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INVITED REVIEW

Horizontal branch stars: the interplay between observations and theory, and insights into the formation of the Galaxy

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Abstract We review and discuss horizontal branch (HB) stars in a broad astrophysical context, including both variable and non-variable stars. A reassessment of the Oosterhoff dichotomy is presented, which provides unprecedented detail regarding its origin and systematics. We show that the Oosterhoff dichotomy and the distribution of globular clusters in the HB morphology-metallicity plane both exclude, with high statistical significance, the possibility that the Galactic halo may have formed from the accretion of dwarf galaxies resembling present-day Milky Way satellites such as Fornax, Sagittarius, and the LMC—an argument which, due to its strong reliance on the ancient RR Lyrae stars, is essentially independent of the chemical evolution of these systems after the very earliest epochs in the Galaxy's history. Convenient analytical fits to isochrones in the HB type–[Fe/H] plane are also provided. In this sense, a rediscussion of the second-parameter problem is also presented, focusing on the cases of NGC 288/NGC 362, M13/M3, the extreme outer-halo globular clusters with predominantly red HBs, and the metal-rich globular clusters NGC 6388 and NGC 6441. The recently revived possibility that the helium abundance may play an important role as a second parameter is also addressed, and possible constraints on this scenario discussed. We critically discuss the possibility that the observed properties of HB stars in NGC 6388 and NGC 6441 might be accounted for if these clusters possess a relatively minor population of helium-enriched stars. A technique is proposed to estimate the HB types of extragalactic globular clusters on the basis of integrated far-UV photometry. The importance of bright type II Cepheids as tracers of faint blue HB stars in distant systems is also emphasized. The relationship between the absolute V magnitude of the HB at the RR Lyrae level and metallicity, as obtained on the basis of trigonometric parallax measurements for the star RR Lyr, is also revisited. Taking into due account the evolutionary status of RR Lyr, the derived relation implies a true distance modulus to the LMC of $(m–M)_0 = 18.44 \pm 0.11$. Techniques providing discrepant slopes and zero points for the M_V(RRL)–[Fe/H] relation are briefly discussed. We provide a convenient analytical fit to theoretical model predictions for the period change rates of RR Lyrae stars in globular clusters, and compare the model results with the available data. Finally, the conductive opacities used in evolutionary calculations of low-mass stars are also investigated.

Keywords Galaxies: Local Group · Galaxy: formation · Galaxy: globular cluster: general · Stars: evolution · Stars: Hertzsprung-Russell diagram · Stars: horizontal-branch · Stars: variables: other

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1 Introduction

1.1 A bit of history

In her beautiful review of (hot) horizontal-branch (HB) stars, Moehler (2001) notes that Barnard (1900) was the first to detect the presence of (blue) horizontal-branch stars in globular clusters. The term *horizontal branch* appears to have been coined by ten Bruggencate (1927), to

whom Moehler (2004) assigns the discovery of the horizontal branch—which he noticed when plotting the color-magnitude data obtained by Shapley (1915) in the latter's study of NGC 5272 (M3). Of course, with the development of nuclear astrophysics and the establishment of modern stellar evolution theory still several years away, it was not until three decades later that Hoyle and Schwarzschild (1955) first correctly identified HB stars as the progeny of low-mass red giant branch (RGB) stars, burning helium in their center and hydrogen in a shell around the core.

The first successful HB models were actually computed by Faulkner (1966), and Castellani and Renzini (1968) and Iben and Rood (1970) were the first to recognize that substantial mass loss on the RGB phase was needed to explain the observed colors of HB stars in globular clusters, with moreover a significant spread in mass loss amounts from star to star in any given globular cluster being needed to explain their observed color ranges—blue HB stars losing, on average, more mass than red HB stars. The distribution of masses along the HB often resembles a normal or Gaussian distribution (Rood and Crocker 1989; Dixon et al. 1996; Valcarce and Catelan 2008), and normal deviates are accordingly often adopted in the construction of "synthetic horizontal branches" (e.g., Rood 1973; Castellani and Tornambè 1981; Caputo et al. 1987; Catelan 1993; Lee 1990; Lee et al. 1990; Cassisi et al. 2004). The presence of mass distributions that resemble Gaussian deviates strongly suggests the presence of *stochastic mass loss processes* on the RGB. However, deviations from a Gaussian shape are also not uncommon among globular clusters, particularly in the cases of those having bimodal HBs and/or long blue tails with gaps (Catelan et al. 1998; Ferraro et al. 1998; Piotto et al. 1999; Momany et al. 2004).

