Mem. S.A.It. Vol. 93, 47

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On the early formation of the Galactic halo traced by RR Lyrae stars

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Received: 1 December 2022; Accepted: 21 December 2022

Abstract. We investigate the early formation of the Galactic halo by using as old stellar tracer the RR Lyrae variables (RRLs). Thanks to extended photometric and spectroscopic surveys we can provide firm constraints on the link between the Halo and the Milky Way satellite systems (dwarf galaxies). The comparison between pulsation properties (periods, luminosity amplitudes) for fundamental mode RRLs in these stellar systems suggests that the Halo has been mainly formed by major merging events and in-situ formation. We also found that similar outcomes can be drawn by using short-amplitude, short-period (SASP) RRc variables. Preliminary results based on the comparison between the [α/Fe] vs [Fe/H] plane for RRLs and red giants collected by APOGEE indicate that RRLs overlap quite well with field Halo stars. In particular, they define an old-sequence that goes from metal-poor and α-enhanced to α-poor and solar/super solar iron abundance.

Key words. Galaxy: Halo – Stars: Variables: RR Lyrae stars – Dwarf galaxies: Resolved stellar populations

1. Introduction

The use of ancient stars to investigate the early formation of the Milky Way and the role of dwarf galaxies in this process has been defined as nearby Cosmology or Galactic Archaeology. Several spectroscopic investigations have been aimed at constraining the chemical abundances, and in particular, to their alpha over iron abundance ratio of Halo stars and dwarf galaxies (Venn et al. 2004; Lemasle et al. 2012, 2014; Fabrizio et al. 2015). Elemental abundances have the imprint of the giant molecular cloud from which they originate. This approach brings forward some drawbacks because truly old Galactic halo (hereinafter, Halo) stars are compared with bright red giant branch stars of dwarf galaxies. However, red giants are a mixed bag concerning stellar ages because they can cover an age interval of several Gyrs Gallart et al. (2015).

Another common approach to look for ancient stars is to search extremely metal poor stars ([Fe/H]≤ -3) belonging to the Halo and to dwarf galaxies (Frebel & Norris 2015). However, these objects are extremely rare (Caffau et al. 2020). A complementary approach is to compare purely old stars, such as RR Lyrae stars, i.e. Horizontal branch stars typically older than 10 Gyrs, (Monelli & Fiorentino 2022). This last approach, thanks to the current and future extended photometric and spectroscopic surveys appears very promising. RR Lyrae stars have two key advantages, they are excellent distance indicators, they trace quite well the different Galactic components, and they are also very common. Moreover, RRLs have been identified in all the nearby stellar systems in which they have been searched for, with the obvious exception of young stellar systems.

This approach dates back to the 1939 (Oosterhoff 1939), when based on five globular clusters, he suggested that the mean period of fundamental mode RRLs in Galactic globular clusters showed a dichotomic distribution, named after him Oosterhoff dichotomy. RR Lyrae stars in metal-poor globular clusters, namely (M15, M53, M68, M92) showed longer periods (P_{ab} ~0.65 days) than metal-rich ones (M3, M5) with P_{ab} ~0.55 days, see Monelli & Fiorentino (2022) for a recent review. This dichotomy does not show up in dwarf galaxies that instead show intermediate mean periods, P_{ab} ~0.6 days. In this paper we discuss recent findings that have been possible thanks to long term photometric surveys (Gaia, Catalina, OGLE) and spectroscopic public surveys (SDSS, LAMOST, RAVE) and to the huge effort of a group of researchers that succeeded at reanalysing and homogenizing data coming from several different observing facilities.

