Age and Metal Abundance of a Globular Cluster, as Derived from Strömgren Photometry

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Introduction

The age of the universe is a cosmological parameter of fundamental importance. When compared to the Hubble constant, H_0, the age can in the standard Big Bang model inform us about the large-scale structure of the universe, i.e. whether the universe is open or closed. Alternatively, such a comparison may reveal that the two parameters are not compatible, so that either the standard Big Bang model is wrong or something is wrong in the methods by which the age and H_0 are determined.

A lower limit to the age of the universe can be obtained from the ages of globular clusters—the oldest objects known in our galaxy. Their ages are determined from the position of turnoff stars in an effective temperature-luminosity (T_e-L) diagram. These stars represent the phase of stellar evolution for which nearly all of the hydrogen at the centre of the star has been burned by nuclear reactions. The turnoff stars are leaving the main sequence and on their way toward the red-giant branch. The temperature and luminosity, at which this happens for a given cluster, depend strongly on the age of the cluster.

Turnoff stars in globular clusters are quite faint—even in the nearest clusters. Typical magnitudes are V = 16-20. Temperatures and luminosities are therefore usually determined from broad-band BV photometry, the calibration of which is rather difficult. Some of the problems encountered are the determination of interstellar reddening and the calibration of the B-V colour index in terms of T_e. However the most severe problem is which metal abundance to use for the cluster, because the position of the theoretical isochrones in the T_e-L diagram depends critically on this parameter. Usually one takes the value derived from photometry or spectroscopy of red giants in the cluster, but unfortunately we cannot be sure that this value applies to turnoff stars. The chemical composition in the atmospheres of the giants may be affected by mixing of elements produced by nuclear reactions in the stellar interior. Furthermore, the metal abundance of the giants in some clusters—e.g. ω Cen—show a dispersion of about a factor of 10. In other cases the metal abundances derived from photometry and spectroscopy do not agree. For 47 Tuc the photo-

