OBSERVATIONS OF LOW MASS STARS IN CLUSTERS: SOME CONSTRAINTS AND PUZZLES FOR STELLAR EVOLUTION THEORY

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1. INTRODUCTION

This review will attempt to do two things: (i) discuss some of the data which are available for testing the theory of evolution of low mass stars, and (ii) point out some problem areas where observations and theory do not seem to agree very well. This is of course too vast a field of research to be covered in one brief review, so I shall concentrate on one particular aspect, namely the study of star clusters and especially their colour-magnitude (CM) diagrams. Star clusters provide large samples of stars at the same distance and with the same age, and the CM diagram gives the easiest way of comparing theoretical predictions with observations, although crucial evidence is also provided by spectroscopic abundance analyses and studies of variable stars. Since this is primarily a review of observational data it is natural to divide it into two parts: (i) galactic globular clusters, and (ii) old and intermediate-age open clusters. Some additional evidence comes from Local Group galaxies, especially now that CM diagrams which reach the old main sequence are becoming available. For each class of cluster I shall consider successive stages of evolution from the main sequence, up the hydrogen-burning red giant branch, and through the helium-burning giant phase.

2. GLOBULAR CLUSTERS

2.1 The overall picture

The conventional wisdom is that globular clusters are massive, independent, gravitationally bound systems containing up to a million stars, that they are of great antiquity with ages of around 15 billion years, and that they were born from chemically homogeneous material over a timescale very short compared with their ages. It is usually assumed that the original (generally low metal abundance) chemical composition can be determined spectroscopically from the surface layers of luminous, highly evolved, stars.

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A cluster CM diagram thus provides an instantaneous picture of the points of evolution reached in a given time by stars of different masses, and this can be compared directly with theoretical isochrones in the equivalent diagram of luminosity versus temperature, provided that those parameters can be transformed to or from observed magnitudes and colours.

Recent work has raised uncertainties concerning the validity of nearly all of the fundamental assumptions about globular clusters, but it seems that those assumptions are probably still approximately true for most of the clusters most of the time.

2.2 The main sequence

The position of the zero age main sequence (ZAMS) is expected to be a function of chemical composition. Unfortunately, unless some other feature is used to fix a cluster's distance, the absolute magnitude of a globular cluster ZAMS cannot be determined, while one of the most important parameters is helium abundance which is not directly observable. An independent measure of distance can be found for some clusters from the properties of RR Lyrae variables (e.g. Sandage, 1982), but it can only be applied to clusters with enough variables and its reliability depends on the adequacy of pulsation theory as well as on having very precise observational data. The usual procedure is to adopt a chemical composition and to use unevolved main sequence stars to determine cluster distance, either via an empirical calibration of the ZAMS-abundance relation (Sandage, 1970; Carney, 1980) using nearby subdwarfs with trigonometrical parallaxes, or by appealing directly to theoretical predictions (e.g. Simoda & Iben, 1968; VandenBerg, 1983).

The main sequence turn-off is used to determine the second major parameter, a cluster's age, and hence also the masses of stars evolving up the giant branch. Since there is no other way of determining these two parameters, there is again little scope for checking the predictions of stellar evolution theory. Furthermore, even the mass is not well-determined since for a given turn-off position the mass is once more a strong function of the helium abundance. Luckily the age determination itself is not much affected by the uncertainty in helium abundance.

Some consistency checks on the theory are nevertheless possible. The overall shape of the theoretical isochrone for the presumed chemical composition of the cluster should match the observed shape. Only recently have the many theoretical and observational parameters begun to be well enough known to make this a useful test, and even so VandenBerg (1983) effectively used the turn-off shape to fix the best value of yet another uncertain parameter, the convective mixing length in his models. Unfortunately very few clusters have observationally well-determined turn-offs, since these require accurate photometry for large samples of faint (usually $V > 18$) stars (cf Cannon, 1981).

