Horizontal-Branch Stars as an Age Indicator

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Abstract. Surface temperature distribution of horizontal-branch (HB) stars is very sensitive to age in old stellar systems, which makes it an attractive age indicator. In this paper, we present the recent revision of our model calculations for the HB morphology of globular clusters. The result is more updated version of our earlier models (Lee, Demarque, & Zinn 1994), which suggests that the HB morphology is more sensitive (∼40%) to age. We also present our new model calculations on the effect of HB stars in dating old stellar systems using the Hβ index. Our results indicate that the effect of HB stars is rather strong, and suggest a possibility for the systematic difference in age between the globular clusters in the Milky Way Galaxy and those in giant elliptical galaxies. Finally, we compare these results with the relative ages estimated from our far-UV dating technique for giant elliptical galaxies.

1. Introduction

For sufficiently old (t > 8 Gyr) stellar populations, evolutionary models (e.g., Lee et al. 1994, LDZ) predict that the surface T_{eff} distribution of horizontal-branch (HB) stars is very sensitive to age, which makes it an attractive age indicator. Because the HB stars are much brighter than main-sequence (MS) stars, the interpretation of HB morphology in terms of relative age differences would be of great value in the study of distant stellar populations where the MS turnoff is fainter than the detection limit. In the more distant stellar populations where even HB is fainter than the detection limit, HB stars still should have some crucial effect in spectrophotometric dating of old stellar populations based on integrated colors & spectra. In this paper, we report our progress in the use of HB as an age indicator, both from the interpretation of HB morphology in the color-magnitude (CM) diagrams, and from the integrated spectra.

2. Age as the Major Second Parameter

Some five years ago, LDZ have concluded that age is the most natural candidate for the global second parameter, because other candidates can be ruled out from the observational evidence, while supporting evidence do exist for the age hypothesis. There is still much debate about this issue, and Table 1 summarizes the current situation. Although it may not be a complete list, it is clear from Table 1 that many pieces of supporting evidence still suggest that age is the
Table 1. Age as the major 2nd parameter

**PROS**

| Object                        | Author                              | Result                                                                 |
|-------------------------------|-------------------------------------|------------------------------------------------------------------------|
| Galactic globular cluster (GGC) system as a whole | Lee et al. (1988, 1994)             | Variation of age with HB type over a narrow range in [Fe/H]             |
|                               | Sarajedini & King (1989)            |                                                                         |
|                               | Chaboyer et al. (1992, 1996)        |                                                                         |
| NGC 288 vs. NGC 362           | Bolte (1989)                        | $\Delta t \approx 2 \sim 3$ Gyr                                       |
|                               | Green & Norris (1990)               |                                                                         |
|                               | Sarajedini & Demarque (1990)        |                                                                         |
| Pal 12                        | Gratton & Ortolani (1988)           | Considerably younger                                                   |
|                               | Stetson et al. (1989)               |                                                                         |
| Rup 106 vs. M68/NGC6397       | Buonanno et al. (1990)              | $\Delta t \approx 3 \sim 5$ Gyr                                       |
|                               | Kubia (1991)                        |                                                                         |
|                               | Da Costa et al. (1992)              |                                                                         |
| Ter 7, Arp 2                  | Buonanno et al. (1994)              | Considerably younger                                                   |
|                               | Buonanno et al. (1995a,b)           |                                                                         |
|                               | Sarajedini & Layden (1997)          |                                                                         |
|                               | Stetson et al. (1996)               |                                                                         |
| IC 4499                       | Ferraro et al. (1995)               | Considerably younger                                                   |
|                               | Stetson et al. (1996)               |                                                                         |
| Pal 1                         | Rosenberg et al. (1998)             | Significantly younger than 47Tuc/M71                                   |
| Pal 14 vs. NGC6752/M5         | Sarajedini (1997)                   | $\Delta t \approx 3 \sim 4$ Gyr                                       |
| Pal 3, Pal 4, Draco Dwarf      | Hesser et al. (1997)                | 1.5~3 Gyr younger than M3/M5                                           |
| Eridanus                      | Stetson et al. (1999)               |                                                                         |
| M3 vs. M2                     | Lee & Carney (1999)                 | $\Delta t \approx 2$ Gyr                                              |
| M3 vs. M13                    | Yim et al. (1999)                   | $\Delta t \approx 2$ Gyr                                              |

