The Ages of the Globular Clusters

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Abstract. The recent results for the relation between M_V and $[Fe/H]$ for RR Lyrae variables and horizontal branch stars are reviewed: $< M_V(RR) > = 0.15[Fe/H] + 1.08$. If $[O/Fe] = 0.3$, the oldest clusters' ages approach 20 Gyrs, and the the most metal-poor clusters are older than the most metal-rich by several Gyrs. If $[O/Fe] \propto -0.4[Fe/H]$, the most metal-poor clusters have ages of about 14 Gyrs and the most metal-rich clusters are not much younger. In both cases, there are age spreads among the intermediate metallicity clusters of up to 6 Gyrs.

Key words: Globular Clusters - RR Lyrae Variables

1. Introduction

Relics of the Galaxy's earliest years, the globular clusters probe not only the date of the very first star formation events, but also the timescale and coherence of the Galaxy's formation. Precise relative and absolute cluster ages have not yet been achieved, but considerable progress has been made. The basic technique is, of course, the comparison of cluster color-magnitude diagrams with theoretical isochrones. A full match requires knowledge, preferably empirical, of bolometric corrections to convert V into m_{bol}, relations between color indices and $T_{\rm eff}$, distances, and chemical compositions, including separate handling of helium, CNO elements, and iron-peak elements. The isochrones also require accurate treatment of convection, which for low-mass stars is confined to the outer envelope, plus all the other details involved in solving the differential equations of stellar structure and nucleosynthesis. It is our opinion that the excellent matches obtained between isochrones and color-magnitude diagrams (e.g., Hesser et al. 1987; Richer and Fahlman 1987) do not provide optimum age estimates because of the reliance upon convection theory. We prefer to estimate ages solely from the turn-off luminosity, which is insensitive to convection conditions for low-mass stars and to outer surface boundary conditions.

One must still deal with distance and composition determinations for clusters. This paper deals primarily with the former problem, but illustrates the importance of the second as well.

2. Cluster Distances

The most direct method of measuring the distances to globular clusters is main sequence fitting to similar-metallicity field stars with accurate trigonometric parallaxes. One of the key reasons for deriving ages is to test the rapidity of the formation of the halo, and to discern 10% effects in ages requires a minimum precision (all other factors being equal) of 10% in distance. Only one field halo dwarf, HD 103095, has a trigonometric parallax with such precision; hence we can estimate distances only to those clusters with metallicities like that of HD 103095. Until improved parallax data are available, either from HIPPARCOS or HST, we will continue to rely instead on the absolute magnitudes of horizontal branch stars, especially the RR Lyrae variables. The basic idea is to estimate $< M_V(RR) >$ as a function of $[Fe/H]$. Measurement of the gap in magnitude between a cluster's observed

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horizontal branch and its main sequence turn-off yields the turn-off luminosity, independent of distance and reddening. Knowledge of the slope of the relation yields relative cluster ages, whereas additional knowledge of the zero point yields absolute ages, assuming the full chemical composition profile is also known.

2.1. THE SLOPE

A wide variety of techniques have been used to estimate M_V vs. $[Fe/H]$ (see Carney et al. 1992; hereafter CSJ). Four merit special attention. Lee et al. (1990) and Lee (1990) have published theoretical models of horizontal branch evolution, and argued that the slope of the relation is 0.17. This shallow slope conflicts with that determined by Sandage (1990 and references therein), who used the relation between the fundamental period, the mass, the luminosity, and the temperature for RR Lyraes derived by van Albada and Baker (1971). Neglecting the minor mass effect, the essence of the method is to compare variables in one cluster with those in a "fiducial" cluster at equal temperatures. Variations in periods at the same temperatures should then reflect variations in intrinsic luminosities. The slope found from this "period shift" technique was found by Sandage to be 0.37, over twice that found from theory. The difference is profound, for at face value the steep slope implies all the globular clusters have the same age (assuming, incorrectly, they all have the same gap between their horizontal branches and their main sequence turn-offs), whereas the shallower slope implies a significant age-metallicity relation, with the metal-rich clusters being several Gyrs younger than the metal-poor clusters. Resolution of this quandry has not been easy. Buonanno et al. (1989; hereafter BCF) utilized model isochrones to determine relative cluster distances by main sequence fitting. The relative distances then yielded relative $< M_V(RR) >$, and the resultant slope was found to be 0.37 ± 0.14. An ensuing debate (King et al. 1988; Buonanno et al. 1990) did not change this result significantly. Finally, several groups (e.g., Jones et al. 1988; Cacciari et al. 1989a,b; Fernley et al. 1990; Liu and Janes 1990; and references within each paper) have been applying variants of the Baade-Wesselink technique to derive distances to individual field RR Lyraes. A recent critical review by Jones et al. (1992), wherein all the systematic effects are taken into account and highly-evolved stars removed from the sample, yielded a slope of 0.16 ± 0.03. How do we resolve this bimodality in the results for the slope of the $< M_V(RR) >$ vs. $[Fe/H]$ relation?

