THE ABSOLUTE MAGNITUDES OF RR LYRAE STARS AND THE AGE OF THE GALAXY

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Abstract. It is shown that the intrinsic spread in the absolute magnitudes of the RR Lyrae variables in a given globular cluster can reach 0.5 magnitudes at a given period or at a given color, due to luminosity evolution away from the zero age horizontal (ZAHB). The size of this intrinsic luminosity spread is largest in clusters of the highest metallicity.

The absolute magnitude of the ZAHB itself also differs from cluster to cluster as a function of metallicity, being brightest in clusters of the lowest metallicity. Three independent methods of calibrating the ZAHB RR Lyrae luminosities each show a strong variation of $M_V(RR)$ with [Fe/H]. The pulsation equation of $P\langle\rho\rangle^{0.5} = Q(M, T_e, L)$ used with the observed periods, temperatures, and masses of field and of cluster RR Lyraes gives the very steep luminosity-metallicity dependence of $dM_V(RR)/d[Fe/H] = 0.42$. Main sequence fitting of the color-magnitude diagrams of clusters which have modern main-sequence photometry gives a confirming steep slope of 0.39. A summary of Baade-Wesselink $M_V(RR)$ values for field stars determined in four independent recent studies also shows a luminosity-metallicity dependence, but less steep with a slope of $dM_V(RR)/d[Fe/H] = 0.21$.

Observations show that the magnitude difference between the main sequence turn-off point and the ZAHB in a number of well observed globular clusters is independent of [Fe/H], and has a stable value of dV = 3.54 with a disperion of only 0.1 magnitudes. Using this fact, the absolute magnitude of the main sequence turn-off is determined in any given globular cluster from the observed apparent magnitude of the ZAHB by adopting any particular $M_V(RR) = f([Fe/H])$ calibration.

Ages of the clusters are shown to vary with [Fe/H] by amounts that depend upon the slopes of the $M_V(RR) = f([Fe/H])$ calibrations. The calibrations show that there would be a steep dependence of the age on [Fe/H] if $M_V(RR)$ does not depend on [Fe/H]. No dependence of age on metallicity exists if the RR Lyrae luminosities depend on [Fe/H] as $dM_V(RR)/d[Fe/H] = 0.37$. If Oxygen is not enhanced as [Fe/H] decreases, the absolute average age of the globular cluster system is 16 Gyr, independent of [Fe/H], using the steep $M_V(RR)/[Fe/H]$ calibration that is favored. If Oxygen is enhanced by $[O/Fe] = -0.14\ [Fe/H] + 0.40$ for

[Fe/H] < -1.0, as suggested from the observations of field subdwarfs, then the age of the globular cluster system decreases to 13 Gyr, again independent of [Fe/H], if the RR Lyrae ZAHB luminosities have a metallicity dependence of $dM_V(RR)/d[Fe/H] = 0.37$.

1 INTRODUCTION

Knowledge of the absolute magnitudes of RR Lyrae variables has been traditionally important in finding the distances of globular clusters and eventually to the nearest galaxies. Ages of individual clusters and of the Galactic globular cluster system can be determined when the absolute luminosities of the main sequence turn-offs are known by combining the apparent magnitudes of the turn-off points with the adopted distances.

Until recently, $M_V(RR)$ for the RR Lyraes had generally been assumed to be a fixed number of small intrinsic dispersion, and to be independent of the metal abundance. These assumptions were originally justified from (1) the observed near horizontal nature of the horizontal branch in the V pass band in most globular clusters, (2) the small observed scatter in V magnitudes of the variables in a given cluster, and (3) the approximate equality of the observationally determined $M_V(RR)$ values in clusters of different metallicity obtained from the early data on main sequence fittings in clusters studied from 1950 to 1970.

Based on modern data, the two assumptions of (1) small intrinsic dispersion in $M_V(RR)$ in a given globular cluster, and (2) independence of the absolute luminosity of the zero age horizontal branch (ZAHB) on metallicity are almost certainly incorrect. The purpose of this report is to show the importance of the changes of these views for the question of the ages of globular clusters as a function of [Fe/H]. Details have been set out in three papers submitted to the Astrophysical Journal. The summary given here is an extension of an earlier discussion on the vertical structure of the globular cluster horizontal branch (Sandage 1987).

2 INTRINSIC DISPERSION OF $M_V(RR)$ DUE TO POST ZAHB EVOLUTION

The observed width of the horizontal branch (HB) in many globular clusters is real rather than due to observational photometric errors. The evidence is that the RR Lyrae variables that are measured to be brighter than others of the same color have measured longer periods. This observed period-magnitude correlation at constant temperature has the slope close to $dV/d(\log P) = 3$ required (at constant mass) by the pulsation equation of $P<\rho>^{0.5} = Q$ that have been calculated by van Albada & Baker (1971), Iben (1971), Cox (1987) and others.

The observed HB data for M3 and M15, based on measurements of many photographic plates in each cluster, are shown in Figure 1. The variables and the nonvariables blueward and redward of the RR Lyrae variable star instability region are shown. If the observed spread in V magnitudes is real, the periods of the brighter variables must be longer than for the fainter variables at a given color. Furthermore, the correlation of magnitude and period shift must have a slope close to 3, as derived from the pulsation equation (assuming constant mass). This test for such a correlation is shown in Figure 2 for M3 and Figure 3 for M15. The slopes of the correlations in the bottom panels of each diagram are, in fact, close to 3.

Figure 4 shows the data for M4. The observed spread in V of the HB is large at dV = 0.5 magnitudes. The good correlation of magnitude and period shift in the bottom panel shows again that the observed spread in

Figure 1. Horizontal branch photometry for M3 and M15 based on many plates in each color such that the photometric measuring errors are less than 0.01 magnitude in each color. RR Lyrae stars are shown as open circles for c types, and crosses for ab types. The colors have been corrected for the adopted reddenings shown in the code.