There are also two external 'consistency checks' or constraints on the ages found for globular clusters, both depending on theories unconnected with stellar evolution. Some dynamical models for the formation of our Galaxy (Eggen, Lynden-Bell & Sandage, 1962) predict that the very extended spherical galactic halo must have formed over a relatively short period of time, so that the globular clusters should all be virtually the same age. On the other hand, Rood & Iben (1968) showed that the spread in formation times of the globular clusters could well exceed 10% of their present age, while Searle & Zinn (1978) argued for a possibly much larger spread. The most recent determinations (Sandage, 1982; VandenBerg, 1983) do make all clusters coeval, with an age of around 17.10^9y, although an alternative metallicity-dependent age spread has also been proposed (Carney, 1980; Demarque 1980).

The second external constraint follows from the very great age found for globular clusters: an age of 17.10^9y is close to the maximum permissable within the framework of Big Bang cosmology if Hubble's constant is 55 km s^{-1} Mpc^{-1} (Sandage, 1982), and is inconsistent with larger values of H_o. If H_o is as high as 100 km s^{-1} Mpc^{-1}, it follows that the age of the Universe is no more than 10^{10}y and that either stellar evolution theory or Big Bang cosmology is badly wrong. Of course no-one would claim that stellar evolution theory combined with globular cluster observations will yield ages more accurate than say 10% (see Cannon, 1982 for a review), but an error of 40% in the ages implies either an unfortunate combination of several errors all acting in the same direction, or a fundamental flaw.

2.3 Giant branch evolution

Giant branch evolution has been regarded as basically understood since the work of Hoyle & Schwarzschild (1955), although there is still an entertaining debate about the underlying physical mechanisms (e.g. Eggleton & Faulkner, 1981; Weiss, 1983). Unfortunately, once again a direct comparison between theory and observations is rather difficult. In this case the problem is that the temperature of a red giant model is determined by the extent of the convective envelope, which is a strong function of the rather arbitrary 'mixing length' parameter. Thus although there is a clear dependence of giant branch colour (as measured by the (B-V)o,g parameter of Sandage & Smith, 1966) on overall metallicity, any theoretical interpretation depends on some assumption relating metallicity, opacity and convection.

Fortunately the luminosities, and hence the rates of evolution, of red giants do not change much with mixing length. Thus a direct comparison is possible between theoretical rates of evolution and observed numbers of stars; this has been used for example as one method for determining the helium abundance of globular clusters (Simoda & Kimura, 1968; Faulkner, 1972).