1.2 The complexity of the "HB phenomenon"

It is virtually impossible to write a short review paper on HB stars covering "observations", "theory", and "implications for the formation of the Galaxy": each one of these subjects covers so much material that one could rather write separate review papers for each one of them. Moreover, a review of HB stars cannot be complete without looking into their progenitors and their progeny. The task of a reviewer of HB stars is accordingly a daunting one, and it is virtually impossible to aim at completeness. In the present paper, while attempting to cover a broad spectrum of HB-related topics, we again hold no hope of providing a complete review of the literature on these subjects. Recent reviews focusing on several more or less specific topics related to HB stars have been provided by Cacciari (1999, 2003), Chaboyer (1999), de Boer (1999), Moehler (2001, 2004), Sweigart (1997b, 1999), Demarque (1999), Landsman (1999), Lee et al. (1999), Walker (2000), Green et al. (2001), Cacciari and Clementini (2003), Bono (2003), De Medeiros (2003), Piotto (2003), Maxted (2004a, 2004b), Cassisi (2005), Storm (2006), Heber (2008), and Rood et al. (2008); and very instructive earlier reviews, covering diverse astrophysical contexts, include those by Sweigart (1985, 1990, 1994), Philip (1994), Cox (1995), Dorman (1995), Smith (1995), Beers (1996), Stetson et al. (1996), Sarajedini et al. (1997), Fusi Pecci and Bellazzini (1997), Rood et al. (1997), and Rood (1998). Similarly, excellent sections focused on HB stars can be found in the reviews on the evolution of low-mass stars, Population II stars, globular clusters, and related topics by Renzini (1977, 1983), Iben and Renzini (1984), Castellani (1985, 1999), Caputo (1985, 1998), Renzini and Fusi Pecci (1988), Rood and Crocker (1989), Iben (1991), Zinn (1993a, 1993b), D'Antona (1999), Feast (1999), Carney (2001), Harris (2001), and Gratton et al. (2004b), among others. Other recent reviews by the present author on the subject of HB stars include Catelan (2004b, 2006, 2008a, 2008b, 2009).

In Fig. 1 we show a visual color-magnitude diagram (CMD) for the Carina dwarf spheroidal (dSph) satellite of the Milky Way, with several different HB components indicated, including both a *red clump* and a *red HB*. The

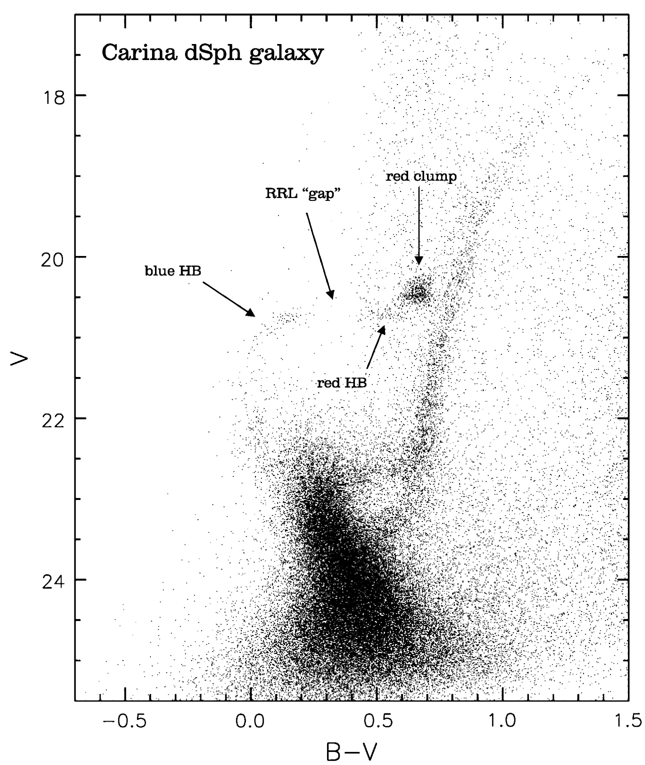

Fig. 1 V, $B-V$ CMD for the Carina dSph galaxy, with the positions of red clump stars, red HB stars, the RR Lyrae "gap," and the blue HB indicated. The red clump is associated with the younger turnoff, at $V \approx 23$ mag, $B-V \approx 0.25$ mag. The other components derive from the old turnoff whose presence is indicated by the faint subgiant branch at $V \approx 23.25$ mag, $B-V \approx 0.55$ mag. Adapted from Monelli et al. (2003)