RR Lyrae Stars in Dwarf Spheroidal Galaxies

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**Abstract.**
With ages comparable to the age of the Universe, the variable stars of RR Lyrae type have eyewitnessed the formation of their host galaxies, and thus can provide information on the processes that led to the assembling of large galaxies such as the Milky Way and the Andromeda galaxy. The present knowledge of the RR Lyrae population in Local Group dwarf spheroidal galaxies is reviewed, calling attention to the “ultra-faint” spheroidal systems recently discovered around the Milky Way by the Sloan Digital Sky Survey. The properties of the RR Lyrae stars and the Oosterhoff dichotomy observed for Galactic globular clusters and field RR Lyrae stars are discussed, since they put constrain on the possibility that the Milky Way and Andromeda halos were built up from protogalactic fragments resembling the dwarf spheroidals we observe today.

**1. Introduction**

In the Λ-cold-dark-matter theory of galaxy’s formation, dwarf Spheroidal (dSph) galaxies are suggested to be the “building blocks” from which larger galaxies were assembled via hierarchical merging and accretion. With their distinctive spheroidal shape, dSphs are the most common type of galaxies in the local universe. They have high mass-to-light ratios and are the most dark matter-dominated objects we know. In the Local Group (LG), they are generally found around the two large spirals, the Milky Way (MW) and M31. The MW is surrounded by 10 “bright” dSph satellites spanning a range from a few to about 250 kpc in distance: Sagittarius, Draco, Fornax, Carina, Sculptor, Leo I, Leo II, Ursa Minor (UMi), Sextans, and the Canis Major overdensity, whose true nature, whether an actual galaxy or the MW warp, is still matter of debate (see, e.g., Mateu et al. 2009, and references therein). Two further “bright” dSphs, Cetus and Tucana, lie more isolated at distances of 780 and 890 kpc, respectively, from the MW. These systems are generally devoid of gas and host predominantly old stellar populations. All dSphs show in the color-magnitude diagram (CMD) prominent red giant branches (RGBs), well extended horizontal branches (HBs), and well populated main sequences (MSs). As an example of “bright” dSph we show in Fig.1 the CMD of UMi. The “bright” dSphs may also contain some younger stars populating the so called “blue plume”, as for instance in Sagittarius (see, e.g., Bellazzini et al. 2006), or intermediate-age stars, like in Fornax (see, e.g., Poretti et al. 2008, and references therein), or show complex star formation histories with multiple bursts of star formation, as in Carina (Monelli et al. 2003). The “bright” dSphs are too few in number, compared to the predictions of the Λ-cold-dark-matter theory, and contain only very few stars
Figure 1. The $V, B - V$ color-magnitude diagram of the UMi dSph galaxy, from Dall’Ora et al. (2010). The solid lines show the location of the classical instability strip for pulsating variable stars. The strip crosses the galaxy horizontal branch where many RR Lyrae stars have been detected, and the blue straggler star region, where several variables of SX Phoenicis type were also found.

as metal poor as the stars observed in the Galactic halo. Since 2005, 15 new dSph satellites were discovered around the MW (see, e.g., Moretti et al. 2009 and references therein, for an updated list), mainly based on data collected by the Sloan Digital Sky Survey (SDSS, York et al. 2000). The new galaxies are mainly concentrated around the North Galactic pole, as this is the region observed by the SDSS, but many more are likely to exist at latitudes not explored yet. Thus the census of the MW satellites is likely to increase significantly when surveys will extend to cover the full sky. The new dSphs are fainter than the previously known spheroidals, with typical surface brightness $\mu_v > 28$ mag/arcsec, they are thus named “ultra-faint” dSphs. They have properties intermediate between globular clusters (GCs) and dSphs, and contain very metal poor stars, as metal poor as $[\mathrm{Fe/H}] \sim -3.0, -4.0$ dex. Often the “ultra-faint” dSphs have irregular shape and appear to be distorted by the tidal interaction with the MW. Like their “bright” counterparts, they have high mass to light ratios. All “ultra-faint” dSphs host an ancient population as old as $\sim 10$ Gyr, and have GC-like CMDs, resembling the CMDs of metal poor Galactic clusters like M92, M15 and M68.