2. RR Lyrae data collection

Thanks to a significant effort made by P. B. Stetson, ground based archival data for Local Group dwarf galaxies satellites of the Milky Way dwarf galaxies and globular clusters have been reduced and reanalyzed for variability under a project called Homogeneous Photometry, this dataset includes: Carina (Coppola et al. 2015), Sculptor (Martínez-Vázquez et al. 2016a,b), Fornax (Stetson et al. 2014; Fiorentino et al. 2017; Braga et al. 2022), Canes Venatici I (Kuehn et al. 2008), Crater II (Vivas et al. 2020). A similar analysis has been made for nearby isolated dwarf spheroidals such as LeoI (Fiorentino et al. 2012), LeoII (in preparation), Tucana and Cetus (Bernard et al. 2009), and for M31 satellites (Martínez-Vázquez et al. 2017; Monelli et al. 2017), for which Hubble Space Telescope photometry was collected.

Concerning the Halo, we are facing a golden age for stellar variability thanks to several ongoing long term optical (Catalina, OGLE, DES, Gaia) and MIR (NeoWISE) photometric surveys. Our group has collected a photometric catalog including optical, near-infrared and mid-infrared photometry for more than 120'000 Halo RRLs. In passing we note that near and mid infrared mean magnitudes are more solid measurements than optical magnitudes to estimate individual distance of RR Lyrae stars (Braga et al. 2015, 2021; Mullen et al. 2021). The reason is quite simple, RRL obey to a well defined period Luminosity relation only for wavelengths longer than the R-band. Furthermore, the slope becomes steeper and the intrinsic dispersion decreases when moving from the optical to the near-/mid-infrared regime.

Spectroscopic data are mandatory to fully exploit the potential of RRLs as Halo stellar tracers. However, RRLs experience rapid atmospheric changes along the pulsation cycle and chemical abundance investigations might be difficult. The opportunity to collect high quality spectra for both faint and bright targets with 2-10m class telescopes, allowed us very detailed studies of the atmospheric phenomena in field and cluster RRLs (For et al. 2011; Pancino et al. 2015; Sneden et al. 2017; Magurno et al. 2019; Crestani et al. 2021b). These investigations confirmed that nonlinear phenomena (shocks) are restricted to a very narrow phase of a few tens of minutes, thus paving the way to random phase observations to secure spectra for RRL abundance determinations.

High resolution spectroscopy is still a resource-consuming endeavor. This means that detailed studies of the Galactic halo require spectroscopic diagnostics based either on low-resolution spectra or on photometric indices. These are the reasons why our group started a long-term observing campaign to secure a large sample of high-resolution (HR) RRL spectra (Magurno et al. 2018, 2019) collected at ESO HR spectrographs (FEROS@2.2m MPG, HARPS@3.6m, UVES@VLT) and at DuPont and Magellan (Las Campanas Observatories) thanks to a collaboration with C. Sneden (University of Texas) and G. Preston (Carnegie Observatories). These spectra were adopted to perform a new calibration of the Delta S method (Preston 1959; Layden 1994; Crestani et al. 2021b) by using more than 5,000 low-resolution spectra collected with SDSS/SEGUE. More recently, our group complemented the spectroscopic data set with ~9,000 low-resolution spectra available in the LAMOST survey (Fabrizio et al. 2021).

We applied the new Delta S method and together with similar estimates available in the literature we ended up with more than 9,500 RRLs for which we have homogeneous iron abundance estimates and at least one radial velocity measurement. Furthermore, we also performed a new calibration of the Fourier parameters of both optical and MIR light curves (Mullen et al. 2021; Mullen et al. 2022) thus doubling the number of field RRLs for which we do have either a measurement or an estimate of the iron abundance.

We build up a catalogue including photometric (mean magnitudes, reddenings, distances), spectroscopic (radial velocity, iron abundance), astrometric (proper motion) and pulsation properties (period, pulsation mode, luminosity amplitude) for field RRLs. This catalogue is the stepping stone we adopted to investigate several open problem concerning the early formation of the Galactic Halo.