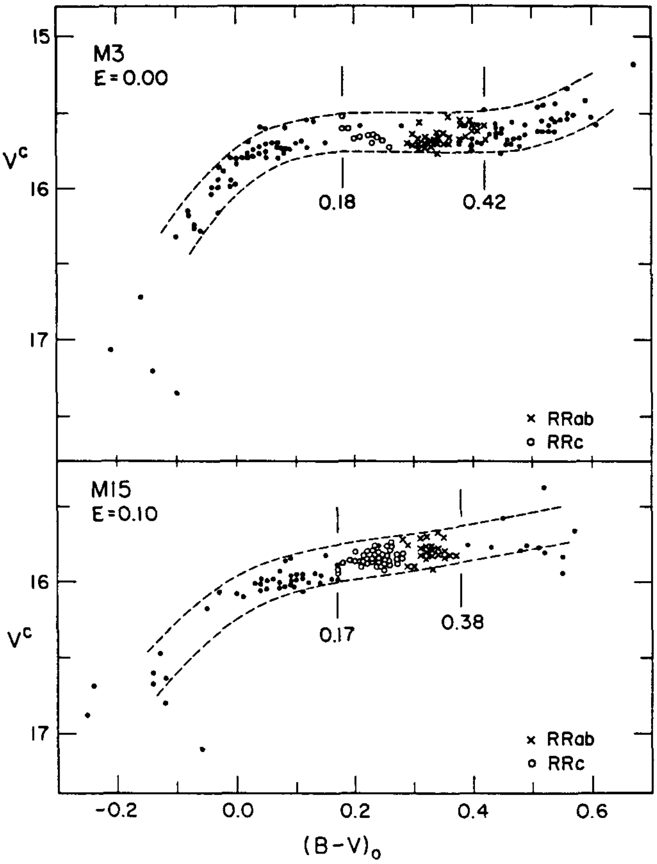


Figure 2. (top): The HR diagram for type ab RR Lyraes in M3 where the data in Figure 1 (top) have been converted to temperatures. (bottom): Correlation of the observed apparent magnitudes for M3 RR Lyraes with the period ratio of observed period to period on the ZAHB at the same temperature. The correlation shows that the observed dispersion in V in the top panel is real.

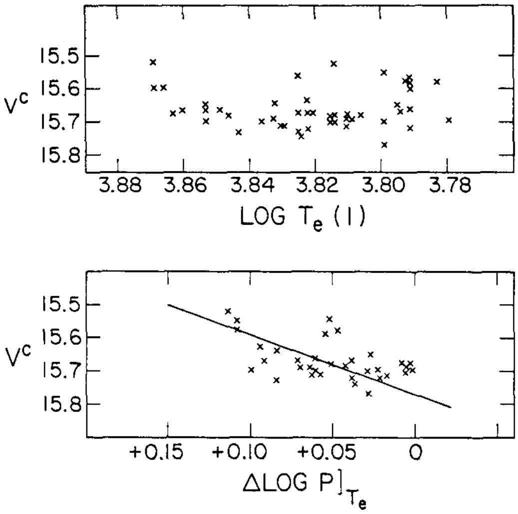


Figure 3. Same as Figure 2, but for the RR Lyrae data in M15. The sense of the correlation in the bottom panel is that the brighter observed stars have longer periods than fainter variables at the same temperature.

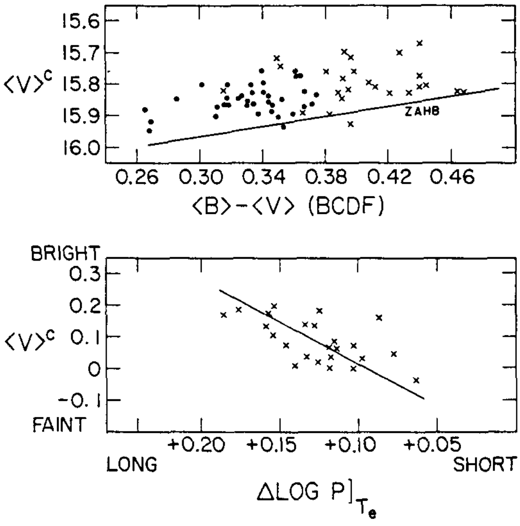


Figure 4. Same as Figures 2 and 3 for the HB stars in M4. The edges of the RR Lyrae region are shown in the top panel.

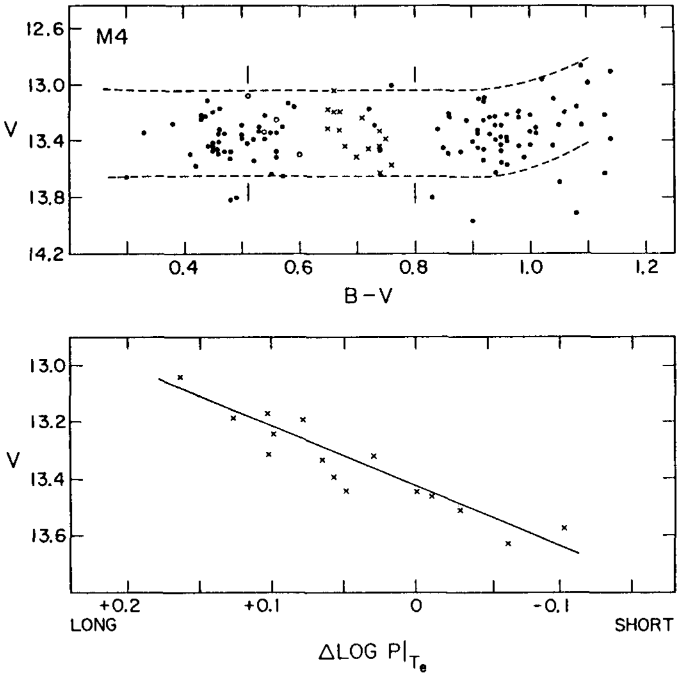
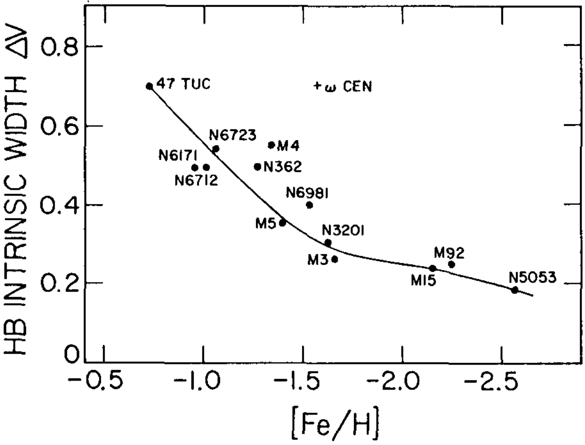