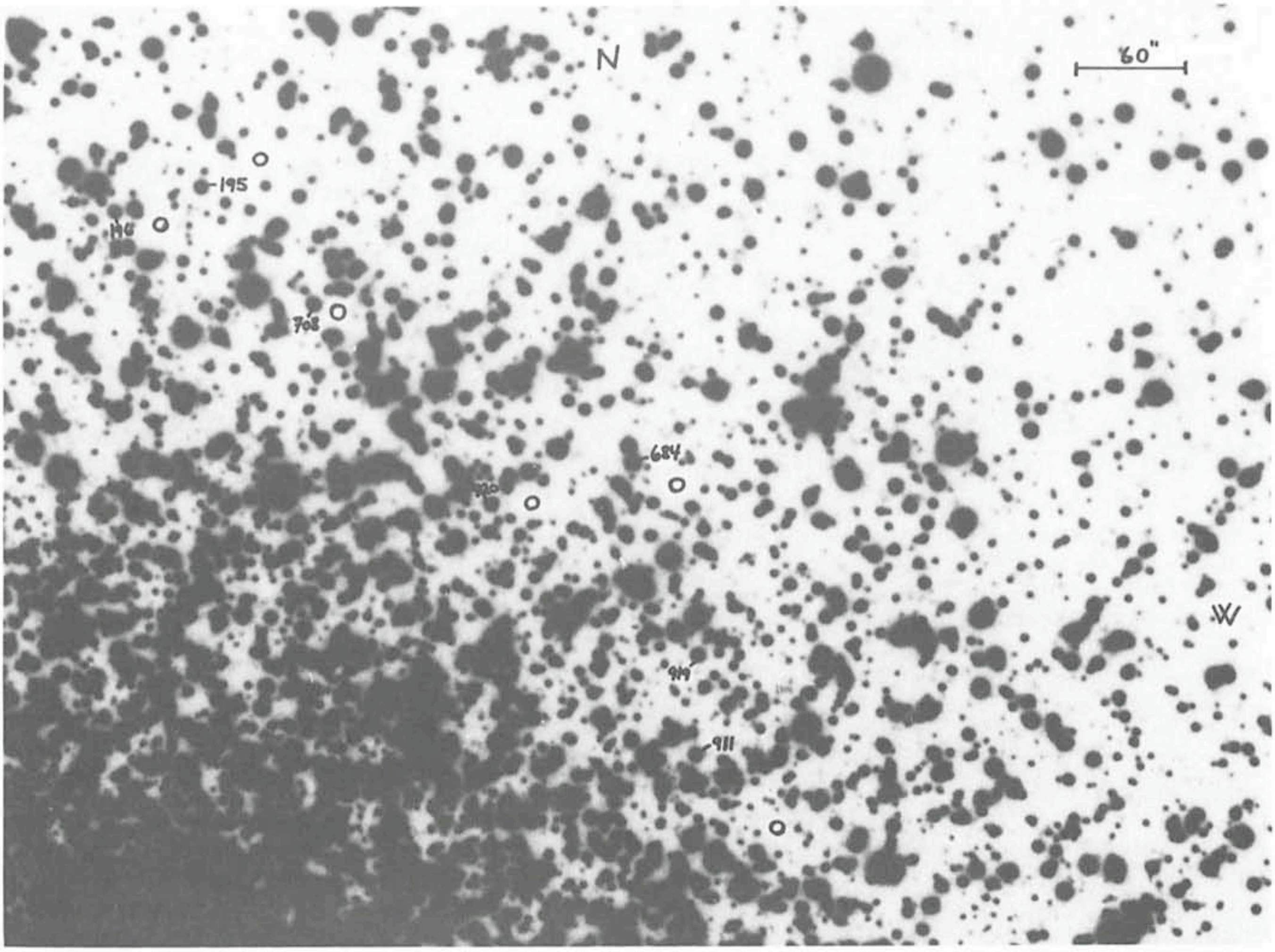

Fig. 1: *Part of the globular cluster NGC 6397 from a 10-min V plate taken with the Cerro Tololo 4-m and kindly provided by G. Alcaíno. The plate limit is around 21 mag. The picture illustrates the main difficulty of doing photoelectric photometry in globular clusters: the crowding of stars. All turnoff stars which are sufficiently separated from neighbouring stars are marked by numbers. The sky backgrounds measured are encircled.*

metry leads to a value of [Me/H] = –0.5, whereas recent high-dispersion spectroscopy gives [Me/H] = –1.2. Here the symbol [Me/H] denotes the logarithm of the metal-to-hydrogen ratio of a star minus the same quantitiy for the sun. Thus the two results differ by a factor of 5. If the high value is adopted for the turnoff stars, an age of $10 \cdot 10^9$ years is derived for 47 Tuc, whereas the low metal abundance leads to an age of about $25 \cdot 10^9$ years.

The case of 47 Tuc shows that the accuracy of age determination of globular clusters needs considerable improvement before a detailed comparison with H_0 can be carried out. Furthermore an important question relating to the formation and evolution of our galaxy remains unsolved: Do all globular clusters have the same age or do they show an age range of say $10 \cdot 10^9$ years. The first case corresponds to a rapid collapse of the protogalaxy and the latter case to a collapse time that is comparable to the lifetime of the galactic disk.

With these problems in mind and aiming at more accurate determinations of ages and abundances of globular clusters the author has, in collaboration with A. Ardeberg, initiated a programme of photoelectric uvbyβ photometry of turnoff stars in globular clusters. In the following I shall report on the first results obtained for one of the clusters and discuss the accuracy of the age and other parameters which can be determined. We shall see that the advantage of using the Strömgren system is that the reddening, metal abundance, and age can be directly determined from the photometry of the turnoff stars.

