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WEAK GALACTIC HALO–DWARF SPHEROIDAL CONNECTION FROM RR LYRAE STARS

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ABSTRACT

We discuss the role that dwarf galaxies may have played in the formation of the Galactic halo (Halo) using RR Lyrae stars (RRL) as tracers of their ancient stellar component. The comparison is performed using two observables (periods, luminosity amplitudes) that are reddening and distance independent. Fundamental mode RRL in 6 dwarf spheroidals (dSphs) and 11 ultra faint dwarf galaxies ($\sim$1300) show a Gaussian period distribution well peaked around a mean period of $\langle \mathrm{Pab} \rangle = 0.610 \pm 0.001$ days ($\sigma = 0.03$). The Halo RRL ($\sim$15,000) are characterized by a broader period distribution. The fundamental mode RRL in all the dSphs apart from Sagittarius are completely lacking in High Amplitude Short Period (HASP) variables, defined as those having $P \lesssim 0.48$ days and $A_V \geqslant 0.75$ mag. Such variables are not uncommon in the Halo and among the globular clusters and massive dwarf irregulars. To further interpret this evidence, we considered 18 globulars covering a broad range in metallicity ($-2.3 \lesssim$ [Fe/H] $\lesssim -1.1$) and hosting more than 35 RRL each. The metallicity turns out to be the main parameter, since only globulars more metal-rich than [Fe/H] ~ -1.5 host RRL in the HASP region. This finding suggests that dSphs similar to the surviving ones do not appear to be the major building-blocks of the Halo. Leading physical arguments suggest an *extreme* upper limit of $\sim$50% to their contribution. On the other hand, massive dwarfs hosting an old population with a broad metallicity distribution (Large Magellanic Cloud, Sagittarius) may have played a primary role in the formation of the Halo.

Key words: Local Group – stars: variables: RR Lyrae

1. INTRODUCTION

The early suggestion by Searle & Zinn (1978) that the Milky Way (MW) outer Halo formed from the aggregation of protogalactic fragments was supported (1) theoretically by ΛCDM simulations of galaxy formation in which small galaxies form first and then cluster to form larger galaxies, and (2) observationally by the discovery of stellar streams and merging satellites in the MW (Ibata et al. 1994) and in other galaxies. However, the characteristics of the halo building blocks is still a matter of debate. In particular, the question of whether the current dwarf spheroidal (dSph) satellites of the MW are surviving representatives of the Halo's building blocks has been explored in several works (Tolstoy et al. 2009). The conclusions of these works differ in some details, but they suggest that there are difficulties in forming the Halo exclusively with dwarfs similar to current MW satellites. Among these, the studies using element ratios (Venn et al. 2004) of stellar populations in dSphs and in the Halo are based on tracers (red giant stars) covering a wide range in age. Thus, they suffer from the drawback that some of the dSph present a complex evolution spanning several gigayears, while the evolution of the halo building blocks was likely interrupted at early times, when they were accreted into the halo. This is the reason why old stellar tracers are crucial in the comparison between the MW halo and dSphs.

A real possibility to isolate the ancient (age $\geqslant$ 10 Gyr) populations in these different stellar systems is offered by a special class of low-mass, radial variables: RR Lyrae stars (RRL). They pulsate in the fundamental (RRab) and in the first overtone mode (RRc). Due to their variability and relatively distinct light curves, RRL can be easily distinguished from other stars. Extensive variability surveys of our Galaxy have been performed and are currently releasing their final catalogs. We have compiled a very large catalog ($\sim$14,700 stars) from the QUEST (Vivas et al. 2004; Zinn et al. 2014), ASAS (Szczygieł et al. 2009), and CATALINA (Drake et al. 2013) surveys that have classified RRL and provided Johnson *V*-band magnitudes and amplitudes. The final catalog is mainly based on CATALINA RRL (85%) and covers a large range in galactocentric distances (5 kpc $\lesssim d_G \lesssim$60 kpc). Moreover, the sample radial distribution does not show evidence of gaps. This makes possible a direct comparison with dSphs where RRL are always observed. We have gathered the results from accurate and quite complete photometric studies of classical dSphs (Draco, Carina, Tucana, Sculptor, Cetus, and Leo I and some ultra faint dwarfs, hereinafter UFDs) that different research groups have carried out during the last 10 yr (see Stetson et al. 2014a).

