THE EVOLUTION OF HIGH-METALLICITY HORIZONTAL-BRANCH STARS AND THE ORIGIN OF THE ULTRAVIOLET LIGHT IN ELLIPTICAL GALAXIES

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ABSTRACT

Evolutionary calculations of high-metallicity horizontal-branch stars show that for the relevant masses and helium abundances, post-HB evolution in the HR diagram does not proceed toward and along the AGB, but rather toward a “slow blue phase” in the vicinity of the helium-burning main sequence, following the extinction of the hydrogen shell energy source. For solar and twice solar metallicity, the blue phase begins during the helium shell–burning phase (in agreement with the work of Brocato and Castellani & Tornambè); for 3 times solar metallicity, it begins earlier, during the helium core–burning phase. This behavior differs from what takes place at lower metallicities. The implications for high-metallicity old stellar populations in the Galactic bulge and for the integrated colors of elliptical galaxies are discussed.

Subject headings: Galaxies: elliptical and lenticular, cD — galaxies; stellar content — stars: abundances — stars: evolution — stars: horizontal-branch — stars: post-asymptotic giant branch

1. INTRODUCTION

High-metallicity stars are known to populate the bulge of our Galaxy and are also believed to be an important stellar constituent of elliptical galaxies. The purpose of this Letter is to describe the preliminary results of calculations of post–horizontal-branch evolution which have profound implications for our understanding of metal-rich stellar populations.

Several authors have observed a positive correlation between UV luminosity and metallicity in elliptical galaxies (Wu et al. 1980; Faber 1982; Burstein et al. 1988). Since upward extrapolation from the behavior of less metal-rich stars suggests that high-metallicity stars evolve into asymptotic giant branch (AGB) stars, which are very red, the UV observations seem difficult to understand. However, our calculations show that low-mass high-metallicity stars (with metal contents 2 or 3 times solar) can spend a significant fraction of their evolutionary lifetime as luminous blue stars. This “slow blue phase,” which should not be confused with the less luminous slow blue phase of core helium burning of blue horizontal-branch stars, does not exist in less metal-rich stars. In this case, it replaces the very red and luminous AGB phase which has been discussed extensively by many authors (Iben & Renzini 1983; Habing 1989; Weidemann & Schönberner 1989). Furthermore, it can also be shown that this behavior is expected on the basis of standard evolutionary models constructed under reasonable assumptions about their helium abundances and masses (Demarque & Pinsonneault 1988, hereafter DP; Pinsonneault et al. 1991). This makes evolved high-metallicity low-mass stars obvious candidates to explain the UV observations of elliptical galaxies and to understand the stellar populations of the Galactic bulge.

The importance of our results is best understood in terms of what is known about the advanced evolution of the old low-metallicity stars in the galactic halo. The possible patterns of advanced evolution have been described by Sweigart, Mengel, & Demarque (1974). Several evolutionary paths can account for the observed UV-bright stars in globular clusters (Zinn, Newell, & Gibson 1972). First, AGB stars will, when their envelope masses decrease below 0.02 M⊙ or less, cross the HR diagram at high luminosity toward the white dwarf cooling curve. Mengel (1973) and Schönberner (1983) have discussed the final H-shell flashes and the post-AGB phase of these objects. Ciardullo & Demarque (1978), and more recently Bertelli, Chiosi, & Bertola (1990), have discussed the possible importance of these post-AGB stars to explain the UV light of elliptical galaxies. For lower masses, evolution on the HB takes a different course, toward the blue, and bypasses the AGB phase of evolution. The name AGB-manqué stars has been used for these stars by Greggio & Renzini (1990). Finally, in the most extreme case, which we shall call HB-manqué, mass loss on the giant branch may force the blueward crossing before the helium core reaches the critical mass for helium ignition.

In § 2 of this Letter we present our results of post-HB evolutionary calculations for stars with metallicities larger than solar (with Z up to 0.06). We will see that indeed, as Z becomes larger than solar, the pattern of evolution of post-HB stars can change dramatically. This change goes beyond the conclusion of DP (which explained primarily the paucity of AGB stars, but not conclusively the increased frequency of UV-bright stars), since it predicts specifically in addition an increased lifetime for UV-bright stars. Even stars that start out their HB evolution on the red HB do not continue to evolve up the AGB, provided their total ZAHB mass is sufficiently low. In this case, the rapid exhaustion of their hydrogen energy supply leads stars to spend the remainder of their helium-burning phase (roughly the time that is spent on the AGB by less metal-rich stars), near the helium main sequence, as UV-bright stars.

