artificially inflated the estimates of stellar distances through the combination of (1) the use of misclassified TO stars (which they suggest could be D stars instead), and in particular, (2) the use of an absolute magnitude scale for the D stars that assigns luminosities to main-sequence stars which displaces them to larger-than-appropriate distances. We have shown above that the first issue is easily corrected for, and that in any case it only applies to some 14% of the total calibration stars from C10, roughly 2300 stars. Of these, 4% of the full sample (680 stars) possess the very low metallicities (below [Fe/H] $= -2.0$) that strongly influence the derived properties of a proposed outer-halo population. Thus, even if there might be some impact, it is substantially diluted by the relatively small numbers of stars for which this concern exists. In any case, we have applied the correction procedures described above, carried out the luminosity classification changes for the cooler TO stars, and in the analysis below, refer to the modified sample as the revised C10 sample. The second issue turns on whether or not one should put faith in our adopted main-sequence absolute magnitude scale, which we address in detail below.

Figure 3 shows the result of the comparison of the revised C10 determinations with those of S10. The upper left panel of this figure shows the CMD for stars with spectroscopic assignments of D ($\log g \geqslant 4.0$), with absolute magnitudes from the revised C10 sample. The upper right panel shows the corresponding CMD obtained using the absolute magnitudes from S10 (Equation (3) below). Note that in the evaluation of both relationships, the $[\mathrm{Fe/H}]_C$ from C10 was employed, although similar results are obtained when the adopted metallicities from the SSPP ($[\mathrm{Fe/H}]_A$) are used. The stars are color-coded to indicate metallicities above and below [Fe/H] $= -2.0$.

Note that S10 did make a number of changes in their adopted absolute magnitude relationship relative to Equation (A1) of

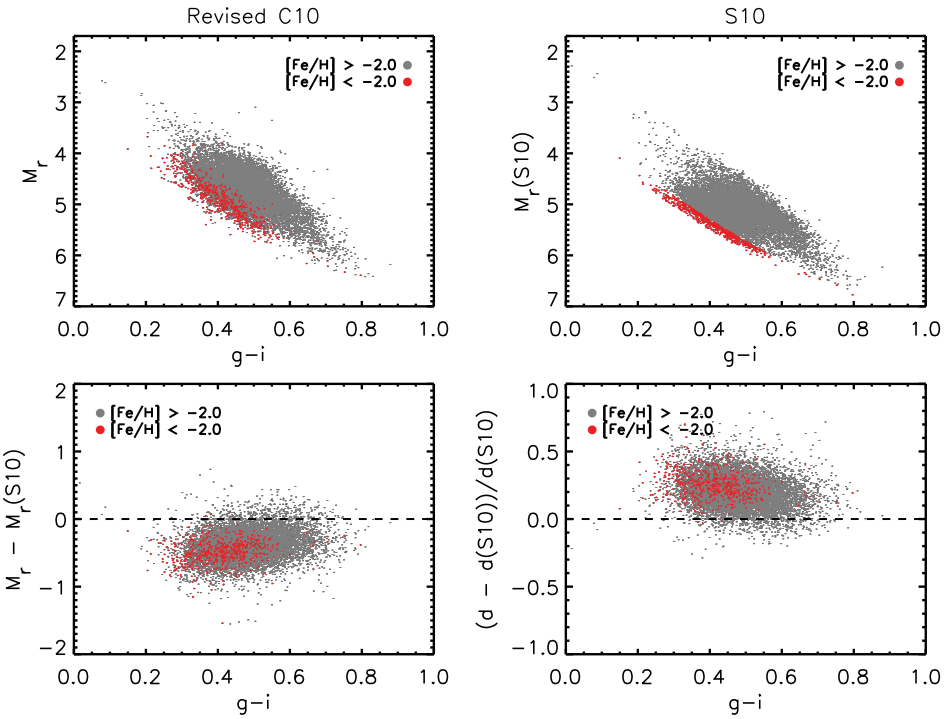

Figure 3. Upper left: M_r, $g-i$ CMD for the revised C10 luminosity classifications and with spectroscopically assigned D classifications. Upper right: M_r, $g-i$ CMD for stars with spectroscopically assigned D classifications, with absolute magnitudes calculated from Equation (A1) of I08, as adopted by S10. The stars with [Fe/H] > -2.0 are shown as gray dots, while those with [Fe/H] < -2.0 are shown as red dots. Lower left: difference between the M_r absolute magnitudes for stars with spectroscopically assigned D classifications for the revised C10 and S10 calculations, as a function of $g-i$. Lower right: fractional change in derived distances from the revised C10 sample as compared to those adopted by S10, as a function of $g-i$.