In Stetson et al. (2014a), we performed a first detailed analysis of the RRL properties using these sizable samples. Very interestingly, comparing their period–amplitude (or Bailey) diagrams, we highlighted that, in the sample of 6 dSphs plus 11 UFDs that we considered, there are *no* RRab stars with $A_V \geqslant 0.75$ mag and $P \lesssim 0.48$ days. This was first found by Bersier & Wood (2002) in Fornax and not explained by the temporal sampling of the observations, since their probability of detecting a period in such a range was always higher than

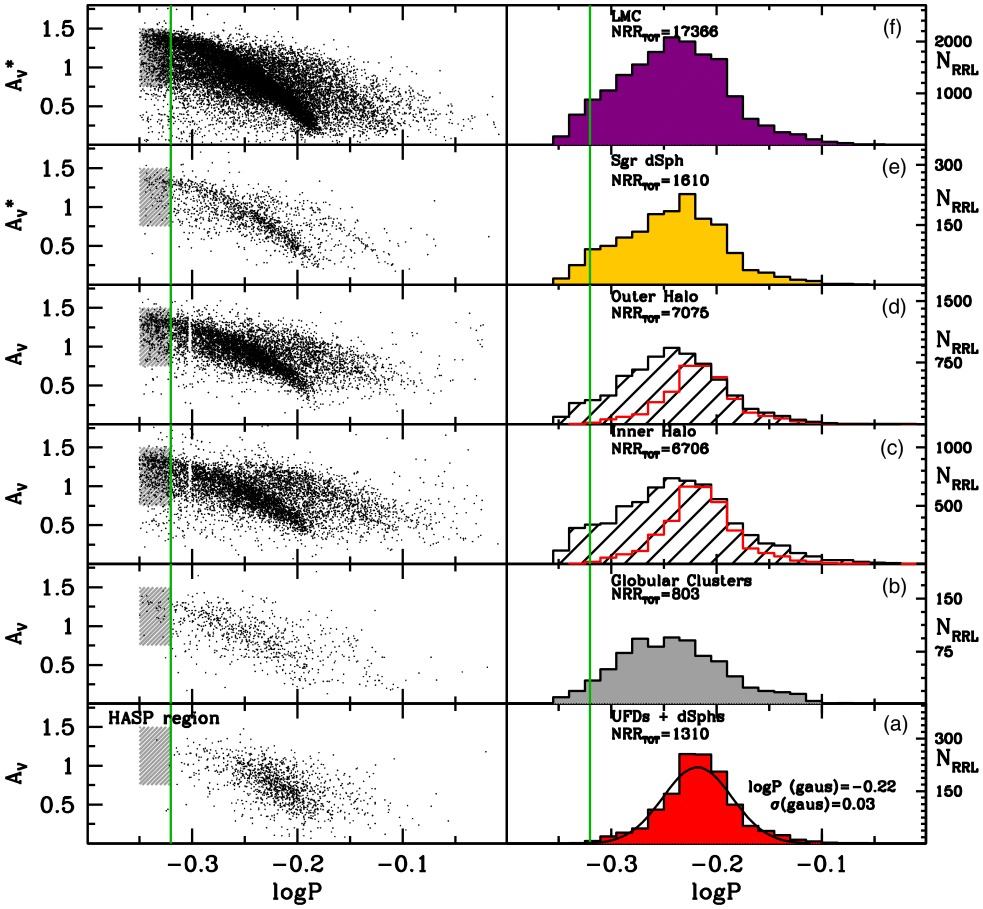

Figure 1. Left: Bailey diagram, period vs. V-amplitude distributions for RRab observed in the LMC (panel (f)), in Sgr dSph (panel (e)), the Halo with $\log P \geqslant -0.35$ (top panels (c) and (d)), in GGCs ((b) panel), in 6 dSphs plus 11 UFDs (panel (a)). A_V^* is derived from A_I using the $A_I/A_V = 0.63$ (Di Criscienzo et al. 2011). The green solid vertical line represents the minimum period observed for RRab in spheroidals, i.e., $P \sim 0.48$ d. We have highlighted the region where HASP RRab are missing (gray). Right: period histograms for the same sample of RRab. Red histograms in panels (c) and (d) represent the UFD + dSphs distribution rescaled to the Halo ones as explained in the text.

66%. The authors attributed it instead to the transition period between RRab- and RRc-type variables. The same applies to the Draco dSph as discussed by Catelan (2009). We have observed this evidence in another 5 dSphs and 11 UFDs and called it the missing High Amplitude Short Period (HASP) RRab problem in dSphs. This evidence cannot be related to photometric incompleteness of a single photometric data set, particularly since high-amplitude RRL are the easiest to recognize among the variable candidates.

In this Letter, using the properties of RRab in Galactic Globular clusters (GGCs) and taking advantage of predictions from theoretical models, we propose an explanation for the missing HASP problem in dwarfs. We also give a rough estimate of the upper limit to the contribution of dSph-like galaxies to the Halo stellar population. We conclude the Letter extending the discussion to the possible contribution to the Halo of systems similar to the Large Magellanic Cloud (LMC) and the Sagittarius (Sgr) dwarfs.

