RR Lyrae Variables Population in M31 and its Satellites

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We briefly present results of RR Lyrae observations in M31 and its satellite galaxies using archival imaging from the *Hubble* Space Telescope. Published data for M31, M33, and several M31 dwarf spheroidal galaxies are also used to study the global properties of RR Lyrae stars in these systems.

From the properties of RR Lyrae stars, we find that the majority of M31 and M33 RRLs are of Oosterhoff I type, while those in M31 dSphs are of Oosterhoff intermediate type. The main parameter affecting these Oosterhoff types is likely to be metallicity. Metallicity also plays a role in the lack of RRLs among the High Amplitude Short Period (HASP, defined as those with $P \lesssim 0.48\,\mathrm{d}$ and $A_V \geqslant 0.75\,\mathrm{mag}$) variables in M31 dSphs. This difference in the properties of RRLs between the parent galaxy and its satellites, as well as the lack of RRLs in the HASP region in dSphs, is also present in the Milky Way. Therefore, systems like these dSphs are unlikely to be the main building blocks of the M31 and Milky Way halo.

1 Introduction

RR Lyrae (RRL) variable stars have long been an important and useful tool to study stellar populations. They are low-mass ($\langle M_{\mathrm{RRL}} \rangle \sim 0.65\,\mathrm{M}_{\odot}$; Koopmann et al., 1994) pulsating variable stars with helium burning cores. To produce low-mass pulsating stars, ages older than $\sim 10\,\mathrm{Gyr}$ are required, and therefore, they provide information on their host stellar systems at early times. Using the RRL light curve, the metallicity and reddening of the stars can be determined. RRL stars can also be used as standard candles to measure the distance to their parent system. They are relatively easy to detect since they are on the horizontal branch (HB) in a color-magnitude diagram (CMD), at least 3 mag brighter than the main sequence turn off (MSTO). Their relatively short periods of less than 1 day and distinct light curves also make them easy to characterize. There are three types of RRLs. The ab-type RRLs pulsate in the fundamental mode with a sawtooth-like light curve. Their luminosities rapidly increase to maximum and slowly decrease to minimum. The c-type stars are first overtone pulsators with sinusoidal light curves and generally shorter period than the ab-type. Lastly, the d-type RRLs pulsate in both the fundamental and first overtone mode. RRL stars have been extensively studied in the Milky Way (MW). In

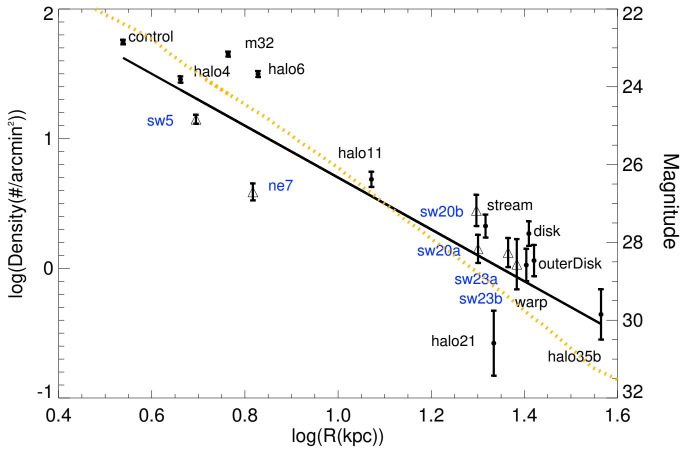

Fig. 1: Radial density profile of M31 RRL stars. The density of RRL stars of every field studied so far are plotted against the projected radius from the galaxy's center. The open triangles represent fields from this study, while the filled circles are from previously published data (halo4 and halo6 from Sarajedini et al. (2009), control and m32 from Sarajedini et al. (2012), warp and outer disk from Bernard et al. (2012) and the rest of the fields from Jeffery et al. (2011)). The solid line is the weighted least squares fit. The dotted line is the M31 spheroid surface brightness profile from Pritchet & van den Bergh (1994).

