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The Formation Chronology of Local Group Spiral Galaxies

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Abstract. The 'Second Parameter Effect' (2ndPE) has long been recognized as an important probe into the formation of spiral galaxies. The concept that the horizontal branch morphologies of globular clusters are primarily affected by metal abundance in the inner halo (R_{GC}<8 kpc) of the Galaxy but require an additional parameter (probably cluster age) to explain their behavior in the outer halo (R_{GC}>8 kpc), suggests that the former experienced a rapid monotonic collapse while the latter underwent a slower chaotic formation scenario. As such, in the Milky Way, the so-called second parameter boundary is located at 8 kpc. We find that, in the other Local Group spirals – M31 and M33 – this boundary lies at ~40 kpc and ~0 kpc, respectively. We therefore speculate that the boundary delimiting rapid monotonic halo collapse from the chaotic accretion of dwarf galaxy fragments is inversely related to the mass of the spiral galaxy.

1. Introduction

The Local Group is a bound agglomeration of some two dozen galaxies held together primarily by the gravitational potentials of the Milky Way and Andromeda (M31) galaxies (van den Bergh 1999). The morphologies of these galaxies span an impressive range, including spirals, dwarf ellipticals, dwarf irregulars, and dwarf spheroidals. Furthermore, Local Group galaxies are found in a range of environments from purely isolated systems such as the Tucana dwarf to intensively interacting systems as exemplified by the Sagittarius dwarf galaxy. As such, understanding the formation chronology of the Local Group promises to yield insight into the physics of galaxy formation in general.

A powerful tool that can be used to probe the formation of the Local Group *spiral* galaxies is the so-called 'Second Parameter Effect' (2ndPE). Theoretical and observational work indicate that the metallicity of a star cluster determines the morphology of its horizontal branch (HB) – the more metal rich clusters have redder HBs. However, Sandage & Wallerstein (1960) and later van den Bergh (1967) and Sandage & Wildey (1967) found Galactic globular clusters that seemed to violate this expectation. For example, M13 was found to have an HB that is too blue for its metal abundance while the HB of NGC 7006 was found to be too red. This argued for the existence of a second parameter that must be affecting HB morphology in addition to cluster metallicity.

What is particularly special about the 2ndPE is that it is a global phenomenon operating on the scale of the entire Galactic halo. Searle & Zinn (1978, hereafter SZ) describe how the inner halo globulars do not exhibit the 2ndPE showing a one-to-one relationship between HB morphology and metal abundance; in contrast the outer halo clusters do show the influence of the 2ndPE which causes clusters with similar metallicities to possess vastly different HBs. SZ consider the various second parameter candidates – cluster age, helium abundance, and C, N, O, abundances. They present convincing arguments that cluster age is the most plausible candidate to be the second parameter. Based on this, SZ were able to construct a formation scenario for the Galactic halo wherein the inner regions formed over a free-fall timescale of $\sim 10^8$ years while the outer regions fragmented and required several billion years to come into 'dynamical equilibrium' with the rest of the Galaxy.

One piece of evidence that SZ presented to support this formation picture is the observed variation of metal abundance with Galactocentric distance. Their Fig. 9 shows that inside 8 kpc where the collapse of the halo was rapid and monotonic, there is a radial gradient in the metallicity of the Galactic globulars; in contrast, outside 8 kpc where the halo formed in a more chaotic fashion, there is little or no dependence of abundance on radial position. This behavior fits precisely into the formation scenario they advocated based on their interpretation of the 2ndPE as due to age.

In any case, whatever the cause of the 2ndPE, it is clearly an important probe into the early formation epoch of the Milky Way. As such, it is imperative that we investigate other spiral galaxies to look for the 2ndPE. In this paper, we will use the 2ndPE along with arguments similar to those of SZ to make inferences about the relative formation chronologies of the *Local Group* spiral galaxies, namely the Milky Way, M31, and M33.

