12. EVOLVED STARS

NON-VARIABLE HORIZONTAL-BRANCH STARS

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Abstract. For 25 years our ignorance of the physical basis of this mass loss process has been the barrier to progress in understanding horizontal branch morphology. I review some recent observational and theoretical results which may be giving us clues about the nature of the mass loss process.

1. Introduction

Much of the effort in horizontal branch (HB) research has been directed toward understanding its most obvious feature—the "horizontal" distribution of stars. How and why does HB morphology change from cluster to cluster. Early observations showed that in general HBs become redder as metallicity (usually measured by the iron abundance—[Fe/H]) increased. Faulkner (1966) showed how this arose naturally in core helium burning stars and led to there identification with the observed HB. However, even early data showed that more than one parameter appeared to be driving HB morphology. The quest to identify this second parameter still continues.

Early attempts to explain observed HBs (e.g. Iben & Rood 1968) were made without invoking mass loss in an effort to circumvent the introduction a free parameter. Unfortunately these efforts failed to reproduce either the centroid or breadth of observed HB log $T_{\rm eff}$ distributions. An alternate hypothesis was that the HB was a mass sequence rather than an evolutionary sequence. Because the mass of the helium core at the time of the helium flash was insensitive to total stellar mass, it was plausible to model the HB as sequence of stars with constant core mass ($M_{\rm core}$) and varying total mass (M). The zero-age HB (ZAHB) of stars just beginning core He burning is populated with stars which have undergone some mean mass loss (ΔM) with dispersion around that mean [$\sigma(M)$](Iben & Rood 1970;

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Faulkner 1972). Subsequent evolution carries stars away from their ZAHB location, but under most circumstances the primary factor affecting HB morphology is what part of the ZAHB is populated. Thus four mass parameters were required to model HBs: $M_{\rm RG}$, $M_{\rm core}$, ΔM, & $\sigma(M)$. Only, two of these, $M_{\rm RG}$ & $M_{\rm core}$, can be determined with evolutionary calculations. The other two are taken as free parameters—with $\Delta M \sim 0.25 M_{\rm RG}$ and a $\sigma(M) \sim 0.1\Delta M$ Rood (1973) could mimic the observed CMDs of many clusters. HBs are still modeled in this fashion (e.g. Lee, Demarque, & Zinn 1990, 1994; Catelan 1993; Catelan & de Freitas Pacheco 1993)

Adopting this model, in addition to [Fe/H], age, helium abundance (Y), and the summed abundance of the CNO elements with respect to iron ([(C + N + O)/Fe]) were found to affect where stars fall on the HB. One could fix [Fe/H] and vary one the others to explore the second parameter problem, but this requires an assumption about mass loss, e.g. that the mean mass loss is a constant or that the mass loss was given by the Reimers' formula (Reimers 1977). Even the early work of Rood (1973) (see his Fig. 4) showed the potential pitfalls of such assumptions. However, age is the most attractive and tractable of the second parameter candidates, and in recent years many (most notably Lee, Demarque, & Zinn 1990, 94) have argued that dominant second parameter is age.

There are two factors which suggest that age differences are not the dominant driver of HB diversity at fixed [Fe/H]. The first of these is that as second parameter pairs are better studied, age differences seem to be disappearing rather than being confirmed. Perhaps the best studied second parameter pair for many years was NGC 288/NGC 362. The case for an age difference seemed particularly strong (Bolte 1989; Green & Norris 1990; Dickens et al. 1991). Yet in very detailed reanalysis Stetson, VandenBerg, & Bolte (1996) argue that the difference in HB morphology is not due to age and point out the difficulties in obtaining differential age measures. One crucial factor that is that the photometry for the brighter cluster stars and fainter turn-off stars be obtained and calibrated in *exactly the same way.* Ferraro et al. (1997) have obtained HST observations of the second parameter pair M3/M13 which satisfy this criterion. Again they find that no significant age difference which could account for the dramatic difference in HB morphology. Earlier, Catelan & de Freitas Pacheco (1995) had reached a similar conclusion. Likewise Richer et al. (1996) find that the M3/NGC 6752 pair have the same age. Indeed, the only clusters with certifiably different ages seem to be two small groups (including Rup 106, Arp 2, & IC 4499) associated with the accretion of other small galaxies by the Milky Way (Fusi Pecci et al. 1995; Richer et al. 1996).