Figure 5. Summary of the intinsic width of the HB as a function of metallicity.



RR Lyrae magnitudes in M4 is real.

Similar data for other clusters, summarized in Figure 5, show that this intrinsic dispersion in M_V(RR) for the RR Lyrae variables in a given cluster is correlated with [Fe/H]. For high metallicity clusters, the spread in RR Lyrae absolute magnitudes at constant [Fe/H] reaches 0.5 magnitudes. Gratton, Tornambé & Ortolani (1986) suggest that the deviation of Omega Cen from the good correlation for the other clusters is due to this post ZAHB evolution, combined with the variation of the luminosity level of the ZAHB as a function of [Fe/H], discussed next.

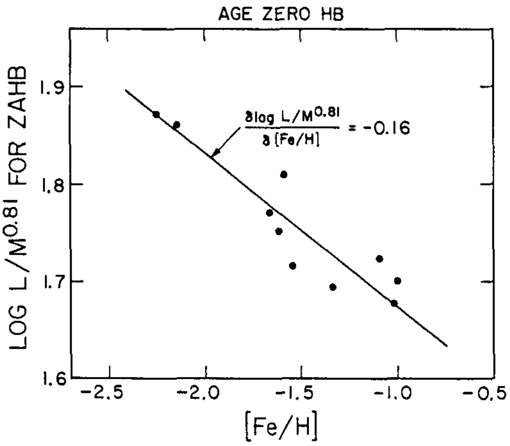
3 VARIATION OF THE ZAHB RR LYRAE ABSOLUTE MAGNITUDES WITH METALLICITY DERIVED FROM THE PULSATION EQUATION

The pulsation equation derived by van Albada & Baker (1967) by a proper integration over that part of the stellar envelope that controls the period of pulsation (similar to the equations derived also by Iben, 1971, and by Cox, 1987) is

$$\log (L/M^{0.81}) = (\log P + 3.48 \log T_e - 11.497)/0.84. \qquad (1)$$

The effective temperature can be obtained from observed colors from a calibration of the color-temperature relation as a function of surface gravity and metal abundance (Bell, as summarized by Butler, Dickens & Epps 1978). Temperatures, and the observed periods, as reduced to the ZAHB values that would apply in the absence of post ZAHB evolution, permit ZAHB values of $L/M^{0.81}$ to be calculated from equation (1). These mass-to-luminosity ratios have been found to be correlated with metallicity (Sandage 1989a,b) with the result shown in Figure 6.

Figure 6. Correlation of metallicity and the luminosity-to-mass ratio for the ZAHBs of 10 clusters as determined from the pulsation properties of their RR Lyraes.



Similar data for the field RR Lyraes from the measurements of Lub (1977, 1987) are shown in Figure 7 over the larger metallicity range of [Fe/H] from 0 to -2.2. The slope of the correlation is $d\log(L/M^{0.81})/d[Fe/H] = -0.11$. The equation of the line in Figure 7 is

$$\log (L/M^{0.81}) = -0.11\ [Fe/H] + 1.71, \qquad (2)$$

where L and M are in solar units. The mass can be eliminated from equation (2) using the RR Lyrae masses determined from the period ratios of the fundamental to first overtone in the double mode RR Lyrae stars in M15, M3, and IC 4499 by Cox, Hudson, & Clancy (1983), and by Clement et al. (1986), following Stellingwerf (1975) and Petersen (1978, 1979). The result (Sandage 1989b) is

$$\log M = -0.1\ [Fe/H] - 0.41. \qquad (3)$$

Equation (3) put into equation (2), and changed into magnitudes by assuming $M_{bol} = 4.75$ for the sun, gives

$$M_{bol}\ (RR) = 0.48\ [Fe/H] + 1.30. \qquad (4)$$

From stellar models by Kurucz and others, the bolometric correction at a surface gravity of $\log g = 3.0$ to 3.5 and a temperature of $\log T_e = 3.85$ appropriate for the RR Lyrae stars is found to be

$$B.C. = 0.06\ [Fe/H] + 0.06, \qquad (5)$$

which, when put into equation (4) gives

$$M_V(RR) = 0.42\ [Fe/H] + 1.24, \qquad (6)$$

as the relation we are seeking. Note that equation (6) has been derived entirely from the pulsation condition of equation (1), together with the empirical correlations of equations (2) and (3). No appeal has been made to theories of the ZAHB. Equation (6) is then an empirical determination based only on the pulsation properties of mechanical oscillators, governed simply by gravity. For this reason, the RR Lyrae luminosities obtained by this method is given the highest weight in what follows.