2. The Second Parameter Effect in the Milky Way

As suggested above, a large number of papers have been devoted to the study of the 2ndPE among the globular clusters of the Milky Way (e.g., Stetson, VandenBerg, & Bolte 1996; Sarajedini, Chaboyer, & Demarque 1997). The traditional method of illustrating the 2ndPE is to examine the radial variation of HB morphology with metal abundance as shown in Fig. 10 of SZ.

In the intervening years, the quantification of the HB morphology has taken many forms. SZ used the Mironov (1972) index defined as B/(B+R), consisting of the number of blue HB stars (B) and the number of red HB stars (R). This quantity ranges from 0 for completely red HB clusters to +1 for those with completely blue HBs. More recently, Lee, Demarque, & Zinn (1994, hereafter LDZ) devised a new more sensitive HB morphology index. This quantity designated $(B - R)/(B + V + R)$ includes the number of blue HB stars (B), red HB stars (R), and RR Lyrae variables (V). It varies from –1 for clusters with purely red HBs to +1 for blue HB clusters. This index works well for globular clusters in the Milky Way halo (which includes the Large and Small Magellanic Clouds and the Fornax dwarf spheroidal) but is more difficult to construct for those in M31 and M33; this is because the current quality of cluster CMDs in these galaxies makes counting individual HB stars, especially RR Lyraes, quite uncertain. In

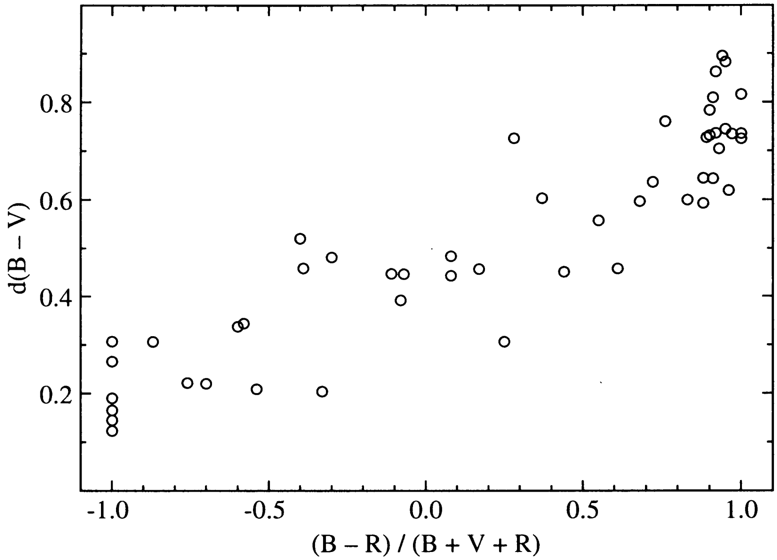

Figure 1. The correlation between the $(B - R)/(B + V + R)$ and $d(B - V)$ for Galactic globular clusters using data from Lee et al. (1994) and Buonanno et al. (1997, see also Sarajedini et al. 1998), respectively.

addition, the $(B-R)/(B+V+R)$ index becomes insensitive to HB morphology for extremely red or extremely blue HBs. These factors led Sarajedini et al. (1998) to introduce a new HB morphology index that is more easily applied to extragalactic populations and does not saturate for extreme HBs. They advocate the use of the color difference between the red giant branch and the HB at the level of the HB $[(B-V)_g - (B-V)_{HB} \equiv d(B-V)]$. Figure 1 shows the relation between $(B-R)/(B+V+R)$ and $d(B-V)$ for Galactic globular clusters using the data of LDZ for the former and Buonanno et al. (1997) for the latter. It is clear that these two quantities are well-correlated and that, unlike $(B-R)/(B+V+R)$, $d(B-V)$ does not become saturated in the case of predominantly red or blue HBs.