2. THE MISSING HASP RRAB IN DSPHS

Figure 1 shows the Bailey diagrams (left) and the period distributions (right) for the RRab observed in dSphs (panel (a)), in GGCs (panel (b)), in the inner ($d_G \lesssim 16$[10] kpc; panel (c)) and in the outer ($d_G \gtrsim 16$ kpc; panel (d)) halo. The boundary between inner and outer halo has been arbitrarily chosen to have comparable numbers of RRL in the two samples and taking into consideration the value found in Carollo et al. (2007; $d_G \sim 15$–20 kpc). We take advantage also of the exceptionally complete LMC sample from Optical Gravitational Lensing Experiment (OGLE) III (panel (f); Soszyński et al. 2010) and of the recent release of OGLE IV that includes Sgr (panel (e); Soszyński et al. 2014). The shaded gray area shows the location in Bailey diagram of the HASP region. Our analysis focuses on fundamental RRL ($\log P \geqslant -0.35$). The shorter period first overtones will not be included because they have smaller luminosity amplitudes and are, at fixed limiting magnitude, more affected than RRab by completeness problems.

The period distributions of RRab stars plotted in the right panels of Figure 1 are quite different even if the mean periods achieve similar values to within 1σ (Table 1). In particular, the shape of the histogram corresponding to dSph and UFD is strikingly different from the rest. Not only are the HASP absent (except for two in Cetus which appear to be peculiar for other reasons), but there is also a dearth (or a lower fraction) of short-period variables ($\log P \lesssim -0.25$) compared to the other five samples. The symmetry of the dSphs period distribution can be fitted with a Gaussian function ($\sigma = 0.03$; see Figure 1) and suggests also that metal-poor RRab in UFDs are still a minor fraction of the entire sample ($\mathrm{NRR_{UFD}/NRR_{UFD+dSphs}} = 3\%$). Indeed, the RRab in UFDs tend to contribute significantly to the long-period tail of dSphs (see Figure 9 in Stetson et al. 2014a).

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[10] This distance is slightly smaller than the distance adopted by Stetson et al. (2014a; 14 kpc). The difference does not affect the conclusions of the Letter.