I08, which actually serve to bring their estimated distances into closer agreement with ours. We have not attempted to recreate these adjustments in our analysis, as the corrections they apply are themselves uncertain (and in our view not entirely well motivated, e.g., their preference for metallicities on a scale that our own analysis does not support). Thus, one should properly consider the comparisons we make here as likely to be the maximum differences that would be obtained. The apparent difference in the scatter in absolute magnitudes seen in the upper left and upper right panels is due to the fact that our adopted distances are calculated based on the empirical cluster-based fits from Beers et al. (2000), taking into account spectroscopic measurements of metallicity and surface gravity in order to assign luminosity classes, while those on the right panel come from application of a simple polynomial, which naturally leads to lack of scatter.

The lower left panel of Figure 3 shows the difference in the assigned M_r absolute magnitudes that arises when one compares the revised C10 estimates with those of S10 for stars spectroscopically classified as D stars ($\log g \geqslant 4.0$). For stars with [Fe/H] > -2.0, the revised C10 determinations are brighter by a median offset of 0.38 mag (rms 0.19 mag) for $0.4 < g-i < 0.8$, while the median offset of revised C10 absolute magnitudes is 0.45 mag (rms 0.20 mag) brighter for bluer stars in the range $g-i < 0.4$. The offsets are even larger for stars with [Fe/H] < -2.0. For the redder stars with $0.4 < g-i < 0.8$, the median offset of the revised C10 determinations compared with S10 is 0.45 mag (rms 0.16 mag) brighter; for bluer stars with $g-i < 0.4$, the median offset is 0.52 mag (rms 0.18 mag) brighter.

The lower right panel of this figure shows the fractional difference in the derived distances between the revised C10 and S10 scales. For stars with [Fe/H] > -2.0 and $0.4 < g-i < 0.8$, the median offset of the revised C10 distances with respect to the S10 distances is 19% (rms 10%). In the bluer range, $g-i < 0.4$, the offset increases to about 23% (rms 11%). For stars with [Fe/H] < -2.0 and $0.4 < g-i < 0.8$, the median offset of the revised C10 distances with respect to the S10 distances is 23% (rms 10%). In the bluer range, $g-i < 0.4$, the offset is 27% (rms 11%). All distance differences are in the sense that the revised C10 scale is (as expected) longer than the S10 scale.

3. ABSOLUTE MAGNITUDES AND DISTANCES BASED ON ALTERNATIVE SCHEMES

Since much of the discord between the conclusions reached by C10 and S10 arises from their adopted absolute magnitudes and distances, we now consider two additional approaches for obtaining estimates of these quantities. It is worth keeping in mind that these comparisons are only valid for stars that are confidently assigned D status, for which we enforce the requirement that they have spectroscopic gravity estimates assigned by the SSPP of $\log g \geqslant 4.0$.

3.1. The Empirical Calibration of I08

We first consider the relationship adopted by I08, as summarized by their Equation (A7), used in conjunction with the metallicity correction in their Equations (A2) and (A3). When combined into a single equation, one obtains

$$M_r(g-i, \mathrm{[Fe/H]}) = -0.56 + 14.32\,x - 12.97\,x^2 + 6.127\,x^3 - 1.267\,x^4 + 0.0967\,x^5 - 1.11\,\mathrm{[Fe/H]} - 0.18\,\mathrm{[Fe/H]}^2, \quad (2)$$

