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Memorie della

The Second Parameter Problem(s)

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Abstract. The Second Parameter (2ndP) Problem recognizes the remarkable role played by horizontal branch (HB) morphology in the development of our understanding of globular clusters, and the Galaxy, over the last 50 years. I will describe the historical development of the 2ndP and discuss recent advances that are finally providing some answers. I will discuss how the controversies surrounding the nature of the 2ndP can be reconciled if we acknowledge that there are actually two distinct problems with entirely different solutions.

Key words. Stars: abundances – Galaxy: formation – Galaxy: globular clusters – Stars: evolution

1. Introduction

The Second Parameter (2ndP) Problem arose in the 1960's when astronomers were first able to assemble a considerable sample of globular cluster (GC) color-magnitude diagrams (CMDs). The CMDs revealed that horizontal branch (HB) morphology was mainly driven by the metallicity, but that metallicity alone was insufficient to explain the observed diversity of HB morphology. Early references to an 'other' or 'second' parameter can be found in Sandage & Wildey (1967) and van den Bergh (1967).

Searle & Zinn (1978) tied the 2ndP problem to the larger problem of formation of the Galaxy with the argument that the appearance of metal-poor GCs with red HB morphologies in the outer Galactic halo was indicative of it having formed by the gradual accretion of so-called 'protogalactic fragments.' Thus, Searle & Zinn (1978) linked the 2ndP with age. While the 'hierarchical' formation scenario proposed by Searle & Zinn (1978) has gained wide acceptance as a galaxy formation model over the years, the suggestion that the 2ndP is age remains controversial.

The remainder of this paper will discuss the reasons for the controversy surrounding the identity of the 2ndP and attempt to explain the root cause(s).

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2. An historical view of globular cluster ages

At least since the seminal paper by Searle & Zinn (1978), the ages of the Galactic GCs have been the subject of many studies; for a review see, for example, the introduction to Dotter et al. (2010). Here I focus on those studies that target large samples of GCs. The chief interest of these studies is the question of whether or not the Galactic GC population exhibits an age gradient as a function of metallicity, Galactocentric radius, or some other parameter.

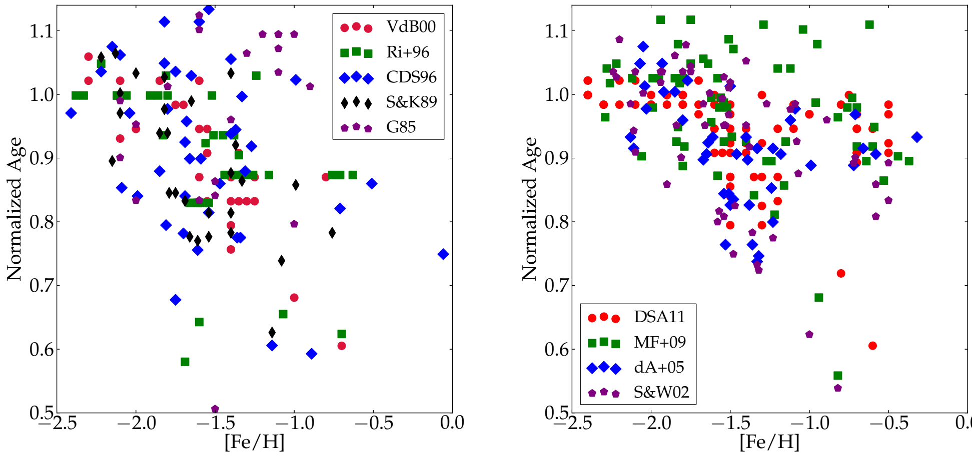

Fig. 1. Normalized ages for a total of 9 studies published between 1985 and the present. References: G85=Gratton (1985), SK89=Sarajedini & King (1989), CDS96=Chaboyer et al. (1996), Ri+96=Richer et al. (1996), VdB00=VandenBerg (2000), S&W02=Salaris & Weiss (2002), dA+05=De Angeli et al. (2005), MF+09=Marín-Franch et al. (2009), DSA11=Dotter et al. (2011)

Figure 1 displays a comparison of GC age studies published between 1985 and the present. The studies considered here are not necessarily complete, but should be representative. The left panel of Figure 1 shows studies published between the years 1985 and 2000. The right panel shows studies published between the year 2001 and the present. In order to put the ages on a comparable scale a Normalized Age has been defined as the age relative to the average age of the metal-poor GCs in each sample. Here ‘metal-poor’ means all GCs with [Fe/H] ≤ -1.7.[1] This step is necessary to compare in particular the older studies since the typical age scale of GCs decreased substantially from the 1980’s to the present as a result of improvements to stellar evolution models. The range of plotted Normalized Ages and [Fe/H] is the same in both panels.

