AGES OF THE GALACTIC GLOBULAR CLUSTERS

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ABSTRACT: Using stellar evolutionary models which have been computed for the preferred set of element abundances, ages of 13-14 Gyr are derived for the Galactic globular clusters. No significant (> 1.5 Gyr) spread in age is found as a function of either metal content or galactocentric distance. The lack of an age-metallicity relation is shown to be contingent upon the assumption that [O/Fe] is anticorrelated with [Fe/H]: the use of scaled solar abundance calculations would predict that the most metal-poor systems are about 3×10^9 yr older than the most metal-rich clusters. Some evidence in support of high oxygen-to-iron ratios is discussed.

1. INTRODUCTION

The goal of much of the globular cluster (GC) research that is presently being conducted is to answer two basic questions: (1) what is the highest cluster age?, and (2) are all globulars coeval? The answer to the first of these sets a lower limit to the age of the universe - thereby constraining cosmological models - while that for the second tells us whether the collapse of the Galactic halo was rapid or slow - thus providing vital input into our understanding of the evolution of galaxies. Unfortunately, in spite of a lot of effort, precise answers to these two questions have yet to be forthcoming. However, considerable progress is being made and it seems clear that the uncertainties in the derived ages are steadily being reduced. This review presents a status report of our current understanding.

2. GLOBULAR CLUSTER AGES

In principle, the preferred way to determine the age of a given globular cluster is to perform a main-sequence fit of appropriate isochrones onto photometric data. In practice, however, this cannot yet be regarded as the most reliable method. Too many things have to be known too accurately - not only the temperature scale of the models and the transformation relations between T(eff) and color, but also the

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reddening of the cluster and its metallicity. On the theoretical side, predicted effective temperatures depend sensitively on the assumed structure of the outer atmosphere and on the treatment of convection in the stellar interior - neither of which is well understood. In addition, it is well known that synthetic colors, particularly for cool/metal-rich stars, err in the sense of being too blue by a few to perhaps several hundredths of a magnitude in B-V (e.g., Magain 1983). Since the ratio of magnitude to color along a zero-age main sequence (ZAMS) is ≃ 5, every 0.02 mag error in either the predicted colors or in the observed cluster reddening would translate to an error of about 0.1 mag in the derived distance modulus and hence approximately 1.5 Gyr in age.

The tremendous range in "observed" metallicities for many clusters is also a major problem. For example, according to the compilation by Hesser and Shawl (1985), support may be found in the literature for a metal content for a well-studied system like NGC 6752 anywhere between [m/H] = -1.09 and -1.66. Certainly, the interpretation of its very tight main-sequence locus on the (V,B-V)-plane, which has recently been obtained by Penny and Dickens (1986) and by Buonanno et al. (1986), is going to depend on the composition which is assumed in the models. And if the computations for a particular [m/H] don't fit, is it because there are problems with the theory or simply that the wrong metallicity was initially assumed?

In order to avoid virtually all of these problems, Iben and Renzini (1984) have argued that the best way at the present time to determine ages is from a calibration of the magnitude difference between the horizontal branch and the main-sequence turnoff, at the color of the turnoff. Figure 1 illustrates what this method involves. Since the

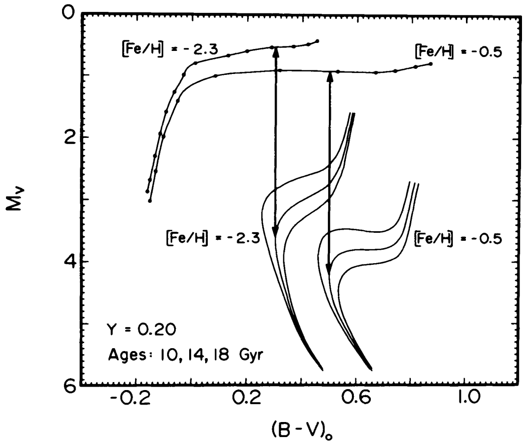

Fig. 1. - Plot of VandenBerg and Bell (1985) isochrones for the noted ages and metallicities, along with fully consistent zero age horizontal branches (VandenBerg 1986). Arrows illustrate the definition of the age-dependent quantity ΔV_{TO}^{ZAHB}.