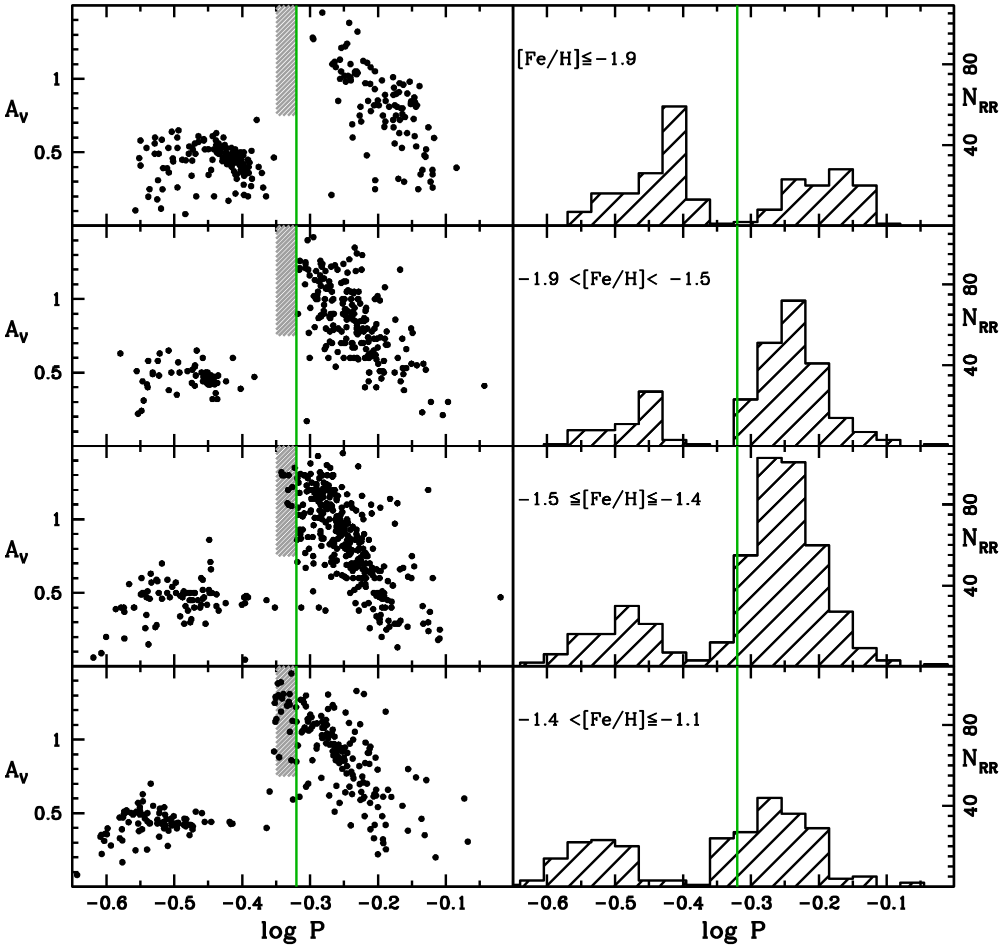

Figure 2. Same as in Figure 1 but for 2 LMC and 16 Galactic GCs. They are grouped according to Harris (1996) in metallicity bins increasing from the top to bottom panels. (First bin) NGC 7078, NGC 4590, NGC 5024, NGC 2257; (second bin) NGC 1466, NGC 5286, NGC 7006, NGC 3201, IC4499; (third bin) NGC 6715, NGC 6934, NGC 6229, NGC 6981, NGC 5272; (fourth bin) NGC 5904, NGC 6266, NGC 6121, NGC 6362. Most of the RRL used in GCs belong to the catalog of Clement et al. (2001) with few exceptions, namely, NGC 6121 (or M4; Stetson et al. 2014b), NGC 6934 (Kaluzny et al. 2001), NGC 7006 (Wehlau et al. 1999), NGC 2257 (Walker 1993), and NGC 1466 (Walker 1992).

