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The luminosities of horizontal branches and RR Lyrae stars in globular clusters

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Abstract. We have utilized the latest stellar models of the Y^2 (Yonsei-Yale) collaborators and color-magnitude diagrams of globular clusters to infer ages and absolute magnitudes of their horizontal branches (HB). The intrinsic $(B-V)$ color indices of the turn-offs, $(B-V)_0^{TO}$, of the globular clusters were used to find ages. For 47 clusters that appear to be coeval (within ± 0.7 Gyr), we find an average age of 12.5 Gyr. We adopt this age and infer the absolute magnitudes of the turn-offs, M_V^{TO}, from the clusters [Fe/H] values. The absolute magnitude of the horizontal branches or RR Lyrae stars are then determined from the difference between the apparent magnitudes of the horizontal branches (or RR Lyrae stars) and the apparent magnitude of the turn-offs, V^{TO}. We conclude: 1) The slope of the M_V(HB), [Fe/H] relation is $\sim$0.3 for clusters with [Fe/H] values between -0.5 to -1.5. The relation has zero slope for [Fe/H] values smaller than -1.5. 2) For [Fe/H] < -1.3, the M_V(HB) or M_V values of RR Lyrae stars are not only a function of [Fe/H], but the horizontal-branch type in the sense that the clusters with the blue horizontal branches have more luminous horizontal branches than clusters with red horizontal branches. The same results are found by inferring the luminosities of the HBs from pulsating blue stragglers.

The luminosities of the horizontal branches (HB) and RR Lyrae stars in globular clusters are long standing problems in astronomy. There is ample evidence that the luminosities of both the HB and RR Lyrae stars are a function of the metallicity, [Fe/H]. If the absolute magnitudes, M_V, of the HB and/or RR Lyrae stars are given by [Fe/H], then the luminosity levels of other regions of the color-magnitude diagrams of globular clusters can be derived.

In this brief discussion we will "back step" and describe how the luminosities of the HB and/or RR Lyrae stars can be derived from a) adopting a uniform age for each cluster and b) blue-straggler variables (SX Phe or δ Sct stars).

In Fig. 1 we plot the intrinsic $(B-V)$ color indices of the turn-offs of the main sequences, $(B-V)_0^{TO}$, of globular clusters versus [Fe/H], and age. Reddening corrections according to Schlegal et al. (1998) were applied to the observed $(B-V)^{TO}$ values of the clusters. For small reddening, $E(B-V) \leq 0.25$ mag, the Schlegal et al. values are 0.01 mag larger on average than the color excess values given in the Harris (1996) catalog. For about half the clusters fiducial curves are available to estimate the turn-off color indices, for the other clusters the turn-off color indices have been estimated from the color-magnitude

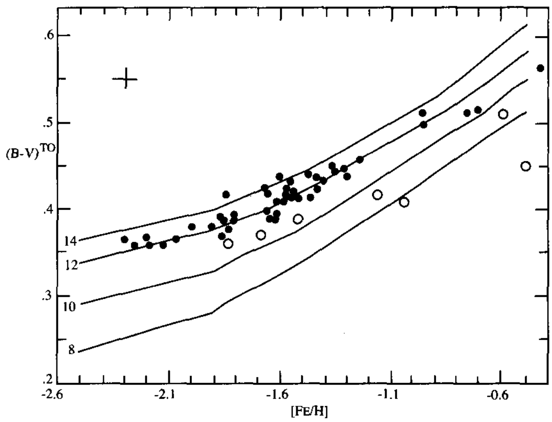

Figure 1. The intrinsic $(B-V)_o^{TO}$ of globular clusters as a function of the abundance parameter [Fe/H]. The solid curves give the $(B-V)_o^{TO}$ values as a function of [Fe/H] and age (Yonsei-Yale models (Y^2)). Solid dots are clusters we judge to have a common age (~12.5 Gyr), the open circles are clusters that are probably younger.

diagrams displayed in the literature. The data are by no means homogeneous, but are sufficiently accurate for our purposes.

The solid dots in Fig. 1 are clusters that we judge to have a common age (approximately 12.5 Gyr) while the clusters plotted as open circles are most likely younger. The solid curves in Fig. 1 are the turn-off, $(B-V)_o^{TO}$, color indices as a function of age and [Fe/H] ((α/Fe) = 0.3) inferred from the Yonsei-Yale (Y^2) collaborators (Kim et al. 2002).

