AGES OF GALACTIC AND EXTRAGALACTIC STAR CLUSTERS OF VARIOUS ABUNDANCES

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1. INTRODUCTION

In this review I shall concentrate mainly on globular star clusters in our Galaxy since these are the objects for which most work has been done recently, both observationally and theoretically. However, I shall also discuss briefly the oldest open clusters and clusters in the Magellanic Clouds. Little can be said about more distant cluster systems, since the only observations available are of integrated colours or spectra and these seem to be rather unreliable indicators of age. It is perhaps worth pointing out that the title may be slightly misleading; the problem is not so much to determine the ages of clusters of known abundances, as to obtain the best simultaneous solution for both age and composition, since some of the most important abundances (notably helium and oxygen) are virtually unobservable in little-evolved low mass stars.

2. THE SIGNIFICANCE OF CLUSTER AGES

The globular clusters are among the oldest objects in the Galaxy, and as such provide valuable information on its early evolution with regard to both dynamics and chemical enrichment. One crucial question is whether or not there is a significant spread in ages within the globular cluster system; the clusters should be almost coeval in the classic Eggen, Lynden-Bell and Sandage (1962) picture of rapid halo collapse. The second and perhaps even more fundamental problem concerns the absolute ages of the globular clusters. It has long been realised that the ages of globular clusters are comparable with the Hubble time, i.e. the age of the Universe in big-bang cosmologies. The most recent determinations of cluster ages set a lower limit to the Hubble time which corresponds to a surprisingly low upper limit to the Hubble constant, H_o.

Old open clusters are of significance to the question of formation of the galactic disk, and whether or not simple two-component models

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 109–117.

(i.e. disk and halo, or Populations I and II) can give an adequate description of the Galaxy.

The Magellanic Clouds are the only external galaxies whose star clusters can be observed star-by-star, and thus provide a crucial test on the universality of star cluster formation.

3. METHODS OF AGE DETERMINATION

The fundamental method for determining cluster ages is by comparison of the observed colour-magnitude (CM) diagram with theoretical isochrones constructed from the evolutionary tracks of individual stars. In particular, the location of the main sequence turn-off point is a direct measure of cluster age. However, it should be noted that this turn-off is not very well defined in old clusters so that a better procedure is to try to fit the shape of the entire locus between slightly evolved main sequence stars and the subgiant branch.

An alternative method which does not involve obtaining photometry of such faint stars is to compare the strength of the horizontal branch, or its equivalent 'clump' in old open clusters (Cannon, 1970), with the strength of the upper giant branch. The lifetime of a star in the double (helium core plus hydrogen shell) energy source phase, corresponding to the horizontal branch or clump, is only weakly dependent on total mass. However, the rate of evolution up the ordinary hydrogen-burning giant branch slows down markedly as stellar mass decreases. Therefore the clump dominates the giant branch of an intermediate-age ($\sim 2.10^9$ y) open cluster such as NGC 7789 (Burbidge and Sandage, 1958) but is much less conspicuous in an older cluster such as M67 (Eggen and Sandage, 1964). This technique is obviously less precise than using the main sequence turn-off, but has proved very useful in giving an initial assessment of the ages of clusters in the Magellanic Clouds, where even to reach the horizontal branch or clump requires photometry down to $V \sim 19$.

A secondary method of age determination is via integrated colours, but this can give misleading results if a cluster happens to have a peculiar CM diagram (e.g. the anomalous 'second-parameter' globular clusters, whose horizontal branches do not conform to the general pattern), or if a substantial contribution to the total light comes from one or two very bright, highly evolved stars.

Finally, the presence of particular types of stars can sometimes be used as age indicators, for example the RR Lyrae variables and carbon stars seen in some Magellanic Cloud clusters, which seem to indicate great ($> 10^{10}$ y) or intermediate ($2 - 5.10^9$ y) age respectively.

4. UNCERTAINTIES IN AGE DETERMINATIONS USING THE CM DIAGRAM

There are many separate causes of uncertainty in age determinations, some of which can be more easily quantified than others. The observational errors have been discussed in recent reviews by Cannon (1981) and by Shipman (1981). The combined effects of finite sample size, measuring errors, calibration errors and interstellar reddening mean that the colour of any given globular cluster turn-off can easily be in error by 0.05 mag, corresponding to an error of about 25 percent in age.