Figure 2 shows the variation of metal abundance (on the Zinn & West 1984 scale) with $d(B-V)$ for Galactic globular clusters inside of 8 kpc (filled circles) and outside of 8 kpc (open circles); the data are taken from Buonanno et al. (1997) supplemented by those presented by Sarajedini, Lee, & Lee (1995). The solid line is the eyeball fit to the inner halo clusters illustrating the tight relationship between HB morphology and metallicity, the first parameter. Outside of 8 kpc, a second parameter must be at work to produce the clear spread in HB morphology at a given metal abundance.

Of all the second parameter candidates that have been proposed, none has received as much observational support as cluster age (e.g., LDZ; Sarajedini et al. 1997; Sarajedini 1999; Lee et al. 2001, and in this volume). Turnoff stars

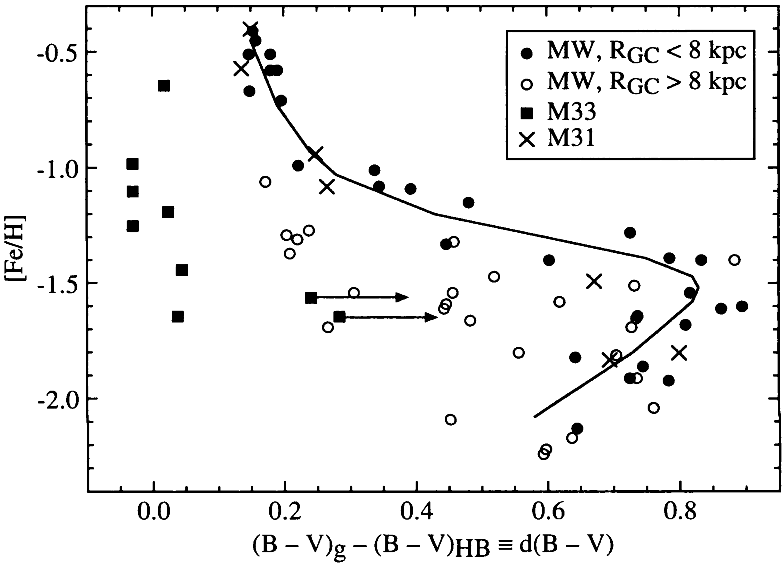

Figure 2. The variation of cluster horizontal branch morphology as quantified by the $d(B-V)$ parameter (see text) with metal abundance on the Zinn & West (1984) scale. The filled circles are Galactic globulars with Galactocentric distances less than 8 kpc while the open circles are those outside of 8 kpc. The filled squares are M33 halo clusters from the study of Sarajedini et al. (1998; 2000), and the crosses are M31 globular clusters from the literature.

in older clusters have lower masses as compared with younger systems leading to bluer HB morphologies for the former. Within this paradigm, which is the one advocated by SZ, the age range among the inner halo globulars is small or nonexistent while the outer halo clusters exhibit an age range of a few Gyr. In addition, the mean age of the inner halo is older than that of the outer halo.

Recently however, a relatively new second parameter candidate, first proposed several years ago, has received a great deal of attention. Fusi Pecci et al. (1993)[1] and Buonanno et al. (1997) investigated the possibility of stellar density playing a role in affecting the HB morphology. These studies found that the higher the central density of a cluster, the more likely it is to have an extended blue HB tail (see also Testa et al. 2001). In this scenario, red giant stars in the central regions of clusters are stripped of their outer envelopes thus reducing their masses and placing them on the blue side of the RR Lyrae instability strip.

Fusi Pecci et al. (1996a) adopted a more global view; they attempted to explain the extended-blue HBs of some globular clusters as a linear combination

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[1] See van den Bergh & Stephens (1993) for possible problems with the methodology of Fusi Pecci et al. (1993).

of age and central density. They were generally successful in this regard and were able to make a convincing case for age as the second parameter and cluster central density as a possible third parameter. We return to this scenario later in this section.