Table 1
Mean RRab Properties

	Gal. In Halo	Gal. Out Halo	dSphs +UFDs	LMC	Sgr	GGCs
⟨Pab⟩	0.584 ± 0.001	0.576 ± 0.001	0.610 ± 0.001	0.575 ± 0.002	0.576 ± 0.001	0.580 ± 0.002
$\sigma_{\rm Pab}$	0.08	0.07	**0.05**	0.07	0.07	0.07

The mean and the σ of the period distribution observed in dSphs (in bold in Table 1) does not increase when the RRab sample is almost doubled due to the inclusion of newly detected RRab stars (Peter B. Stetson 2014, private communication) in Fornax ($\gtrsim$1000 RRab) and Sculptor (∼300).

2.1. Why HASP RRL are Missing in dSph?

GCs are fundamental laboratories to constrain old stellar populations, since they individually host stars with similar age and chemical composition. To investigate the fine structure of the instability strips (IS), we selected 16 Galactic GCs hosting at least 35 RRL according to the Clement et al. (2001) catalog (2013 edition; see Figure 2). To extend the metallicity range covered by the selected GGCs, we included two LMC globulars, namely NGC 1466 and NGC 2257 (Walker 1992, 1993). The entire sample covers a range in metallicity of [Fe/H] from ~ -2.3 to -1.1 (Harris 1996, 2010 edition). To constrain the metallicity dependence, the entire sample of GCs was split into four arbitrary metallicity bins. Every bin in metallicity includes at least four GCs.

A glance at the data plotted in Figure 2 clearly shows that the HASP region starts to be filled only when RRL have a metallicity $\gtrsim -1.5$ dex. It becomes more populated when the metal content increases to -1 dex. The above evidence suggests the hypothesis that metallicity is the key parameter causing the lack of HASPs in dSphs. It would imply that the maximum metallicity reached by the stellar population to which the RRL belong in dSphs is [Fe/H] $\lesssim -1.5$, and that the other stellar systems have reached a higher metallicity at the early time when they were still able to produce stars of a mass suitable for becoming today's RRL. Additionally, a firm dependence of the *mean* periods on the metallicity can be observed in Figure 2. The ⟨Pab⟩, when moving from the metal-poor to the metal-rich regime, decreases from 0.644 ± 0.007 to 0.599 ± 0.006 days, while the ⟨Pc⟩ decreases from 0.364 ± 0.003 to 0.300 ± 0.004 days. Moreover and even

Table 2
HASP Fractions

	Gal. In[1] Halo	Gal. Out[1] Halo	dSphs[2] +UFDs	LMC[3]	SMC[4]	M31[5] halo	M31[6] field	M32[7]	M33[8]	Sgr[9]	Gal.[9] Bulge
$N_{\rm HASP}$/NRRL	8%	6%	0%	6%	1%	3%	9%–12%[a]	7%[a]	2%[a]	6%	17%
$\langle$[Fe/H]$\rangle \pm \sigma$	n.c.	n.c.	$\lesssim -1.4 \pm 0.1$[11]	-0.5 ± 0.4[11]	-1.0 ± 0.2[11]	n.c.	n.c.	-0.25 ± 0.1[11]	-0.5 ± 0.1[12]	-0.4 ± 0.2[11]	-0.3 ± 0.5[13]

Notes.
[a] These numbers should be treated cautiously due to the limited temporal sampling of the data used to identify and characterize RRL.

References. (1) Compilation in this Letter; (2) Compilation made in Stetson et al. (2014a); (3) Soszyński et al. 2010; (4) Soszyński et al. 2009; (5) Brown et al. 2004; Jeffery et al. 2011; Bernard et al. 2012; (6) Jeffery et al. 2011; (7) Fiorentino et al. 2012; (8) Yang et al. 2010; (9–10) Soszyński et al. 2014; (11) McConnachie 2012; (12) Bresolin et al. 2010; (13) Uttenthaler et al. 2012.

more importantly, the fraction of HASPs over the total number of RRab stars is vanishing in the two most metal-poor bins and becomes of the order of 3% and 14% in the two most metal-rich bins in order of increasing metallicity.