Sources of error in the theoretical models are more difficult to quantify; they include such matters as uncertainties in stellar interior opacities, deficiencies in the simple convection theory usually employed, and doubts about neutrino production (VandenBerg, 1982).

A third class of error arises in making transformations between the theoretical bolometric luminosities and temperatures, and the corresponding observed magnitudes and colours: this problem has been most recently addressed by Carney (1980).

Finally, there are uncertainties in the chemical composition parameters; these include the still unobservable abundances of helium and oxygen, whether or not the CNO group of elements varies in step with the heavier elements, and of course such problems as the uncertain abundance scale for the more metal-rich globular clusters, as discussed by Gustafsson at this meeting.

5. THE AGES OF GALACTIC GLOBULAR CLUSTERS

The results of age determinations made over the past five years are summarized below.

GLOBULAR CLUSTER AGES (UNITS 10^9 y)

1977	Demarque and McClure	14-16 10-14	Metal-poor clusters 47 Tuc
1977	Saio, Shibata & Simoda	18	M92 (metal-poor)
1977	Saio	Metal-rich clusters younger	
1980	Demarque	Similar trend of age with metallicity	
1980	Carney	18 10	Metal-poor clusters 47 Tuc, M71
1982	Sandage	17 ± 2	All clusters
1982	VandenBerg	15-18	All clusters

https://doi.org/10.1017/S1539299600005025 Published online by Cambridge University Press

All these determinations were made by variants of the classical technique of fitting the cluster CM diagrams with theoretical isochrones. Sandage (1982a) relies only on the luminosities which seem to be more secure than the colours both observationally and theoretically, and makes extensive use of data on the RR Lyrae variable stars.

The most striking feature of these data is the close agreement between the ages obtained for the classical metal poor clusters such as M92 and M15, although at least four separate sets of evolutionary calculations have been used. All the results are consistent with ages of $16-17.10^9$ y for this group of clusters. This immediately implies that the Hubble constant is no larger than about 50 km s^{-1} Mpc^{-1}. Several factors could push this upper limit even further down: one must allow some time for galaxy and star cluster formation; globular clusters may not be the oldest objects in the Galaxy, witness the recent interest in 'Population III' stars; there is evidence (see below) that even some globular clusters may be older than those studied up to now; and the value of the deceleration parameter q_o may be significantly larger than zero. How reliable are these large globular cluster ages? The good agreement between authors shows that no trivial errors are likely to have been overlooked. Uncertainties in the various observational and model parameters could certainly give rise to errors of ten or twenty percent. However the only way that the ages could be reconciled with values of H_o in the neighbourhood of 100 km s^{-1} Mpc^{-1} would be if either a large number of small errors all happen to have contributed in the same sense, or if there is some major deficiency in all of current stellar evolution theory. Whether one prefers to regard stellar evolution as well-founded and cosmology as more dubious, or vice-versa, is more or less a matter of personal choice.

The second noticeable feature of the most recent estimates is that similar ages (to within ± 10%) are obtained for all clusters studied, implying at least consistency with a rapid halo collapse, whereas the earlier estimates all found a strong trend of decreasing age with increasing metallicity. The principal reason for this change seems to lie in the colours of the theoretical isochrones. Sandage (1982a) in fact gave no weight to the colours, while VandenBerg (1982) incorporated several important improvements in his stellar evolution calculations (the most significant of which turned out to be using internally consistent values of the convective mixing length) compared with the calculations used by Demarque and McClure (1977), and was able to obtain a much better fit to the overall shapes of the CM diagrams of clusters such as 47 Tucanae.