4 RR LYRAE ABSOLUTE MAGNITUDES DERIVED FROM GLOBULAR CLUSTER MAIN SEQUENCE FITTINGS

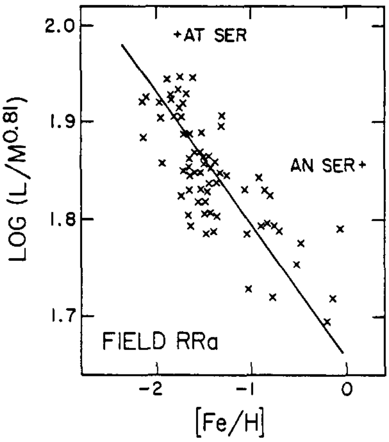
Buonanno, Corsi, & Fusi Pecci (1988), in an important paper where the consequences of the HB models of Sweigart & Gross (1976) and Sweigart, Renzini, & Tornambé (1987) are discussed concerning the observed period-shift, metallicity effect, again determine RR Lyrae star luminosities in globular clusters by the method of main sequence fitting. Their result has high weight because of the new precision in their main sequence photometry for their program clusters. Using a particular adopted series of fiducial main sequences for various metallicities, their result is

$$M_V(RR) = 0.37\ [Fe/H] + 1.29, \quad (7)$$

similar to equation (6) in the last section. However, both equations differ in their slope dependences from the results found by four independent research groups that have used the Baade-Wesselink method on field RR Lyrae field variables, as discussed in the next section. To determine how sensitive the main sequence fitting results are to the adopted positions of the fiducial main sequences for different [Fe/H] values, Cacciari & Sandage (1989) have carried out a series of main sequence fittings, using the Buonanno et al. basic main sequence observational data. They began with a different set of assumptions for the positions of the various fiducial main sequence positions than were used by Buonanno et al. with the following result.

Consider first the position of the fiducial main sequence to be used for stars with [Fe/H] = 0. It has often been assumed that the distance to the Hyades is required to establish this ZAMS relation. However, the Hyades distance can be circumvented by using trigonometric parallax stars of high weight, such that the error in absolute magnitude of any given MS star is less than say 0.15 magnitudes (one sigma value). There are 34 such high weight trigonometric parallax stars with metallicities between [Fe/H] of +0.05 and -0.08 in the first Yale Parallax Catalog. The data are shown in Figure 8, where the adopted ZAMS line is drawn as given originally for a similar purpose (Sandage & Eggen 1959, Table III). In an independent study, based on theoretical unevolved main

Figure 7. Same as Figure 6 but for the field variables studied by Lub. The temperatures required to calculate $L/M^{0.81}$ from equation (1), and the metallicities plotted on the abscissa have been determined by Lub from his Walraven photometry.



sequence stellar models, VandenBerg (1987) has derived an interpolation equation for the solar abundance ZAMS as

$$M_V = 2.837 - 6.796(B-V) + 31.77(B-V)^2 - 31.6(B-V)^3 + 10.57(B-V)^4. \qquad (8)$$

This equation produces the empirical line that is drawn in Figure 8 to better than 0.01 magnitudes at all colors, and, to be emphasized again, is independent of the Hyades distance.

As the metallicity is decreased, the position of the MS in B-V becomes fainter, due to the combined effects of (1) a fundamental change in the stellar models in the M_{bol} , log T_e plane and (2) to the blanketing effects on the B-V colors. Ideally, the main sequence depression could be calibrated empirically from trigonometric parallax stars (e.g. Sandage & Eggen 1959, Eggen & Sandage 1962, Cameron 1985), but the parallax data are not yet of adequate quality to give a definitive solution. Nevertheless, Figure 9 shows that the MS depression does, in fact, occur with decreasing metallicity, but because the scatter of the data is too large to be of quantitative use, we have relied on calculated models of the effect in the M_V, B-V plane.

Figure 8. Adopted fiducial main sequence for stars with [Fe/H] = 0. The points are trigonometric parallax stars with parallax values larger than 0.067 arc sec, whose parallax errors are smaller than 7%, giving magnitude errors (one sigma) of less than 0.15 magnitudes. The line is the ZAMS adopted by Sandage & Eggen (1959), and is closely defined by equation (8) due to Vandenberg. The fiducial main sequence defined in this way is independent of the distance to the Hyades.

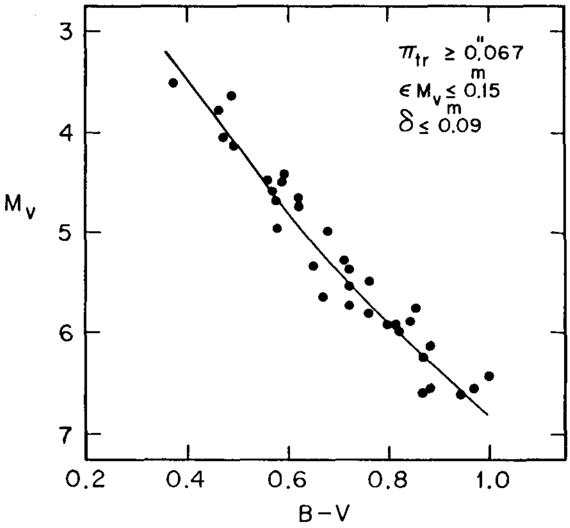


Figure 10 shows our adopted calibration of the depression of M_V below the fiducial main sequence. The solid line in Figure 10 has been read from Figure 3 of VandenBerg & Bridges (1984) and Figure 4 of VandenBerg & Bell (1985), both at B-V = 0.6. The four plotted points are the adopted mean values from trigonometric parallax star data summarized elsewhere (Sandage 1970, Table 11) based on the earlier discussion by Eggen & Sandage (1962). Use of the solid line relation to be discussed in the next paragraph, gives a steeper slope to the resulting M_V(RR) calibration than does the dashed line which gives the slope of $dM_V(RR)/d[Fe/H] = 0.21$ discussed later.