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luminosity (though not the color) of a computed zero-age horizontal branch (ZAHB) star is largely independent of the mass of the red-giant precursor, it is essentially independent of age. (Recall that the canonical explanation for the observed wide range in color of HB stars is that, while all such stars have nearly the same core mass, their envelope and hence total masses differ because of prior mass loss - either during evolution up the red-giant branch or as a result of the helium flash event itself.) Given then that the luminosity of the ZAHB is not a function of age, while that of the turnoff obviously is, the magnitude difference between these two features is clearly an excellent indicator of age. A particularly desirable attribute of this quantity is that, for a given age, it is not very sensitive to uncertainties in composition (note the example given in Figure 1).

In practice, there are some important limitations to this method. Many globulars show only a very blue or a very red horizontal branch and it is by no means a straightforward task, especially in the former instance, to estimate the location of the ZAHB at the color of the turnoff. Also, the distribution of stars at the turnoff is often vertical for several tenths of a magnitude with the result that the precise magnitude of the turnoff is difficult to define. Primarily because of these two uncertainties, the observed magnitude difference in most clusters cannot be estimated to within ± 0.15 - 0.2 mag, which means that precise age estimates are not possible.

The lower panel of Figure 2 illustrates a calibration, from theory, of the magnitude difference between the ZAHB and the turnoff as a function

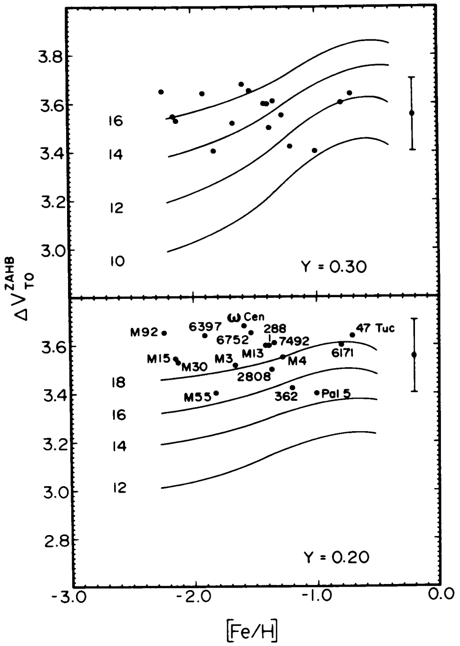

Fig. 2. - Theoretical calibration, for two Y values, of the magnitude difference between the ZAHB and the main-sequence turnoff, at the color of the turnoff, as a function of [Fe/H] and age. The latter is indicated in units of 10^9 yr to the left of each solid curve. Filled circles give the observed data for a number of GCs as reported by Buonanno (1986).

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of [Fe/H] and age. Superimposed on this diagram are the observed values of ΔV_{TO}^{ZAHB} recently reported by Buonanno (1986) for 17 GCs for which he and his colleagues have obtained CCD photometry. The metallicity scale which they adopt and which is assumed here is largely that given by Zinn (1985). It is clear that if the helium content is close to Y = 0.20 and the heavy elements have solar number abundance ratios (which are assumed in the VandenBerg and Bell (1985) isochrones), then the globular clusters are predicted to have a very high age indeed. It is tempting to conclude that a number like 18 Gyr or slightly older is the preferred value, but one must keep in mind the large error bar associated with each datum and be wary of possible biases regarding how one actually chooses to extrapolate to the ZAHB location at the color of the turnoff - when none of the observed HB stars have such colors - and how the turnoff magnitude is selected when the distribution of stars is vertical. Such subjective sources of error may well affect the mean ΔV_{TO}^{ZAHB} value which is obtained. The main point of this plot is that there is no evidence, from this particular sample of GCs, for ages younger than about 14 Gyr (if Y = 0.2) or for large cluster-to-cluster variations in age.