To further validate the above trend, we investigated the occurrence of HASPs in other nearby stellar systems (see Table 2). For some of these systems, space observations (in F606W filter) are available. In order to select the HASP RRab we converted F606W amplitudes into the Johnson–Cousin photometric system, assuming $A_{F606W}/A_V = 0.92$ (Brown et al. 2004). We selected RRab with periods shorter than 0.48 days and luminosity amplitudes larger than A_{F606W} =0.69. We found that the ratio of HASP RRL to total number of RRab follows a trend similar to GCs and, indeed, they range from a few percent in systems where the mean metallicity is poor (Small Magellanic Cloud, SMC) to more than ∼10% in more metal-rich systems (Bulge).

In this context, the two peculiar RRab in Cetus (Bernard et al. 2009), located in the HASPs region, might trace the tail of a metal-rich stellar component. Their luminosity is ∼0.1 mag fainter than the remaining ∼500 RRL, thus suggesting an important metallicity increase in the early star formation event experienced by this quite massive galaxy.

2.2. *Insights from Pulsation and Evolutionary Theory*

Nonlinear, convective hydrodynamical models of radial variables indicate that RRab have their largest amplitudes close to the fundamental blue edge (FBE; Bono et al. 1994).

The FBE boundary is almost constant over a broad range of metal abundances ($-2.3 \lesssim$ [Fe/H] $\lesssim -1.3$; Bono et al. 1995). This means that the pulsation properties of an RRL across the IS are dictated mostly by its evolution. A change in chemical composition causes a change in stellar mass and in luminosity, and in turn a change in the morphology of the evolutionary paths crossing the IS. Pulsation and evolutionary prescriptions indicate that the minimum period reached by RRab, i.e., the period at the FBE, decreases as the metal content increases. In particular, Bono et al. (1997) showed that log $P^{\rm min}_{\rm ab}$ decreases from −0.26 to −0.37 when Z increases from 0.0001([Fe/H] ∼ −2.3, using α-enhanced values) to 0.001([Fe/H] ∼ −1.3). These predictions agree quite well with the minimum period observed in M3 and in M15—globulars characterized by sizable samples of RRL.

This scenario suggests that old stars in dSphs, in spite of their complex star formation and chemical enrichment history, are characterized by a narrow metallicity distribution when compared with relatively "simple" stellar systems in the MW such as GCs. A complementary conclusion was reached by Salaris et al. (2013), who studied in detail the horizontal branch morphology of the Sculptor dSph. They found that this can be explained, at odds with GCs, without invoking He-enhanced models (Rood 1973). This evidence further supports the above findings, since an increase in the helium content would imply, at fixed intrinsic parameters, a steady increase in the pulsation period (Marconi et al. 2011), thus further exacerbating the HASPs problem.