**CONS**

| Object                        | Author                              | Argument                                        | Our Comment                                      |
|-------------------------------|-------------------------------------|-------------------------------------------------|--------------------------------------------------|
| GGC system as a whole         | Stetson et al. (1996)               | $\Delta t$ is too small                         | New models are more sensitive to age             |
| M3 vs. M13                    | VandenBerg et al. (1990)            |                                                 |                                                  |
|                               | Catelan & Pacheco (1995)            |                                                 |                                                  |
|                               | Ferraro et al. (1997)               |                                                 |                                                  |
|                               | Johnson & Bolte (1998)              |                                                 |                                                  |
|                               | Paltrinieri et al. (1998)           |                                                 |                                                  |
|                               | Davidge & Courteau (1999)           |                                                 |                                                  |
| Draco Dwarf                   | Grillmair et al. (1998)             | Older than M92                                  | Very poor data                                  |
| Blue tail & Bimodal HB        | Buonanno et al. (1986)              | Internal 2nd parameter effect                   | Most likely a local effect (see also text)      |
|                               | Sosin et al. (1997)                 |                                                 |                                                  |
|                               | Rich et al. (1997)                  |                                                 |                                                  |
|                               | Ferraro et al. (1998)               |                                                 |                                                  |
major global second parameter. Recent addition to this list include red HB clusters in the outer halo, such as Palomar 3 & 4, and Eridanus from the HST photometry (Stetson et al. 1999), and Palomar 14 from the WIYN photometry (Sarajedini 1997). Before these observations, they used to say that these clusters will eventually solve the second parameter problem because they represent the most extreme cases of the second parameter effect. Now the observed age differences for these clusters, as estimated from the color difference method, are consistent with the age scenario of the 2nd parameter effect. Furthermore, J.-W. Lee & Carney (1999) and Yim et al. (1999) recently report that their high quality observations of blue HB clusters M2 and M13 are consistent with the age hypothesis when compared to the redder HB clusters of similar metallicity, such as M3.

On the other hand, we see that there are now some papers in the literature arguing that age may not be the major second parameter. Their argument, mostly based on M3-M13 pair, is that they did find some age difference, about 1~2 Gyr, but they think it is not enough to explain the difference in HB morphology. However, as described below, to within the observational errors, both in the age dating technique and in the HB type and metallicity measurements, our new models with the effects of recent developments are completely consistent with the observations. Other arguments include the HST photometry of Draco dwarf spheroidal galaxy (Grillmair et al. 1998), which has a red HB, in which they argue that Draco is not apparently younger than the blue HB clusters of similar metallicity. However, as they admit, the quality of their data is still very poor to reach any conclusion.

We are not arguing that age can explain every aspect of the HB. In fact, LDZ also admitted that something else is also required to explain some peculiar features on the HB, such as long “blue tail” and bimodal HB color distribution (see Table 1). However, these features are widely considered to be a result of local effect, such as enhanced mass-loss in high density environment. Given the overwhelming supporting evidence for the age hypothesis, these local effects should be considered to be a third parameter effect, which is less important than the second parameter effect (see also Binney & Merrifield 1998). Certainly, there is noise, and it is important to understand the origin of this third parameter effect in order to use the HB as a more reliable age indicator. In this respect, it is encouraging to see that recent observations with the Keck HIRES spectrograph (Behr et al. 1999) provide some compelling evidence that the “blue tail” phenomenon is a natural result of abrupt diffusion mechanisms for stars hotter than 11,500K (see also Moehler et al. 1999). If, as suggested by these observations, the “blue tail phenomenon” is a universal characteristic of clusters with stars hotter than 11,500K, then this phenomenon should not be considered to be a third parameter effect, since it is then rather a general feature of the very blue HB clusters. Furthermore, several lines of evidence now suggest that some globular clusters with peculiar CM diagram morphology, such as M54 (Sarajedini & Layden 1995; Larson 1996) and ω Centauri (Lee et al. 1999), are nuclei of disrupted dwarf galaxies with internal age-metallicity relations. We suspect, therefore, a globular cluster with peculiar bimodal HB distribution, NGC 2808, may also represent such case. Note that it is among the most massive globular clusters in our Galaxy (Harris 1996). In any case, as demonstrated by Fusi Pecci et al. (1996), a procedure is available through which the measured HB morphol-
ogy can be depurated from the effects of parameters (i.e., third parameter) other than age. So even in the clusters with peculiar HB morphology from unknown origin, a rough estimate of relative age is still possible from their HBs.