In § 3 we discuss the significance of the evolutionary tracks in the broader context of pre-HB evolution and explain why our choices of masses and helium abundances are realistic. We summarize our results in § 4.

2. EVOLUTIONARY CALCULATIONS

Seven families of horizontal-branch evolutionary tracks were constructed. Each family consists of a set of stellar models of the same metallicity, helium abundance, and helium core
mass, but which together span a large range in total mass. All models were constructed using Cox & Stewart (1970) opacities, as were the DP evolutionary tracks. Because of the exploratory nature of this work, and the need to construct a large number of models, no attempt was made to achieve high numerical accuracy, although care was taken to preserve the necessary internal consistency in the models. Whenever possible, comparison were made with the tracks of Seidel, Demarque, & Weinberg (1987), which were constructed with the same physical assumptions and evolution code. Future, more detailed studies will require the use of more up-to-date opacities and energy generation, and more refined numerical models. A summary of the parameters used in each family is given below in Table 1.

In all but family 7, 10 stellar models were calculated with masses from 0.49 to 0.90 $M_\odot$. Family 7 consists of six tracks with masses from 0.56 to 0.90 $M_\odot$. The last column is the transition ZAHB mass, below which stars enter the slow blue phase (see below).

As Table 1 shows, we studied two values of $R$ [where $R = (\Delta Y/\Delta Z)$], the helium enrichment parameter. This parameter is not well known, and our hope was to cover an adequate range with these two values. Starting from the family 1 parameters of $Y = 0.25$ and $Z = 0.01$, choosing an enrichment parameter fixes $Y$ for a given $Z$. The core mass $M_{\text{core}}$ for each family is derived from Table 1 in the Sweigart & Gross (1976) paper. This table gives core mass as a function of $Y$ and $Z$. $M_{\text{tr}}$ is the ZAHB mass at which the transition to AGB-manqué track morphology takes place.

A selection of evolutionary tracks which cover the mass range for studies 2 and 3, 4 and 5, and 6 and 7 are shown in the theoretical HR diagram in Figures 1a and 1b, 1c and 1d, and 1e and 1f, respectively. It is evident that at high metallicities the pattern of evolution differs dramatically from what an extrapolation of lower than solar metallicities would suggest. For a given metallicity, we note that higher $Y$ means a more luminous and bluer ZAHB model for the same total mass. Higher $Y$ also means a hotter hydrogen-burning shell because of the increase in mean molecular weight, and the more rapid exhaustion of the hydrogen-rich envelope. These two effects, coupled with enhanced CNO abundances, further favor the production of luminous blue stars. It is interesting to note the rapid rise in luminosity before the star settles down near the helium-burning main sequence. It is recognizable by the spacing of tickmarks in Figure 1c to 1f. This is due to a hydrogen flash before the disappearance of the hydrogen-burning shell. Note also that unlike lower metallicity HB stars (e.g., Sweigart & Gross 1976; Lee & Demarque 1990), even high-metallicity HB stars which begin their evolution at the red end of the ZAHB do not necessarily evolve into luminous AGB stars, but rather can end up as blue AGB-manqué stars.

The most striking result is the existence of a “slow blue phase,” where a low-mass HB star can remain at log $T_{\text{eff}} > 4.5$ and log $(L/L_\odot)$ between 1.5 and 2.0 for 20 Myr or more. This phase becomes more prevalent for values of $Z$ 2-3 times solar. The physical explanation is that for a given total mass the CNO processing is greatly enhanced, so that the star burns most of its hydrogen envelope much faster than a similar star of low $Z$. Helium burning, however, remains essentially unaffected by $Z$. Once the envelope mass drops below a critical threshold, the star shrinks and evolves to the vicinity of the helium-burning main sequence and the locus in the HR diagram of evolving helium-burning stars (Aller 1959; Cox & Salpeter 1961; Divine 1965; Caloi, Castellani, & Tornambé 1978). By this time, the models shown in Figures 1c and 1f have exhausted the helium in their convective core and are deriving their luminosity from helium-shell burning. This result is in agreement with the recent studies of Brocato et al. (1990) for solar $Z$, and of Castellani & Tornambé (1991) for stars with solar $Z$ and $Y$ and with twice solar $Z$, for the $R = 2$ case. Note that for still higher values of $Z$ and $Y$, the pattern of evolution again becomes qualitatively different, as seen for the lowest mass tracks shown in Figures 1e and 1f.