The CMD of an “ultra-faint” dSph galaxy, Ursa Major I (UMa I), is shown in Fig. 2.

The number of the M31 satellites is poorly constrained. Twelve dwarf galaxies were known to be M31 companions until 2004, among which only 6
Figure 2. The $V, B - V$ color magnitude diagram of the UMa I “ultra-faint” dSph galaxy, from Garofalo (2009). The solid line is the ridge line of the Galactic globular cluster M68 which has been shifted in magnitude and color to match the horizontal branch and the red giant branch of UMa I. Solid circles mark the RR Lyrae stars detected in the galaxy.

dSphs, but several new M31 satellites were discovered afterwards. The most recent census is reported by Martin et al. (2009) along with the discovery of two new M31 dSph satellites: And XXI and And XXII. As for the MW, the number of M31 satellites is likely to increase significantly in the near future.

Fig. 3 shows the location of “bright” and “ultra-faint” dSphs in the absolute magnitude versus half-light radius ($r_h$) diagram. The plot is an adapted and updated version of Belokurov et al. (2007) Fig. 8. The MW globulars and some of the M31 GCs are also shown in the figure, for a comparison. With their faint luminosities and large dimensions, the “ultra-faint” dwarfs sample a totally unexplored region of $M_V - \log(r_h)$ plane. Among the “ultra-faint” dSphs only Canes Venatici I (CVn I), the brightest of these systems, lies close to the “bright” dSphs.

2. Pulsating variable stars in the dSph galaxies

The study of the pulsating variable stars offers an additional, very powerful tool to get hints on the structure, formation and evolution of the dSph galaxies, and to infer whether they can have contributed to the formation of the MW and Andromeda halos. The pulsating variables in dSphs include: the SX Phoenicis stars, the RR Lyrae stars, the BL Herculis and W Virginis variables (which
are often referred to as Population II Cepheids), and the anomalous Cepheids. Table 1 summarizes their main characteristics. Among them, the RR Lyrae variables are the most common type. These low mass ($M < 1M_\odot$), old ($t \geq 10$ Gyr) stars can pulsate in the fundamental radial mode (RRab), in the first overtone mode (RRc) or in both modes simultaneously (RRd). They have been found in “all” Local Group galaxies, irrespective of the galaxy morphological type, thus implying that all nearby galaxies started forming stars at an early epoch, just after they were formed. The RR Lyrae stars are also primary distance indicators to measure the distance of their host systems, since they obey a luminosity–metallicity relation ($M_V(RR) - [\text{Fe/H}]$) in the visual band, and a period-luminosity–metallicity ($PLZ$) relation in the $K$ band. They can be used to map the 3D structure and the radial trends occurring in a galaxy, and to trace halos and streams. For instance, a local overdensity of RR Lyrae stars in the Galactic halo turned out to be the northern tidal stream left over by the Sagittarius dSph which is disrupting itself into the MW halo, a clear observational evidence of a merging phenomenon still going on today in the MW halo. But most importantly, the RR Lyrae stars can provide constrains on whether the
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Table 1. Main characteristics of different types of pulsating variables found in dSph galaxies.

| Type            | Period (days) | $M_v$ (mag) | Population | Age (Gyrs) | Evolutionary Phase |
|-----------------|---------------|-------------|------------|------------|--------------------|
| SX Phoenicis    | $\leq 0.1$    | 2±3         | II         | $>10$      | MS                 |
| RR Lyrae        | 0.2±1.0       | 0±1         | II         | $>10$      | HB                 |
| BL Herculis     | $< 7 \div 10$ | $-1 \div 0$ | II         | $>10$      | post-HB            |
| W Virginis      | 10±30         | $-3 \div -1$| II         | $>10$      | post-HB            |
| Anomalous Cepheids | 0.3±2.5    | $-2 \div 0$ | ?          | $\sim 4 \div 8$ | HB                 |

