EVOLUTION OF GLOBULAR CLUSTER STARS WITH MASS LOSS AND CORE ROTATION

F. Fusi-Pecci and A. Renzini

Osservatorio Astronomico, Italy

During the last decade theoretical and observational research on globular cluster stars has fairly conclusively demonstrated that the mass of horizontal-branch (HB) stars is substantially smaller (by $\sim 0.2\ M_\odot$) than the mass of their main-sequence progenitors (cf. Rood 1973, Fusi-Pecci and Renzini 1975, hereafter MPS V and FPR respectively, and the literature quoted therein). Also well established is the fact that HB stars in a single cluster do not follow a unique evolutionary path but that some dispersion in at least one HB parameter (e.g. total mass, core mass, or composition) is required. Further, a growing body of astrophysical evidence shows that the HB morphology is poorly correlated with the abundance of low-ionization potential elements (ALIPE) such as Mg, Ca, Si, and Fe. This has raised the well known problem of the "second parameter" in the sense that something else besides ALIPE has to vary from cluster to cluster, the most popular candidates being age, t, helium, Y, and CNO abundance, Z_{CNO}. Therefore, the main problems which research on globular cluster stars is presently facing are i) a quantitative knowledge of the mass loss process, ii) the identification of the origin of the HB dispersion in a single cluster, and iii) the identification of the second parameter(s). The solution of the last point has profound implications for the theory of the early chemical and dynamical evolution the Galaxy.

As far as point i) is concerned, extant mass loss rate (MLR) expressions for red giant stars (FPR, Reimers 1975, Fusi-Pecci and Renzini 1976) can be used to predict the total mass

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in pre-HB phases. In both the FPR and Reimers MLR expressions a proportionality factor - respectively η_{FPR} and η_R - is present. Such coefficients can be determined by imposing the condition that the observed position of the HB in the HR diagram be reproduced. We find $\eta_{FPR} \simeq (4.4 \pm 0.2) \times 10^{-4}$ and $\eta_R \simeq 0.38 \pm 0.02$ (for details see Renzini 1977). The emphasis here is on the narrow range of the allowed MLR of red giants stars if observed HB's have to be reproduced. Conceivably, neither the theory of stellar winds nor direct observations in the near future will be able to provide an independent estimate of the mass loss rate of Population II red giants at this accuracy level ($\sim$ 4%). In other words, the only way to treat mass loss will continue to be through a "free parameter" (η) to be determined a posteriori. A second crucial question concerns the Z-dependence of the MLR. Assuming M proportional to Z^α (for Z larger than, say, 10^{-4}), one has $\alpha = -0.04$ for the FPR - MLR and $\alpha \simeq + 0.08$ for the Reimers-MLR. It is worth emphasizing that the arguments leading to the evaluation of α are very weak both in the FPR and in the Reimers approach. However, differences in the HB morphology using the FPR and Reimers MLR expressions are quite small. The fact that "metal rich" clusters have a stubby red HB sets a severe upper limit on α, i.e., $\alpha < \sim + 0.2$. This is an important constraint for the theory of stellar winds. Concerning point ii) we have explored the possibility that the HB spread is due to different initial rotation of the stars in one cluster. Following Mengel and Gross (1976) both the core mass and the luminosity at the helium flash (L_{fl}) increases for increasing initial stellar angular velocity (ω). Since total mass loss is a strong increasing function of L_{fl}, the mass of the HB stars decreases with increasing ω. (It is worth emphasizing that rotation affects mass loss only through its influence on L_{fl}, the MLR itself being unaffected by rotation in this approach.) Therefore, fast rotators will arrive on the HB with a larger core mass and a smaller total mass than slow rotators. As a consequence, the larger is ω the larger will be the initial effective temperature of HB stars. With an assumed distribution function for ω of the type

$$P(\omega) = \text{const.} \times \omega(\omega_c-\omega) \exp [-(\omega-\omega_o)/\sigma^2]$$