For 47 clusters that appear to be coeval (within ±0.7 Gyr), we find an average age of 12.5 Gyr. The uncertainty of ±0.7 Gyr can be primarily accounted for by observation errors in the $(B-V)^{TO}$ and reddening values. We adopt 12.5 Gyr and infer the M_V^{TO} of the clusters from the models. With the aid of the observed V magnitudes of the HBs and/or RR Lyrae stars plus the V magnitudes of the turn-offs, we infer the M_V values of the HB or RR Lyrae variables in each cluster.

In Fig. 2 we plot the M_V values of the HB, M_V(HB), versus the [Fe/H] values of the cluster. We also denote the horizontal-branch types (*HBR*) of the clusters according to the legend given with Fig. 2. Note that the HB type, *HBR* (where $HBR \equiv (B-R)/(B+V+R)$), where B is the number of stars blueward of the instability strip, R is the number of stars redward of the instability strip and V is the numbers of variable stars) is generally negative for metal-strong clusters and positive for the metal-poor clusters. The Harris (1996) catalog is the source for the metal abundances, [Fe/H], and the horizontal-branch types, *HBR*.

Note that the M_V(HB) values increase in luminosity with a slope of ~0.3 between [Fe/H] of −0.5 and −1.25 and all clusters have similar *HBR* values. For [Fe/H] between −1.25 and −1.75 a variety of *HBR* values are found and the M_V values exhibit a large scatter (~0.5 mag), with the HBs of clusters with

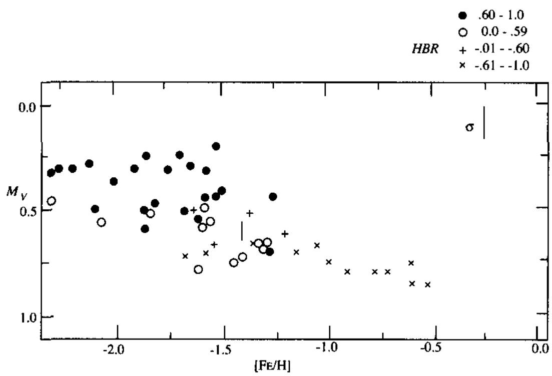

Figure 2. Horizontal-branch luminosities, M_V, of globular clusters as a function of the abundance parameter [Fe/H], and the horizontal-branch type *HBR*. A large scatter in the M_V values is evident for the second-parameter clusters with [Fe/H] in the range of −1.25 to −1.75. The vertical line at [Fe/H]$\sim$ −1.4 is RR Lyrae.

predominately blue branches (*HBR* types > 0.6) being more luminous than the clusters of intermediate type or with predominantly red HBs (*HBR* < 0.00). This [Fe/H] domain is clearly the region where we encounter the second-parameter problem - clusters with similar [Fe/H] values exhibiting different HB types. Our data shows that the HB luminosity is a function of the HB type as well as the [Fe/H] value. This implies that the M_V values of the HB are a function of the second parameter. The majority of the clusters with [Fe/H] values between −1.5 and −2.35 have predominantly blue HB (*HBR* between 0.6 − 1.0) types and there is little or no increase in luminosity with decreasing [Fe/H] values in this interval.

Another way of presenting the data is to plot the M_V values of the HBs verses the HB types as in Fig. 3. Note that the scatter is small and while the blue HB clusters have the most luminous HBs, there is apparently little change in M_V from HB types −0.5 to 0.12 and an apparent drop in M_V at *HBR* values of $\sim$ 0.25 followed by a steep increase in the luminosity at *HBR* values of 0.5 and greater.

It is well to keep in mind that the M_V(HB) values displayed in Figs 2 and 3 are inferred from observed V magnitudes of HBs and not from inferred zero-age horizontal branches and thus are subject to evolutionary effects. Not only do ZAHB models suggest that the M_V(HB) of metal-poor HB should be more luminous than the M_V(HB) of metal-strong clusters, but that evolution of stars into the instability strip should also yield higher luminosities of HB stars. Thus, the general overall tendency of the metal-poor clusters to have more luminous HBs than the metal-strong clusters is consistent with expectation. What is not clear is why the HB luminosity of the second-parameter clusters depends not only on [Fe/H], but the horizontal-branch type as well.

In Fig. 4 we plot the absolute magnitudes, M_V, of HBs as a function of [*HBR*] for clusters that contain pulsating blue stragglers (δ Sct stars). The M_V

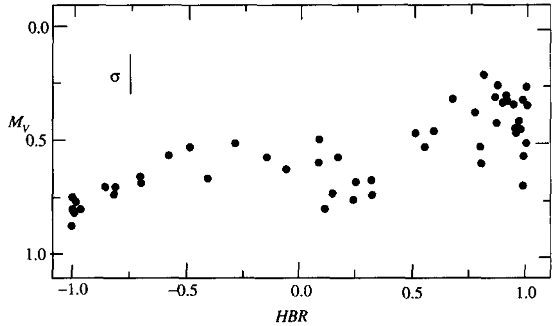

Figure 3. Plot of the M_V values of the horizontal branches of globular clusters verses their horizontal-branch type *HBR*.