Observations

The first cluster selected was NGC 6397—the second nearest globular cluster. The uvbyβ observations were carried out with the single channel photometer at the 3.6-m telescope during two nights in July 1981. Transformations to the uvbyβ standard system were established by observing a number of standard stars in the magnitude range $8.0 < V < 11.0$. The rms scatter in the transformations is of the order of 0.01 mag for the colour index b-y, the metal-line index m_1, the Balmer-discontinuity index c_1, and the β index that measures the strength of the Hβ absorption line.

The selection of turnoff stars in NGC 6397 was based on photographic BV photometry by Alcaíno and Liller (1980). Fig. 1 shows part of a 10-min V plate taken with the Cerro Tololo 4-m and kindly provided by G. Alcaíno. It illustrates the problem of crowding of stars. Generally it is impossible to carry out accurate photometry with an entrance diaphragm less than 5 arcsec in diameter, and in the centre of the cluster the average distance between stars is much less. One is therefore forced to observe in the outer regions of the cluster, where a higher fraction of the stars will be non-members.

A list of stars to be observed in NGC 6397 was selected by the criteria $16.0 < V < 16.7$ and $0.40 < B\text{-}V < 0.65$. This corresponds to the upper part of the turnoff region in the colour-magnitude diagram. The region contains about 100 stars. However, a star was included in the final observing list only if it appeared perfectly round on the photographic plate, and if the field within a radius of 10 arcsec around the star was not contaminated by other stars brighter than the plate limit, V = 21. This condition reduced the observing list to 19 stars, all of which were observed using a diaphragm of 7 arcsec in diameter. Two of these stars turned out to be non-members according to their position in the c_1-(b-y) diagram (see later). The sky background was measured in regions where no stars brighter than 21 mag occurred within 10 arcsec from the diaphragm centre (see Fig. 1). In order to count a suitable number of photoelectrons for each filter, a total integration time of about 20 min per star was needed. From repeated observations the mean error of the indices b-y, m_1 and c_1 is estimated at 0.02-0.03 mag. The largest contribution to this error is due to fluctuations in the seeing, which was not particularly good (2–3 arcsec). For the β index the error is higher (of the order of 0.04 mag) because of the relatively small number of photons observed through the narrow filter.

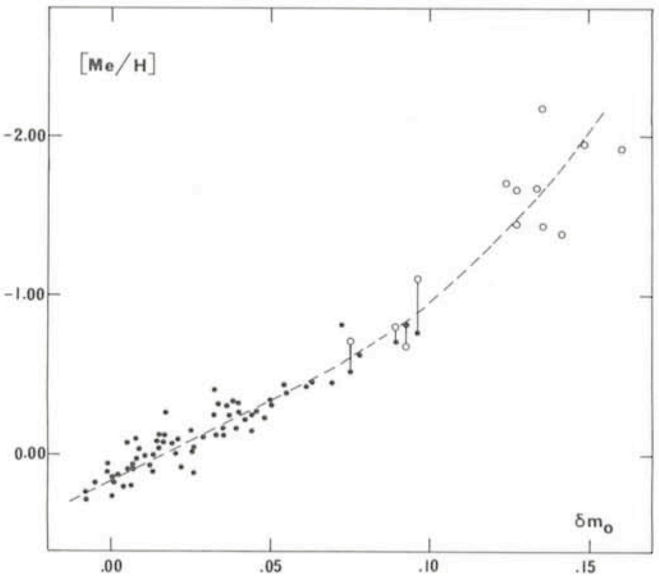

Fig. 2: *Calibration of the Strömgren δm_0 index as a function of the logarithmic metal-to-hydrogen ratio, [Me/H]. •, [Me/H] values from Nissen (1981). ○, [Me/H] from Carney (1979). Stars in common are connected by vertical lines.*

As described in more detail in the ESO Users Manuel, the star field around the diaphragm in the 3.6-m photometer can be seen by reflection through the TV viewing system in the Cassegrain adapter. This facility made it fairly easy to identify the stars, centre the right star or sky in the diaphragm, and keep it there during the integration by guiding on another star. Furthermore, an on-line photometric reduction system, recently made by F. Gutiérrez, was of great help.