Combining Figures 8 and 10 gives the adopted main sequence positions for different metallicities shown in Figure 11, using the same coding as in Figure 10. Note the very high sensitivity of the slope of the $M_V(RR)/[Fe/H]$ relation to the small changes in the main sequence positions, shown by the dashed lines.

The solid lines in Figures 10 and 11 are well fit by the equation for the chemical composition correction to equation (8) as

$$\Delta M_V = 2.6(Y-0.27) - \{[Fe/H]\}(1.444 + 0.362[Fe/H]) \qquad (9)$$

Figure 9. Trigonometric parallax stars with parallaxes larger than 0.045 arc sec whose ultraviolet excess values are larger than 0.16 magnitudes, corresponding to [Fe/H] values smaller than - 1.

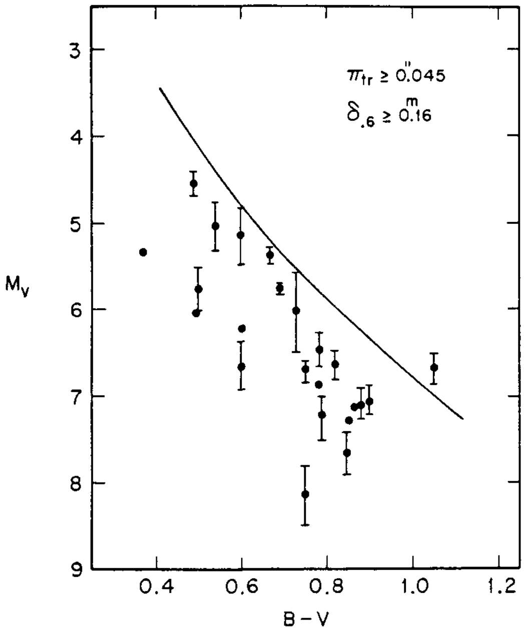


Figure 10. The depression in V magnitudes below the fiducial main sequence as a function of metallicity. The solid line is read from Figure 4 of Vandenberg and Bell (1985) at B-V = 0.6. It is given closely by equation (9). The open circles are from trigonometric parallax stars as discussed by Eggen and Sandage (1962) and Sandage (1970). The dashed line is that required to give the indicated M_V(RR) relation using MS fits for the program globular clusters.

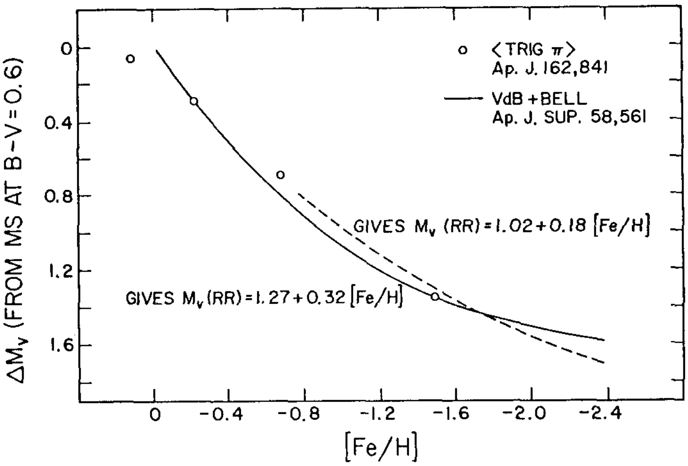
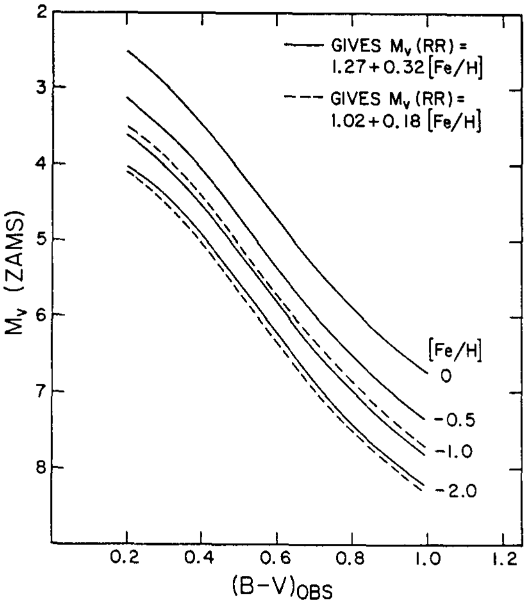


Figure 11. The adopted CMD for different metallicities, obtained by combining Figures 8 and 10.



for [Fe/H] > -1.5 derived by VandenBerg (1987). The final result of fitting the MS photometric data of Buonanno, Corsi & Fusi Pecci (1988) to the solid curves in Figures 10 and 11 is shown in Figure 12. The impartial least squares line (averaging the two solutions by interchanging M_V and [Fe/H] as the independent variable) is

$$M_V(RR) = 0.39\ [Fe/H] + 1.39. \qquad (10)$$

If only M_V(RR) is used as the independent variable, then the equation is

$$M_V(RR) = 0.32\ [Fe/H] + 1.27, \qquad (11)$$

as marked in Figures 10 and 11.