It is worth pointing out that a fairly wide range in galactocentric radius (Rg) is encompassed by these clusters, from 3.9 kpc for NGC 6171 to 18.7 kpc for NGC 7492 (Webbink 1985). Clearly, on the basis of their measured ΔV_{TO}^{ZAHB} values, the ages of these two clusters must be nearly the same. In the latest review of globular cluster ages, Gratton (1985) suggested that there was a significant age-Rg relation among the globulars, primarily on the basis of available observations of NGC 7006 and the three Palomar clusters, numbered 5, 12, and 13. However, new CCD photometry of NGC 7006 (Rg = 36.3 kpc) by Cohen (1985) has demonstrated that its turnoff is fully consistent with usual estimates of GC ages (though the data is still sufficiently imprecise not to exclude the possibility that it is younger by 3-4 Gyr). Regarding Pal 5 (Rg = 16.5 kpc), which has the lowest ΔV_{TO}^{ZAHB} value of those plotted in Figure 2, it is apparent from Figure 3 that its C-M diagram is not distinctly different from that of M5,

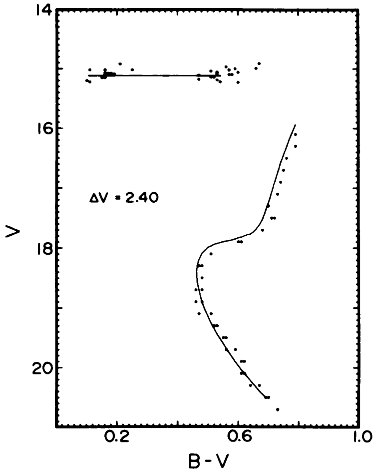

Fig. 3. - Superposition of the fiducial sequence for Pal 5 (solid curve) by Smith et al. (1986) onto that for M5 (dots) by Richer and Fahlman (1986). The M5 HB observations are due to H. Arp (Ap.J., 135, 31, 1962): their accuracy has been confirmed by Richer and Fahlman. The distance moduli of the two clusters, which have similar metallicities and reddenings, are assumed to differ by 2.4 mag.

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which has a similar metal abundance and reddening, but is much nearer at Rg = 6.6 kpc. Considering the uncertainties in fitting the sparse (but tightly-defined) horizontal branch of Pal 5 to that of M5, the ages of the two clusters are probably the same to within about 10^9 yr.

In the case of Pal 12 (Rg = 16 kpc), the photographic photometry by Harris and Canterna (1980) certainly indicates a small ΔV^{ZAHB}_{TO} ; but closer inspection of the data suggests that it may suffer from some calibration problems. In the left-hand panel of Figure 4, the published mean locus of Pal 12 is superimposed on the composite C-M diagram of 47 Tucanae (Harris and Hesser 1986) such that the mean horizontal-branch luminosities agree. But this produces a large discrepancy near the main sequence - one which is impossible to reconcile. Regardless of whether or not two clusters have different ages, their unevolved main sequences must be nearly coincident on the C-M plane if allowances are made for differences in distance and reddening and if, as is believed to be the case here, the two systems have similar metallicities. The right-hand panel shows that acceptable agreement of the lower main sequences can be obtained if the cluster moduli are assumed to differ by 2.65 mag - but then the horizontal branch of Pal 12 is much fainter than that of 47 Tuc. This would be just as hard to understand. Certainly the preferred explanation is that there are problems with the main-sequence photometry; which could well be possible since it relied on the calibration of secondary images produced by the Racine wedge. A follow-up study using the CCD is obviously in order.

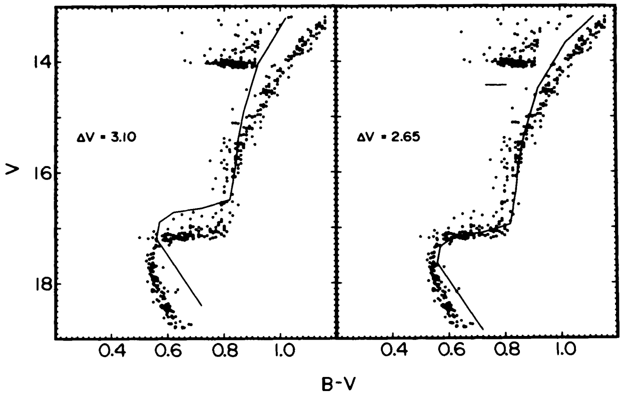

Fig. 4. - Comparison of the fiducial sequence for Palomar 12 (solid curve) with the composite C-M diagram of 47 Tuc. The Pal 12 locus was shifted horizontally by 0.02 mag, to allow for reddening differences, and by the two indicated values of ΔV in the vertical direction.