where ω_c is the main-sequence break-up angular velocity, we find that the required HB spread is well reproduced when $\omega_o = (1.8 \pm 0.1) \times 10^{-4}$ sec^{-1} and $\sigma/\omega_o = 0.4 \pm 0.1$. This value of ω_o is very close to the value expected for Population I solar mass stars ($\sim 2 \times 10^{-4}$) when the observed trend between A and F type stars is extrapolated to the lower main sequence (*cf*. Renzini 1977). The conclusion is that dispersion in the original rotational velocities provides a plausible explanation of the HB spread provided the cores of evolving Population II stars retain most of their original angular momentum. Langer (1977) has shown that a dispersion of CNO abundance $\Delta \log Z_{CNO} \simeq 0.3$ would also produce the desired effect and Carbon et al. (1978) have actually observed this range of variation in the nitrogen abundance in M92. However, nitrogen is (mostly) a secondary element and its abundance is expected to suffer large fluctuations in comparison with carbon and oxygen which are primary elements (Trimble, 1975). In solar proportions (C:N:O ≈ 20:5:43) a variation by a factor of two in nitrogen will produce a variation of only 7% in Z_{CNO}. Therefore the observation of the CN band strength could be of little help for the determination of Z_{CNO}. What actually matters is carbon and, in particular, oxygen. A possible observational check for disentangling the two suggestions (rotational vs. compositional spread) comes from the fact that the bluer HB stars obtained following the rotational hypothesis are significantly brighter (by more than $0^m.5$) than those obtained in the framework of the composition hypothesis. We find some support for the rotational hypothesis from the photoelectric photometry of pre-gap blue HB stars of NGC 6752 (Newell and Sadler 1977). Further effort in this direction would be conclusive. Finally, concerning point iii), from our "rotationally" spread HB's we find the required ranges for the candidate "second parameters", namely $\Delta t \simeq 1$ billion years and $\Delta Y \simeq 0.03$ (in agreement with MPS V). A range of [CNO/Fe] = ±0.5 would also produce the desired effect (here for Fe we mean the whole ALIPE). As there is presently no hope of "measuring" such "small" age and helium variations, the only really crucial observations will be those attempting a determination of C and O abundances in globular clusters.

An extended paper covering these topics is in preparation.

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DISCUSSION

WEIDEMANN: You might be interested to learn that Reimers (together with Kudritzki at Kiel) has recently recalibrated the mass loss formula by an investigation of α Her and Antares B and now finds $\eta_R = 0.3$. Which law of rotation has been assumed for the first giant branch? The core mass increase which you need in order to get the higher luminosities is probably obtained for differential rotation. However there are indications that on the first giant branch angular momentum must also be transported outward effectively (Weidemann, Astron. Astrophys. 59, 411, 1977).

RENZINI: What matters here is that the inner ∿0.3 $M_\odot$ of the stellar core retains its original angular momentum up to the core helium flash, and we are suggesting an observational test to see if this is actually the case: the blue end of the HB should be ∿$0^m.5$ brighter than in the non-rotating case - Dr. J. Mengel could briefly comment on how rotating models were computed.

MENGEL: Our calculation was very crude. We assumed solid-body rotation on the main sequence followed by conservation of angular momentum in spherical shells in radiative zones. The convective envelope was assumed to be non-rotating. No transport of angular momentum was included.

KRAFT: I thought you said that the total mass loss rate was changed by rotation. Maybe you meant that the total mass loss, itself, was what was changed.

RENZINI: Yes. The total mass loss is changed, through the effect on evolution.

DEMARQUE: My question also has to do with the treatment of the angular momentum - are the effects of internal rotation included on the horizontal branch as well as on the giant branch? Or are you rather considering horizontal branches composed of non-rotating models with core masses consistent with the Mengel-Gross models?

RENZINI: Yes, we used the Sweigart and Gross non-rotating zero age HB models - this is justified considering that rotation begins to affect the stellar structure only when the star is very close to the red giant tip, that is, when the stellar core gets very small. Since the helium flash forces the core to expand (the core radius increases by about a factor of three) we expect that rotation will be much less important in HB stars.

HARDORP: I am still confused about the input angular momentum on the M.S. If I understood correctly, the core of the star is assumed not to be influenced by the slowing down of the rotation of the envelope due to the outer convection zone. So you expect for example the Sun to have a rapidly rotating core now.

RENZINI: What we have shown is that if core angular momentum is conserved then one gets the desired HB spread. On the other hand we are also exploring other alternatives like for instance a composition range within one cluster - concerning the Sun we cannot say anything about one single star.

CONTINUED ON PAGE 406