3. A new spin on the Oosterhoff dichotomy

In this section we will briefly summarize the analysis already presented in (Fabrizio et al. 2019, 2021) and also discussed in (Monelli & Fiorentino 2022), to further support the potential of an homogeneous spectroscopic catalogue. Chemical abundances based on a mix of low- and high-resolution spectra for more than 9,000 field RRLs (6,150 fundamental mode [RRab], 2,865 first-overtone mode [RRc]) clearly indicate that both periods and amplitudes display a linear anti-correlation with the metallicity. An increase in the metal-content causes a steady decrease in the pulsation period and in the visual amplitude (see Figure 9 in Fabrizio et al. (2021)). In this context, it is worth mentioning that the coefficient of the metallicity term is similar for both RRab and RRc Period-Metallicity and Amplitude-Metallicity relations (see formulae 5/6 and 7/8 in Fabrizio et al. (2021)). Moreover, we found that the Halo mean period of RRab variables at the edge of the Oosterhoff I classification is P_{ab} = 0.58 days. This means that the dichotomy disappears once we are dealing with large samples of field RRLs. Indeed, the current empirical evidence indicates a linear trend as predicted by the pulsation relation (van Albada & Baker relation, (van Albada & Baker 1973)) taking account for evolutionary (stellar mass, luminosity, effective temperature, chemical composition) and pulsation (periods, pulsation mode) properties of RRL variables Caputo et al. (1998).

The dichotomy discovered by Oosterhoff in 1939 by observing cluster RRLs and confirmed by many following photometric investigations, appear to be the consequence of a poor

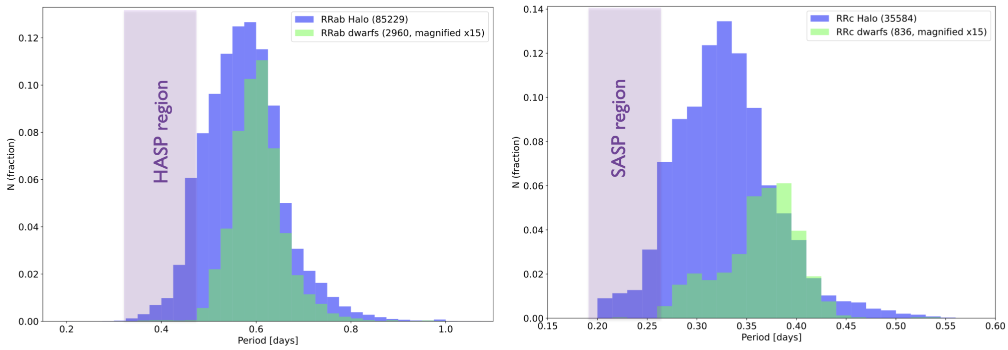

Fig. 1. *Left panel:* Period distribution for 2960 RRab stars in dwarf (green) and 85229 RRab in the Halo (blue). Catalogues are updated when compared with (Fiorentino et al. 2015, 2017). The HASP region is highlighted with a light purple color. *Right panel:* Same as the right panel but, for RRc variables. The SASP region (see the text for more details) has been highlighted with a light purple color.

populated Instability Strip for cluster RRLs at the intermediate metallicity ([Fe/H]~-1.5). It is clear that the *second parameter* problem, affecting, together with the metallicity (the *first parameter*) the Horizontal Branch morphology, can play a fundamental role in the global properties of cluster RRLs

but we still lack a detailed knowledge of the metallicity distribution of field RRLs in the Magellanic Clouds or in nearby dwarf galaxies hosting globular clusters to reach a firm conclusion.

These circumstantial evidence, together with spectroscopic studies of chemical anomalies in globular clusters when compared with the MW halo (Carretta et al. 2009), suggest that Globular clusters are not solid tracers of the Galactic halo, since they do not share similar chemical enrichment histories.

4. HASP and SAPS in the Halo and in dwarf galaxies

In this Section we discuss some new results based on the presence of High Amplitude Short Period (HASP, Fiorentino et al. 2015) RRLs in the Galactic halo. These stars appear when a stellar system undergoes a fast early chemical enrichment, so that its old stars, such as RRLs, reach metal abundances of [Fe/H] ≥ -1.4 dex. This result, firstly tested using cluster RRLs (Fiorentino et al. 2015), has been confirmed by low resolution (Fabrizio et al. 2019) and high resolution spectroscopy of Halo field RRLs (Crestani et al. 2021b).