the MW globular clusters (GC), RRL populations displays two distinct sub-groups in the period-amplitude diagram. This is called the Oosterhoff dichotomy (Oosterhoff 1939). RR Lyrae in Oosterhoff type I (OoI) GCs have shorter mean periods ($\sim$0.55 d), with a smaller ratio of c-type to total RRL stars and are more metal-rich ($-1.6 <$ [Fe/H] < -1.0), while RR Lyrae in Oosterhoff type II (OoII) GCs have longer mean periods ($\sim$0.65 d) with a larger ratio of c-type to total RRL stars and are more metal-poor ([Fe/H] < -1.6). The two Oosterhoff types occupy different regions of the period-amplitude diagram with the so-called Oosterhoff gap between them. RRL stars in the field of the MW, unlike those in the GCs, tend to be OoI (Cacciari & Renzini 1976) and still show the Oosterhoff gap. Studies in the MW dwarf spheroidal (dSph) galaxies show that these stars tend to have an intermediate Oosterhoff type. The intermediate Oosterhoff type has also been observed in the M31 halo (Brown et al. 2004) and M31 dSph galaxies. However, some regions of M31 do not show this intermediate Oosterhoff type but tend to be OoI (Jeffery et al. 2011). What are the reasons behind these differences in RRL populations of the two most massive spiral galaxies in the Local Group? What do these differences imply about the early formation history of the two galaxies?

2 Radial Density Profile of RR Lyrae Stars

Using previously published data, as indicated in Figure 1 and this study, we construct a radial density profile of RRL stars in M31. The number density of RRL stars in each field is calculated and plotted against the projected distance from the galaxy's center. We fit a line using a weighted least square fit to the radial density plot in Figure 1. The error bars shown in the plot are based on Poisson noise propagated through the density calculation. The slope of the fitted line agrees with slopes found in the Milky Way (MW) and M31 halos (~ -2, see Bell et al. 2008, Tanaka et al. 2010). This suggests that most of the observed RRL stars are part of the halo of the M31. We also plotted the spheroid surface brightness profile on the M31 radial density profile. The surface brightness profile follows the same trend as our data confirming that RRLs in this study are from the halo of M31. Radial density profile of RRLs in M33 also shows the same trend (Tanakul et al., 2017).

3 RR Lyrae Stars in M31

Dwarf spheroidal (dSph) galaxies are the most common type galaxies in the Local Group. They are found around massive host galaxies such as the MW and M31. In the ΛCDM (Lambda cold dark matter; Universe dominated by cold dark matter with a cosmological constant Λ; Moore et al., 1999) theory of galaxy formation, dSphs are suggested to be the present-day counterparts to systems from which spheroids and stellar halos of larger galaxies were assembled.

Recently, there have been more studies on RRLs in M31 dSphs (for example Monelli et al. 2016, Cusano et al. 2015, Cusano et al. 2013). RR Lyrae studies in these dSphs and their host galaxy can give us information on their early formation history.

From previously published data, we have compiled all RR Lyrae properties in each dSph galaxies and construct the period-amplitude diagrams of all the M31 dSph fields as shown in Figure 2. The circles and triangles represent RRab and RRc type variable stars, respectively. The solid lines in the diagrams show the locations of RRLs in Oosterhoff I while the dot-dashed lines represent Oosterhoff II globular clusters using the relations from Zorotovic et al. (2010). From the Bailey diagrams, we can see that the majority of M31 dSph RRLs tend to be between OoI and OoII or Oosterhoff intermediate with some OoI RRLs. This is the same with RRLs in the MW dSphs.

Fiorentino et al. (2015) found that the fundamental mode RRL in most of their MW dSphs were lacking in High Amplitude Short Period (HASP) variables, which they defined as those with $P \lesssim 0.48$ days and $A_V \geqslant 0.75$ mag. These HASP RRLs are common in the MW halo and globular clusters. They further studied these HASP RRLs in 18 globular clusters hosting more than 35 RRL each and found that the metallicity seems to be the main parameter since RRL in the HASP region are only present in globular clusters that are more metal-rich than [Fe/H] ~ -1.5. The HASP region is shown as the shaded area in Figure 2. We can see that most of our dSphs are also lacking RRLs in the HASP regions. To confirm that metallicity is the main parameter affecting the lack of RRLs in the HASP region, we plot the fraction of RRLs in HASP region against the mean metallicity as shown in Figure 3. We can see that the more metal-rich galaxies do have a higher fraction of stars in the HASP region.