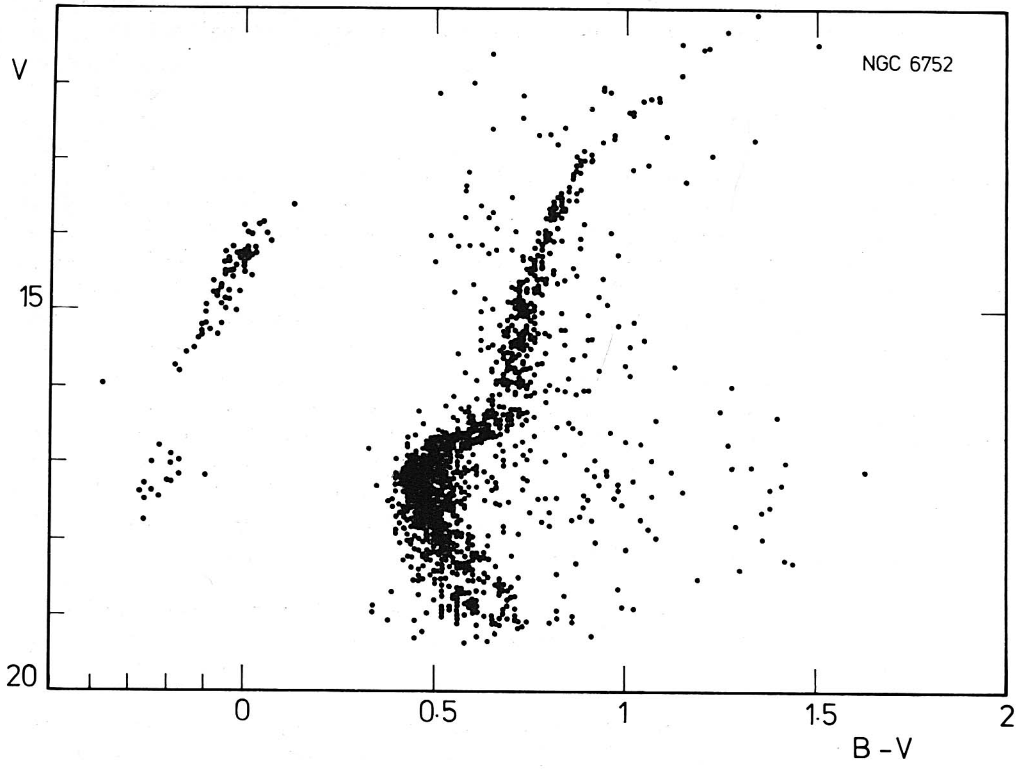

Fig. 1 The CM diagram of NGC 6752

There is one clear conflict between theory and observation, right at the base of the giant branch. In 1972 Cannon & Lee found a small gap, about 0.1 mag wide, at V = 16.2 in NGC 6752. Since the CM diagram of this cluster illustrates some other points discussed subsequently, and since the data are regrettably still unpublished, it is shown here as Fig. 1. Careful checking, involving remeasurement and re-calibration of all stars within one magnitude of the gap, showed that it is certainly a real feature. A similar gap may be present in some other clusters, but in no case are the data yet completely convincing; equally there are no clusters for which one can definitely say no such gap exists, since accurate photometry is needed for large samples of faint stars. There is no theoretical prediction of a corresponding fast phase of evolution which would give rise to such a gap, although possible clumps and gaps are predicted at higher luminosities when the hydrogen-burning shell encounters composition discontinuities left behind by previous convective zones (Sweigart & Gross, 1978). Unfortunately the predicted perturbations in the number density of stars seen are generally of order only ten percent, and such fluctuations would be swamped by stochastic variations in the relatively small numbers of red giants observed in most clusters.

2.4 The horizontal branch

It is generally accepted that globular cluster stars move rapidly on to the horizontal branch (HB) after the 'helium flash' at the tip of the giant branch, following the classic work of Faulkner (1966) and the subsequent detailed core-plus-shell energy source evolutionary models of Sweigart & Gross (1976). There is however a major hiatus in the theory, in that the details of the very rapid onset of helium burning and lifting of degeneracy have not been fully worked out, and there may be considerable amounts of core-envelope mixing and mass loss during the helium flash. Recent hydrodynamical calculations by Deupree & Cole (1983), give considerably different results from the earlier 'static' predictions. Thus the two principal parameters determining the initial location of a star on the HB, the core mass and the envelope mass, are both uncertain, while the HB lifetimes may be wrong by as much as 50 percent.

The original Faulkner (1966) and Faulkner & Iben (1966) theory explained the existence of the HB and gave the correct evolutionary lifetimes (as required to explain the numbers of HB stars seen) of order 10^8y, and was also consistent with the general correlation between metallicity and morphology (i.e. most metal poor clusters have blue HBs whereas relatively metal rich clusters usually have red HBs). However, this latter consistency may have been fortuitous since there was no explanation for the now well-established anomalous 'second-parameter' clusters such as NGC 7006 (Sandage & Wildey, 1967) and NGC 288 (Cannon, 1974), while Iben & Rood (1970) showed that there must be a spread in mass along the HB. Rood (1973) and Renzini (1977) showed that quite small variations in the essentially arbitrary mass loss parameter could lead to great variations in HB structure. The debate on the 'second parameter' is continuing with still no single simple explanation, or rather, an embarrassing abundance of plausible explanations, able to accommodate all of the data (e.g. Freeman & Norris, 1981), and perhaps one should say that it is all too easy to explain a wide range of HB morphology by rather minor variations in any of several parameters (Rood & Seitzer, 1981).