Since the Pal 13 photometry used by Gratton (1985) in his analysis has not yet been published, no comment can be made of the reliability of the derived age for this system. But on the basis of the available evidence, the dependence of age on galactocentric distance appears to be

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rather small. What about a relation between the age of a cluster and its metallicity? The lower panel of Figure 2 does give the impression that the most metal-poor clusters are a little older than the most metal-rich systems. Such a trend is very much more pronounced if the observed ΔV_{TO}^{ZAHB} values are plotted on the theoretical calibration for Y = 0.30, as given in the upper panel of Figure 2. In this case, the size of the effect would seem to be about 4-5 Gyr over a 1.5 dex range in [Fe/H] - though again it should be emphasized that part of the trend may be associated with how one estimates the luminosity of the ZAHB and the main-sequence turnoff. An interesting way to view these results is that, if all GCs have the same age and if the present models are basically correct, then the cluster helium content and the metallicity must be anticorrelated - i.e., higher Y in more metal-poor systems - just as Sandage (1982) has found necessary to explain the correlation which he discovered between the period of an RR Lyrae star and its metallicity.

Thusfar, we have made use of only one small aspect of observed C-M diagrams and surely such things as the morphology of stellar distributions in different evolutionary phases will provide important constraints on our interpretation of the data. A good example is given in Figure 5, where theoretical ZAHBs for [Fe/H] ≃ -2.25, Y = 0.24, and three different assumptions regarding the oxygen abundance are compared with published photometry for M15 by Sandage (1970) and by Bingham et al. (1984). If one remembers that a ZAHB should provide a good fit to the lower bound of the observations, then one must conclude that the best fits are found when it is assumed that oxygen is significantly overabundant with respect to iron. In fact, if the stars in M15 are similar to the metal-poor field dwarfs and giants which have been subjected to detailed abundance

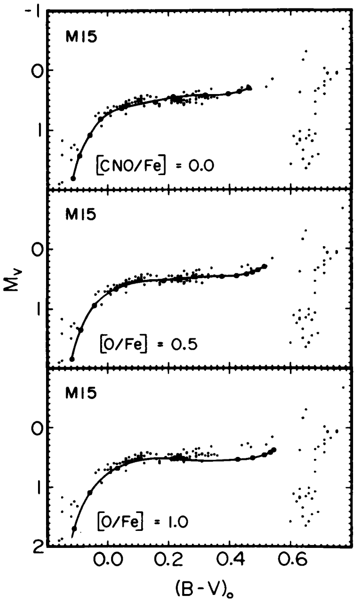

Fig. 5. - Fits of theoretical ZAHBs for [Fe/H] ≃ -2.25 and three different values of [O/Fe] to published photometry of M15. Differences in oxygen abundance affect the shape and extent of the ZAHB locus redward of B-V ≃ 0.2.

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analyses (see the review by Sneden 1985), then there is reason to believe that the cluster oxygen-to-iron ratio should be up by about a factor of 5 compared to the solar value. Therefore, another important variable, [O/Fe], has to be taken into account in the stellar models.

Clearly further refinements of cluster age estimates must involve the entire C-M diagram. The magnitude difference between the HB and the MS turnoff is arguably still the best constraint on age, but improved determinations of this quantity can be obtained by fitting the model loci to the observed stellar distributions. The preferred procedure for doing so is best explained with the aid of the example given in Figure 6. This illustrates one of the finest CCD C-M diagrams yet obtained for a globular cluster: unlike several other examples of such results, enough bright stars were observed to be able to very accurately define the shape of the turnoff region and the subgiant branch. This is, of course, critically important for the determination of precise ages. In order to ensure that color uncertainties have a negligible effect on the ages derived, the absolute luminosity (and hence distance) scale should first be established by matching the observed and predicted ZAHBs. Granted, in this particular instance, the observational ZAHB is not well defined. However, it was noticed in the analysis of the M68 data that its appearance on the (V,B-V)-plane is morphologically identical to that of M15. The much more populous HB in the latter cluster was therefore used as an additional constraint on the location of the ZAHB of M68. Once a satisfactory match of the horizontal branches is found, then the isochrones can be shifted in color, if necessary and by whatever amount is necessary, until they provide a best-fit of the main-sequence turnoff observations.