### Table 1

<table>
<thead>
<tr>
<th>Family</th>
<th>$Y$</th>
<th>$Z$</th>
<th>$M_{\text{core}}/M_\odot$</th>
<th>$R$</th>
<th>$M_{\text{tr}}/M_\odot$</th>
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</table>

3. PRE-HORIZONTAL-BRANCH EVOLUTION

As discussed in DP (see also Pinsonneault et al. 1991), there are two main factors which tend to reduce the masses of metal-rich HB stars. Not as important in more metal-poor systems, these factors become dominant in controlling the evolution of high-metallicity stars. They are the following:

1. Metal-rich stars are also helium rich. It is generally believed that the helium abundance $Y$ increases in a stellar system as the metallicity increases due to nucleosynthesis. The amount of helium enrichment is usually given in terms of the ratio $R$ of galactic enrichment. $R$ is not well known and is believed to lie in the range 2-4 (Peimbert et al. 1988). It is clear that as $Z$ increases over the solar value (about 0.02), the increase in $Y$ for a given $R$ becomes substantial. In addition a study by Maeder (1990) of the evolution of massive stars with different initial metallicities predicts that $R$ increases and $Z$ increases. Therefore stars with metallicities above a certain threshold will have a lower mass at the same age.

2. Metal-rich stars have high mass-loss rates. This is true even though the mass-loss process may not be directly related to metallicity. In addition to lower masses, high-metallicity red giants also have larger radii (lower $T_{\text{eff}}$) at the same luminosity, and therefore lower surface gravities, than metal-poor red giants. They should therefore, at the same age, lose mass at a higher rate, according to Reimers's (1975) empirical formula.

4. SUMMARY AND DISCUSSION

In the light of these results and of the earlier findings of DP and Pinsonneault et al. (1991), we can summarize the evolutionary patterns of old stars with high $Z$, which have important implications for studying the stellar population in the Galactic bulge and in elliptical galaxies.
EVOLUTION OF HIGH-METALLICITY HB STARS

Fig. 1.—(a) Selected post-HB evolutionary tracks for solar metallicity. The “+” symbols delimit equal time intervals of 5 Myr along each track. M_{core} denotes the mass in the helium core when the model begins its evolution on the ZAHB. (b) Same as (a), but for a higher initial helium content. (c) Same as (a), but for twice solar metallicity. (d) Same as (b), but for twice solar metallicity. (e) Same as (a), but for 3 times solar metallicity. (f) Same as (b), but for 3 times solar metallicity.

1. For metallicities higher than solar, post-HB stars spend more and more time as luminous OB-stars in a “slow blue phase” of high luminosity in the vicinity of the evolved helium-burning main sequence in the HR diagram. This blue evolutionary phase is at the expense of part or even the whole AGB phase. Its lifetime, and the mass for which this occurs, both increase with increased metallicity. The effect is further enhanced by the expected higher helium abundance of high-metallicity stars. The luminosity of this phase is near or below 100 L_{\odot}, consistent with the upper limit found for the brightness of point sources in M31 by O'Connell (1991).

2. The transition ZAHB mass M_{tr} for which the transition from AGB to AGB-manqué evolution occurs is a function of metallicity. As the metallicity increases, M_{tr} increases. In addition, for each Z, M_{tr} is itself a steep function of the chemical enrichment ratio, in the sense that the larger R (the higher Y), the larger M_{tr} becomes (see Table 1). This result will put strong constraints on the dependence of the spectral energy distribution of stellar systems on age, metallicity, and helium content because the low masses that are required to produce luminous blue stars are the natural consequence of the effects of high Z on standard evolution and mass loss, and do not require any fine tuning or the introduction of additional ad hoc mass-loss mechanism.

3. Finally, there is an age threshold above which the masses of giant branch stars drop below the critical mass for helium to ignite in their core. Such stars evolve as HB-manqué stars directly to the white dwarf cooling curve. Standard stellar evolution theory predicts that as the most metal-rich stellar populations of the Galactic bulge and elliptical galaxies age beyond this threshold, their M/L ratio should increase abruptly, since the luminous post-HB phases are bypassed.

The consequences for stellar population synthesis of these findings are potentially far-reaching, since relatively few evolved high-metallicity stars could affect in a major way the blue and UV spectral energy distribution of stellar systems.

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The advanced evolution of high-metallicity stars thus explains in a natural way why galaxies emit increasingly more blue and UV light as their mean metallicity increases (Burstein et al. 1988). The theoretical predictions are also consistent with the UV observations of M31 (O’Connell 1991), and the paucity of high-metallicity M-giants in the Galactic bulge (J. Frogel 1991, private communication). More extensive evolutionary calculations, now in progress (Pinsonneault et al. 1991), are required to put these results on a firmer quantitative basis, and to apply them to the population synthesis of metal-rich stellar systems.

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