5 SUMMARY OF VARIOUS RECENT DETERMINATIONS OF M_V(RR) USING THE BAADE-WESSELINK METHOD

Combining the Baade-Wesselink results of Cacciari, Clementini & Buser (1988), Liu & Janes (1988), Jameson, Fernley & Longmore (1987), and Jones, Carney & Latham (1988), gives the correlation shown in Figure 13, which has the regression equation of

$$M_V(RR) = 0.21\ [Fe/H] + 1.05. \qquad (12)$$

The consistency of the independent data from the four investigations that are combined in Figure 13 would seem, of course, to give considerable weight to equation (12). However, the B-W method is much more complicated (e.g. Gautschy 1987) than the quite direct determination from pulsation data that gives equation (6). In addition, each of the four analyses of the B-W data, although independent, use the same basic assumptions in their central details of the computations. They also use the same Kurucz model atmospheres, which, although the best currently available, are not yet definitive (Kurucz, comment at the Van Fleck Age Dating Workshop, 1988). It might then be that all present B-W results could contain a common systematic error, if such exists. The large slope difference between equation (12) and equations (6), (7), (10), and (11) might be explained in this way.

6 SUMMARY OF VARIOUS DETERMINATIONS OF RR LYRAE LUMINOSITIES

Figure 14 shows four assumptions for the variation of RR Lyrae star luminosities with metallicity. The line labeled "pulsation" is from equation (6) of §3. The line labeled MS is equation (11) of §4. The result from equation (12) is labeled B-W. Also shown is the assumption of a constant absolute magnitude of $M_V = 0.70$, based on the statistical parallax solution of Hawley et al. (1986), as slightly modified by Barnes & Hawley (1986). Ages based on these four assumptions are discussed in the next two sections, with and without Oxygen enhancement.

Various other determinations from the literature are compared in Figure 15. The line marked <BCF>(MS) is the calibration obtained by Buonanno, Corsi & Fusi Pecci (1988), mentioned previously, from their direct main sequence fits, giving equation (7) of §4. The dashed line marked Lub (field) is from Lub's (1987) determination of the $L/M^{0.81}$ ratio using

Figure 12. The calibration of M_V(RR) as a function of [Fe/H] obtained by main sequence fitting the program globular clusters studied by Buonanno, Corsi, & Fusi Pecci (1988) to the grid of solid lines in Figure 11, defined by equations (8) and (9).

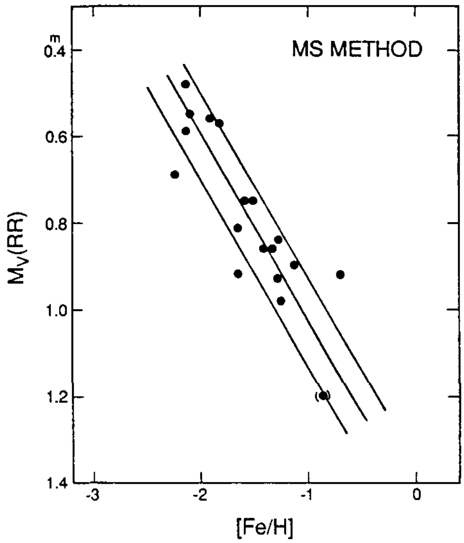
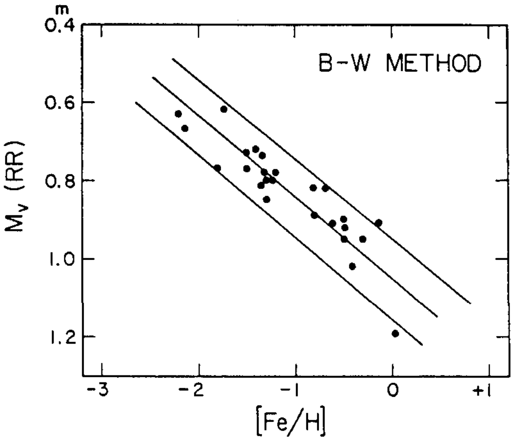


Figure 13. Summary of the calibration of M_V(RR) as a function of [Fe/H] obtained from the Baade-Wesselink method obtained by the four research groups discussed in the text.



equation (1), applied to his field star data, assuming a fixed value of the RR Lyrae mass. The dashed line marked ND is by Noble & Dickens (1988) from their direct fitting of globular cluster CMDs to an adopted fiducial main sequence defined by subdwarfs with moderaltely large trigonometric parallaxes. The two lines marked theory are from the HB models of Sweigart, Renzini & Tornambé (1987, SRT) for two values of the Helium abundance. From their Figure 1, and by applying the bolometric correction of equation (5), one can read the predicted calibrations from their theory to be

Figure 14. Comparison of four calibrations of M_V(RR) = f([Fe/H]).

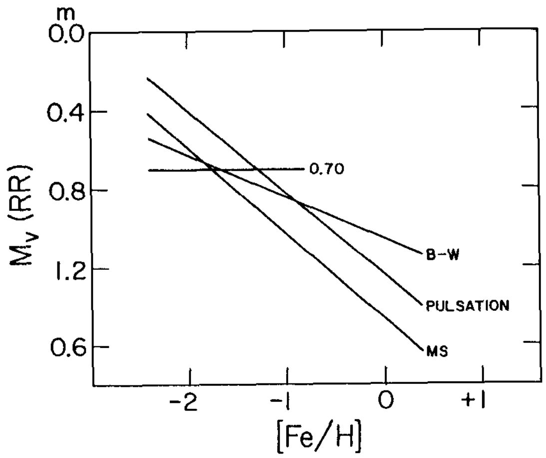
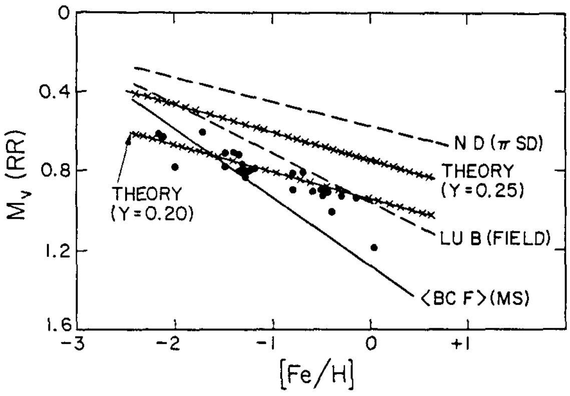