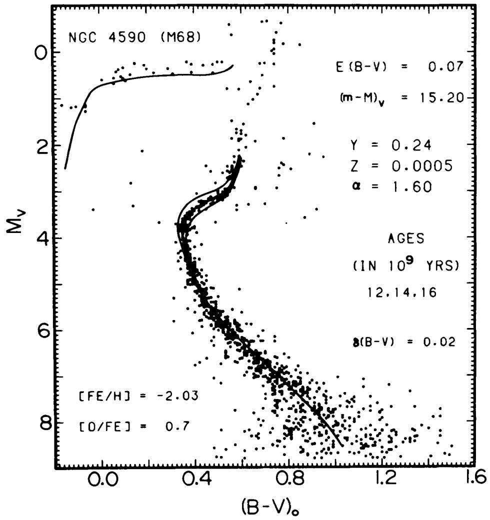

Fig. 6. - Fit of appropriate models (solid curves) to recent observations of NGC 4590 by McClure et al. (1986).

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Here, the isochrones which are used have been calculated for the primordial helium abundance, Y = 0.24 (e.g. Boesgaard and Steigman 1985), and what we believe to be the appropriate [Fe/H] and [O/Fe] values for M68. It is clear that an exceedingly fine match of the theory to the observations is obtained for an age close to 14 Gyr. What is particularly encouraging is that the shape of the model loci reproduces that of the data over the entire range of the fit. Even the steepening slope of the faintest stars seems to be consistent with the model predictions - which is further evidence that the adopted distance is close to being correct. There does appear to be a zero-point error in the color scales in the sense that the colors of the isochrones are too blue by 0.02 mag (if the adopted E(B-V) value is realistic). In fact, such a color error is suggested by the subdwarfs.

Figure 7 illustrates a comparison of representative isochrones for three metallicities, from the VandenBerg and Bell (1985) compilation, with the Carney (1979) subdwarfs which have the most accurate parameters. Lutz-Kelker corrections have not been applied to the data - but this is arguably the proper procedure (see Richer and Fahlman 1986). For the present fit, one finds that, in the mean, the isochrones are too blue by about 0.02 mag. Alternatively, if cluster distances are found by the main-sequence fitting of the VandenBerg-Bell isochrones to the data, they will be about 0.1 mag smaller than those based on the subdwarf standards. But the subdwarf sequences are obviously not well-defined - better data is urgently needed - and it may well be that the models actually have larger errors than the present analysis suggests.

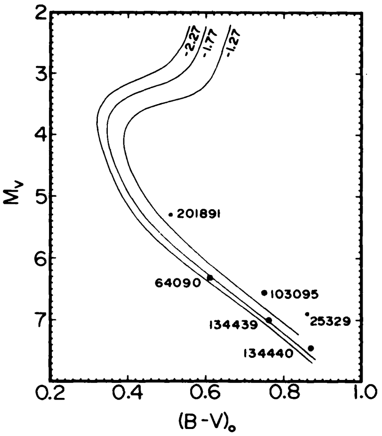

Fig. 7. - Comparison of 16 Gyr isochrones for the metallicities noted at the top of each curve with the Carney (1979) subdwarfs which have the best-determined properties. Revised parameters for some of these were provided by G.S. Da Costa (private communication). HD 64090 has [Fe/H] ≃ -1.75; the [Fe/H] values for the five other stars scatter about -1.34. Large symbols indicate that the relative uncertainty of the parallax determination is less than 10 percent.