One particular aspect of this problem is the great variation in the morphology of the HB in different clusters. NGC 1851 (Stetson, 1981) has separate bunches of blue and red HB stars, with relatively few stars in between, and the same is true of NGC 2808 (Harris, 1974, 1978), and M4 (Lee, 1977a). The NGC 6752 HB (Fig. 1) is even more clearly split into two groups, but this time both are at the high temperature blue end of the branch, while M15 (Buonanno, Corsi & Fusi Pecci, 1981a) has a break at intermediate colours. This type of structure can be contrasted with that in M3 (Sandage, 1953) or M5

(Buonanno, Corsi & Fusi Pecci 1981b) which have long almost uniformly populated HBs or with IC 4499 (Fourcade, Laborde & Arias, 1974); Cannon & Lloyd, in preparation) where the HB is so concentrated that almost all of the stars lie in the RR Lyrae instability strip. The variations in HB structure are so great that each cluster is unique and 'afficionados' can readily identify their favourite clusters from the appearance of the HB alone. This great variation is perhaps not surprising in view of the sensitivity of HB models to small changes in several parameters (Rood & Seitzer, 1981), and it may well be that the striking differences have no great physical significance. What is more surprising is that the horizontal branch should be such a prominent feature of all globular clusters, since the theoretical models show that in order to reach the higher temperature end of the HB it is necessary for a star to have a very small hydrogen-rich envelope. If there is no mass loss on the giant branch, then blue horizontal branches can only appear in clusters having ages in a narrow interval, which would mean that the present is a favoured epoch. It is perhaps philosophically more acceptable, as well as being consistent with the predicted difference in masses between subgiants and HB stars, if there is a mass loss mechanism such that nearly but not quite all of the hydrogen rich envelope of globular cluster red giant stars is lost prior to or during the helium flash.

Direct confirmation of the relatively low masses for HB stars in globular clusters has come recently from the discovery of RR Lyrae variables with beat periods in M15 (Sandage, Katem & Sandage, 1981). Cox, Hodson & Clancy (1983) have used these to deduce masses of around 0.6 M_o, whereas VandenBerg (1983) and others find that their progenitor red giant stars leave the main sequence with masses around 0.8 M_o if the helium abundance is near Y = 0.23. However more direct evidence for mass loss from pre-HB stars comes from the older open clusters, discussed below.

Returning to the unusual extremely blue HB of NGC 6752, recent optical and IUE ultraviolet observations by Caloi et al. (1983) show that these stars are indeed the same as the field subdwarf OB stars of Greenstein & Sargent (1974), which the latter had postulated must be extreme HB stars of a type not up till then known in any globular cluster. Such very hot BHB stars do exist in some other clusters, including M13 (Simoda & Tanikawa, 1972), but are certainly not present in comparable numbers in some others including NGC 288 (Buonanno, Corsi, Fusi Pecci & Alcaino, 1983)) and ω Cen (Cannon & Stewart, 1981). In most clusters the samples of faint stars which have been measured are too small to say whether or not extreme BHB stars are present. The very clear gap between the two groups of BHB stars in NGC 6752, which occurs at the same temperature as a gap in the field star HB population noted by Newell & Graham (1976), can perhaps be understood in terms of two different types of evolution. The hotter group being almost on the helium main sequence may evolve towards higher luminosities whereas the cooler group will follow the usual HB evolution back towards the asymptotic red giant branch (AGB), as postulated by Heber et al. (1983) for a sample of field sdO and sdB stars. On the other hand, Norris et al. (1981) have speculated that the bimodal HB of NGC 6752 may be related to the bimodal distribution of CN band strengths seen on the giant branch; the same may be true for M4 which also has both a bimodal (but cooler) HB and a bimodal CN band strength distribution (Norris, 1981), although NGC 2808 does not seem to fit into this pattern (Norris & Smith, 1983).