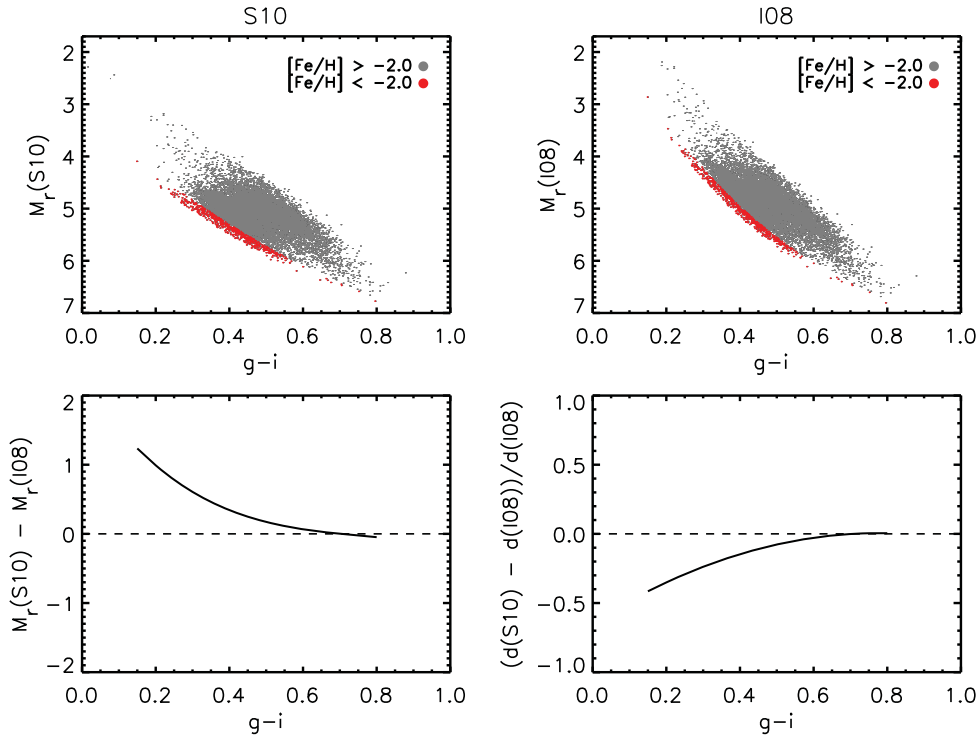

Figure 4. Upper left: M_r, $g-i$ CMD for stars with spectroscopically assigned D classifications, with absolute magnitudes calculated from Equation (A1) of I08, as adopted by S10. Upper right: M_r, $g-i$ CMD for stars with spectroscopically assigned D classifications, with absolute magnitudes calculated from Equation (A7) of I08, as adopted by I08. The stars with [Fe/H] > -2.0 are shown as gray dots, while those with [Fe/H] < -2.0 are shown as red dots. Lower left: difference between the M_r absolute magnitudes for stars with spectroscopically assigned D classifications for the S10 and I08 calculations, as a function of $g-i$. Lower right: fractional change in derived distances from those adopted by S10 as compared to those adopted by I08, as a function of $g-i$.

where $x = (g-i)$. This was the recommended final photometric parallax relationship from I08, where it is claimed to be valid (for main-sequence stars) over a wide color range ($0.2 < g-i < 4.0$).

The S10 study did not make use of the above equation, but rather, adopted an absolute magnitude relationship taken from a previous stage of the I08 analysis, given there as Equation (A1), and applied a metallicity correction from Equations (A2) and (A3) to obtain

$$M_r(g-i, [\mathrm{Fe/H}]) = 1.65 + 6.29\,x - 2.30\,x^2 - 1.11\,[\mathrm{Fe/H}] - 0.18\,[\mathrm{Fe/H}]^2, \quad (3)$$

where $x = (g-i)$.

The S10 paper argued that their adopted absolute magnitude determinations agreed better with their preferred set of isochrones (the BaSTI isochrones: Pietrinferni et al. 2004, 2006), but in fact I08 did not expect this relationship (which is from an early step in their development of the appropriate absolute magnitude prediction) to perform well for bluer stars near the MSTO. This is a crucial limitation, as the calibration-star sample considered by C07 and C10 includes a considerable number of bluer objects—19% of the C10 sample, for example, have $g-i < 0.4$. The fraction becomes even larger at low metallicity—31% for [Fe/H] < -1.0 and 46% for [Fe/H] < -2.0. This relationship also does not take into account corrections for differing ages of the underlying stellar populations that were applied by I08 in seeking a more generally useful photometric parallax method. The combination of these two effects accounts for much of the discrepancy cited by S10 in the absolute magnitudes (hence distances) used by the C07 and C10 studies.

The upper left panel of Figure 4 shows the CMD for stars with spectroscopic assignments of D ($\log g \geqslant 4.0$), with absolute magnitudes assigned by the relationship adopted by S10 (Equation (3) above). The upper right panel shows the corresponding CMD obtained using the absolute magnitudes from Equation (2) above, which is the recommended relationship from I08. Note that in the evaluation of both relationships above, the $[\mathrm{Fe/H}]_C$ from C10 was employed, although similar results are obtained when either the photometric metallicity estimates from I08 or the adopted metallicity from the SSPP ($[\mathrm{Fe/H}]_A$) are used. The stars are color-coded to indicate metallicities above and below [Fe/H] $= -2.0$. Note, however, that since both procedures adopted the same metallicity correction scheme, there are *no differences* in their behavior over different intervals of [Fe/H].

The lower left panel of Figure 4 shows the difference in the assigned M_r absolute magnitudes that arises when one compares the adopted S10 and I08 relationships. For stars with $0.4 < g-i < 0.8$, the median offset is 0.23 mag, with the S10 assignments being fainter. The difference for bluer stars with $g-i < 0.4$ ranges from ~0.23 mag fainter at the red end of this interval to roughly 1.0 mag fainter at the blue end (median difference of 0.48 mag).

The lower right panel of this figure shows the fractional difference in the derived distances between S10 and I08. For redder stars with $0.4 < g-i < 0.8$, the difference amounts to no more than about 15% at the blue end of this range (median offset of 10%), but for the bluer stars with $g-i < 0.4$ the difference increases from ~15% up to roughly 40%, with a median offset of 20%. All distance differences are in the sense that the S10 scale is shorter than the I08 scale.