3. Recent Developments & New HB Population Models

There are several recent developments that can potentially affect the relative age dating technique from HB morphology. The following effects are included in our most recent update of the LDZ HB models (Yoon & Lee 1999):

1. There is now a reason to believe that absolute age of the oldest Galactic globular clusters is reduced to about 12 Gyr, as suggested by new Hipparcos distance calibration and other improvements in stellar models (Gratton et al. 1997; Reid 1997; Chaboyer et al. 1998). As LDZ already demonstrated in their paper, this has a strong impact in the relative age estimation from HB morphology, because the variation of the red giant branch (RGB) tip mass (after the mass-loss, HB mass) is more sensitive to age at younger ages.

2. Now, we have new HB tracks with improved input physics (Yie et al. 1997) and corresponding new Yale isochrones (Demarque et al. 1996).

3. It is now well established that $\alpha$-elements are enhanced in halo populations. Specifically, we adopt $[\alpha/Fe] = 0.4$ for clusters with $[Fe/H] < -1.0$, and thereafter we assume that it steadily declines to 0.0 at solar metallicity (e.g., Wheeler et al. 1989). In practice, the treatment suggested by Salaris et al. (1993) was used to simulate the effect of $\alpha$-elements enhancement.

4. Finally, Reimers' (1975) empirical mass-loss law suggests more mass-loss at larger ages. The result of this effect was also presented in LDZ, but unfortunately most widely used diagram (their Fig. 7) is the one based on fixed mass-loss.

We found that all of the above effects make the HB morphology to be more sensitive to age (see Yoon & Lee 1999 for more details). Therefore, as illustrated in Figure 1, now the required age difference is much reduced compared to Figure 7 of LDZ. Now, only 1.2 Gyr of age difference, rather than 2 Gyr, is enough to explain the systematic shift of the HB morphology between the inner and outer halo clusters. To within the observational uncertainties, age differences of about 1.5~2 Gyr are now enough to explain the observed differences in HB morphology between the remote halo clusters (Pal 3, Pal 4, Pal 14, & Eridanus) and M3, and also between M3 and M13 (or M2). These values are consistent with the recent relative age datings both from the HST and high-quality ground-based data.

4. Effect of HB on the Integrated Spectra

If age is indeed the major parameter that controls HB morphology in addition to metallicity, then we expect some effect of it on the integrated spectra. For example, Figure 2 presents our models (Lee, Yoon, & Lee 1999) that illustrate the effect of age sensitivity of the HB on the $H/\beta$ index. First, we have compared in panel (a) our models without the HB with those of Worthey (1994) in order to make sure that our calculations are consistent with previous investigations.
Figure 1. Our new HB population models with the effects of recent developments (b) are more sensitive to age compared to our earlier models (a). $\Delta t = 0$ corresponds to the mean age of the inner halo ($R < 8$ Kpc) clusters, and the relative ages are in Gyr.
Figure 2. Variation of H$\beta$ index with metallicity ($\text{Mg}_2$) and age for simple stellar populations (see text). In panel (c), observational data are compared with our models with HB, and the observational errors are indicated for clusters in NGC 1399.
Thus, panel (a) illustrates only the effect of MS turnoff $T_{\text{eff}}$ variation with metallicity and age. Confirmed that there is no systematic difference with previous investigations, we then added HB stars in our models, along the HB isochrones similar to those in Figure 1b, but including some very old ages ($\Delta t = +2$ & $+4$ Gyr). The result is very striking as shown in panel (b). Of course, the wave-like features are due to the variation of the HB with metallicity and age. For given age, HB gets bluer with decreasing metallicity, and when the mean $T_{\text{eff}}$ of the HB reaches around 9500K, the population models produce peak in the H$\beta$ index. But as metallicity decreases further, HB is becoming too hot to contribute significantly to the integrated H$\beta$ index.

