An age difference of two billion years between a metal–rich and a metal–poor globular cluster

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Globular clusters trace the formation history of the spheroidal components of our Galaxy and other galaxies, which represent the bulk of star formation over the history of the Universe. The clusters exhibit a range of metallicities (abundances of elements heavier than helium), with metal–poor clusters dominating the stellar halo of the Galaxy, and higher-metallicity clusters found within the inner Galaxy, associated with the stellar bulge, or the thick disk.4–6. Age differences between these clusters can indicate the sequence in which the components of the Galaxy formed, and in particular which clusters were formed outside the Galaxy and were later engulfed along with their original host galaxies, and which were formed within it. Here we report an absolute age of 9.9 ± 0.7 billion years (at 95 per cent confidence) for the metal–rich globular cluster 47 Tucanae, determined by modelling the properties of the cluster’s white–dwarf cooling sequence. This is about two billion years younger than has been inferred for the metal–poor cluster NGC 6397 from the same models, and provides quantitative evidence that metal–rich clusters like 47 Tucanae formed later than metal–poor halo clusters like NGC 6397.

The ages of globular clusters are most easily determined by modelling the properties of main–sequence and horizontal–branch stars,5–9 but doing so leads to uncertainties caused by covariance between the measured age and the spectroscopic metallicity required to compare observed colours and magnitudes to theoretical models. The metals in the atmospheres of white dwarfs sediment out because of the strong stellar gravity, resulting in an age determination more robust with respect to metallicity correlations. In such cases, the age is based on the monotonic cooling of white dwarfs, because the luminosity function peak moves to fainter magnitudes for older populations. The consistency of the two approaches has been demonstrated with the determination of absolute ages for the globular clusters Messier 4 and NGC 6397 (refs 10–13). Our attempt to extend the application of this method (fitting the cooling sequence of the white dwarfs) to the metal–rich cluster 47 Tucanae is driven by the fact that the covariance between metallicity and age in the main–sequence fitting method becomes stronger with increasing metallicity, indicating the need for an independent determination.

We observed a field at roughly the half–mass radius of the cluster with the Hubble Space Telescope. The primary science observations were performed with the Advanced Camera for Surveys, with observations split between the wide F606W (total integration of 163.7 ks) and F814W (total integration of 172.8 ks) bandpasses. The field was also chosen to overlap with prior Hubble Space Telescope observations, so that the cluster motion results in positional shifts of cluster members with respect to background stars, and so cluster and non–cluster members can be separated. Details of the photometry, completeness and measurement of the proper motions is described in the Supplementary Information.

The white–dwarf population is isolated by both colour and proper motion, as shown in Fig. 1. The distribution of white dwarfs with luminosity (the luminosity function) can be compared (Fig. 2) with the white–dwarf luminosity function of a metal–poor, globular cluster with deep Hubble Space Telescope observations, called NGC 6397 (ref. 12). The abrupt truncation of these luminosity functions is a manifestation of the finite age of a population, as white dwarfs cool monotonically, and this cutoff moves to fainter magnitudes as a population ages. In Fig. 2 we have adjusted the magnitudes of the NGC 6397 population to correct for the different cluster distances, and so placed it on the same magnitude scale as the 47 Tucanae population. The 47 Tucanae luminosity function drops to half of the peak value at approximately 0.4 magnitudes brighter than that of NGC 6397, a direct demonstration that this cluster is younger. A comparison to a third cluster, Messier 4 (ref. 13), shows a similar age difference.

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To determine a quantitative measure of the age difference, we construct Monte Carlo models for the cooling of the cluster white-dwarf population, including a model for photometric shifts, scatter and incompleteness, based on artificial star tests. We fit these models, including the uncertainties in distance and extinction, to both the observed luminosity function and the two-dimensional distribution of the white-dwarf population in colour and magnitude (the Hess diagram). If we use the same models to fit the 47 Tucanae data as we did for NGC 6397 (ref. 12), we obtain an age of $9.7 \pm 0.4$ billion years (Gyr) (at 95% confidence) for 47 Tucanae, compared to the corresponding value of $11.7 \pm 0.3$ Gyr for NGC 6397. Therefore, the relative age difference is $2.0 \pm 0.5$ Gyr.