The observation of these variable stars in the Bailey diagram (amplitude vs period) and in the period distribution is a relevant diagnostic to interpret the formation of the Halo (see Fiorentino et al. 2015, 2017, for more details). In Figure 1, we show an updated period distributions of the Halo, by using our new photometric catalogue cross-correlated for the first time with Gaia DR3 data. This includes more than 120,000 RRLs and we compare them with RRLs in nearby dwarf galaxies. The sample of dwarf galaxies includes ~ 4,000 RRLs and has been updated by using the following list of galaxies: Bootes, Canes Venaticorum I, Canes Venaticorum II, Carina, Cetus, Coma Berenices, Draco, Fornax, Hercules, LeoI, LeoIV, LeoT, Sculptor, SEGUE 2, Tucana, Ursa Major I, Ursa Major II. The RRLs from these galaxies are treated all together to increase the statistics of the sample and relies on the assumption that dwarf galaxies bring forward similar contributions to the early formation of the Halo. Moreover, we also compare for the first time RRc variables.

The period distribution of RRLs in dwarf galaxies have been arbitrarily scaled (by a factor 15) to the Halo RRLs in order to highlight

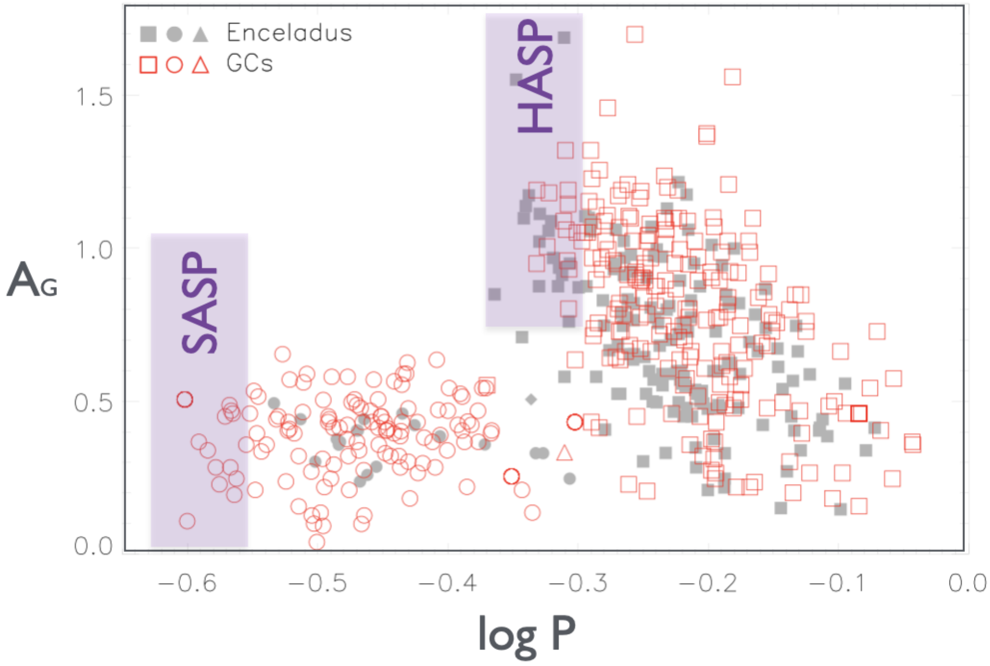

Fig. 2. The Bailey diagram for Enceladus, (grey dots) and for the RRLs in globular clusters that have been suggested to belong to Enceladus by Massari et al. (2019). The visual amplitude of cluster RRLs was transformed into Gaia A_G by using Eq.2 in Clementini et al. (2019). Squared, circles and triangles represent fundamental (RRab), first-overtone (RRc) and double mode pulsators (RRd).