There is an independent test of the Baade-Wesselink results. As part of the analyses, as summarized by Jones et al. (1992), a relation between $< M_K(RR) >$ and log P is obtained, which has a slope of -2.33 ± 0.20. Longmore et al. (1990) obtained the slope of the M_K vs. log P relation in each of 8 globular clusters with a wide range of metallicities. Upon eliminating the two clusters with 5 or fewer variables, leaving six clusters with 20 or more variables, the slope is found to be -2.31 ± 0.06. The field stars, which lie at a wide variety of derived distances, thus yield the same slope as the variables within any one cluster. Hence the slope of the M_K vs. log P, and by inference the slope of the $< M_V(RR) >$ vs. $[Fe/H]$ relation, obtained from the Baade-Wesselink analyses must be considered secure.

The focus must now be upon the main sequence fitting results of BCF and the period shifts analyses done by Sandage (1990). CSJ argue that the main sequence results are affected by a subtle but crucial metallicity effect. The transformation from $T_{\rm eff}$ into $B - V$ necessary for the isochrone-based main sequence fits relies upon the synthetic colors of model atmospheres computed by Kurucz (1979). Since these synthetic colors predict colors for the Sun that are too blue, it has long been thought that the synthetic flux distributions lack opacity, probably due to atomic and molecular line blanketing, in the blue and violet regions. CSJ tested this hypothesis by using the large sample of proper motion stars being studied by Carney, Latham, and Laird. Considering only those stars with $[Fe/H] \leq -0.45$, $M_{\rm V} \geq +5.0$, $E(B - V) \leq 0.05$ and which are neither evolved nor double-lined, CSJ found 355 stars for which they could determine temperatures using infrared (metallicity insensitive) $V - K$ color indices, based ultimately in fact on Kurucz's predictions of the slope of the flux distribution in the Paschen continuum, a region also insensitive to line blanketing. The metallicities were determined from the echelle spectra (cf. Laird et al. 1988). CSJ could therefore estimate the $B - V$ value *predicted* by the isochrones for a star of known metallicity and temperature and compare that the each star's *observed* value. The difference was found to be a function of metallicity, and in a sense consistent with increasingly deficient line blanketing in the models as the metallicities increase. While not a large effect, only 0.034 mag per 1 dex change in $[Fe/H]$, the steep slope of the main sequences resulted in a decrease in BCF's derived $< M_{\rm V}(RR) >$ vs. $[Fe/H]$ slope from 0.37 to 0.12!

CSJ also found the period shift analysis to require revision. The major problem was found to be the proper definition of the temperature. Sandage (1990) had relied upon either the magnitude-averaged or intensity-averaged $B - V$ color index and the conversion to $T_{\rm eff}$ given by Butler et al. (1978). As Jones (1988) has shown, however, the Baade-Wesselink photometric angular diameters derived using any blue color index ($B - V$ or $b - y$) fails to predict the correct temperatures of RR Lyraes during their expansion phases. Thus any mean blue color index will fail to predict the correct temperature, and the failure will be greater for larger amplitude stars (zero amplitude non-pulsating stars' temperatures may, of course, still measured by blue color indices). Even were the temperatures derived from the color indices correct, however, the mean color yields an average of the temperature over the pulsation cycle. This is not what is required for the analysis. Instead, one needs the equilibrium temperature, $T_{\rm eq}$, which is defined by $[L_{eq}/4\pi\sigma R_{eq}^2]^{1/4}$. The Baade-Wesselink results yield L_{eq} and R_{eq}, so new relations between observable parameters and $T_{\rm eq}$ may be obtained and the period shift analysis redone. CSJ found that the $< M_{\rm V}(RR) >$ vs. $[Fe/H]$ slope then became 0.14, based on variables in 8 globular clusters, and 0.16, based on 141 field stars studied by Suntzeff et al. (1991). (They noted analyses based on Lub's 1977 sample are inappropriate since, by selecting stars to fully sample both metallicity and period space, Lub built in a bias toward evolved, brighter stars.) An indication that the new temperature calibrations are correct has been pointed out by Storm et al. (1991) and Carney et al. (1991). Their respective studies of the light curves of RR Lyraes in the globular clusters M5 and M92 showed that a V vs. $B - V$ plot showed the non-variables, fundamental mode, and first overtone mode pulsators overlap, but not in the V vs. $T_{\rm eq}$ plane.