2.5 The asymptotic giant branch

A comprehensive review of the AGB and later stages of evolution has been given very recently from a theoretical point of view by Iben & Renzini (1983), so only a few observational topics are discussed here. In the CM diagram, the AGB is more clearly separated from the first (hydrogen-burning) giant branch in some clusters than in others, but it always becomes difficult to separate the two as the luminosity increases. Many clusters show apparent clumps and gaps on both giant branches, but it is very difficult to be sure of the reality of these features since the samples of stars are usually small (even when every star in a cluster is measured: most globulars simply do not contain a large enough number of red giants) (Lee, 1977a,b,c,d). Detailed modelling has been carried out by Gingold (1974,1976) but only for one metallicity. Theory indicates that the luminosity at the tip of the AGB, without mass loss, would be much higher than that of the first giant branch. This result has been used e.g. by Ciardullo & Demarque (1978) as another argument that very significant mass loss must occur on the RGB and/or AGB. It may well be that many of the brightest red giants in clusters (which are often those which have spectroscopically determined abundances) are highly evolved AGB stars which have undergone both mass loss and mixing. Such stars may include the very rare CH stars found in ω Cen (Dickens, 1972); it certainly seems that the brighter carbon stars which are relatively common in dwarf spheroidal galaxies are AGB stars. If the AGB and normal giant branch could be reliably and completely separated, their luminosity functions would put constraints on the helium abundance, but once again the statistical fluctuations mean that this method is not very successful in practice (Green, 1980); the best results seem to come from comparing the total number of giants above the HB with the number of HB stars (the 'R-method', reviewed recently by Buzzoni et al., 1983).

2.6 Late stages of evolution

Planetary nebulae are too rare in globular clusters to contribute significantly to an understanding of that phase of evolution (M15 contains the only example known (Pease, 1928; Peimbert, 1973)), but there are considerable numbers of 'UV bright' (Zinn, Newell & Gibson, 1972) or 'supra-horizontal branch' stars which are generally taken to be in rapid advanced stages of evolution. There are also the occasional sdO stars such as one each in NGC 6752 (the star with V = 16.00, B-V = -0.36 in Fig 1; Caloi et al., 1983) and NGC 6397 (Searle & Rodgers, 1966); these may either be evolving from the AGB

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to the white dwarf region, or directly from the BHB. The difficulty is that no cluster contains more than one or two such stars, so that it is difficult to plot out evolutionary tracks or calculate lifetimes. However their presence in globular clusters does give a good determination of their luminosities, ages and original masses, so that it should be possible to fit them into a stellar evolution framework.

The final white dwarf stage should be very highly populated, and any determination of the numbers of white dwarfs would be immensely valuable for checking evolution theory, for giving estimates of the original luminosity function for higher mass stars in globulars, and for providing an important missing parameter in dynamical models of clusters since the total mass involved may be very considerable. Direct searches for white dwarfs have been carried out in NGC 6752 (Richer, 1978) and in M4 (Richer et al., 1981), two of the nearest globular clusters. These did find a population of faint blue stars but they are considerably brighter ($M_V \sim 10$) than the expected bright end of the white dwarf cooling curve and so it is not yet certain whether these really are white dwarf cluster members. An intriguing new possibility is that the compact remnants of old massive cluster stars may now be detectable as X-ray sources. In addition to the well-known bright X-ray sources in globular clusters, a new population of weak X-ray sources has recently been discovered in several clusters by Hertz & Grindlay (1983). These are interpreted as due to accretion on to white dwarfs which have formed binary systems with late-type dwarfs in the clusters. However, a proper study of white dwarfs will have to await the advent of the Space Telescope; the exciting possibilities have been outlined by Castellani (1979). Since in many respects the theory of cooling white dwarfs is simpler and probably better understood than even that of ordinary main sequence stars, the white dwarfs might eventually give the best determination of cluster distances and reddenings.