Figure 1 reveals that the earlier studies (plotted in the left panel) show some evidence of an age-metallicity relation but there is considerable scatter in age at a fixed [Fe/H]. The later studies (plotted in the right panel) shows much tighter agreement among the different studies *and* all of them indicate the presence of a bifurcation in the age-metallicity relation for GCs with [Fe/H] ≥ -2 (see discussions in, e.g., Marín-Franch et al. 2009; Dotter et al. 2011). It is my contention that the majority of the improved agreement among the later studies is due to the improved quality and homogeneity of the observations afforded by the Hubble Space Telescope (Piotto et al. 2002; Sarajedini et al. 2007).

To finish the discussion of GC age and HB morphology, I present the side-by-side comparison of the HB morphology-metallicity and age-metallicity diagrams based on Dotter et al. (2011) in Figure 2. Figure 2 is my version of the famous diagram by Searle & Zinn (1978, their Figure 10); it shows the relationship between HB morphology and age for several bins of Galactocentric radius *in this diagram*. It is important to emphasize the final three words in the previous sentence because the way in which in HB morphology is represented has important consequences, as will be discussed in the following sections.

[1] The Normalized Age for a given study relies only on the information provided within that study. That is, it uses both the adopted ages and metallicities of that study.

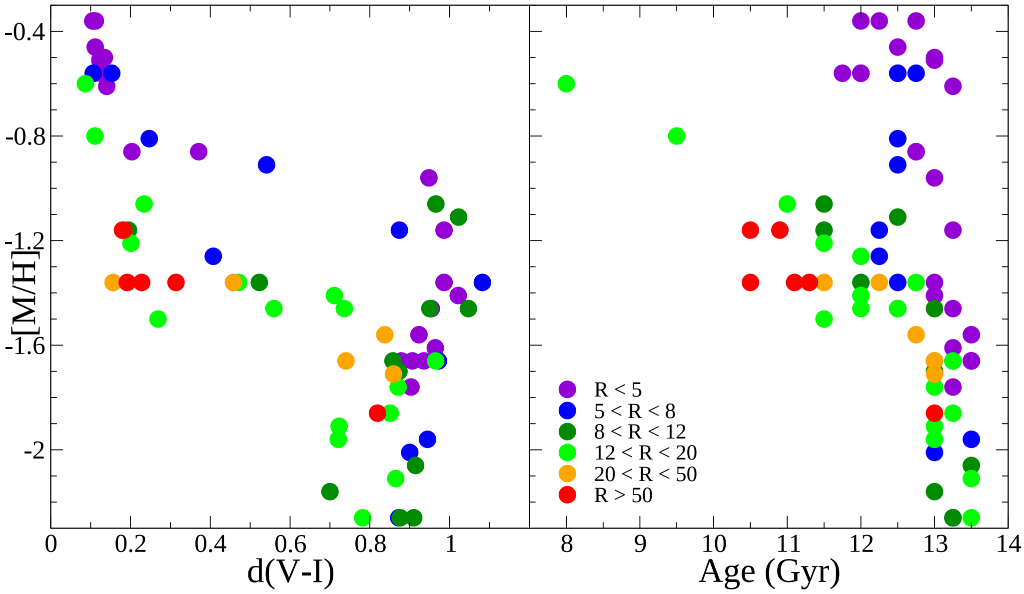

Fig. 2. The HB morphology-metallicity and age-metallicity relations from Dotter et al. (2011) plotted side-by-side to demonstrate the correspondence between age and HB morphology *in this diagram.*

3. Whence the 'faint blue tails?'

HB morphology is often complex and cannot be condensed into a single number without (sometimes considerable) loss of information. The studies mentioned in Section 2 all rely on HB metrics that favor the central tendency of the distribution. Furthermore, these studies rely on optical CMDs that favor the redder HB stars. Clearly, such emphasis focuses the outcome of these studies to parameters that most strongly influence the center or red edge of the distribution. What about the blue edge of the distribution?