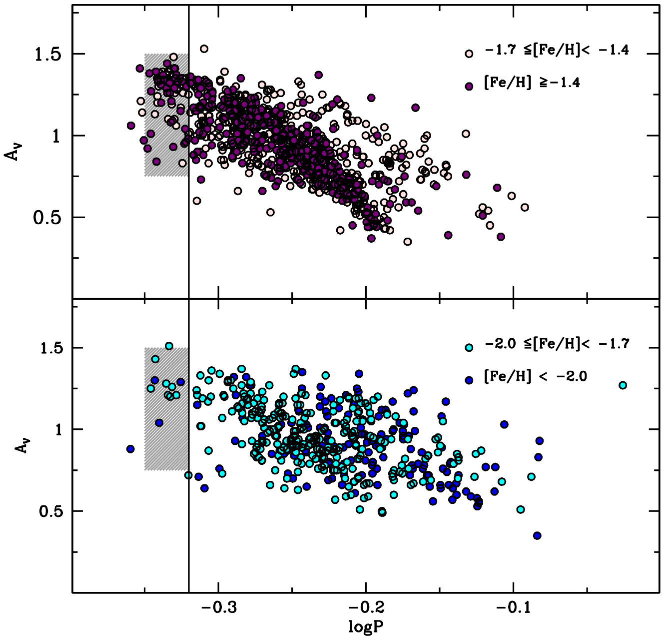

Figure 3. Same as Figure 1, but for the RRL for which an estimate of metallicity exists from SDSS (Drake et al. 2013).

2.3. *Evidence from SDSS Optical Spectra*

The recent evidence of multiple stellar populations in GCs (Monelli et al. 2013, and references therein) and the fact that the horizontal branch in dSphs can be reproduced without assuming any helium enrichment or complex mass-loss law (Salaris et al. 2013) induce us to question whether we are using too complex stellar systems to understand the HASP dearth in dSph. In order to corroborate the hypothesis that low metallicity is the cause of the missing HASP in dSphs, we take advantage of the medium-resolution Sloan Digital Sky Survey (SDSS) spectra available for a sample of ∼1400 fundamental mode RRL (Drake et al. 2013). Given that the RRL span a magnitude range from 14 and 20 mag, the error bar of each individual metallicity estimate has been estimated of $\lesssim$0.2 dex, as discussed in Yanny et al. (2009). In Figure 3 we show the Bailey distribution of these stars grouped in four metallicity bins. Note that RRL in the above metallicity bins cover similar ranges in Galactocentric distances ($5 \lesssim d_G \lesssim 60$ kpc). We can clearly see that metal-rich groups of RRL ($[\mathrm{Fe/H}] > -1.7$, top panel) tend to populate the HASP region, whereas the metal-poor ones ($[\mathrm{Fe/H}] \lesssim -1.7$) leave this region almost empty, starting from period lpgP $\lesssim -0.3$. Although the absolute value of the metallicity at which the transition occurs would need a careful calibration of these data, we find a trend in agreement with that observed in GCs.

3. IMPLICATIONS FOR THE EARLY FORMATION OF THE HALO

We have shown that the period distribution of RRL in nearby dSphs follows a Gaussian distribution with a smaller dispersion ($\sigma = 0.03$) than the Halo one, which is more skewed to short periods. This peculiarity of the dSphs is not observed in GGCs, the LMC, or the Sgr dwarf. Furthermore, we found evidence that, in order to populate the HASP region, an old component more metal-rich than $[\mathrm{Fe/H}] \sim -1.5$ is required (see Figure 2). In the following, we will analyze the evidence provided by the RRL populations on the building of the Halo from the combination of different types of progenitors. In this exercise, we will assume that the Halo sample is statistically significant, i.e., that an increase in its size would not affect the shape of the period distribution.[11]

We will first try to obtain an upper limit on the Halo fraction originating in dSph-like systems. For that, the period distribution of RRab in dSph (panel (a) of Figure 1) has been rescaled to fill the maximum possible area under the curves representing the period distribution for both the inner and outer Halo (red histograms in Figure 1, panels (c) and (d)). Assuming that the RRab falling inside the area covered by the red distribution have been entirely accreted from dSphs, we find that the maximum contribution of dSph-like systems into the inner and the outer Halo cannot be more than ∼50%. This fraction has to be cautiously treated. In fact, it is *an extreme upper limit* since the *difference* between the black and red histograms consists almost entirely of short-period variables, completely unlike the observed LMC and Sgr distributions. Any admixture at all of these latter two population types to fill in the short periods would result in far too many halo variables with $\log P \sim -0.22$ days.