What is increasingly clear from these studies is that variations in stellar density are more likely to make an HB bluer rather than redder. For example, the globular clusters NGC 6441 and NGC 6388 are two metal-rich clusters with ostensibly red HBs (Hesser & Hartwick 1976; Silbermann et al. 1994). Rich et al. (1997; see also Layden et al. 1999) found that, if we look in the central regions of these clusters where stellar dynamical interactions are likely to be most severe, we see a small but significant population of blue HB stars. Analogous results have also been reported by Testa et al. (2001). In contrast, if we observe the outer low density regions of M15, which is ostensibly a blue HB cluster, we do not see additional red HB stars.

If stellar density is to be an important parameter affecting any portion of the HB (e.g., the entire HB or just the extended blue tails) and if it is to influence the HB in the same way as cluster age following the claims of Fusi Pecci et al. (1996a), then this implies that inner halo clusters must have higher central densities (ρ_o) than outer halo clusters. Examining the latest update of the Harris (1996) catalog of globular cluster parameters, we find that this is in fact the case; clusters inside 8 kpc have $\langle \mathrm{Log}\ \rho_o \rangle = 3.82 \pm 0.14$ while those outside 8 kpc have $\langle \mathrm{Log}\ \rho_o \rangle = 2.25 \pm 0.25$ representing a difference of over 5σ. However, some of this effect is undoubtedly the result of dynamical processes wherein only the higher density clusters survive the tidal forces present in the inner regions of the Galaxy. An additional effect could be that the higher gas densities in the inner halo give rise to denser clusters.

What is the fundamental difference between age effects and stellar density effects on HB morphology? Age effects (i.e., older clusters have lower mass turnoff stars and thus lower mass HB stars which results in a bluer HB) are established during the epoch of halo globular cluster formation, which, as noted above, lasted for a few Gyr. In contradistinction, the effect of stellar density (i.e., the stripping of red giant star envelopes to produce lower mass HB stars which results in a bluer HB) occurs mainly during the subsequent dynamical evolution after the globular cluster stars are in place. This fits nicely with the empirical evidence presented by Fusi Pecci et al. (1996a) that age is the second parameter and cluster central density is a plausible third parameter. It also fits with the findings of Rich et al. (1997) who conclude that the effects of central density are not sufficient to explain the differences in HB morphology between NGC 6388 and 47 Tuc (their Fig. 1). To place this assertion on a firmer foundation, more work needs to be done on the timescale of mass loss associated with the dynamical interactions between stars in the central regions of globular clusters.

3. The Second Parameter Effect in M33

As emphasized in the Introduction, understanding the 2ndPE is important to unlocking the secrets of galaxy formation. As such, several years ago, we (Sarajedini et al. 1998; 2000, hereafter SGSH) began to investigate the halo globular cluster system of M33 in search of the 2ndPE. We drew extensively upon the