Table 1. List of the mean, medians and sigma of the RRL period distributions shown in Figure 1.

Host	type	mean	median	σ
dSphs	ab	0.606	0.602	0.065
dSphs	c	0.363	0.363	0.040
Halo	ab	0.574	0.571	0.083
Halo	c	0.327	0.326	0.052

the main differences of the two samples. The scaling factor was fixed in such a way that the period distribution of RRL in dwarf galaxies remains within the Halo one.

One can notice that the period distribution (left panel of Figure 1) of RRab in dwarf galaxies is a Gaussian with a well defined peak at P∼ 0.606 days (see Table 1), whereas the period distribution of Halo RRLs is more skewed with a significant short-period tail. The period distribution of RRab in dwarfs, as already noticed in Fiorentino et al. (2015), never rich the short period tail of the Halo (Periods ≤ 0.48 days), the so called HASP RRLs are in fact missing.

This evidence is telling us that dwarfs galaxies of small size (less than 10^9 $M_\odot$) were not able to enrich their metallicity enough to reach a metal content of [Fe/H]≥-1.4. Th reader interested in a more detailed discussion concerning the correlation between HASP RRLs and galaxy mass-metallicity relation is referred to Fiorentino et al. (2017).

The right panel, of Figure 1 shows a similar result, but for RRc variables. RRc in dwarf galaxies do not reach periods shorter than ~0.26 days, whereas the periods of Halo RRc are as short as ~0.2 days. This evidence is once again correlated to the metallicity effect: an increase in the metal content causes a steady decrease in the pulsation period. A glance at the Bailey diagram colour-coded according to the metal content based on high resolution spectra (see Figure 4 of Crestani et al. 2021b), clearly shows that only RRLs more metal rich than [Fe/H] ∼ -1.4 fill the short period tail that we call the Small-Amplitude and Short-Period (SASP) region of RRc variables. They can be considered the counterpart of the HASP for RRab variables. The period distribution of RRc in less massive dwarfs when compared with the Halo, are clearly indicating that this sample played a minor role in building up the Halo. The marginality is even more evident than for RRab variables.

In passing we note that the possible occurrence of metal-rich RRc variables was early suggested, on the basis of theoretical models, by Bono et al. (1997). Indeed, they interpreted the evidence of a secondary peak in the period distribution of field RRc variables at P~0.28 days as an evidence for a more metal-rich RRL component.

The use of HASP RRLs allowed us to figure out that dSph galaxies less massive than $10^9 M_\odot$ played a minor role in the Halo formation. In Figure 2 we show the Bailey diagram for the newly discovered dwarf galaxy Gaia Enceladus (Helmi et al. 2018; Belokurov et al. 2018). This sample is based on the selection performed by (Helmi et al. 2018). The presence of HASP RRLs further supports the key role that this major merger played in the Halo formation. The same figure also shows the RRLs from globular clusters that have been associated, according to their proper motion, to Enceladus (NGC 1261, NGC 1851, NGC 1904, NGC 2298, NGC 2808, NGC 288, NGC 362, NGC 4147, NGC 4833, NGC 5286, NGC 5897, NGC 6205, NGC 6229, NGC 6235, NGC 6284, NGC 6341, NGC 6779, NGC 6864, NGC 7089, NGC 7099 and NGC 7492) as suggested by Massari et al. (2019). The presence of HASP RRLs in Enceladus RRLs is a further evidence suggesting that these stellar systems experienced a fast early chemical enrichment. The lack of SASP RRLs might be suggestive of an observational bias in the identification of low-amplitude RRc variables. This working hypothesis is further supported by RRLs in globular clusters that have been associated to Enceladus, since they do show both SASP and HASP RRLs.