Even though the above results rely on rough preliminary estimates, they pose a serious question: *Where does the rest (in fact most) of the Halo mass come from?* There are two main scenarios proposed: (1) from few large and metal-rich stellar systems LMC or Sgr-like (as suggested by Zinn et al. 2014; Tissera et al. 2014); (2) in situ stellar formation (Brusadin et al. 2013; Vincenzo et al. 2014).

From the exceptionally complete OGLE III and the new OGLE IV data for the LMC and the Sgr dwarf, respectively, presented in Section 2, we have noticed that their RRab populations share similar properties with that of the Halo in terms of mean period and sigma, and HASP fraction (Table 2). We remember here that the application of a one-dimensional Kolmogorov–Smirnov (K-S) test on the LMC, dSphs, GGCs, inner and outer halo period distributions (Stetson et al. 2014a) strongly support the evidence that their cumulative distributions are not drawn from the same parent population (probability $\lesssim$0%). Interestingly enough, the one-sample K-S test applied to the new Sgr RRab population does support, with a not negligible probability (10%[12]), that the outer Halo and Sgr are drawn from the same distribution. We highlight here that the exceptional completeness of the very large OGLE LMC sample may partially hide similarities between the RRab Halo and LMC distributions.

We performed the same exercise described above in order to estimate the fraction of the Halo that may have formed from systems similar to the LMC or Sgr. We apply a scaling factor to the LMC and Sgr RRab period distribution in order to match the largest possible fraction of the halo distribution. We find that ∼80%–90% of the halo may have been formed from this kind of stellar systems, thus supporting hypothesis (1). The HASP fraction of the Halo further supports previous conclusions (Venn et al. 2004; Helmi et al. 2006) that typical dSphs played a minor role, if any, in its early formation. In this Letter, we have provided evidence that HASP RRL are missing in dSph because these galaxies did not reach a metallicity high enough during the time they were able to produce RRL. In other words, in their internal chemical evolution the dSphs achieved a metallicity $[\mathrm{Fe/H}] \sim -1.5$ *too recently in the past* for stars of a mass suitable for making RR Lyraes to be currently evolving from the main sequence. The LMC, Sgr, and the Halo, in contrast, achieved these higher metallicities more quickly. This gives an indication that the early chemical enrichment histories of dSphs and more massive stellar systems are dissimilar, in the sense that chemical enrichment was faster in larger galaxies. This is in agreement with the well-defined scaling relation between mass/luminosity and metallicity (Chilingarian et al. 2011; Schroyen et al. 2013; Kirby et al. 2008) obeyed by dwarf galaxies, with more massive galaxies being more metal-rich, and having a broader metallicity distribution. It follows that the Halo was made primarily from progenitor galaxies larger than those that survived to become today's dSphs. Future surveys like GAIA will provide a census of a significant fraction of the Halo, discovering more than 70,000 new RRL (Eyer & Cuypers 2000). This is the required new information to constrain whether the major contributors of the Halo should be sought in massive dwarf galaxies—LMC and/or Sgr-like—or in some different formation scenario.

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[11] The validity of this assumption depends on the Galactocentric distance. The new variability surveys (CATALINA; Drake et al. 2013, their Figure 13) appear to be quite complete (∼50%) out to 40 kpc ($V \sim 18$ mag). If this assumption is wrong—that is, if the Halo is affected by a significant amount of uncompleteness—this could affect the results of the Kolmogorov–Smirnov test presented in this section. However, we can be confident that it would not affect the HASP fractions: in all the stellar systems, including the Halo, the HASP fraction is not sensitive to the cut in amplitude used. This evidence suggests that the Halo sample incompleteness is far from severe.

[12] This result is not affected by possible presence of Sgr RRL in the outer Halo. We neglected RRL with $d_G \gtrsim 30$ kpc (Zinn et al. 2014; Drake et al. 2013) and both the mean period ($\langle \mathrm{Pab} \rangle = 0.576 \pm 0.001$ [0.07]) and the correlation (10%) attain similar values.

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