Reddening

As we shall see later, it is of crucial importance for the age determination of a globular cluster to have an accurate value of its reddening. It is for this purpose that the β index, which is unaffected by interstellar reddening, was observed.

In the spectral range, A5-G2, both the b-y colour index and the β index are good indicators of effective temperature. For unreddened stars we therefore expect a close relation between the two indices. This has been confirmed empirically by Crawford (1975), who found that the relation is slightly dependent on metal abundance. For reddened stars we can therefore use the observed β index to calculate the intrinsic colour index, $(b\text{-}y)_0$.

Application of this method to the turnoff stars in NGC 6397 yields an average colour excess of $E(b\text{-}y) = 0.14 \pm 0.02$. This value is slightly higher than the value of $E(b\text{-}y) = 0.11$ found from photometry of horizontal branch stars, but agrees very well with a recent reddening value based on ultraviolet data.

The Metal Abundance of NGC 6397

The metal-line index m_1 is defined as a colour index difference $m_1 = (v\text{-}b) - (b\text{-}y)$ which means that it is not very much affected by interstellar reddening. A careful study by Crawford

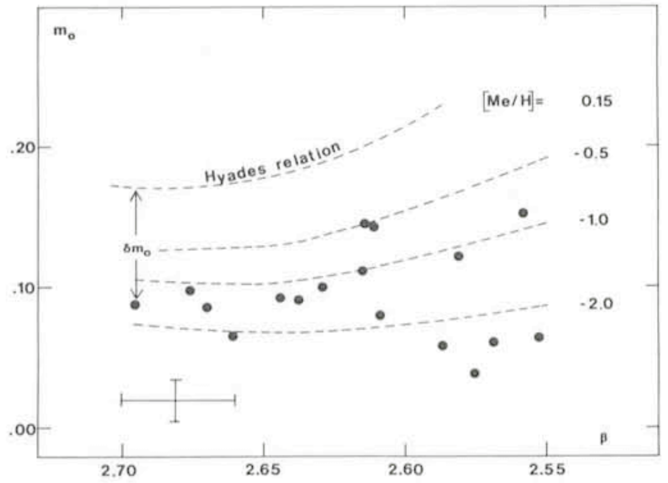

Fig. 3: *The $\beta - m_o$ diagram for turnoff stars in NGC 6397. The observed relation between β and m_o for the Hyades is drawn, and the definition of δm_o is shown for one of the stars. Curves corresponding to constant values of [Me/H] are given. Interpolation between these curves leads to an average metal abundance of [Me/H] = -1.6 ± 0.2 for NGC 6397. The error bars indicate the mean errors of the indices.*

and Mandwewala (1976) shows that the excess of m_1 is given by $E(m_1) = -0.32 \cdot E(b\text{-}y)$. We can then compute the dereddened metal-line index $m_0 = m_1 + 0.32 \cdot E(b\text{-}y)$, using $E(b\text{-}y) = 0.14$.

The number of metallic absorption lines in the v band is much higher than the number of lines in the b and y bands. We therefore expect the m_o index to depend on metal abundance. m_o also depends somewhat on temperature. However, by introducing the difference between m_o for the Hyades and for a star, the so-called δm_o index (see Fig. 3), we obtain an index which is less temperature dependent. Fig. 2 shows a calibration of δm_o in terms of [Me/H] for the spectral region corresponding to the turnoff stars. Indeed there is a rather good correlation between δm_o and [Me/H].