MW was formed by accretion of protogalactic fragments resembling the early counterparts of its present-day dSph satellites, since field and cluster RR Lyrae stars in the MW show well distinct properties, that should be also shared by any possible contributor to the MW halo. In particular, most of the MW GCs containing RR Lyrae stars divide into two separate groups according to the mean period of the fundamental-mode RR Lyrae stars $\langle P_{ab} \rangle$ and the number of fundamental and first overtone pulsators. This phenomenon is called Oosterhoff dichotomy (Oosterhoff 1939). Oosterhoff type I clusters (OoI) have $\langle P_{ab} \rangle = 0.55$ days, while Oosterhoff type II clusters (OoII) have $\langle P_{ab} \rangle = 0.64$ days (Oosterhoff 1939). The Oosterhoff dichotomy is related to the metallicity, since OoII clusters are generally metal poor with [Fe/H] $\sim -2.0$ dex, while OoI clusters are more metal rich, with [Fe/H] $\sim -1.4$ dex. In the MW Oo I and Oo II GCs lie well separated in the $\langle P_{ab} \rangle$ versus [Fe/H] plane (see Fig. 2 of Smith et al. 2009). The Oosterhoff properties of the MW GCs are summarized in Table 2.

Table 2. Oosterhoff properties of the MW GCs

| Type  | $\langle P_{ab} \rangle$ (days) | $\langle P_{c} \rangle$ (days) | $N_c/N_{total}$ | [Fe/H] |
|-------|---------------------------------|-------------------------------|-----------------|--------|
| Oo I  | 0.55                            | 0.32                          | 0.17            | $\sim -1.4$ |
| Oo II | 0.64                            | 0.37                          | 0.44            | $\sim -2.0$ |

The MW field RR Lyrae stars also seem to show an Oosterhoff dichotomy, as the RR Lyrae stars within the halo belong predominantly to the Oo I group, but with a significant Oo II component appearing to be more concentrated to the Galactic plane that the Oo I halo component (see Kinemuchi et al. 2006, Miceli et al. 2008, De Lee 2008, in comparison with Szczygieł et al. 2009).

2.1. RR Lyrae stars in the MW dSph satellites

The pulsation properties of the RR Lyrae stars observed in the “bright” dSphs surrounding the MW are summarized in Table 3. Only Sagittarius and UMi show distinct Oosterhoff types, while an Oosterhoff dichotomy is not observed among the other “bright” dSphs, as field and cluster RR Lyrae stars in these galaxies have $\langle P_{ab} \rangle$ intermediate between the two Oosterhoff types and fill the Oosterhoff
gap observed in the MW (see Fig. 4 in Smith et al. 2009). Thus, the MW is unlikely to have formed by accretion of protogalactic fragments resembling the early counterparts of its present-day “bright” dSph satellites.

