Near-Field Cosmology with RR Lyrae Stars in Globular Clusters and Dwarf Galaxies

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Abstract

We argue that the Galactic halo globular cluster system cannot have formed from the accretion of "protogalactic fragments" resembling the very early counterparts of the present-day dwarf satellite galaxies of the Milky Way, or else its RR Lyrae properties would be very different from what is currently observed.

1 Introduction

How did the Galactic halo form? Modern ΛCDM cosmology favors a hiearchical picture much like the one envisaged by [17], with a galaxy like the Milky Way being the process of merger and accretion of hundreds of smaller entities (e.g., [1, 12]) not unlike the dwarf satellite galaxies that are still seen orbiting the Galaxy today. Indeed, there is at least one well-documented example of a dwarf galaxy—the Sagittarius dwarf spheroidal (dSph)—being currently accreted by the Milky Way [10]. On the other hand, a significant body of evidence points, perhaps rather surprisingly, to a scenario which appears largely inconsistent with ΛCDM predictions.

Indeed, much of the current evidence appears to suggest that dwarf galaxies such as the ones currently orbiting the Milky Way cannot have been primarily responsible for the formation of the Galactic halo (see also [7] for evidence favoring monolithic collapse in the case of Coma cluster galaxies). Among the better known inconsistencies between the modern hierarchical paradigm and the empirical evidence are the following: i) The Galactic halo contains but a few stars younger than the bulk of the halo population, unlike most of the Milky Way's satellite dSph galaxies which often do contain sizeable young components—thus suggesting that dSph galaxies cannot have been the primary "building blocks" of the Milky Way [21]. ii) The detailed abundance patterns among stars in dwarf satellite galaxies [8, 15, 18, 20, 22] is strikingly different from that in the Galactic halo, again suggesting that the latter cannot have been built up from protogalactic fragments resembling the former.

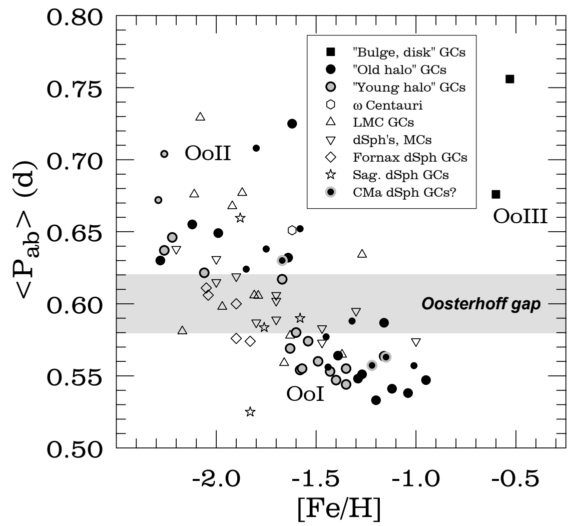

Fig. 1. Systematics of the Oosterhoff dichotomy. Note its clear presence among bona-fide Galactic globular clusters, but not among the Milky Way dwarf satellite galaxies and their globular clusters.

However, most such objections to the hierarchical model for the formation of the Milky Way can be avoided if the vast majority of the accretion events took place *very early on* in the Galaxy's history (e.g., [6, 9]). In this scenario, the satellites that survived to this day have undergone additional chemical enrichment *over a prolonged timespan*. For these reasons, in order to place meaningful constraints on the way our (undoubtedly old) Galactic halo formed, we should really compare the *very oldest stars* in both the present-day halo and the Milky Way dwarf satellite galaxies.

RR Lyrae stars, as unmistakable tracers of the oldest populations of galaxies—NGC 121 in the SMC, the youngest object known to contain RR Lyrae stars [23], appears to be at least 10 Gyr old ([5, 16, 19])—provide us with an excellent means to probe into these earliest stages of the Galaxy's formation history. In particular, if the Galaxy formed by the accretion of protogalactic fragments that resembled our dwarf satellite galaxies *as they were over 10 Gyr ago*, then the RR Lyrae pulsation properties in the Galactic halo and in the dwarf galaxies should be basically indistinguishable. The main goal of the present paper is to check whether this is the case or not.