A completely different method for determining cluster ages was used recently by van Albada, Dickens and Wevers (1981). They used integrated ultraviolet colours measured with the ANS satellite, having shown that a very significant part of the UV emission comes from the relatively hot stars at the main sequence turn-off. The ages obtained were in the range $11-14.10^9$ y for a sample of nine clusters of different metallicities. However, these determinations require a very good knowledge of both the UV fluxes of the different types of star in a globular cluster and the distribution of stars in the CM diagram, particularly at the blue end of the horizontal branch. It is not clear that these basic data are well enough known to give reliable absolute ages to the clusters. Perhaps more importantly, van Albada et al. noted that the observed UV colours for a subset of metal poor clusters were very similar. Unless several factors which should affect the UV colours happen to be cancelling almost exactly, it seems that this implies a very small age spread indeed for this group of clusters, less than 3.10^8 y or within ± 1% of their total ages.

6. UNRESOLVED PROBLEMS

Lest it appear that all problems in determining globular cluster ages have now been solved it seems worthwhile to point out some uncertainties and difficulties which remain.

In his recent series of papers, Sandage (1982a,b and references therein) has set out a detailed self-consistent solution to the problems of determining globular cluster ages and explaining the properties of RR Lyrae variable stars. However this solution is not necessarily unique. From the RR Lyraes, Sandage (1982a) deduces that there is a strong relation between metallicity and horizontal branch luminosity, but there is no proof that this necessarily applies globally. Even if the rule does apply to those clusters with RR Lyraes, it may not be valid to use a simple linear extrapolation for the crucial metal-rich globulars like 47 Tucanae, which do not contain such stars. Third, Sandage is led to propose a very unexpected anti-correlation between metallicity and helium abundance, for which no physical explanation is offered.

VandenBerg (1982) has produced a comprehensive series of isochrones for globular clusters, in a format which can be very easily used by observers wishing to interpret a new CM diagram. However, these isochrones are so far available for only the upper main sequence, the subgiants and the base of the giant branch. It will be very important to extend these to more highly evolved stars, especially on the horizontal branch whose luminosity is a crucial observational datum, as well as to lower mass main sequence stars.

The Sandage (1982a) solution requires that there is very little variation in the luminosity difference between the horizontal branch and the main sequence turn-off, with a mean value of 3.4 mag. However, there are several clusters, including ω Centauri (Cannon and Stewart, 1981), which appear to have a significantly larger luminosity difference. The most important of these may be NGC 288, for which at least five recent faint CM diagrams have been obtained using a variety of modern techniques. Since these data are still mostly unpublished and 'sub judice' it is inappropriate to discuss them in a review article, but the indications are very strong that the turn-off is more than four magnitudes below the horizontal branch. Unfortunately, NGC 288, like 47 Tuc, does not contain any RR Lyrae variables so no independent check on the horizontal branch luminosity is available. In principle it should be possible to determine whether the exceptional luminosity difference in NGC 288 is due to a very bright horizontal branch which might indicate exceptionally high helium abundance, or to a very faint turn-off which might indicate exceptionally great age, by obtaining accurate photometry of unevolved main sequence stars.

Another source of uncertainty at present is the controversial metallicity of the more metal-rich clusters such as 47 Tuc and M71, as discussed by Gustafsson in this Joint Discussion. Carney (1981) has shown that the drastically lower abundances indicated by some high dispersion spectroscopic analyses will actually make these clusters much <u>older</u> than the majority of metal-poor clusters.

Turning lastly to the helium abundance, VandenBerg (1982) finds a better overall fit to the ensemble of cluster CM diagrams with helium mass fraction Y = 0.2 rather than Y = 0.3. However, Cox, Hodson and Clancy (1981) have used the latest data on multi-mode RR Lyrae variables to deduce that Y = 0.29, while as mentioned above Sandage requires an anti-correlation between Y and the heavy element abundance. Clearly there is still no consensus on the helium abundance.

7. OLD OPEN CLUSTERS

Only a very brief summary of recent results can be given here; a review has been given by McClure and Twarog (1977) and a comprehensive discussion by Janes and Adler (1982). NGC 188 (Eggen and Sandage, 1969) is possibly still the oldest known open cluster, although recently Melotte 66 (Anthony-Twarog, Twarog and McClure, 1979) has challenged that position and several other clusters with ages close to that of NGC 188 have been identified. These are of interest because they seem to have quite low metallicity (Gratton, 1982) and bridge the gap between classical globular and open clusters, whereas NGC 188 has abundances much closer to the solar value. For NGC 188 itself, some recent age estimates are 5.10^9 y (Demarque and McClure, 1977), 8.10^9 y (Saio et al., 1977), and 10.10^9 y (VandenBerg, 1982). However, VandenBerg (private communication) has pointed out that his temperature scale may be in error, in the sense that he may have over-estimated the age. In any event, it seems that the oldest open clusters are only about half the age of the majority of the globular clusters.