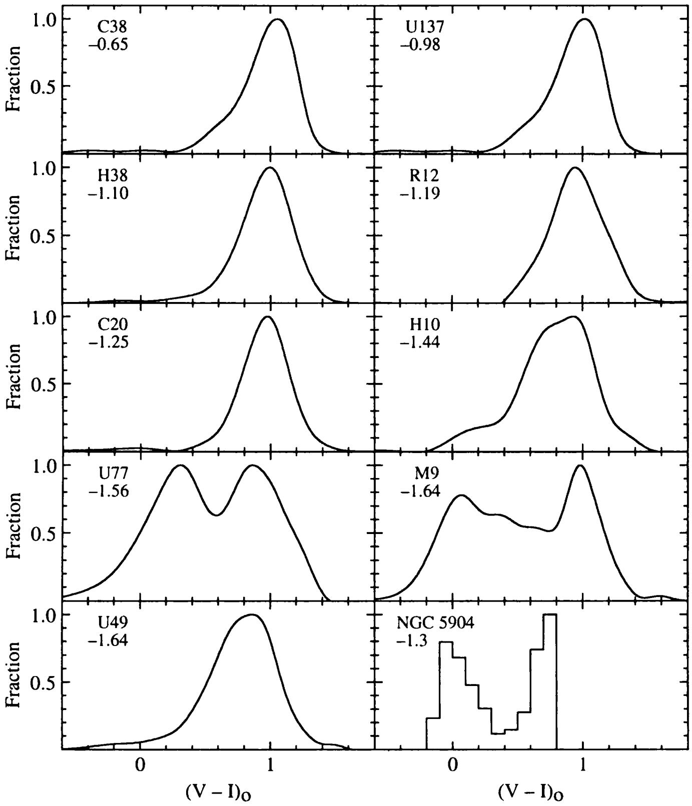

Figure 3. The background subtracted generalized histograms for the HBs of 9 M33 halo clusters along with that of the Galactic globular cluster NGC 5904 (M5) from Sandquist et al. (1996). The metal abundances are also indicated in each panel.

work of Christian & Schommer (1983; 1987; 1988) and Schommer et al. (1991) in our selection of cluster targets seeking to observe analogues of Milky Way halo globulars in M33. We were awarded 40 orbits of HST/WFPC2 time in cycle 5 to obtain V and I photometry for 10 M33 halo clusters.

The observations required over two years to complete because of scheduling conflicts, but once they were taken and analyzed, a startling conclusion began to emerge. As the filled squares in Fig. 2 and the generalized histograms in Fig. 3 illustrate, of the 10 M33 halo clusters observed, 8 possess completely red HB morphologies, much redder than the Milky Way clusters at their metallicity. One of the red HB clusters is not plotted because of extreme differential reddening effects, and the two clusters with blue portions to their HBs are plotted as lower limits. This is because our observations are not sensitive to the presence of extended blue tails. In any case, the M33 clusters also suffer from the 2ndPE and to a greater degree than the Milky Way globulars.

In SGSH, several pieces of evidence were presented showing that the red HB clusters in M33 are likely to be several billion years younger than the halo globular clusters in the Milky Way. We estimated a mean age of roughly 7 Gyr for these clusters. Therefore, assuming that the two clusters with 'normal' HB types for their metallicities are similar in age to the oldest Galactic globulars (12–14 Gyr), then the age range among the M33 halo clusters is somewhere around 5–7 Gyr.

What do the M33 halo clusters show in terms of their radial abundance variation? Our sample of 10 clusters covers a substantial range in distance from the center of M33. As Fig. 24 of SGSH shows, there is no relation between the metal abundance of our M33 clusters and their radial location. We note that there may be as yet undiscovered clusters further than ~6 kpc in deprojected distance from the center of M33. In any case, taken together and interpreted in terms of the formation hypothesis of SZ, the available data suggests that the halo of M33 (as manifested in its globular clusters) experienced a similar fragmentation and chaotic-accretion formation scenario as the outer halo of the Milky Way (see also Chandar et al. 2001 and in this volume).

4. The Second Parameter Effect in M31

We are now in a position to inquire about the 2ndPE in the nearest spiral galaxy to our own, M31. Currently, the largest database of HST CMDs for M31 halo clusters is that of Fusi Pecci et al. (1996b; see also Ajhar et al. 1996). We can also make use of the G302 and G312 cluster CMDs published by Holland, Fahlman, & Richer (1997). From these diagrams, we are able to measure $d(B-V)$ and adopting metallicities from Fusi Pecci et al. and Holland et al., we can place the nine M31 clusters in Fig. 2 as represented by the crosses.

Having done this, we are left to conclude that, at least among these nine clusters, M31 does not suffer from the 2ndPE.[2] Taken at face value, this result suggests that the halo globular clusters in M31 (and by implication, perhaps the M31 halo field stars also) formed over a very short timescale akin to the inner halo of the Milky Way.

In light of this, what are we to make of the results presented by Da Costa et al. (1996; 2000) on the dwarf spheroidal galaxies, And I and II, that are companions to M31? These authors find that both of these galaxies suffer from an internal 2ndPE in the sense that the HB morphology of their stellar population is redder than the mean metal abundance of these populations would imply. This in turn suggests that the formation of these dwarf galaxies likely encompassed several billion years, in direct contrast with the M31 globulars which apparently formed over a freefall timescale.