The advent of large ground-based telescopes making it possible to obtain some absorption features of globular clusters in nearby giant ellipticals so that our models can be compared directly with the observations. Data plotted in panel (c) of Figure 2 were obtained at Keck telescope by Kissler-Patig et al. (1998) and Cohen et al. (1998), using the same instrument, both for the globular clusters in the giant elliptical galaxy NGC 1399 and those in the Milky Way Galaxy. At first glance, they may appear to be more or less the same, especially when considering still large errors in NGC 1399. However, some careful examination of the data indicates that there is some systematic difference in that the metal-rich clusters in NGC 1399 have higher H$\beta$ compared to the Galactic counterparts, while the opposite seems to be the case for more metal-poor clusters. Comparing this with our models, we can say that NGC 1399 system is probably several billion years older, in the mean, than the Galactic globular cluster system. Of course, given the large observational uncertainty, more observations are badly needed to confirm this possible scenario. If confirmed by future observations, this would indicate that the star formation in proto giant ellipticals started at an earlier epoch than in the less massive galaxies, such as our Milky Way Galaxy.

What is interesting to us is that a similar age difference is also inferred from the “metal-poor HB solution” of the UV upturn phenomenon of giant ellipticals (Park & Lee 1997; Yi et al. 1999). Our composite models (see also Lee et al., this volume) indicate that age difference of about 3 billion years can also explain the systematic difference in UV upturn between the giant ellipticals and the spiral bulges of the Local Group. Whether the UV upturn phenomenon is indeed a natural extension of the global second parameter effect observed in Galactic globular clusters (“metal-poor HB solution”), or it is rather due to the high $\Delta Y/\Delta Z$ and enhanced mass-loss in super metal-rich population (“metal-rich HB solution”) is still under debate. Fortunately, there are several observational tests for this problem that will eventually provide us more concrete calibration of the far-UV dating for old stellar populations. First, as pointed out by Lee (1994), the “metal-rich HB solution” predicts many super metal-rich RR Lyrae stars in the Galactic bulge because super metal-rich HB stars must cross the instability strip as they move back to blue HB with increasing metallicity. In fact, detailed models by Lee & Lee (1999) indicate that the expected number of super metal-rich RR Lyraes is compatible with more metal-poor ones actually observed in the bulge. Although extensive $\Delta S$ observations by Walker & Terndrup (1991) found not a single super metal-rich RR Lyrae stars in this field, more efficient observations with the Caby photometric system (Rey et al. 1999) would be useful to confirm this result. Second, UIT observations found strong radial gradients
in UV colors within elliptical galaxies (O’Connell et al. 1992), and thus it is important to see whether they are correlated with internal metallicity gradients. Indeed, Ohl et al. (1998) report that they found no correlation between the far-UV gradients and internal metallicity gradients, from which they conclude that UV upturn phenomenon may not be simply related to overall metal abundances in galaxies. They even suggested age as an alternative, which is consistent with our “metal-poor HB solution”. Ongoing STIS/HST observations will provide more clear result on this problem. Finally, far-UV observations with the planned GALEX UV space facility will also provide useful database that is crucial in calibration of our UV dating technique for old stellar systems. Although the importance of new observations can not be overstated, it is already clear now that the detailed modeling of the HB is crucial in spectrophotometric dating of old stellar populations.

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