When these four major techniques are now compared, and a few other lower-weight results are added in, CSJ found the final slope of the $< M_V(RR) >$ vs. $[Fe/H]$ relation to be 0.15 ± 0.01.

2.2. THE ZERO POINT

As CSJ discuss, the zero point determination remains somewhat uncertain. It is based on the statistical parallax analyses of Strugnell et al. (1986) and Barnes and Hawley (1986), and the main sequence fit of HD 103095 to the similar-metallicity, only slightly reddened main sequence obtained by Richer and Fahlman (1987). The formal relation is then

$$< M_V(RR) > \; = 0.15(\pm 0.01)[Fe/H] + 1.01(\pm 0.08). \qquad (1)$$

3. Cluster Ages

CSJ compiled apparent magnitudes of horizontal branches and main sequence turn-offs, plus $[Fe/H]$ values, for 24 clusters, and used Equation 1 and the empirical bolometric corrections of Carney (1983) to determine turn-off luminosities. Before they could derive ages, however, they had to adopt helium abundances and estimate the effects of the CNO elements. Caputo et al. (1987) and Steigman (1989) have, for different reasons, urged adoption of $Y = 0.23$. However, it is inappropriate to adopt $[Z] = [Fe/H]$, for in halo stars it is well known that the lighter elements do not scale with iron abundance in solar proportions. CSJ adopted two cases. In Case A, they assumed that all the "α-rich" species (such as Ne, Mg, Ca, Si, S) *and* oxygen are enhanced by 0.3 dex relative to iron. Since oxygen is such an important contributor (roughly 50% of the heavy element atoms), the net effect is to increase the $[Z_{eff}]$ value over $[Z]$ by typically 0.2 dex. In Case B, CSJ assumed the Abia and Rebolo (1989) results for $[O/Fe]$ vs. $[Fe/H]$ are correct, with enhancements in oxygen increasing as iron abundance declines. This raises $[Z_{eff}]$ by 0.3 to 0.8 dex over $[Z]$. As noted already by Stranierro and Chieffi (1991), the use of $[Z_{eff}]$ is the appropriate metallicity for use in isochrones computed with scaled solar abundances, $[Z]$.

The results for Cases A and B differ dramatically, showing we can make no claims for accurate relative or absolute ages of globular clusters until the oxygen abundances are better known. In Case A, the most metal poor clusters have ages of roughly 20 Gyrs, whereas the most metal rich clusters are about 15 Gyrs old. In the intermediate metallicity domain, however, some clusters, such as Palomar 12 and Ruprecht 106, are found to be 6 Gyrs younger than comparable metallicity clusters like NGC 288. There may be a crude age-metallicity relation, in other words, but it is clearly not applicable to all clusters. The derived age spreads are in excellent cluster-by-cluster agreement with the results of VandenBerg et al. (1990), who estimated relative ages for clusters of similar metallicity by comparing the color differences between their turn-offs and their giant branches. In Case B, the most metal-poor clusters have ages of about 16 Gyrs, and the most metal-rich clusters are not obviously much younger than that. Again, however, the 6-Gyrs age spread among the intermediate-metallicity clusters is found.

4. Future Work

The tasks ahead of us are clearly defined. We still need to improve our zero points of the $< M_V(RR) >$ vs. $[Fe/H]$ relation, perhaps by using statistical parallaxes of field halo dwarfs and, of course, using trigonometric parallaxes as they become available. We obviously must improve the precision of the $[O/Fe]$ abundance ratios in halo stars, preferably unevolved halo dwarfs and preferably by using means that do not rely on the high excitation (9.15 eV) O I lines used by Abia and Rebolo (1989). We recommend, instead, a program using the ultraviolet electronic or the infrared vibration-rotation transitions of the OH molecule.

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HESSER: I would like to make two comments on your excellent review of this very active area. First, the development of the relative age-dating technique via the color difference technique (which has been one of the most exciting ideas in many years for those of us who struggle to understand the age profile of the Galactic halo) is limited to certain metallicity ranges, as you stressed. Very recently Paltoglou and Bell have shown that the $[Fe/H]$ range over which reliable relative ages may be determined can be extended considerably by use of more appropriate filters, a set of which exists on the FOC aboard the HST. Second, some of our most convincing data for a range of ages among intermediate metallicity globulars comes from the NGC 288/NGC 362 comparison. Dickens et al., in a recent Nature paper, have shown from high dispersion spectra of numerous giants that these two clusters have virtually identical abundances. (Note, however, in the impressive recent study by Chieffi and Straniero of cluster color-magnitude diagrams interpreted through their new isochrone grid that they may infer an $[M/H]$ difference of 0.3 to 0.4 dex between them.) I am disturbed by Dickens et al.'s demonstration that the mixing history of NGC 288 and NGC 362 have been quite different, and wonder if this is affecting the relative age determinations in some way not presently appreciated.