2.7 Other problems

Two major areas (at least!) have been omitted from this review. One is the problem of abundance variations within globular clusters. The first indications that there might be significant variations in the abundances of stars within a cluster came from the demonstration of an exceptionally broad giant branch in ω Cen (Cannon & Stobie, 1973). Following this up has become a major industry, well-reviewed recently by Kraft (1979) and by Freeman & Norris (1981). Part of the debate centres on whether such surface abundance variations are primordial, due to self-enrichment by mixing, or due to some sort of accretion process; current evidence is conflicting and it may well be that several mechanisms are operating. It is worth noting that ω Cen is certainly unusual in this respect, perhaps because it is the largest globular cluster in our Galaxy. Most other clusters have much better-defined giant branches, although in many there are significant variations in some spectral features such as CN band strengths.

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The second problem concerns 'blue straggler' stars. These were first found in M3 by Sandage (1953), and although some have probably been found in other clusters, M3 remains much the clearest example. A major puzzle here is that similar stars certainly do not occur in comparable numbers in several other clusters (including NGC 6752, see Fig. 1). As with the extended BHB, it is necessary to remember that the total number of clusters where enough faint stars have been measured to prove the existence or otherwise of blue stragglers remains very small, certainly fewer than ten clusters. However, blue straggler stars do occur in significant numbers in most intermediate-age and old open clusters and so will be further discussed in the next section.

3. OLD AND INTERMEDIATE-AGE OPEN CLUSTERS

3.1 General considerations

It is convenient to divide the older open clusters into two main classes: 'old' clusters with ages $\geqq 3.10^9$y, and 'intermediate-age' clusters with ages of around 0.5 - 2.10^9y. The first group, typified by clusters such as M67 (Racine, 1971) and NGC 188 (Eggen & Sandage, 1969), have CM diagrams somewhat similar to those of globular clusters, with a continuous subgiant and giant branch consisting of stars with masses 1.0 - 1.25 M_o. The 'intermediate-age' clusters, first considered as a group by Arp (1962), have rather different CM diagrams with a Hertzspurg gap and a strong clump of red giants with presumed masses in the range 1.5 - 2.25 M_o; typical examples are NGC 7789 (Burbidge & Sandage, 1958) and NGC 2477 (Hartwick, Hesser & McClure, 1972). Of course this is a rather artificial division, with clusters now known which cover a continuous range of ages and CM diagram types, and Patenaude (1978) has fitted theoretical isochrones to a number of clusters with well-determined CM diagrams.

There are several ways in which the study of the CM diagrams of old open clusters is harder than that of globular clusters: open clusters contain far fewer stars (often by several orders of magnitude) and are generally at lower galactic latitudes, so that it is difficult to get well defined sequences in the CM diagram, while contamination by field stars and differential reddening often cause problems. Thus there are areas where there may well be problems in reconciling observations with evolution theory, such as the shape of the subgiant branch, the location of the base of the giant branch and the width of the upper giant branch, but the observational data are not yet adequate for a definitive conflict with or confirmation of the theory. In this review I shall concentrate on just three problems.

3.2 The main sequence gap

A clear main sequence gap was first seen in M67 (Eggen & Sandage, 1964), and this remains the best-observed example. Qualitatively, the feature is readily explained as being due to the rapid gravitational contraction of stars following the exhaustion of hydrogen fuel in a convective core, prior to the ignition of a hydrogen-burning shell. However, early standard evolutionary models did not give a good quantitative fit: the observed gap occurs too near the top of the main sequence (at least in M67), while the theory predicts a significant bluewards shift as stars cross the gap whereas no colour shift is observed. The problem has been well reviewed by Maeder (1974). Several possible resolutions have been proposed: Prather & Demarque (1974) invoked a simple form of convective overshooting to give larger convective cores and hence brighter predicted gaps, while Maeder (1975, 1976) gave more extensive and elaborate theoretical models. However, Morgan & Eggleton (1978) showed that a reasonable fit to the observed M67 CM diagram could be obtained using conventional models when the effects of unresolved binary stars and observational errors were taken into account.