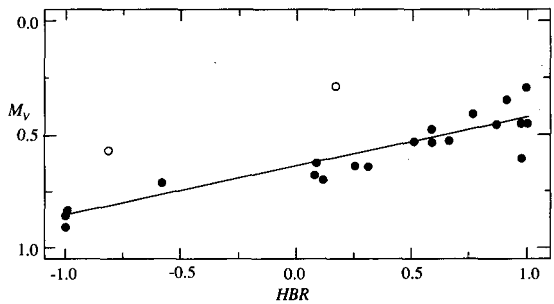

Figure 4. The absolute magnitude of the HB, M_V, as a function the horizontal-branch type *HBR*. The M_V values of the HB are inferred from pulsating blue stragglers (δ Sct stars). Compare with Figure 3. The open circles are clusters with poor data

values were inferred entirely from the luminosity of the δ Sct stars given by the equations:

$$M_V = -2.90 \log P - 0.190[\mathrm{Fe/H}] - 1.26 \qquad ([\mathrm{Fe/H}] \geq -1.5),$$

and

$$M_V = -2.90 \log P - 0.089[\mathrm{Fe/H}] - 1.11 \qquad ([\mathrm{Fe/H}] < -1.5).$$

With the aid of the V magnitudes of the variables and HBs the absolute magnitudes of the HBs can be inferred. Note this is an entirely independent approach, but yields similar results. The M_V values of HBs and consequently RR Lyrae stars are a function of both [Fe/H] and horizontal-branch type.

References

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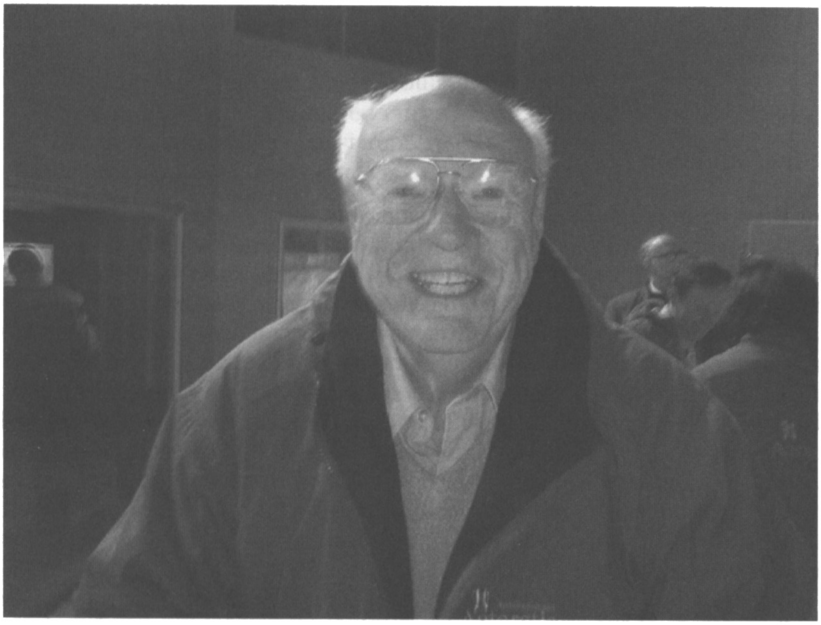
Discussion

Catelan: Did you study the case of ω Cen? What procedure did you follow in this case, and what do you find?

McNamara: Yes. We attempted to use only the oldest population stars. We found that in an old population cluster the age is ~12.6 Gyr. Many δ Sct stars are known in the cluster and allow the Horizontal Branch M_V value to be accurately determined.

Dambis: The decrease of the slope of the M_V – [Fe/H] relation at low metallicities is easily explainable by the fact that [Fe/H] is a logarithmic function of Z and when [Fe/H] $\rightarrow -\infty$, we have Z $\rightarrow 0$. The absolute magnitude remains almost constant if we pass from [Fe/H]= -2.0 to, say [Fe/H]= -10.0 (because Z values are negligible in both cases and hence differ negligibly from each other).

McNamara: I agree that the slope should approach 0 as [Fe/H] $\rightarrow -\infty$.



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