Using the calibration of δm_o shown in Fig. 2 and taking into account a slight temperature dependence of δm_o, we can calibrate the β-m_o diagram in terms of [Me/H], i.e. draw the curves of constant [Me/H] (see Fig. 3). In the same figure the NGC 6397 stars are plotted. It is seen that they fall well below the Hyades relation, which indicates that their metal abundance is much smaller. The average metal abundance of NGC 6397 is found to be

$$[\mathrm{Me/H}] = -1.6 \pm 0.2,$$

which means that the metal-to-hydrogen ratio is a factor of 40 lower than the ratio in the sun. Assuming that the fractional weight abundance of elements heavier than helium, Z, is proportional to the metal-to-hydrogen ratio we get

$$Z_{\mathrm{NGC\ 6397}} = 0.0004,$$

where we have used $Z_{sun} = 0.017$. This result is about a factor of 2 higher than the heavy element abundance found from spectroscopy of giant stars in NGC 6397.

The Age of NGC 6397

The c_1 index is defined as $c_1 = (u\text{-}v) - (v\text{-}b)$, and the dereddened index is given by $c_0 = c_1 - 0.20 \cdot E(b\text{-}y)$. The u band is centered at 3500 Å and the v band at 4100, which means that c_o is sensitive to the size of the Balmer discontinuity at 3650 Å. Thus for a given value of $(b\text{-}y)_o$, c_o is a measure of the surface acceleration or luminosity of stars. The $(b\text{-}y)_o$–c_o diagram can therefore be used to derive effective temperatures and luminosities of stars. In this respect the diagram is equivalent to a traditional HR-diagram.

Fig. 4 shows the $(b\text{-}y)_o$–c_o diagram for NGC 6397. The zero-age main sequence (ZAMS) for Pop. II stars has been determined as the lower boundary of the distribution of field Pop. II stars. A number of these stars have recently been observed in the Strömgren system with the 50-cm and the 150-cm Danish telescopes on La Silla.

As mentioned earlier, membership can be estimated from the position of the stars in the $(b\text{-}y)_o$–c_o diagram. Two stars, well separated to the left of the main group of stars, are considered non-members and have been omitted.

$(b\text{-}y)_o$ has been calibrated in terms of T_e by model atmosphere computations of R. Bell and B. Gustafsson. Such computations give reliable data for the *change* of $(b\text{-}y)_o$ as a function of T_e and [Me/H]. The zero point is determinded from the (b-y) index of the sun.

In order to compute the bolometric magnitude, $M_{bol} = -2.5 \log L + \mathrm{const}$, we first introduce the quantity δc_o (see Fig. 4). From a study of nearby stars with accurate trigonometric parallaxes, Crawford (1975) has shown that δM_{bol}, defined as M_{bol} (ZAMS) – M_{bol}, is linearly correlated with δc_o. The coefficient is 10 for late F-type stars, i.e. $\delta M_{bol} = 10 \cdot \delta c_o$.

By using the calibrations of $(b\text{-}y)_o$ and δc_o, we can now find the distribution of NGC 6397 stars in the $T_e - \delta M_{bol}$ diagram (Fig. 5). In the same diagram theoretical isochrones corresponding to 10, 16 and $25 \cdot 10^9$ years are drawn. The isochrones have been computed by Hejlesen (1980). It is seen that the $25 \cdot 10^9$ year isochrone gives a fairly good fit to the distribution of stars. A comparison with isochrones recently computed by D.A. VandenBerg, University of Victoria, leads to an age of $22 \cdot 10^9$ years. Thus independent computations of isochrones agree very well. However, before we compare the age of NGC 6397 with H_o, we shall briefly discuss the most important possible errors in the age determination.

The Uncertainty of the Age Determination

Several problems contribute to the uncertainty of the derived age of NGC 6397:

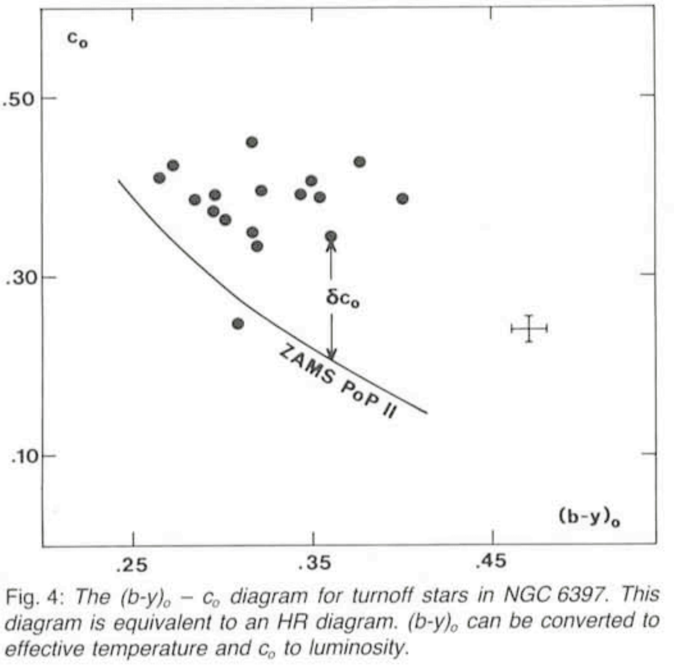

Fig. 4: *The $(b\text{-}y)_o$ – c_o diagram for turnoff stars in NGC 6397. This diagram is equivalent to an HR diagram. $(b\text{-}y)_o$ can be converted to effective temperature and c_o to luminosity.*

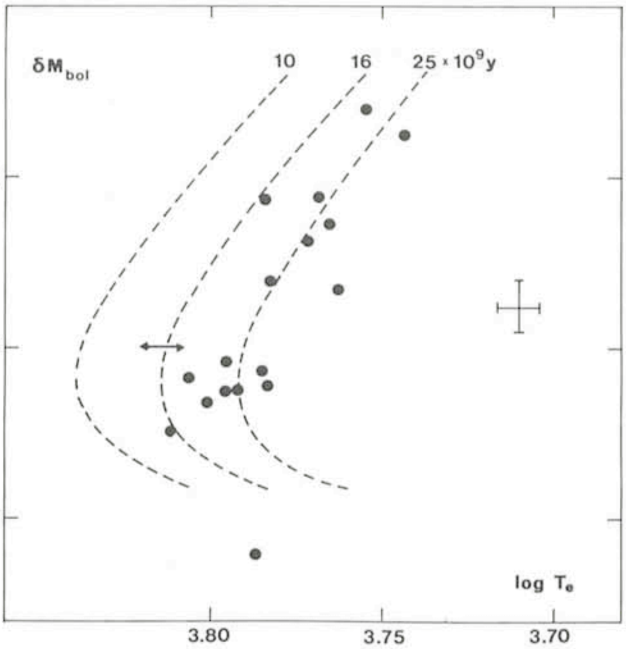

Fig. 5: *The log T_e – δM_{bol} diagram for turnoff stars in NGC 6397. The definition of δM_{bol} is given in the text. Isochrones corresponding to ages of 10, 16 and $25 \cdot 10^9$ years have been computed by Hejlesen (1980). A helium abundance of $Y = 0.20$ and a metal abundance of [Me/H] = −1.6 have been adopted. The log T_e shift of the isochrones corresponding to $\Delta Y = 0.1$ is indicated by the left arrow. The shift corresponding to Δ[Me/H] = 0.2 is given by the right arrow.*

Error bars indicate the errors of log T_e and δM_{bol} inferred from observational errors. Within these errors there is a fairly good fit to the $25 \cdot 10^9$ years isochrone. Systematic errors of the age determination are discussed in the text.