This uncertainty can probably never be resolved with reference to M67 alone; the greatest need is for better quality data (i.e. of higher accuracy as well as with less field star contamination) for a larger sample of clusters. There are unfortunately few clusters which are sufficiently populous ever to give a well-defined observational gap, but it is very difficult to avoid the conclusion that there should already be <u>some</u> evidence for a marked jump towards higher temperatures (i.e. with shifts of ~ 0.1 mag. in B-V) on the upper main sequences of some clusters, if conventional evolutionary theory is correct.

3.3 The red giant clump

The strongest feature in all intermediate-age cluster CM diagrams is a tight clump of red giants near $M_V = +1$, B-V = 1.0; a similar but less prominent feature appears in old open clusters as well. These 'clump giants' were identified by Cannon (1970) as the Population I analogues of horizontal branch stars in globular clusters, i.e. stars which had passed through the helium flash and were powered by both a helium-burning core and a hydrogen-burning shell. This interpretation was confirmed with theoretical models by Faulkner & Cannon (1973), who showed that both the location and the lifetime of the clump phase were correctly predicted. Furthermore, the constancy of the clump luminosity for a wide range of cluster ages (and hence of stellar masses) is direct evidence that stars with masses less than 2.25 $M_\odot$ do indeed have electron degenerate cores and hence undergo a helium flash when their cores reach some critical mass which is almost independent of the total mass.

Although the observed clump in most clusters shows no structure, the theoretical models show that it should in fact be almost a vertical sequence in the CM diagram, running parallel to the Hayashi fully-convective boundary. This has not yet been clearly verified observationally; there are very few clusters which contain enough red giants, and those which are rich enough either have inaccurate photometry or suffer from differential reddening (e.g. Cannon, 1971), or both. There is one related puzzle which has not yet been resolved either observationally or theoretically: most relatively metal rich globular clusters such as 47 Tuc have a red horizontal branch which is short but nevertheless covers a range in temperature, i.e. is truly horizontal, while intermediate-age open clusters seem to have a red giant clump which is more vertical than horizontal. At some stage there must be a transition between these two types, and there are indications that the oldest open clusters such as NGC 188 may have a range in B-V colour among clump-type giants.

In old clusters with populous red giant clumps, the clump stars are generally spatially less concentrated towards the cluster centre than stars on the upper main sequence. This provides more evidence that significant mass loss must occur during the red giant phase of evolution, after which dynamical relaxation leads to the now lower-mass clump giants becoming more spread out (Hawarden, 1975).

3.4 Blue stragglers

Most old and intermediate-age clusters contain 'blue straggler' stars lying well above the main sequence turn-off. In many cases the cluster membership of these stars is unambiguously established by both their proper motions and their spatial distribution. Although most clusters contain only a few blue stragglers, they can be quite numerous. Most striking is the case of NGC 188, which was originally thought to be a relatively young cluster (Barkhatova, 1956) on the basis of a CM diagram for only the brighter stars, until Sandage (1962) showed that there was a well-defined turn-off at much fainter magnitudes. Indeed, the blue stragglers are as numerous as the red giants in NGC 188, an observation which may have far-reaching implications for population synthesis studies of galaxies.

In a still regrettably unpublished thesis study (Cannon, 1968), I used proper motions to obtain 'pure' samples of blue stragglers in several clusters, and showed that almost all of these stars do lie within the hydrogen-burning main sequence band, and are less than two magnitudes above the turn-off. Furthermore, at least in the oldest clusters the blue stragglers are very strongly concentrated towards the cluster centres, and hence are presumably relatively massive. All of these data indicate that blue stragglers are hydrogen-burning stars up to twice as massive as current turn-off stars and giants. The two leading theories to explain their continued existence on the main sequence are that either they are binary systems which have undergone mass exchange (McCrea, 1964), or they have for some reason managed to mix themselves (Wheeler 1979; Saio & Wheeler, 1980).

There are difficulties with both of these explanations. If mixing is the right answer, there has to be some rather arbitrary reason why a minority of stars become mixed while the majority do not.