4 Comparison Between RRLs in M31 and its Satellites

To compare RRL properties in M31 dSphs with those in M31 and M33, we plot the period-amplitude diagram of each region as shown in Figure 4. To examine the Oosterhoff type of RRLs in each region, we plot the distribution of period difference

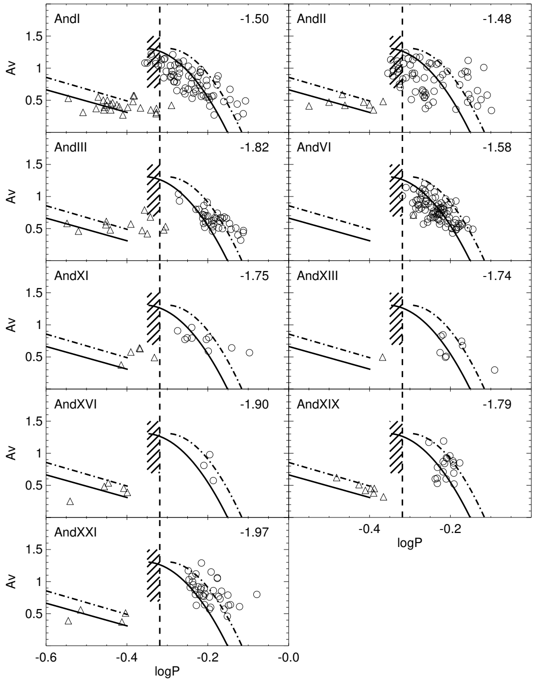

Fig. 2: Period-amplitude diagram of RRL stars in each M31 dSph galaxy. The lines show the locations of RRL stars in Oosterhoff I (solid lines) and Oosterhoff II (dot-dashed lines) clusters using the relations from Zorotovic et al. (2010). The gray area designate the region of HASP RRLs. The mean metallicity of each galaxy is shown in the top-right corner of each panel.

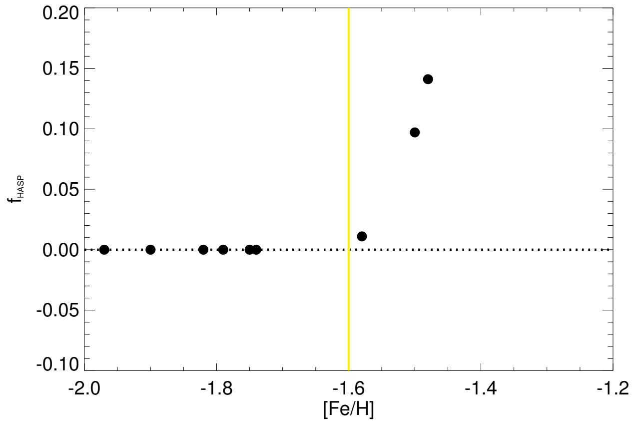

Fig. 3: The fraction of RRL in the HASP region, plotting against the mean metallicities of each dSph. The yellow vertical line indicates the metallicity of −1.6.

of each RRL from each Oosterhoff type. From this, we found that RRLs in M31 and M33 tend to be OoI, while the M31 dSphs tend to be OoI and Oosterhoff intermediate. This difference, and the fact that M31 dSph RRLs tend to be lacking in the HASP region, suggests that systems similar to the present dSphs do not appear to be the main building-blocks of the halo. This observation can also be seen in the Milky Way (Fiorentino et al. 2015).

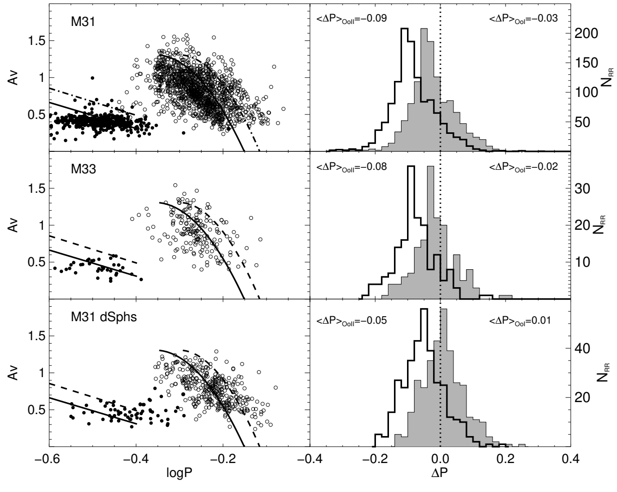

Fig. 4: This figure shows pulsation properties of different regions. The left panels are the period-amplitude diagrams of RRL stars in M31, M33, and M31 dSphs. The lines show the locations of RRL stars in Oosterhoff I (solid lines) and Oosterhoff II (dot-dashed lines) clusters. The right panels show the distribution of the difference in period of each RRL from each Oosterhoff type. The gray histograms are the difference from OoI, while the white histogram are from OoII.

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