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NEAR-FIELD COSMOLOGY WITH HORIZONTAL BRANCH AND RR LYRAE STARS

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RESUMEN

Se discute la importancia de estrellas de rama horizontal y variables RR Lyrae en el contexto cosmológico de la formación del halo Galáctico y de sus galaxias-satélite. Se muestra, en particular, que el sistema Galáctico de cúmulos globulares no puede haberse formado a partir de la incorporación de "fragmentos protogalácticos" similares a las contrapartes primordiales de las galaxias enanas satélites de la Vía Láctea, porque, de ser así, las propiedades de las variables RR Lyrae en aquél sistema resultarían muy distintas a lo que hoy se observa.

ABSTRACT

The importance of horizontal branch and RR Lyrae stars is discussed in the context of cosmological arguments for the formation of the Galactic halo and its satellite dwarf galaxies. It is shown, in particular, 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.

Key Words: **GALAXIES: DWARF — GALAXY: FORMATION — GALAXY: GLOBULAR CLUSTERS: GENERAL — STARS: HORIZONTAL-BRANCH — STARS: VARIABLES: OTHER**

1. INTRODUCTION

How did the Galactic halo form? Modern ΛCDM cosmology favors a hiearchical picture much like the one envisaged by Searle & Zinn (1978), with a galaxy like the Milky Way being the process of merger and accretion of hundreds of smaller entities (e.g., Abadi et al. 2003) 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 (Ibata, Gilmore, & Irwin 1995). 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 Forbes, Sánchez-Blázquez, & Proctor 2005, 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 (Unavane, Wyse, & Gilmore 1996). ii) The detailed abundance patterns among stars in dwarf satellite galaxies (Shetrone et al. 2003; Tolstoy et al. 2003; Venn et al. 2004; Geisler et al. 2005; Pritzl, Venn, & Irwin 2005) 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.

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., Font et al. 2006; Grebel 2006). 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, 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* $\gtrsim$ *10 Gyr ago*, then the RR Lyrae pulsa-

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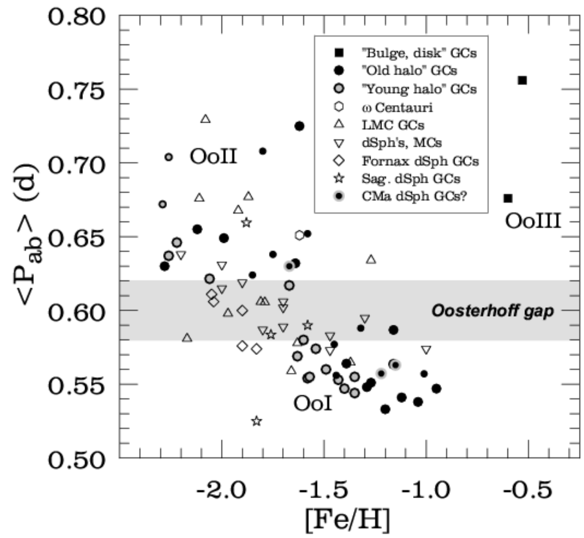

Fig. 1. Systematics of the Oosterhoff dichotomy. Note that it is clearly present among bona-fide Galactic globular clusters, but not among the Milky Way dwarf satellite galaxies and their globular clusters.

tion 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 Catelan (2006).

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* (Oosterhoff 1939, 1944), 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 Mackey & van den Bergh (2005) 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 (Ashman, Bird, & Zepf 1994) 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. HORIZONTAL BRANCH MORPHOLOGY: GALACTIC VS. NEARBY EXTRAGALACTIC GLOBULAR CLUSTERS

RR Lyrae stars occupy the evolutionary phase known as the *horizontal branch* (HB) phase (see Catelan 2006, for a review). As such, it is legitimate to ask: is there a systematic difference in HB morphology (i.e., in the relative proportions between red, blue, and variable HB stars) between the RR Lyrae-bearing Galactic globular cluster system, on the one hand, and the RR Lyrae-bearing nearby extragalactic globular cluster system, on the other, that may help explain their different Oosterhoff behaviors?