The second factor causing me to doubt the ubiquity of age differences is the growing complexity of observed HB morphology. The first hint of what was to come was the CMD of NGC 6752 presented by Russell Cannon at the 1973 Frascati Globular Cluster workshop (Cannon 1985). It showed a very hot vertical HB with a very distinct *gap* in the stellar distribution. The ensuing years have given even more surprises. Strongly bimodal HBs are found in NGC 2808 (Ferraro et al. 1990) and NGC 1851 (Walker 1992). Clusters which we thought we knew, like M13, turn out to have gaps (Ferraro et al. 1997). There are additional BHB gaps in NGC 2808 (Piotto et al. 1997; Sosin et al. 1997). There are prominent blue extensions to the HBs of the metal rich clusters NGC 6388 and NGC 6441 (Rich et al. 1997; Sosin et al. 1997).

Neither blue HB gaps as found in NGC 6752 (Crocker, Rood, & O'Connell 1988) nor bimodal HBs as in NGC 2808 (Rood et al. 1993) can easily be accommodated into a simple HB scheme. One needs more than an age difference to turn a "classic" HB like that of M3 into a "NGC 6752" or a "NGC 2808." Since some factor other than age must be invoked for these extreme cases, perhaps it is a factor all of the time.

2. HB Evolution Does Not Produce Gaps & Bimodality

One might wonder whether HB evolution could naturally lead to the exotic HB morphologies described above. Indeed, it has been long know that there are families of HB track types, and Newell (1973) suggested that BHB gaps might arise in the region where the tracks were changing from the mode where evolution eventually carries the star back toward the RGB to the mode where all HB evolution takes place at high log T_{eff}. Our current results suggest that this is not the case (Rood, Whitney, & D'Cruz 1997; Whitney, Rood, & O'Connell 1997a). This is most clearly shown using Hess Diagrams (Hess 1924). A Hess Diagram represents the CMD as an "image" rather than a collection of points. The "intensity" of each pixel is the observed or theoretical density of stars in the CMD. Such a representation combines the advantages of a CMD with the temporal information contained in number counts and luminosity functions (LFs). Theoretical HB Hess Diagrams are constructed by weighting each pixel of the CMD image according to the amount of time evolving stars spend in that region of the CMD. The resulting image is a population density plot, indicating where evolving HB and post-HB stars spend their lifetimes, and thus, where they are most likely to be observed. Our point here is best illustrated in Figs 1–4 of Rood et al. (1997). In these a flat ZAHB mass distribution ($\mathcal{P}(M)$ = constant) has been assumed. While this is unphysical it illustrates one very important point. The HB shown is analogous to a block of clay from which an observed HB must be sculpted. Any "observed" features like gaps which are not present in this block of clay must be introduced either by the transformation to the observed quantities or by sculpting "structure" using $\mathcal{P}(M)$. The conversion to colors and magnitudes is analogous to bending and stretching the clay block. It introduces only mild features. The resulting Hess diagram has neither BHB gaps nor strong HB bimodality. Thus, these structures are a product of the mass loss process.

3. Natural Sources of Bimodality

Our assumption is that HB structure like gaps and bimodality must arise naturally. It is quite possible to produce HB bimodality by assuming a bimodal mass distribution (and 4 free parameters), but that is a most unsatisfying approach (Rood et al. 1993). This structure must be telling us something about the mass loss process.