The sample of old open clusters is now large enough to invalidate the earlier statistical argument (King, 1968) that one might not expect to see any open clusters as old as the globulars; Janes and Adler (1982) argue that at least in the outer parts of the galactic disk, there was no cluster formation between 8 and 15.10^9 y ago. On the other hand, there are metal-rich RR Lyraes in the galactic halo (Sandage, 1982b) which have no counterparts in any star cluster but which presumably represent the oldest metal-rich population. Thus it is still not possible to answer the question as to whether or not the oldest disk stars are as old as the halo, and it may be that a two-component model is too simple to explain the early history of the Galaxy.

8. MAGELLANIC CLOUD CLUSTERS

Age data on these clusters have been recently collated and reviewed by Hodge (1981) and by Gascoigne, Bessell and Norris (1981). The crucial points seem to be that the Magellanic Clouds contain very few 'true' globular clusters, and a much higher proportion of intermediate-age clusters than the Galaxy. This can be deduced from the considerable number of faint CM diagrams now available, and is confirmed by the very rare occurrence of RR Lyrae stars and relatively frequent occurrence of carbon stars. NGC 2257 in the Large Cloud is the only Magellanic cluster so far shown to be of comparable age to galactic globular clusters by direct use of a very faint CM diagram (Stryker, 1982). There is also considerable evidence for a dominant $2\text{-}4.10^9$ y intermediate-age population in the general field (e.g. Hawkins and Brück, 1982) of the Small Magellanic Cloud. The metallicity range observed in Magellanic Cloud clusters is rather smaller than that seen in the Galaxy, with in particular no clusters known with metallicities more than about a third of the solar value.

Some of the Magellanic Cloud data given by Hodge (1981) illustrate the point made earlier about the unreliability of integrated colours, since the ages of some clusters were changed by almost a factor of ten when faint enough CM diagrams were obtained.

The overall conclusion is that the patterns of cluster formation have been rather different in the Clouds and in the Galaxy. Indeed there are very young ($< 10^8$ y) clusters in the Large Magellanic Clouds which in all other respects would be classified as globular (Freeman, 1980). Therefore it would seem very dangerous to assume that all galaxies have similar populations of bright clusters, as has to be done when clusters are used to determine the extragalactic distance scale, although it may be that the different pattern seen in the Magellanic Clouds is due to their being dwarf satellites of the Galaxy, and having had repeated gravitational encounters with the parent system.

https://doi.org/10.1017/S1539299600005025 Published online by Cambridge University Press

9. CONCLUSIONS

Our current state of knowledge on the ages and abundances of old star clusters can be summarized as follows:

(i) The majority of globular clusters studied so far have ages of about $16-17.10^9$ y.

(ii) This implies that the Hubble constant H_o is no higher than 50 km s^{-1} Mpc^{-1}.

(iii) The evidence for a correlation between age and metallicity is less convincing today than it seemed a few years ago.

(iv) The small age spread is consistent with fast collapse of the galactic halo, although not necessarily small enough to eliminate some slow collapse models.

(v) A few clusters are difficult to fit into this simple picture and may be considerably older.

(vi) There is no agreement on the appropriate value of the helium abundance(s) for globular clusters.

(vii) The oldest open clusters have ages of about 8.10^9 y and abundances between solar and a tenth of solar.

(viii) The gap in age between the oldest open clusters and the globular clusters now seems to be real, and not just a statistical accident.

(ix) The Magellanic Clouds contain very few 'true' globular clusters and many intermediate-age clusters; the most metal-rich clusters attain only about a third of the solar abundances.

(x) Thus the pattern of cluster formation in the Magellanic Clouds has been rather different from that in our Galaxy.

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