Table 3. Oosterhoff properties of RR Lyrae stars in the “bright” MW dSphs

| Name          | Distance$^1$ (kpc) | $\langle [\text{Fe}/\text{H}] \rangle^1$ | N(RRab+c+d)$^1$ | $\langle P_{\text{ab}} \rangle^1$ (days) | Oo Type$^1$ |
|---------------|-------------------|------------------------------------------|-----------------|------------------------------------------|-------------|
| Ursa Minor    | 66±3              | −2.2                                     | 47+35           | 0.638                                    | Oo II       |
| Draco         | 82±6              | −2.0                                     | 214+30+26       | 0.615                                    | Oo Int      |
| Carina        | 101±5             | −2.0                                     | 54+15+6         | 0.631                                    | Oo Int      |
| Fornax        | 138±8             | −1.3                                     | 396+119(~ 2000) | 0.595                                    | Oo Int(field+GCs) |
| Sculptor      | 79±4              | −1.8                                     | 132+74+18;      | 0.587                                    | Oo Int      |
| Leo I         | 250±30            | −1.7                                     | 47+7(~ 250)     | 0.602                                    | Oo Int      |
| Leo II        | 205±12            | −1.9                                     | 106+34+8;       | 0.619                                    | Oo Int      |
| Sextans       | 86±4              | −1.7                                     | 26+7+3          | 0.606                                    | Oo Int      |
| Sagittarius   | 24±2              | −1.55                                    | >4200           | 0.574                                    | Oo I(field),I,II,Int(GCs) |
| Canis Major   | 7.1±0.1           | −1.2/− 1.7                               | 26+17           | 0.57                                     | Oo I/Oo II(GCs) |
|               |                   |                                          | 10+8            | 0.56                                     |             |
|               |                   |                                          | 30+22           | 0.66                                     |             |
| Cetus         | 780±40            | −1.8                                     | 147+8+17        | 0.614                                    | Oo Int      |
| Tucana        | 890±50            | −1.8                                     | 216+82+60       | 0.604                                    | Oo Int      |

$^1$The distance for the Canis Major dSph is from Martin et al. (2004), for Cetus and Tucana from Bernard et al. (2009), for all other galaxies from Mateo (1998).

Table 4 summarizes the properties of the RR Lyrae stars observed in the “ultra-faint” dSphs. Most of these galaxies contain very few RR Lyrae stars. Only Bootes I and Canes Venatici I have significant numbers of variables, and can be safely classified respectively as Oo II and Oo Int systems. The Oosterhoff classification of the other “ultra-faint” dSphs is more insecure given the few variables they contain, nevertheless, in so far they can be classified, they all tend to be Oosterhoff type II systems. Thus, it seems that the MW may have formed early on by accretion of protogalactic fragments similar to the present-day “ultra-faint” SDSS dwarfs as they were at earlier times.

2.2. RR Lyrae stars in the M31 satellites

Very little is known about the existence of an Oosterhoff dichotomy in M31, since only recently studies providing a characterization of the RR Lyrae stars in the M31 field and globular clusters have commenced to appear in the literature, thanks to the collection of Hubble Space Telescope (HST) observations. Twenty-nine RRab’s, 25 RRc’s, and 1 RRd were discovered in an ACS@HST field 11 kpc from the center of M31 by Brown et al (2004). According to their $\langle P_{\text{ab}} \rangle = 0.594$ days, and $\langle P_{\text{c}} \rangle = 0.353$ days values Brown et al. concluded that the M31 field is Oo-Intermediate. A different conclusion was reached instead by Sarajedini et al. (2009), who obtained $\langle P_{\text{ab}} \rangle = 0.557$ days, and $\langle P_{\text{c}} \rangle = 0.327$ days, from 555 RRab’s and 126 RRc’s in two ACS fields near M32, thus concluding that these M31 fields have Oo I properties. RR Lyrae stars in 4 M31 GCs were detected by Clementini et al. (2001) using HST archival data, but no reliable period
Table 4. Oosterhoff properties of RR Lyrae stars in the “ultra-faint” MW dSphs

| Name                        | Distance$^1$ (kpc) | $\langle [\text{Fe}/H]\rangle$ | N(RRab+c+d)$^1$ | $\langle P_{ab}\rangle^1$ (days) | Oo Type$^1$ |
|-----------------------------|-------------------|--------------------------------|----------------|---------------------------------|-------------|
| Boote I                     | 66$^{+3}_{-2}$    | −2.5                           | 7+7+1          | 0.69                            | Oo II       |
| Canes Venatici I (CVn I)   | 210$^{+4}_{-3}$   | −2.1                           | 18+5           | 0.60                            | Oo Int      |
| Canes Venatici II (CVn II) | 160$^{+4}_{-3}$   | −2.3                           | 1+1            | 0.74                            | Oo II?      |
| Coma Berenices (Coma)      | 42$^{+2}_{-1}$    | −2.3                           | 1+1            | 0.67                            | Oo II?      |
| Leo IV                     | 154 ±5            | −2.3                           | 3              | 0.66                            | Oo II?      |
| Ursa Major II (UMa II)     | 34.6±0.7          | −2.4                           | 1              | 0.66                            | Oo II?      |
| Ursa Major I (UMa I)       | 95 ±4             | −2.2                           | 3              | 0.64                            | Oo II?      |