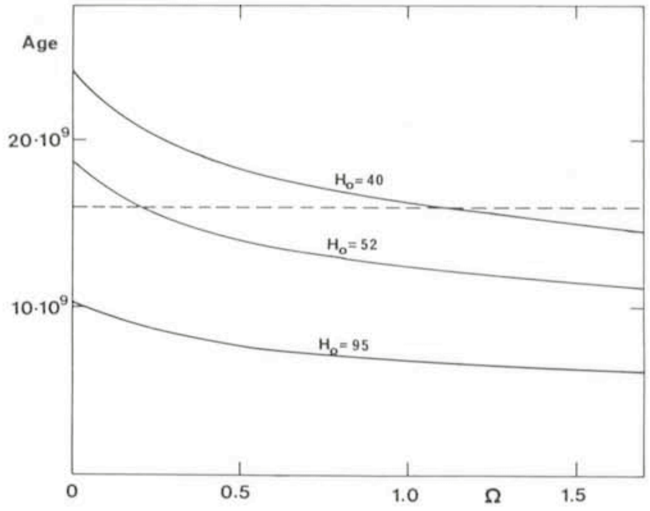

Fig. 6: *The age of the universe in years as a function of the density parameter Ω for various values of the Hubble constant. The horizontal line indicates the lower limit for the age of the universe as derived from the age of NGC 6397.*

(i) The interstellar reddening may be wrong by $\pm 0\overset{m}{.}02$. This converts to an error of ± 0.01 in log T_e and as seen from Fig. 5 the corresponding error of the age is $\pm 4 \cdot 10^9$ years.

(ii) The zero point of the b-y calibration could be wrong by up to 0.02 mag. In the present calibration a colour index for the sun, $(b\text{-}y)_\odot = 0.395$, was adopted. Some recent investigations give a value of $(b\text{-}y)_\odot = 0.415$, which would decrease the age determined by about $4 \cdot 10^9$ years.

(iii) The error of the metal abundance is ±0.2 in [Me/H]. As seen from Fig. 5 the corresponding error of the age is $\pm 2 \cdot 10^9$ years.

(iv) In the age determination we have assumed the weight fraction of helium to be Y = 0.20. However, it could be as high as Y = 0.30. This would increase the age by about $2 \cdot 10^9$ years.

Comparison with the Hubble Constant

From the error discussion above we conclude that the age of NGC 6397 lies between 16 and $25 \cdot 10^9$ years. Thus a lower limit for the age of the universe deduced from this particular cluster is $16 \cdot 10^9$ years. Other recent investigations of globular clusters, e.g. Sandage and Tammann (1981), have also resulted in similar high ages. It is therefore of interest to make a comparison with determinations of H_o.

It is a well-known result from Friedman models of the universe, that for a given value of H_o, the age is a function of the present mass density, ϱ_o. In Fig. 6 the age has been plotted as a function of $\Omega = \varrho_o/\varrho_c$, where ϱ_c is the critical density, for various values of the Hubble constant. $H_o = 52$ km/s/Mpc is the value recently found by Sandage and Tammann (1981) from a study of distances and recession velocities of 16 type-I supernovae. $H_o = 95$ is the value found by Aaronson et al. (1980) from distances of galaxies derived by the Tully-Fischer method. Both determinations refer to galaxies at distances well beyond the Virgo cluster. The values should therefore represent the *global* value of H_o.

It is seen from Fig. 6 that $H_0 = 52$ is consistent with the age limit of $16 \cdot 10^9$ years if $\Omega < 0.2$, which corresponds to an open universe. On the other hand there is a large discrepancy between the age limit and the value of H_o found by Aaronson et al.

Finally, Fig. 6 shows that a Hubble constant, $H_o \leq 40$ km/s/Mpc, is compatible with a closed universe, i.e. $\Omega \geq 1$. Such a low value of H_o cannot be totally excluded in view of the present uncertainty of the value of H_o.

The discussion above illustrates why it is interesting to determine accurate ages of globular clusters. We think that Strömgren photometry of turnoff stars provides an important method for this purpose, a method which in many respects is more accurate than BV photometry. The final cosmological conclusions should await improvement in the calibration of the photometry and further observations of other globular clusters.

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Second ESO Infrared Workshop

About 70 external participants in addition to ESO staff met from 20th–23rd April 1982 to discuss a variety of topics ranging from the infrared work going on at major ground-based observatories to proposals for future space missions. Although mainly devoted to technical aspects, the rapid progress in instrumentation and facilities made in recent years was best