Returning to the question of whether or not there is an age-metallicity relation, the lower right-hand panel of Figure 8 illustrates a best-fit of isochrones for Y = 0.24 and [Fe/H] = -0.65, assuming scaled-solar abundances of the heavy elements, to the 47 Tuc data. Although not shown, the distance was derived by matching predicted and observed hori-

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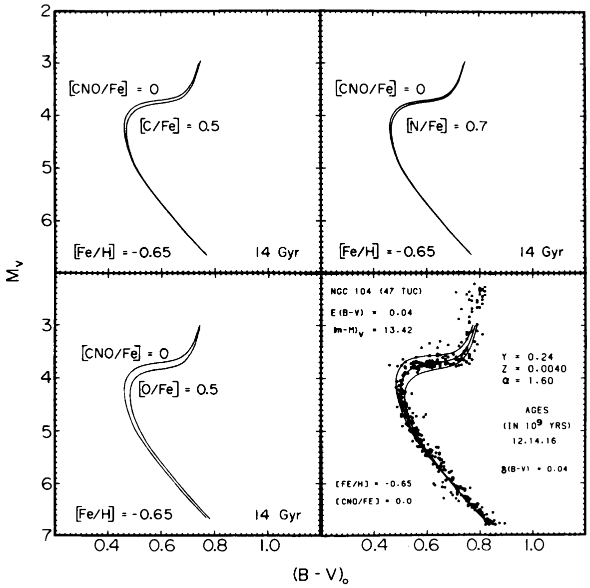

Fig. 8. - Comparisons of computed isochrones for the same Y, [Fe/H], and age (0.24, -0.65, and 14 Gyr, respectively) but for different assumed C, N, and O abundances. The lower right-hand panel illustrates the adopted fit of the [CNO/Fe] = 0.0 models for the indicated ages to the Harris and Hesser (1986) C-M diagram for 47 Tucanae.

zontal branches, which can be accomplished with little uncertainty. The fit at the turnoff indicates an age of 14 Gyr. The other three panels show that higher C, N, or O abundances tend to make the turnoff for a given age somewhat fainter. That is, the effect of enhanced [CNO/Fe] is to make the age corresponding to a given turnoff luminosity younger. The effect is most pronounced if oxygen is enhanced because it is the dominant constituent of the CNO group while the variation of nitrogen has little effect because it is the least abundant of the three elements. Thus, there is no inconsistency, for example, between the observation, on the one hand, that 47 Tuc has a very tight C-M diagram, and the abundance work by Bell et al (1983), on the other, which found star-to-star nitrogen abundance variations by about a factor of five. According to our present understanding (e.g., see Sneden 1985), carbon and nitrogen scale with iron - except perhaps at extremely low metallicities. Oxygen, on the other hand, is believed to become steadily overabundant with respect to iron as the [Fe/H] value drops though the trend may flatten below [Fe/H] = -1. If the adopted metal abundance for 47 Tuc is correct, then on the basis of field star studies, one expects an oxygen enhancement [O/Fe] ≃ 0.3 - in which case, the derived cluster age would be closer to 13 Gyr. This is about 1 Gyr smaller than our best estimate for M68 (and M15, which seems to be morphologically identical to M68 on the C-M plane) and one could argue that there is some evidence for an age-metallicity relation among the Galactic globular clusters. However, such a small age difference

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is obviously within the uncertainty. One therefore concludes that if there is a variation of age with metallicity, it must be very slight.

A final point about Figure 8: note that a redward color correction of 0.04 mag was applied to the models in order to reproduce the observed colors of stars in 47 Tuc. This could well be the expected error of the VandenBerg and Bell (1985) isochrones for metal-rich compositions. If a metallicity of [Fe/H] = -0.8 were assumed instead of [Fe/H]= -0.65, then the corresponding theoretical loci would have to be adjusted by 0.08 mag to yield a similar fit. Such a large color correction seems rather unlikely. This suggests that the metal content of 47 Tuc must be greater than [m/H] = -0.8, at least in the mean. If iron is underabundant, then there must be enhancements in other elements to partially take the place of iron as a main source of opacity and blanketing.