Figure 15. Comparison of additional calibrations of RR Lyrae absolute magnitudes. The plotted points are the same as shown in Figure 13, obtained from the Baade-Wesselink method.



$$M_V(RR) = 0.15\,[Fe/H] + 0.95, \tag{13}$$

for Y = 0.20,

$$M_V(RR) = 0.13\,[Fe/H] + 0.74, \tag{14}$$

for Y = 0.25,

$$M_V(RR) = 0.10\,[Fe/H] + 0.54, \tag{15}$$

for Y = 0.30 where the zero points are based on the theoretical calculations. These model values for $M_V(RR)$ have consistently been brighter than those favored by the observers by about 0.2 magnitudes for any reasonable He abundance such as Y = 0.23. Concerning the He abundance, Figure 15 shows the well known fact that the Sweigart and Gross, and the SRT HB models require an anticorreleation of Y and [Fe/H] if the steep slope of the the <BCF> calibration of equation (7), or the pulsation calibration of equation (6), is adopted. The steeper lines labeled <BCF> and Lub in Figure 15 cut across the two theory lines, showing that higher Y is required for lower [Fe/H] if these ZAHB models are correct.

7 CLUSTER AGES USING THE VARIOUS $M_V(RR)$ CALIBRATIONS ASSUMING NO OXYGEN ENHANCEMENT

The age, T, of a cluster whose bolometric luminosity at the main sequence turn-off is M_{bol} (TO) is

$$\log T = 8.319 + 0.41 M_{bol}\,(TO) - 0.15[Fe/H] - 0.43(Y - 0.24), \tag{16}$$

as interpolated (Sandage, Katem & and Sandage 1981, equation (18) and Figure 14) from the extensive Yale tables of Ciardullo & Demarque (1977, CD). The results are very similar to those obtained earlier by Simoda & Iben (1968, 1970), and Iben & Rood (1970), and later by VandenBerg (1983) and by VandenBerg & Bell (1985). The accuracy of equation (16) in reproducing the CD tables is better than 5% over the range of Y, [Fe/H], and T of interest for the globular system.

Equation (16) can be related to $M_V(RR)$ by noting that the observed magnitude difference between the ZAHB and the main sequence turn-off is 3.54 magnitudes in V, and that the bolometric correction for MS stars at the turn-off is 0.1 magnitudes to give, from equation (16) with Y = 0.24,

$$\log T = 9.734 + 0.41\,M_V(RR) - 0.15\,[Fe/H]. \tag{17}$$

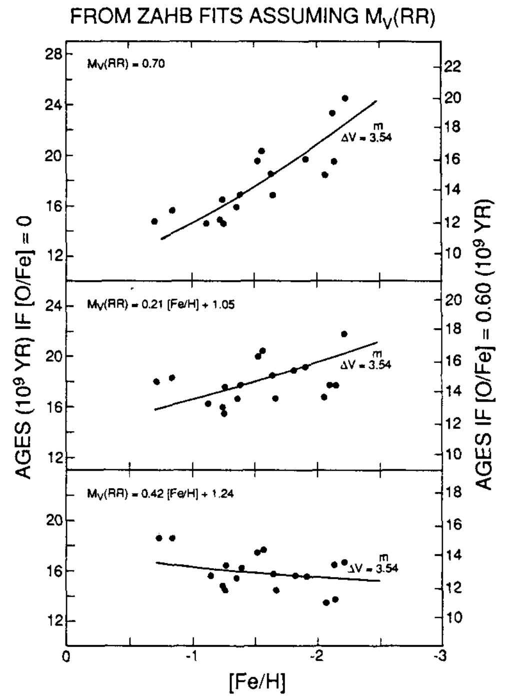
Substituting $M_V(RR) = a\,[Fe/H] + b$ for the RR luminosity in equation (17) shows directly how the age T should vary with metallicity. Clearly, the condition for no variation of T with [Fe/H] is

$$a = 0.15/0.41 = 0.37,$$

which is close to the calibration values determined from the pulsation data [equation (6)] and from the MS fitting (equations (7), (10), and (11)].

The ages calculated from equation (17), using three assumptions for how M_V(RR) varies with metallicity, are shown in Figure 16. If the observed Fe abundance tracks the total metal abundance which determines the interior opacity, the resulting ages, calculated from equation (17), are on the left. Age determinations for each of the program clusters, based on the individual magnitude differences between the ZAHB and the MS turn-off are shown as dots. The trend, assuming that each cluster has a 3.54 magnitudes difference (in V) between the ZAHB and the MSTO, is shown as the solid lines. Our preferred calibration of M_V(RR), which lies between the bottom two panels, gives a mean age of 16 Byr with no measurable variation with [Fe/H]. Ages with an Oxygen enhancement of [O/Fe] = +0.6, discussed in the next section, along the right hand ordinate, are smaller by a factor of 1.2.

Figure 16. Summary of the age determinations for the program clusters using three different assumptions for the RR Lyrae absloute magnitudes as a function of metallicity. Left hand ordinate is with no Oxygen enhancement. Right hand ordinate assumes [O/Fe] = + 0.6 for all relevant [Fe/H] values.