Fusi Pecci et al. (1993) demonstrated that a class of HB metrics that target the blue end of the distribution, the so-called 'faint blue tails,' reveal a tight correlation with the absolute magnitude of the GC. Since absolute magnitude and mass are tightly linked quantities, the total mass of the cluster must be related to the prevalence of hot, blue HB stars. Similar results were later obtained by, e.g., Recio-Blanco et al. (2006) and Gratton et al. (2010). It is important to note that Fusi Pecci et al. (1993), Recio-Blanco et al. (2006), and Gratton et al. (2010) all rely on optical CMDs for their analyses. Yet, even using data that undervalues the hottest HB stars, it is still possible to define an HB morphology metric that is sensitive to them.

At the close of Section 2, the point was made that the way in which an HB morphology metric is defined weighs heavily on the outcome of a study which adopts that metric. However, it also becomes clear that different parameters influence the distribution of HB stars in different ways. While the traditional HB metrics seem to correlate with age, at least in some studies (Gratton et al. 2010; Dotter et al. 2010), the blue-sensitive HB metrics used by Fusi Pecci et al. (1993), Recio-Blanco et al. (2006), and Gratton et al. (2010) correlate with absolute magnitude. That absolute magnitude is in some way connected with the strength of the second generation GC stars, and therefore initial He content, is discussed by, e.g., Recio-Blanco et al. (2006) and Gratton et al. (2010).

The comparison of different HB metrics indicates that they probe different aspects of the distribution of HB stars. See, for example, the discussions in Section 2.2 (Figures 7 and 8) of

Gratton et al. (2010) and Section 3.3 (Figure 2) of Dotter et al. (2010). As already mentioned, this leads to a different outcome, even when using the same data set, if only one HB metric is considered.

When weighing the relative contributions of different candidates for the 2ndP, it therefore becomes necessary to consider more than one HB metric. Studies by Gratton et al. (2010) and A. Milone (this volume) deserve special attention in this regard.

The difficulty encountered in using optical CMDs can be largely removed by using combined UV-optical CMDs. An example of the UV-optical studies is that of NGC 2808 by Dalessandro et al. (2011), who study the complex HB of this peculiar, massive GC using WFPC2 data. Their Figure 3 shows the NGC 2808 HB (and also that of M 80) in the $F160BW - F555W$ CMD, which spans more than 6 magnitudes in the color dimension while it is nearly flat in $F160BW$ magnitude, except for a few of the reddest HB stars.

4. Discussion

In the language of *descriptive statistics*,[2] some HB metrics probe the central tendency of the distribution while others probe the extremes. It is easy to imagine that one parameter (e.g., metallicity or age) can drive the central tendency, while another (e.g., the range of initial He content) can drive the dispersion and/or the shape of the distribution.

Freeman & Norris (1981) wrote

> at least two parameters in addition to [Fe/H] are probably necessary to explain the observed HB morphologies. One of these must be a parameter that varies within clusters (i.e., a non-global parameter) which the second varies from cluster to cluster (i.e., a global parameter). Almost all discussion to this time has centered on the global parameters.

The meaning of 'global' in this context pertains all stars within a single GC. We can identify parameters, such as the bulk metallicity ([Fe/H]) and age, as global in the sense that they do not vary substantially within a (normal) GC; other parameters, such as the degree of internal pollution, can be associated with the sense that a range of these parameters exists within a single GC. Moreover, the degree to which a non-global parameter varies within one GC may differ considerably with the degree to which the same parameter varies within another GC. I close the discussion with the suggestion that the global parameters are, in a sense, connected with the central tendency while the non-global parameters are connected with the shape and dispersion of the distribution.

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[2] See `http://en.wikipedia.org/wiki/Descriptive_statistics`