Oxygen has played a critical role in the present analysis. Indeed, had it not been assumed that [O/Fe] is higher in metal-poor systems than in metal-rich ones, a significant age-metallicity relation would have been found: M68 would have been predicted to be about 3 x 10^9 yr older than 47 Tuc. Some further support (besides Fig. 5) for the possibility that [O/Fe] is high in metal-poor clusters is given in Figure 9. This illustrates the superposition of computed ZAHBs for [Fe/H] = -2.25 and two different [O/Fe] values on new photometry for Draco, a dwarf spheroidal galaxy that has an anomalously red HB for its (M92-like) metal abundance. Note that a considerably-expanded luminosity scale has been adopted to exaggerate the differences between the two ZAHBs: their separation in luminosity at $(B-V)_0$ = 0.4 is actually only 0.12 mag. But this may prove to be another point in favor of enhanced oxygen models since the latter will predict a reduced magnitude difference between metal-poor and metal-rich RR Lyrae stars compared to usual findings. The important point of this figure, however, is that scaled-solar-abundance calculations cannot explain the reddest horizontal-branch stars (cf. Rood and Seitzer 1982) - regardless of whether or not the Draco stars span a wide range in age. The ZAHBs which have been plotted have nearly reached their maximum possible colors - the assumption of even higher masses (younger turnoff ages) will cause the HB loci to bend back toward the blue. No such problem exists if [O/Fe] $\simeq$ 1: a red HB is expected.

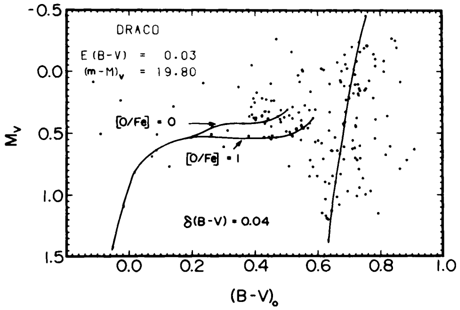

Fig. 9. - Overlay of theoretical loci for [Fe/H] = -2.25 and the noted [O/Fe] values on the recent C-M diagram for Draco by Carney and Seitzer (1986). The computed RGBs have identical locations in the two cases.

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3. SUMMARY

Recent studies (Sandage 1982, Flannery and Johnson 1982, Janes and Demarque 1983, VandenBerg 1983, Gratton 1985) have found ages > 15 Gyr for the oldest Galactic GCs. On the basis of new calculations which assume Y = 0.24 and enhanced [O/Fe] ratios, this investigation suggests that the maximum age of the globulars is close to 13-14 Gyr. Moreover, any variation of age with galactocentric radius or with metallicity appears to be within the limits of detectability. That is, the age spread seems to be less than ∿ 1.5 Gyr.

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DISCUSSION

ALCAINO: The isochrones of VandenBerg and Bell (1985) are given for Y = 0.2 and 0.3. You have mentioned that the best current estimate of the primordial helium abundance is Y = 0.24. Could you explain the basis on which this value is preferred?

VANDENBERG: A value of Y ~ 0.24 had been obtained from the analysis of extragalactic H II regions by Sargent and colleagues. Such a value has also been found to be consistent with lithium abundance determinations of Pop. II stars by F. Spite. Boesgaard and Steigman provide a recent summary of our present understanding in the 1985 Annual Review of Astronomy and Astrophysics.

TRIMBLE: By the fit to M 68, all the dots for the horizontal branch are above the line.

VANDENBERG: Yes, the ZAHB must necessarily be fitted to the lower bound of the observed HB distribution because subsequent evolution will tend to make the stars move above the ZAHB.

BELL: Can you estimate how much of the changes due to changing [O/Fe] are due to changes in opacity and how much is due to changes in energy generations?

ROOD: I have done such calculations. I was surprised to find that opacity was the most important factor in determining the turnoff age. Even though the CNO cycle dominates just after core hydrogen exhaustion I think the gradient set up in hydrogen during the earlier stages is the determining factor.

NORRIS: Given that blue horizontal-branch stars have been found by Ruth Peterson to have anomalously high rotational velocities, and that these effects are generally neglected in standard stellar evolution calculations, would you comment on how internal rotation in low mass stars might affect the results you have shown us?