8 CLUSTER AGES FROM M_V(RR) ASSUMING OXYGEN ENHANCEMENT

Strong evidence exists from field subdwarfs that [O/Fe] > 0 for [Fe/H] less than -1. Figure 17 from Sneden's (1985) review shows that for [Fe/H] less than -1, the [O/H] enhancement is at least = 0.5. Because Oxygen is more abundant than Fe in any standard adopted chemical cosmic mixture by about a factor of 250, the opacity in a mix that has an O enhancement is not as low at a given [Fe/H] value as it would have been otherwise. The approximate effect on the ages can be estimated from equation (17) by replacing [Fe/H] by the true metal abundance [M/H] relative to the sun.

Suppose the curves in Figure 17 are represented by

$$[\mathrm{O/Fe}] = c\ [\mathrm{Fe/H}] + d. \tag{18}$$

To a good approximation, $[\mathrm{M/H}] = [\mathrm{O/H}] = (c + 1)\ [\mathrm{Fe/H}] = d$. This, put into equation (17) by replacing the [Fe/H] term, gives

$$\log T = 9.734 + 0.41\ M_V(\mathrm{RR}) - 0.15\ \{(c + 1)\ [\mathrm{Fe/H}]\} - 0.15\ d. \tag{19}$$

As a compromise between curves A and B in Figure 17 we adopt

$$[\mathrm{O/Fe}] = -\ 0.14\ [\mathrm{Fe/H}] + 0.40 \tag{20}$$

for the Oxygen enhancement. This, put into equation (19) gives the age dating results shown in Figure 18. Again, our preferred solution, based on the most reliable M_V(RR) calibration between the last two panels in Figure 18, gives the average age of the globular cluster system to be 13 Byr.

Figure 17. Summary of the observed Oxygen enhancement given by Sneden (1985). The adopted variation of [O/Fe] = -0.14 [Fe/H] + 0.40 for [Fe/H] smaller than -1 is between curves A and B.

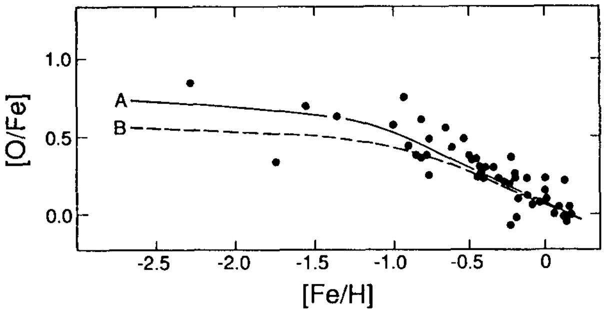


Figure 18. Same as Figure 16 but assuming an Oxygen enhancement given by equation (20).

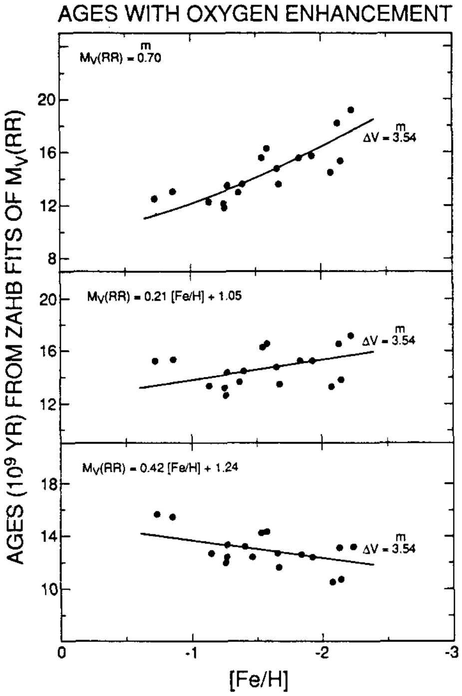
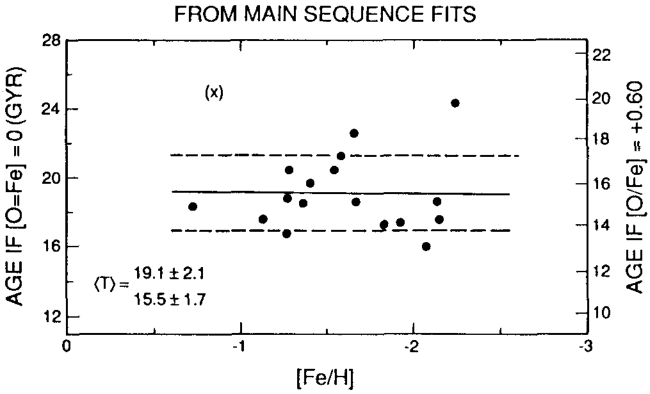


Figure 19. Ages with and without Oxygen enhancement using direct main sequence fits to determine M_V(TO). The ages are larger than in Figures 16 and 18 because of the 0.2 magnitudes offset shown in Figure 14 between the lines labeled MS and pulsation.



9 CLUSTER AGES FROM M_{bol} (MSTO) VALUES USING DIRECT MS FITTING

The M_V values of the main sequence turn-offs for each of the program clusters can be used directly in equation (16), (adding the bolometric correction of -0.1 magnitudes) to obtain ages, independent of any assumption about the RR Lyrae calibration. The result is shown in Figure 19, with and without [O/Fe] enhancement. The ages of 19.1 Byr and 15.5 Byr are longer than those given in Figures 16 and 18 because the main sequence fitting data for M_V(RR) are fainter in the mean by about 0.2 magnitudes from those given either by the pulsation or the B-W M_V(RR) calibrations. This is shown by the off-set of the MS curve from the others by this amount in Figure 14. As with our preferred RR Lyrae calibrations in Figures 16 and 18, there is no measurable variation of cluster ages with metallicity in Figure 19 within the scatter of about 10% on either side of the mean horizontal line. This independence of age on metallicity is consistent with the rapid formation of the galactic halo in about the free fall time (no dissipation, i.e. no pressure support in the halo formation phase) envisaged in the model suggested by Eggen et al. (1962).

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