The key to this apparent paradox lies in the relative galactocentric distances of these M31 halo components. In particular, all nine of the globular clusters are located within ~40 kpc of the center of M31 (adopting a distance of 790 kpc for M31), while And I and II are located at ~45 kpc and ~130 kpc, respectively, from M31. Thus, the available data indicate that the inner halo of M31 ($R <$ 40 kpc) formed via a monotonic collapse over a timescale of less than 1 Gyr

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[2] However, we note that, in this volume, the poster paper by Rich et al. shows results that support the existence of a 2ndPE in M31. It is difficult for us to assess the validity of this result as of yet.

while the outer halo (R > 40 kpc) required several Gyr to form and did so by the fragmentation and gradual accretion of dwarf galaxy sized subunits. As expected, the data of Barmby et al. (2000) suggest that there exists a weak radial abundance gradient among the M31 globular clusters, though this result is not particularly compelling.

5. What Does It All Mean?

With regard to the 2ndPE in Local Group spiral galaxies, we find that the Milky Way possesses a second parameter boundary of 8 kpc, where inside this radius, globular clusters are not affected by the 2ndPE while outside this radius, they are so affected. In M31, this boundary occurs at ~40 kpc while in M33, the boundary is effectively nonexistent (i.e., R~0 kpc). This boundary separates inner halo regions which experienced a rapid formation chronology via a monotonic collapse from outer regions which formed relatively slowly via the accretion of SZ fragments. One can imagine that the location of this boundary is somehow related to the mass of the parent galaxy, since we know that M31 is the most massive and its boundary is furthest out in its halo while M33 is the least massive and its boundary is nonexistent. Of course, the Milky Way represents the intermediate case.

Needless to say, the primary caveat in this hypothesis is the status of the 2ndPE in M31; this is because of a serious dearth of observational material in this, the nearest large spiral galaxy! As noted in Sec. 4, new results presented in this volume may contradict the findings of the present paper. Obviously, if they do, the assertions made herein will have to be modified. In any case, it is important to again emphasize that the 2ndPE is a very important tool in unlocking the formation of spiral galaxies.

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Discussion

J. Frogel: What about the HBs of LMC clusters? Also, bright stars in M33 clusters could be LPVs or blends since V-I is hopeless in picking LPVs because of blanketing. LPVs have absolute magnitudes brighter than the tip of the RGB.

A. Sarajedini: Generally speaking, the HBs of LMC clusters do not show the 2ndPE. Although the LMC is about the same luminosity as M33, this fact does not contradict my theory that the threshold R_{GC} for the existence of the 2ndPE depends on galaxy mass. This is because my theory only applies to spiral galaxies with kinematically hot halo populations. In contrast, the LMC clusters are in an irregular galaxy and have disk-like kinematics. I agree with your point re: LPVs.

C. Cacciari: In our poster paper, we present some evidence of 2ndPE globular clusters in M31. We still need to do some work, probably better field subtraction; but if confirmed, this result would not fit with your scenario: our candidate 2ndPE clusters have relatively small galactocentric distances. On the other hand, it is not unanimously accepted that age is "the" 2ndP, or at least the only 2ndP. And, sure enough, we do need observations of more clusters in M31 - so far we have only 19 CMDs.

A. Sarajedini: Indeed, we need to confirm the nature of your 2ndP clusters in M31. This is very important to do. We also need CMDs of more M31 globulars, preferably those located away from the disk to minimize contamination in the CMD.

T. Armandroff: A comment on your inference that the 2ndPE is occurring for galactocentric distance $\geq$ 40kpc in M31. In adition to Andromeda I and II that you mentioned, our work on And III (Da Costa, Armandroff and Caldwell, in prep.) reveals that it exhibits the 2ndPE. Thus, And III supports your conclusion.

A. Sarajedini: Yes, it does, and I'm looking forward to the results on other dwarf spheroidals around M31. Do they also show internal 2ndPE's?