In Figure 3, we show the Bailey diagram for the disrupted Sagittarius dwarf spheroidal galaxy together with the globulars associated (Callingham et al. 2022) to this dwarf galaxy, namely M54 (NGC6715) and Arp 2. The other clusters that have been associated to Sagittarius are: Ter 8, Ter 7, Pal 12 and Whi 1, but they do not host RRLs. Even at a cursory look the data plotted in this figure display that the Bailey diagram for M54 and Sagittarius are quite similar, in particular, they display both HASP and SASP RRLs. In this context Arp 2 should be cautiously treated, since it includes HASP, but not SASP RRLs. However, this apparent peculiarity is probably due to the limited RRL sample (8 RRab, 1 RRc) hosted by this cluster. This evidence is also suggesting that RRL pulsation properties are a solid diagnostic to trace back in time the origin of cluster and field RRLs. More spectroscopic data are required to further investigate the role that chemical enrichment, dynamical evolution and pulsation properties play in constraining the origin of globular clusters.

5. The [α/Fe] vs [Fe/H] plot for RR Lyrae stars: a comparison with APOGEE

Galactic archaeology relies on the use of the [α/Fe] vs [Fe/H] plane as a very efficient diagnostic to investigate the formation timescale

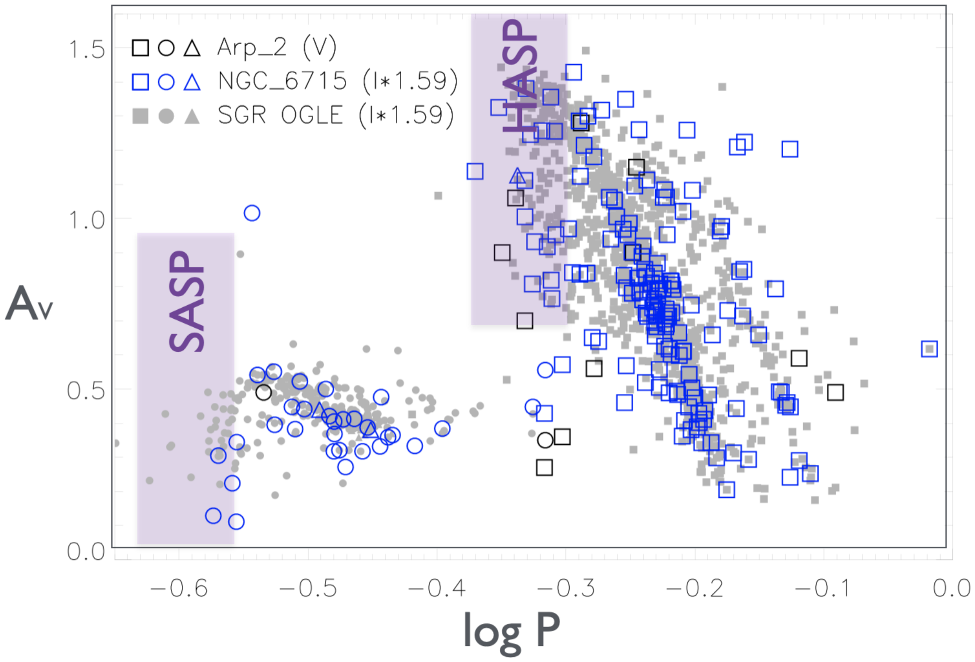

Fig. 3. Bailey diagram of the Sagittarius dSph (grey symbols) and two associated Globular clusters: NGC 6715 (M54, blue symbols) and ARP2 (black symbols). Squared, circles and triangles represent fundamental (RRab), first-overtone (RRc) and double mode pulsators (RRd).

of the various Galactic components. This plot is generally made for stars coming from different episodes of star formation. Their individual ages are usually known with large uncertainties (up to ∼ 50%), but asteroseismology (Miglio et al. 2021). In this context RRLs play a key role, because theory and observations indicate that they are typically older than ∼10 Gyrs. In the following, we discuss some preliminary results concerning the comparison between the [αFe]vs[Fe/H] based on APOGEE (H-band high resolution spectra, DR17 Horta et al. 2021, and reference therein) and chemical abundances of field RRLs based on optical high resolution spectra provided by Crestani et al. (2021a). RRL measurements (blue dots) are the mean of four different species [Ca, Mg, Ti I, Ti II lines], while the black solid line shows the logarithmic relation found by (Crestani et al. 2021a) and ranging from metal-poor and α-enhanced to solar/super-solar iron abundance and α-poor.