2 RR Lyrae Stars in Galactic Globular Clusters and Nearby Dwarf Galaxies

Galactic globular clusters provide a well-known tracer of the properties of the Galactic halo. In the present section, we compare the properties of the

RR Lyrae stars in Galactic globular clusters with those of RR Lyrae stars in globular clusters and the general field of the Milky Way dwarf satellites. Specifically, we compare the average periods of the ab-type (fundamental-mode) RR Lyrae stars in the different populations. The empirical data, along with extensive references, can be found in [3].

In Figure 1 we compare the RRab period distribution of Galactic globular clusters and nearby extragalactic systems (the LMC, the SMC, the dSph satellites of the Milky Way, and their associated globular clusters). Clearly, the Milky Way globulars present the well-known *Oosterhoff dichotomy* [13, 14], or the lack of systems with average RRab periods in the range between 0.58 d and 0.62 d. This is valid both for the "old halo" and "young halo" subsystems of globular clusters, in the [11] nomenclature. Note that the satellite distribution peaks where the Galactic distribution reaches a minimum. In other words, the Oosterhoff dichotomy is not present among the Milky Way satellite galaxies.

We can quantify the above statements by carrying out statistical tests. The KMM test [2] shows that the distribution of $\langle P_{\rm ab} \rangle$ for the Galactic globular clusters is better described by a bimodal rather than a unimodal distribution, with 99.99% confidence (or higher, depending on whether the metal-rich clusters NGC 6388 and NGC 6441, marked "OoIII" in Fig. 1, as well as ω Centauri, are included or not). More specifically, the fit assigns 59% of the Galactic globulars into the OoI mode, with a $\langle P_{\rm ab} \rangle = 0.563$ d, and 41% of the clusters into the OoII mode, with $\langle P_{\rm ab} \rangle = 0.662$ d. The estimated common covariance is only 8.8×10^{-4}. This amounts to quantitative proof that the Oosterhoff dichotomy is indeed present among Galactic globular clusters. Figure 1 clearly shows, in contrast, that the satellite systems do not primarily belong to either of these two groups: in fact, a fit with two Gaussians provides one mode, containing 86% of the objects, that is centered right in the middle of the "Oosterhoff gap" zone, with $\langle P_{\rm ab} \rangle = 0.592$ d. These conclusions remain basically unchanged whether we introduce the dwarf galaxy populations (i.e., their field stars) or not. This demonstrates that the Oosterhoff gap is *not* present among the satellite populations.

3 Cosmological Implications

In terms of the ΛCDM paradigm, the preceding discussion strongly suggests that the "protogalactic fragments" that may have given rise to the Galactic halo must have had little to do with even the *very early* Sagittarius, Fornax, or LMC dwarf galaxies. In other words, if the Galaxy had formed from accretion of galaxies resembling the aforementioned ones, even its *oldest stellar populations*, as traced by the RR Lyrae stars, would have looked significantly different from what is currently observed.

By indicating that, even at the very beginning, dwarf galaxies such as Sagittarius, Fornax, and the LMC must have looked fundamentally different from any protogalactic fragments that may have helped build the Galaxy, RR Lyrae stars allow us to push further the constraints that had been previously available on the role played by dwarf galaxies in the formation of the halo.

More extensive discussions of the points raised in this article, including the role of field stars, extensive references to the data used, and the role of horizontal branch morphology in explaining the Oosterhoff dichotomy and constraining the formation history of the spheroid, can be found in [3, 4].

Acknowledgments

This work was supported by Proyecto Fondecyt Regular #1030954.

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http://www.springer.com/978-3-540-76960-6

Globular Clusters - Guides to Galaxies
Proceedings of the Joint ESO-FONDAP Workshop on Globular Clusters held in Concepción, Chile, 6-10 March 2006
Richtler, T.; Larsen, S. (Eds.)
2009, XX, 456 p. 189 illus., Hardcover
ISBN: 978-3-540-76960-6