VANDENBERG: Rotation has not been studied properly. From simplistic considerations, it is commonly believed that rotation will delay the onset of the helium flash, leading to higher core masses and smaller envelope masses than the canonical models, thereby favoring the formation of brighter and bluer horizontal-branch stars. In addition one expects rotation to increase turnoff ages since rotation will tend to support the star, thereby leading to lowered nuclear burning rates. But the tightness of observed CM diagrams must constrain the amount of rotation which is allowed. Clearly more work is needed.

SCHOMMER: Would you or Roger care to comment on the possible origin of the 0.02 - 0.04 (B-V) shifts you apply? Does this depend on the color or effective temperature, or is this result the best value for the

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turnoff region?

VANDENBERG: Roger has shown that his color - T_{eff} relations look pretty good (Though, these may still be the source of the small problem with the colors.). Problems with the T_{eff} scale of the models may well be the most likely explanation of the discrepancy. While infrared photometry has tended to confirm the predicted T_{eff}'s of red giant stars in globular clusters, confirmation of turnoff temperatures has yet to be obtained. Until this happens, one must be wary of the possibility that predicted T_{eff}'s (and hence synthetic colors) are somewhat in error, and one should continue to rely on luminosity criteria to derive distances and ages. I suspect that the error will become systematically larger as [Fe/H] increases. However, the error seems to be primarily in the zero-point. As shown in Fig. 6, the systematic variation of computed colors for a given [Fe/H] compares very well that observed.

CAYREL: The ages for M 68 and 47 Tuc you have were based on the $\Delta V^{ZAHB}{}_{TO}$ to mag. differences. Is it not true to say that, from the same diagrams you have shown, the age derived from main-sequence fitting would be the same?

VANDENBERG: Main-sequence fitting would lead to somewhat older ages since the models appear to be bluer than the observations. If theoretical loci are too blue, then derived distances are too small and ages too high. However, the uncertainties in color seem to be small enough that the estimated ages will not differ by more than 3 Gyr (or smaller for low-metallicity clusters) if the main-sequence method is employed.

ZINN: I have two questions. First, if I understand what you have done correctly, you have derived the distance moduli of the clusters by matching the observed horizontal branches with ones generated by theoretical calculations. What will happen to your conclusions about the age-metallicity relationship if instead you adopt a shallower or a steeper dependence of HB luminosity on [Fe/H]. For example, the one that Sandage found from his analysis of the Oosterhoff effect. Second, several independent workers, including myself, have concluded that there is a significant range in metallicity in the Draco dwarf spheroidal galaxy. If you accept these results, is it still necessary to conclude from the redness of the HB in Draco that it has an overabundance of oxygen?

VANDENBERG: 1. If all HB stars have $M_V \simeq 0.6$, then the metal-rich clusters must be younger than metal-poor clusters. The reverse would be true if Sandage's relation between M_V(RR) and [Fe/H] is assumed, _in the context of the present models_ since his relation is steeper than my predictions, from which a constant age scenario has been deduced.

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2. Higher metallicities would reduce the color discrepancy but probably not remove it. To first order, a ZAHB with [Fe/H] = -2.25 and [O/Fe] = 1.0 would be similar to one with [Fe/H] ≃ -1.6 and [O/Fe] = 0.0. The enhanced oxygen mix has an effective $Z = 5 \times 10^{-4}$. The [Fe/H] value corresponding to the latter is higher than the upper limit of the observed range in Draco metallicities.

GRINDLAY: Suppose in three years time we knew that the disk globulars really were formed at a different time than the halo clusters, as their apparently distinct population might suggest. What would be the major effects and implications for your models?

VANDENBERG: There are so many possible variables; for example, perhaps low [Fe/H] clusters mix more of their envelopes than metal-rich clusters (for some unknown reason) during red giant branch evolution. Such a possibility is suggested by the work of the Lick group on M 92. In this case, the helium abundances would be larger in low-metallicity clusters than in those of high metal content (recall Sandage's result). This would affect derived distances and ages.

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