An answer to this question is provided in Figure 2, which shows the Lee-Zinn HB type parameter $\mathcal{L} = (B-R)/(B+V+R)$ (where B, R, and V are the numbers of blue, red, and variable HB stars, respectively) plotted as a function of the metallicity (data from Catelan 2006). In the *left-hand panel*, only the Galactic globular clusters are shown, overplotted on isochrones from Catelan & de Freitas Pacheco (1993). The *right-hand plot*, in turn, shows the position of the globular clusters associated with the dwarf satellite galaxies of the Milky Way. In the latter panel, Oosterhoff-intermediate clusters are shown

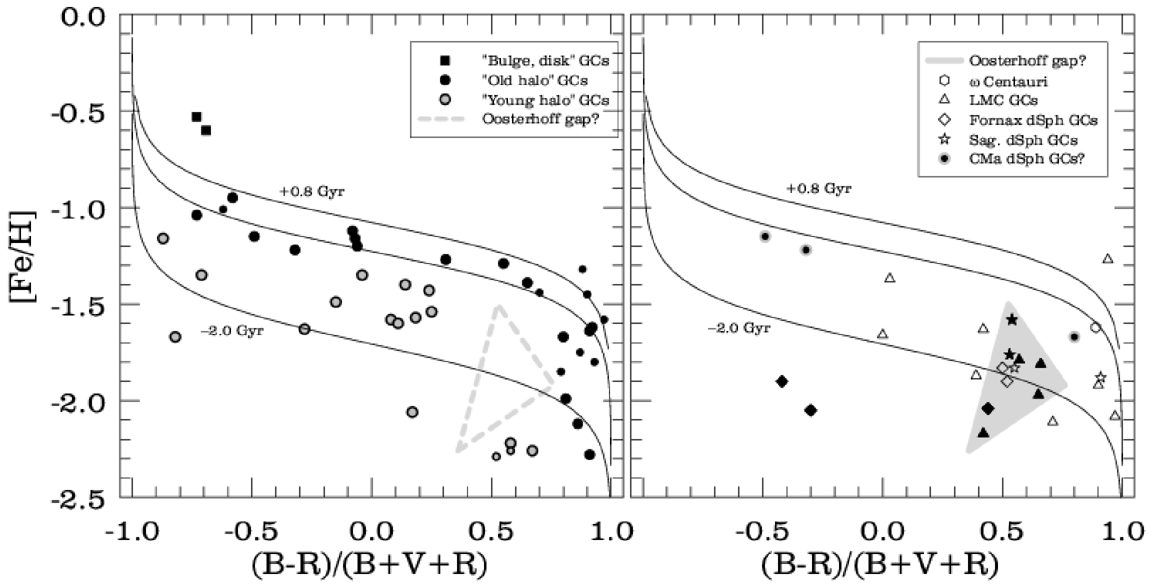

Fig. 2. (*Left panel*) Position of the RR Lyrae-bearing Galactic globular clusters with a defined Oosterhoff type in the metallicity–"HB type" plane. The symbols are the same as in Figure 1. (*Right panel*) To the previous plot the position of the RR Lyrae-bearing globular clusters which have been associated with dwarf satellite galaxies of the Milky Way are added. Filled symbols for the extragalactic systems indicate an *Oosterhoff-intermediate* status. Note the concentration of Oosterhoff-intermediate clusters in the triangular region marked "Oosterhoff gap?"

as filled symbols. Note that the nearby extragalactic globular clusters tend to clump around a triangular region in this plane, which is basically empty in the case of the Galactic system (Catelan 2006).

The fact that the nearby extragalactic globular clusters appear to clump around a region of the $\mathcal{L} - [\mathrm{Fe/H}]$ plane where basically no Galactic globular clusters can be found again suggests that the two systems may be profoundly different. We test this hypothesis by performing a 2-dimensional, 2-sample Kolmogorov-Smirnov test, as described in §14.7 in Press et al. (1992). Comparing the sample of globular clusters associated with the Milky Way dwarf satellite galaxies with the bona-fide Galactic globular clusters gives a probability of 99.4% that the distributions have been drawn from a different parent population. Removing the metal-rich globular clusters NGC 6388 and NGC 6441 from the Galactic sample still gives a probability of 98.9% that the two distributions are inconsistent.