CARNEY: As I recall, the Paltoglou and Bell filter choice is helped by minimizing line-blanketing effects. However, metallicity still must play a role since convection determines the red giant branch temperature relative to the turn-off at a fixed age. So even were convection wholly understood, we would be unable, I believe, to encompass the whole metallicity range of globulars. The extension of the technique is certainly welcome, but I maintain that the turn-off luminosity must be the fundamental basis for age estimates. As for mixing, it should not in principle affect ages estimates from turn-off luminosities, unless we are seriously in error about the relative $[O/Fe]$ values adopted for the two clusters. I am actually somewhat more worried about the Briley et al. findings of variations of CN strengths on the main sequence of 47 Tuc. Your excellent color-magnitude diagram of the cluster seems to rule out primordial abundance variations, leaving us with the unpalatable idea of mixing on the main sequence.

PINSONNEAULT: I don't believe that main sequence mixing can explain the observed CN anomalies in metal-poor clusters. Evolutionary models including rotation do not predict substantial main sequence mixing of CNO elements, and also predict less mixing in metal-poor than in metal-rich systems. As far as the accuracy of the interior models is concerned, I'd like to note that solar models constructed with the best available physics (Livermore interior opacities, Kurucz molecular opacities) match helioseismology observations to a high degree of accuracy. This indicates that the basic physics in the models is already very good.

CARNEY: But if it's not mixing, a conclusion I would be happy to agree to, I presume the variations are primordial, yet somehow 47 Tuc's main sequence and turn-off widths are very slender, implying very small overall metallicity variations. Perhaps it has something to do with pre-main sequence or binary star evolution.

RENZINI: Could you give us an estimate of the sizes of the systematic errors affecting the Baade-Wesselink method?

CARNEY: The most serious sources of systematic errors are, in my opinion, the conversion from $V-K$ color index into temperature and the conversion of radial velocity in pulsational velocity, which is a function of limb darkening and instrumental resolution. While I believe these are under reasonable control, it means that absolute distances are less well known than relative distances, when the zero points drop out. That's why we seek alternatives for calibrating the luminosity-metallicity zero points. (In fact, the current Baade-Wesselink results yield the "correct" results in zero point to ±0.1 mag or better, if you accept the HD 103095 vs. M5 and statistical parallax results.) There is one additional problem, that the relative depths of the formations of the spectral lines (velocities) and continuum (colors/temperatures) are constant through the critical parts of the pulsational cycle. Work by us and by Abi Saha measuring lines that form at a wide variety of depths suggest this is not a problem for RR Lyraes. Cepheids may be a different matter.

KURUCZ: I worry about your implicit assumption that interior models and evolutionary tracks are correct. 1. There are new opacities by Iglesias and Rogers at Livermore that are as much as four times higher than the Los Alamos opacities that were used at Yale. They also can be sensitive to individual elemental abundances. 2. The surface boundary condition in all interior models and envelope calculations is wrong. The diffusion approximation and the opacities are not correct. They have to use a model atmosphere boundary condition. 3. There are systematic errors in VandenBerg's work because he used Bell's predicted colors which Buser has shown have systematic errors because of missing opacity. 4. The opacities for RR Lyraes are wrong in the atmospheres and in the envelopes. There are strong effects of microturbulent velocity with phase in these atmospheres. The new Livermore opacities strongly affect the theoretical calculations of pulsation. I think it would be useful to assume that all the halo clusters are the same age and then see how the interior calculations would have to be changed to accomplish that.

CARNEY: I see no reason to believe *a priori* that all globular clusters have the same age, and I'd hate to tune physics on the basis of astronomical ideology. Responses to your detailed comments: 1. New opacities are obviosuly important, but the effects are mostly in the 10^5-10^6 K domain, so they won't affect interiors solutions in net luminosity much. Generally higher opacities will only mean greater derived ages. 2. The surface boundary conditions do not affect my conclusions at all since we rely only on the turn-off luminosities. 3. I agree. That was the point of our tests of the isochrones to seek metallicity effects on the $B-V$ vs. temperature relation. 4. Yes, that must be true, but the effect occurs near minimum radius, a phase of strong decelerations and accelerations. We do not rely on those phases in Baade-Wesselink analyses for those and other obvious reasons.