$^1$Distances and properties of the RR Lyrae stars are from Dall’Ora et al. (2006) for Boote I; from Kuehn et al. (2008) for CVn I; from Greco et al. (2008) for CVn II; from Musella et al. (2009) for Coma; from Moretti et al. (2009) for Leo IV; from Dall’Ora et al. (2009) for UMa II; and from Garofalo (2009) for UMa I. Question marks indicate the difficulty of classifying these galaxies due to the small number of variables they contain.

derivation was possible. More recently, Clementini et al. (2009) identified and derived periods for a large number of RR Lyrae stars in B514, one of the brightest ($M_V \sim −9.1$ mag) and largest ($r_h \sim 5.4$ pc) metal poor ($[\text{Fe}/H] \sim −2.0$ dex) clusters in M31, about 55 kpc from the galaxy center. They found 82 RRab’s and 7 RRc’s having $\langle P_{ab}\rangle = 0.58$ days and $\langle P_{c}\rangle = 0.35$ days, and concluded that in spite of the low metal abundance B514 appears to be a borderline Oo I cluster.

RR Lyrae stars have been studied in 5 of the dSphs surrounding M31. Results for these galaxies are summarized in Table 5. Detection of RR Lyrae stars, without reliable period determinations, is also reported for three of the big M31 dSphs, namely, NGC147, NGC185 and NGC205, which were found to contain respectively 36 (Yang & Sarajedini 2010, and references therein), 151 (Saha et al. 1990), and 30 (Saha et al. 1992) candidate RR Lyrae stars. The studies of the M31 variables seem to indicate that the Andromeda RR Lyrae stars may have slightly different properties than the MW variables.

Table 5. Oosterhoff properties of RR Lyrae stars in the M31 dSphs

| Name  | Distance$^1$ (kpc) | $\langle [\text{Fe}/H]\rangle$ | N(RRab+c+d)$^1$ | $\langle P_{ab}\rangle^1$ (days) | Oo Type$^1$ |
|-------|-------------------|--------------------------------|----------------|---------------------------------|-------------|
| And I | 765±25            | −1.5                           | 72+26          | 0.575                           | Oo I/Int    |
| And II| 665±20            | −1.5                           | 64+8           | 0.571                           | Oo I        |
| And III| 740±20           | −1.9                           | 39+12          | 0.657                           | Oo II       |
| And V | 820±16            | −2.2                           | 7+3            | 0.685                           | Oo II       |
| And VI| 815±25            | −1.6                           | 91+20          | 0.588                           | Oo Int      |

$^1$Distances and properties of the RR Lyrae stars are from Pritzl et al. (2002) for And VI; from Pritzl et al. (2004) for And II; from Pritzl et al. (2005) for And I and III; and from Mancone & Sarajedini (2008) and Sarajedini (2009) for And V.
3. Summary

Most of the RRab stars in the MW and M31 halos have Oosterhoff type I properties, but the inner MW halo also contains a significant Oo II component. By contrast the Oo I type is rare among the dSph galaxies, where only Sagittarius is Oo I. The “bright” MW dSphs tend to be Oo-Intermediate, while the “ultra-faint” dSphs tend to have Oo II type, in so far they can be classified. The Galaxy is unlike to have formed by accretion of protogalactic fragments resembling its present-day “bright” dwarf satellites. On the other hand, systems resembling the “ultra-faint” dSphs may have contributed in the past to the formation of the MW halo. The study of the M31 RR Lyrae population is still in pioneering stage. Further data for both field and cluster variables are needed to reach firm conclusions on the Oosterhoff classification of the Andromeda galaxy.

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