It has at times been suggested that the globular clusters in the Milky Way's dwarf satellite galaxies may resemble the so-called "young halo" population (e.g., Mackey & van den Bergh 2005). This is not borne out by these statistical tests, which give a probability of 99.5% that the so-called "young halo" and dwarf galaxy-related globular clusters have been drawn from different parent populations.

4. COSMOLOGICAL IMPLICATIONS

What constraints do the above results pose on the formation history of the Galaxy?

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, these dwarf galaxies must have looked fundamentally different from any protogalactic fragments that may have helped build the Milky Way halo, RR Lyrae stars clearly allow us to push even further the previous constraints on the role played by dwarf galaxies in the formation of the Galactic halo.

As far as the general halo field, the situation is a bit more complicated. While Suntzeff, Kinman, & Kraft (1991) have strongly argued, from a careful analysis of the light curves of halo RR Lyrae stars, that the Oosterhoff dichotomy *is* indeed present in the halo field (see also Fig. 1, right panel, in Catelan 2004), other authors have recently questioned these conclusions on the basis of datasets drawn from sky surveys. As an example, the QUEST survey (Vivas 2006) has led to the discovery of many previously uncatalogued RR Lyrae stars. Based on these data, Vivas & Zinn (2003) have challenged the Suntzeff et al. results, claiming that the Oosterhoff dichotomy is *not* seen among their sample stars. While it remains unclear what the final solution to this baffling discrepancy will be, we note that many of the Oosterhoff-intermediate stars in the QUEST database (Vivas et al. 2004) have very incomplete light curves, which make their classification into an Oosterhoff group highly uncertain. In fact, in the case of individual field stars and dwarf galaxies, a reliable Oosterhoff classification must be based also on a period-amplitude diagram, which requires the rejection of stars showing the Blazhko effect (Catelan 2004). As an example, Figure 3 shows a comparison between RR Lyrae variable 1 in the QUEST catalog and the new (instrumental) lightcurve in V that we have recently obtained for the same star. In this particular case, it is clear that the QUEST and our amplitudes differ substantially, in the right sense to move the star away from the Oosterhoff-intermediate region of the period-amplitude diagram and into the OoII region. More comprehensive surveys of halo RR Lyrae stars will be required before we can confidently rule out (or confirm) the general validity of the Suntzeff et al. results. When we do, we will be able to place additional constraints on the extent to which such dwarf satellite galaxies as Sculptor, Draco, Carina, and Ursa Minor, all of which lack globular clusters, may have taken part in the very early formation history of the Galactic halo.

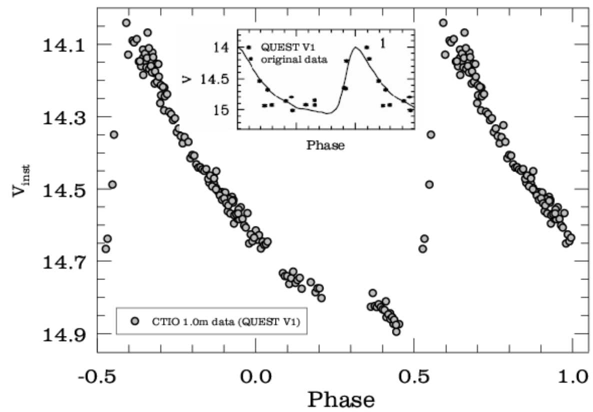

Fig. 3. Light curve for QUEST variable 1, as determined from data collected at the CTIO 1.0m telescope (Smith et al. 2006, in preparation), compared against the original QUEST light curve for the same star (inset). Note the ill-defined light curve minimum and maximum in the QUEST curve, which renders the amplitude—and hence the star's Oosterhoff type—rather uncertain.

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