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On the other hand, a number of attempts to detect binary systems via radial velocity variations have produced conflicting results, mostly negative (e.g. Stryker & Hrivnak, 1983).

4. SUMMARY

Globular clusters provide a number of very significant constraints on stellar evolution theory: for example, their ages presumably have to be less than that of the Universe as a whole; mass loss must occur to explain the horizontal branch; some specific abundance variations are predicted as a consequence of internal mixing. There are also a number of intriguing puzzles: what causes the gap observed at the base of the giant branch in NGC 6752? Which abundance variations are due to mixing and which are primordial or due to accretion? What (and how many?) parameters control horizontal branch type, why are some HBs bimodal, and indeed why do we see blue HBs at all? How common are binary systems in globular clusters, and are these needed to explain either blue stragglers or X-ray sources?

Open clusters place fewer constraints and set fewer puzzles, mainly because the data are less convincing. However, a strong constraint on internal convection is set by the existence or absence of gaps on the upper main sequence, while the red giant clump gives evidence on the size of the core at the time of the helium flash. Some outstanding puzzles are: why is no colour shift observed across main sequence gaps? Why is the red giant branch not better defined, both below and above the clump? What are blue stragglers?

Space did not permit a discussion of the Magellanic Clouds and the dwarf spheroidal satellite galaxies, but exciting new prospects are being opened up there, especially through the use of two-dimensional TV and CCD detectors to obtain superb very deep CM diagrams. Earlier expectations that the stellar populations of the dwarf spheroidals must be similar to galactic globular clusters have been shown to be quite wrong, first through the discovery of ubiquitous carbon stars (Aaronson, Olszewski & Hodge, 1983), and most recently through the direct demonstration that the Carina dwarf has a dominant intermediate-age population (Mould & Aaronson, 1983). Nevertheless, dwarf spheroidal galaxies do contain RR Lyrae variable stars and one (Ursa Minor: van Agt, 1967) has a globular-like blue horizontal branch. Either such features can occur in systems with higher-mass stars, or the dwarfs contain a mixture of stellar populations. Thus these systems open up new domains in the age (or stellar mass) versus metallicity domain, where stellar evolution theory can be checked. No doubt these very nearby galaxies will soon raise as many constraints and puzzles as have star clusters in the past.

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DISCUSSION

Alcaino: Regarding the theoretical yet to be explained gaps in globular clusters at the fainter end of the subgiant branches, I would like to place the comment that in a recent C-M diagram of M4 now shown as a poster paper, William Liller and myself have found a conspicuous gap at about half a magnitude above the turnoff point. For checking purposes the photometry has been redone at 1 mag. above and below the gap's limit which has been confirmed. Furthermore, the gap originally discovered in our joint work with Liller on NGC 288 published in 1980, has been independently confirmed by the work now in press of Buonanno and Corsi and Fusi-Pecci (1984). It is therefore concluded that these gaps are real and await a theoretical interpretation.

Richer: You made the point that it is usually very difficult to distinguish between the RGB and the AGB. Is it not possible that we are looking in the wrong colours (i.e. V, B)? We have some U photometry in a number of globulars which shows a very nice separation between the RGB and AGB in a (B, U-B) diagram.

Cannon: That is very interesting. I have not tried plotting other varieties of C-M diagram but it would be extremely useful to have an unambiguous way of separating the two branches.

Barlai: On the diagram type of HB versus Δ(B-V) the clusters M92, ω Cen, M5, M15 and M3 form a group in the middle (and in the lower) part of the figure. All these clusters contain RR Lyrae variables. Do the other clusters of the diagram also contain variables or has this grouping been formed by chance?

Cannon: The globular clusters with many RR Lyrae variables must occur in the middle of the diagram because the ordinate of the diagram is the Dickens horizontal branch type. In that empirical classification, purely blue horizontal branches are called type 1 and purely red branches are type 7. Intermediate types have horizontal branches spanning the RR Lyrae instability strip.