Stars in the APOGEE catalogues were preliminary selected on the basis of a kinematic criteria to distinguish the different Galactic components: halo, thin and tick disk. We have chosen only stars with $V_{TOT} \geq 200$ km/s, where $V_{TOT} = \sqrt{(U^2 + V^2 + W^2)}$, being U,V,W velocities centered on the local standard rest-frame. In passing, we note that the adopted selection criteria are still affected by some degeneracy. Indeed, data plotted in Figure 4 (grey dots) show that the different Galactic components partially overlap. There is a well defined sequence in the metal-poor regime, reminiscent of the Galactic Halo, that moves from the metal-poor ([Fe/H]∼-2.3) to the metal-intermediate ([Fe/H]∼-1.2) regime, while the α abundances are slightly decreasing. The empirical scenario becomes more complicated in the metal-intermediate/metal-rich

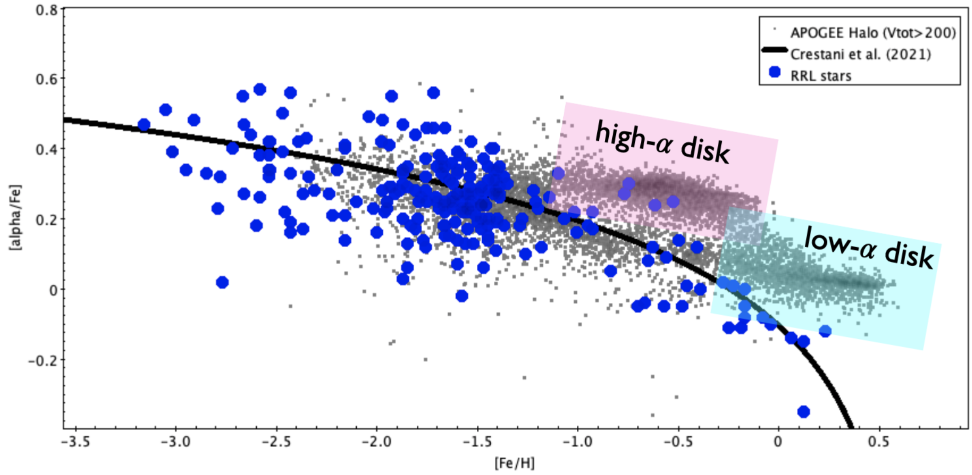

Fig. 4. Comparison in the [α/Fe] vs [Fe/H] plane between Halo field RRLs (blue circles and black solid line) (Crestani et al. 2021a) and field stars observed by APOGEE (grey dots Horta et al. 2021). The APOGEE sample was selected according to a kinematic criterium (Vtot>200 km/s), while the RRL sample according to the Galactocentric distance ($R_G \geq 5$ kpc). The areas shaded in magenta and in cyan mark the high- and the low-α disk sequences.

regime, since the α-abundances display a clear bifurcation for [Fe/H]∼-1.2 with a sequence which seems to be the natural extension of Halo-like stars into the more metal-rich regime and a sequence that is, at fixed iron abundance, systematically more α-enhanced. The latter sequence has been defined in the literature as the high-α disk sequence.