Extreme horizontal branch stars (EHB) are stars with such small envelope masses that the ensuing helium shell burning phase occurs at high log $T_{\rm eff}$—the so-called AGB-manqué and P-EAGB stars (Greggio & Renzini 1990; Dorman, Rood & O'Connell 1993). Some clusters have HB blue tails which extend into the EHB region. There is sometimes a gap at or near the beginning of EHB regions (e.g. M13—Ferraro et al. 1997 and NGC 2808—Piotto et al. 1997). One especially puzzling aspect of clusters with extensive EHB populations is that the EHB is populated by a very narrow range of HB masses. Surely some fine tuning of the mass loss process is required to funnel so many stars into such a small mass range

However, D'Cruz et al. (DDRO) showed that this was not the case. Simply by modeling the HB using $\mathcal{P}(\eta_{\rm ML})$, where $\eta_{\rm ML}$ is a Reimers-like mass loss parameter, rather than $\mathcal{P}(M_{\rm HB})$ one can produce EHB stars without fine tuning and produce a gap just above EHB transition. I conjecture that the lower BHB gap observed in many clusters is this EHB gap. Observations of the location of the EHB gap and the distribution of stars on the hot side of the gap will yield information on the mass loss mechanism.

Bimodality could also arise naturally from stellar interactions. Buonanno, Corsi & Fusi Pecci (1985) first suggested that cluster density, and thus stellar interactions, might play a role in HB morphology. More recently, Fusi Pecci et al. (1993) and Buonanno et al. (1997) have shown a correlation between the presence of long HB blue tails (BT) and cluster central density. Others (e.g. Bailyn et al. 1992) have argued that BT stars arise from stellar collisions and binary mergers.

There are several reasons to think this is not the case: (1) The observed stars have parameters more or less like those of single star models. One would expect that mergers and collisions produce a more diverse population. (2) There is no variation (at least in a gross sense) of BHB/EHB population with position in a cluster (Rich et al. 1997;

Whitney et al. 1997b). This is in contrast to the blue stragglers, which are generally considered to be certifiable interaction products and normally strongly concentrated toward the cluster center. (3) The correlations between BT stars and cluster density are not perfect. In most respects M3 & M13 are twins (with moderate central density), yet M13 has a prominent BT and M3 does not (Ferraro et al. 1997). The richest population of EHB/BT stars of any Galactic globular cluster is that in ω Cen a very "open" cluster. Thus, there has to be a mechanism for making BT stars not involving collisions.

So we are left with a tight, but not one-to-one, correlation between BTs and cluster density. Maybe this is telling us that density affects some parameter which affects mass loss. Basically, high density clusters seem to be able to "turn-on" some additional mass loss process. The mediating parameter must be affected by factors other than cluster density. The most likely candidates are stellar rotation (Peterson, Rood, & Crocker 1995) or helium mixing on the giant branch (Sweigart 1997a; Sweigart 1997b), which in turn may be tied to each other. The degree to which this extra driver of mass loss operates may determine whether there is another BHB gap near where the HB turns sharply downward in the V, $B-V$ plane.

4. Summary

- Gaps along the HB do not arise naturally from the models. ⇒ HB gaps probably tell us something about mass loss.
- There are many strange HBs. There are no simple one-to-one correlations between HB morphology and other parameters. ⇒ It is dangerous to assume HB morphology can be a measure of age.
- If one thinks in terms of $\mathcal{P}(\eta_{\rm ML})$ rather than $\mathcal{P}(M_{\rm HB})$, then (1) Fine tuning is not required to produce stars with very low envelope masses. (2) A gap (the lower, or EHB, gap in M13 and NGC 2808) can arise naturally. (3) As metallicity increases the mid-HB becomes difficult to populate. Bimodality is easy to explain in high metallicity systems. (4) It is just as easy to make EHB stars at high metallicity as at low.
- There may be two or more mass loss mechanisms.

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