Evolutionary scenarios and chemical inhomogeneities of extended horizontal branch stars

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Abstract. Extended Horizontal Branch (EHB) stars are observed in many globular clusters and as field stars in the Galactic halo. They belong to old stellar populations of the halo and the old disk. Their evolutionary status is unclear, and still a current subject of debate. Current interest in these stars arise from their association with the discoveries of helium abundance inhomogeneities in the globular clusters ω Cen and NGC 2808. The origin of the inhomogeneities is not yet understood, but there are many interpretations.

In order to better understand EHB stars, we explore the evolution of standard blue Horizontal Branch (HB) models using up-to-date physics. We present several grids of post Zero Age Horizontal Branch (post-ZAHB) evolutionary models to include both canonical and non-canonical evolutionary scenarios, as well as to compare models that contain semi-convection to models without semi-convection. We follow the models to the termination of nuclear helium burning. The detailed properties of the models, including shell flashes and breathing pulses, are described.

1. Introduction
We have explored the post Zero Age Horizontal Branch (post-ZAHB) evolution of Extended Horizontal Branch (EHB) models with a canonical evolutionary history and without a prescription for semi-convection and learned that they undergo a series of shell flashes after core helium exhaustion. In this poster we want to explore the effects of different evolutionary scenarios as well as the effect of semi-convection on the post-ZAHB evolution of EHB models.

Besides the canonical evolutionary history of evolving onto the EHB after the helium flash at the tip of the Red Giant Branch (RGB), there are alternative evolutionary scenarios that can populate the EHB as well. One such alternative is the late hot flasher scenario [1]. In this scenario there is enough mass loss on the RGB that the helium flash is delayed until the star is on the white dwarf cooling curve. There are two types of mixing that can be associated with this late helium flash, deep and shallow mixing. The details of the two mixing events can be found in Lanz et al., 2004 [1]. We have mimicked these evolutionary scenarios by changing the surface abundances of our models in order to study if different evolutionary scenarios affect post-ZAHB evolution.

We have also created models that contain semi-convection. Semi-convection occurs during core helium burning when a region around the convective core becomes unstable to convection and expands, pulling surface material into the core and depositing core material onto the surface. Semi-convection is known to occur in horizontal branch stars through observations of the ratio of Asymptotic Giant Branch (AGB) stars to RGB stars [2]. Because of this fact we wanted to
include semi-convection in our models in order to study what affect semi-convection has on the post-ZAHB evolution of EHB stars.

2. Models
We have created a grid of Horizontal Branch (HB) models using the Yale Rotating and Evolutionary Code (YREC) in the non-rotating configuration [3]. These models have an envelope mass of \(0.001M_\odot\) and are evolved from the ZAHB to helium core exhaustion. Models with canonical evolution with and without semi-convection were constructed with different helium abundances \(Y = 0.14, 0.24, 0.39\) and metallicities \(Z = 0.0001, 0.0002, 0.01, 0.02\) and \(M = 0.4887M_\odot\).

Models with a non-canonical evolution and without semi-convection were constructed with ZAHB models that have artificially enhanced surface abundances to be consistent with the deep and shallow mixing scenarios as described by Lanz et al. [1] with a mass \(M = 0.4488M_\odot\).

We used the OPAL opacities for moderate to high temperatures [3], the Ferguson opacities [4] for low temperatures, the OPAL equations of state [5] and the nuclear reaction rates from the NACRE collaboration [6].

3. Results
After creating our models we discovered that non-canonical models have evolutionary tracks characterized by oscillations in the Hertzsprung Russell (HR) diagram that occur after the smooth central helium burning phase (Fig. 1).

Figure 1. Evolutionary tracks in the HR diagram for sdB models who arrived on the ZAHB via the late hot flasher scenario as described in Lanz et al. (2004). The model on the left undergoes deep mixing, while the model on the right undergoes shallow mixing. The level of mixing in each models affects the surface abundance on the ZAHB (black dot). Notice how each model enters an evolutionary phase characterized by oscillations in the HR diagram following the smooth phase of core helium burning caused by thin shell flashes just as the models with canonical pre-ZAHB evolution.

These are the same type of oscillations that are exhibited by the evolutionary tracks of the
canonical models as seen in Figure 2. We find no fundamental difference in horizontal branch evolution between models that have different pre-ZAHB evolutionary scenarios.

After creating the models of EHB stars that contain a prescription for semi-convection we discovered that the models with semi-convection evolve to lower temperatures and lower luminosities than the models without semi-convection, and their evolution is characterized by small loops in the HR diagram (Fig. 2).

![Figure 2](image-url) Evolutionary tracks of two models with Y=0.14 and Z=0.01, one that contains a prescription for semi-convection and one that does not and both undergo canonical pre-ZAHB evolution. Notice how the model with semi-convection evolves to lower temperatures and lower luminosities. The evolution of the model with semi-convection is characterized by small loops during the core helium-burning phase caused by breathing pulses. The evolution of the model without semi-convection is characterized by loops in the HR diagram following the core helium-burning phase. The semi-convection model spends most of its evolutionary lifetime above the blue line.

These loops are caused by breathing pulses, where the convective core expands into the envelope, pulling helium-rich material into the core, which increases the central helium abundance (Fig. 3).

The lower luminosity and temperature of the model with semi-convection can be explained through these breathing pulses. When the convective core expands, surface material is brought to the core, and core material, which is extremely metal-rich, is brought to the surface. The increase in the surface metal abundance increases the opacity of the star, which will lower the effective temperature and the luminosity of the star. Including a prescription for semi-convection suppresses the shell flashes that are seen in the models that do not have semi-convection because it increases the size of the carbon-oxygen core. Another important difference between models with and without semi-convection is that due to the increase in helium throughout central helium burning, the lifetime of the star is increased by a factor of 3 over the model without semi-convection.

This work was the necessary preparatory work for an asteroseismic study of EHB stars. The next step in this research is to explore the acoustic spectrum and its dependence on input parameters such as total mass, helium core mass and chemical composition.
Figure 3. Central helium abundance plotted against time for a model with semi-convection (red) and models without semi-convection (black) that have Y=0.14 and Z=0.01. Notice how the addition of semi-convection adds spikes in Yc and lengthens the core-helium burning lifetime by a factor of 3 as compared to the model without semi-convection. The spikes in Yc are caused by breathing pulses that are characteristic of semi-convection. The convective core expands into the envelope, which increases Yc, adding more fuel to the core and thereby lengthening the lifetime.

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