A similar bifurcation is also present at [Fe/H]∼-0.3 where RRL become systematically more metal-rich and α-poor, while the APOGEE sequence is, at fixed iron abundance, systematically more α-enhanced. This latter sequence is called in the literature as the low-α disk sequence. The α-poor and the α-rich disk sequences have been widely discussed in the literature (e.g. Hayden et al. 2015; Horta et al. 2021) and they have been highlighted with magenta and cyan shaded areas. The black solid line and the blue dots indicate that the kinematic selection on the APOGEE data brings forward a sizable sample of field Halo stars. However, the RRL sample shows prominent metal-poor and metal-rich tails that do not show up in the APOGEE data. The logarithmic relation for field RRLs does not overlap with the low- and the high-α disk sequences. The only exception are four RRLs located across the high-α sequence. This circumstantial evidence indicates that the two quoted sequence do not appear to include a significant fraction of old stars, if any. However, we cannot exclude an age difference between low- and high-α disk sequence. Moreover, we cannot investigate the role played by bulge stars in shaping the two α sequences, since RRLs in the current catalog have Galactocentric distances larger than 5 kpc.

6. Conclusions

Old stellar tracers, and in particular RRLs, are fundamental beacons to trace back in time the early formation and early chemical enrichment of the Galactic Halo. The current findings indicate that the period distribution of both fundamental and first overtone RRL is a solid diagnostic to investigate the role that minor/major merging events played in Halo formation. We found that the RRab and the RRc short period tails, called HASP (High Amplitude Short Period) and SASP (Small Amplitude Short Period) trace stellar populations more metal-rich than [Fe/H]~-1.4.

We also suggest to use the period-luminosity amplitude plane (Bailey diagram) as a diagnostic to investigate the merging history of the Galactic Halo, since periods and luminosity amplitudes are independent of uncertainties affecting distance and reddening. Indeed, we found that this plane can be safely adopted to identify RRLs belonging either to globular clusters or to stellar streams associated with Enceladus and Sagittarius dSphs.

Moreover, we also performed a detailed comparison between α-element abundances based on optical high resolution spectra for field RRLs and those based on high resolution H-band spectra for field stars collected by APOGEE. The former sample was selected according to Galactocentric distance, while the latter one was selected according to a kinematic criterium (Vtot>200 km/s). We found that the data sets overlap in the metal-poor regime. However, old stellar tracers minimally overlap with the high- and the low-α disk sequences identified in the literature. These circumstantial evidence indicate that the chemical tagging of field RRLs (Crestani et al. 2021a) can play a key role in constraining the early formation of the Galactic spheroid (Halo, Bulge), since theoretical and empirical evidence indicate that they are older than 10 Gyrs. This age discrimination is not possible with field stars since they lack of very accurate individual absolute ages. The only viable alternatives are either very accurate distances (better than 1%) and reddening or an asteroseismic approach (Miglio et al. 2021).

The current sample of field RRLs is far from being complete. This limitation applies to highly reddened Bulge regions (Navarro et al. 2021) and to the Halo outskirts. However, this field will experience in a few years a quantum jump thanks to the Vera Rubin Observatory (VRO, formerly LSST). This survey will provide a complete census of variable stars in the Local Group in six different photometric bands (u,g,r,i,z,y). VRO will move the Gaia limiting magnitude for the identification and characterization of variable stars from G~21 to g~26-27 mag and for proper motion measurements from G~20 to g~25 mag (Bono et al. 2018). The same outcome applies to forthcoming spectroscopic surveys collecting low- and high-resolution optical (WEAVE, (Jin et al. 2022); 4MOST, (de Jong et al. 2012); SDSS-V, (Abdurro'uf et al. 2022); GALAH (Buder et al. 2021); S^5 (Li et al. 2019)) and NIR (APOGEE, (Majewski et al. 2017); WINERED, (Ikeda et al. 2016)) spectra.

The empirical scenario will be further enriched by high resolution optical and near infrared Adaptive Optics assisted imagers and spectrographs like ERIS@VLT (Riccardi et al. 2022) and in the near future by MAVIS@VLT (Riccardi et al. 2022) and MICADO@ELT (Fiorentino et al. 2020) to investigate crowded stellar fields and highly reddened regions.

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Acknowledgements. G. Fiorentino, M. Monelli and G. Bono are grateful to the IAC visitor Severo Ochoa program 2022.

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