The cluster 47 Tucanae has a metallicity$^{14–16}$ of $[\text{Fe}/\text{H}] = -0.75$, compared to $[\text{Fe}/\text{H}] = -1.8$ for NGC 6397. Although white-dwarf atmospheres are not sensitive to overall metallicity, the cooling may be affected by changes in the nuclear burning history owing to different metallicities. To quantify any difference introduced by variations in progenitor behaviour, we have calculated new evolutionary models using progenitors of appropriate metallicity for 47 Tucanae. Using the MESA code$^{25–27}$, we have calculated the evolution of solar-mass stars with $[\text{Fe}/\text{H}] = -0.75$ and $[\text{Z}/\text{Fe}] = +0.2$, as well as with a range of helium enrichment Y (see Supplementary Information) seen in 47 Tucanae$^{18}$. We have also verified that these calculations produce similar results to the models used to determine the age of the cluster from the main sequence$^{18}$, to facilitate comparison with those earlier analyses. We find that the final age determination is not sensitive to either progenitor metallicity, helium fraction or which of the Schwarzschild or Ledoux criteria for convection is assumed when calculating the mixing of the progenitor core. Neither is the result sensitive to the use of different atmospheric models for correcting effective temperatures to observed colours. Details of this analysis are discussed in the Supplementary Information. Marginalizing over all these models results in an age of $9.9 \pm 0.7$ Gyr for 47 Tucanae. Figure 3 shows the comparison between the best-fit model and the data, binned according to the grid in Fig. 1.

Estimates based on fitting main-sequence models to the main-sequence turnoff report ages between 10 Gyr and 13 Gyr, with the range due to a variety of factors including differences in adopted models physics (such as nuclear reaction rates and gravitational settling) as well as different bandpasses employed in the observational data$^{20–22}$. The most precise age so far obtained from the main sequence of 47 Tucanae comes from the detached, eclipsing binary star V69 (ref. 24). V69 comprises two stars that lie just above and below the main-sequence turnoff, meaning that the pair provides a particularly valuable age constraint. The resulting age is somewhat sensitive to the assumed metallicity of the stars. The original age estimate for V69 (ref. 24) was $11.25 \pm 0.21 \pm 0.85$ Gyr, denoting random and systematic errors, respectively. This result is based on the assumption of $[\text{Fe}/\text{H}] = -0.7$ and $[\text{Z}/\text{Fe}] = +0.4$. Adopting a chemical composition in accordance with more recent studies$^{16–18}$ and employing a more robust estimate of the systematic error implies that the age derived from the binary system is $10.39 \pm 0.54$ Gyr, here citing only the systematic error. This estimate is fully consistent with the white-dwarf result given above, suggesting that consistency between the two age measurement techniques is possible, provided we also have accurate determination of extrinsic properties such as distance, reddening and metallicity.

The bimodality in the metallicity distribution of globular clusters appears to be ubiquitous among large galaxies$^1$, and is held to reflect the sequence in which galaxies at high redshifts assemble their stellar mass. It is still disputed whether the two classes represent two distinct epochs of stellar assembly within a single dark matter halo, or whether some clusters are assembled early in smaller haloes and then later accreted$^{25–27}$. Within this context, our result supports the idea that there is a measurable age difference between metal-poor and metal-rich globular clusters in the Milky Way. Figure 4 shows the relationship between white-dwarf-based age and metallicity for several Galactic populations. Including the uncertainties due to stellar models, 47 Tucanae has an
Figure 4  Age–metallicity relation based on white dwarfs. Each point shows the age of a Galactic population as determined using the white-dwarf luminosity function, and the corresponding metallicity determined from main-sequence stars. The age of 47 Tucanae is determined here, while those of NGC 6397 (ref. 12), Messier 4 (ref. 13) and the open cluster NGC 6791 (ref. 28) are taken from the literature. The age of the thin disk is taken from an analysis of the white-dwarf population in the solar neighbourhood and the metallicity error bar is determined from the range of metallicities measured for nearby stars. The age uncertainties for all populations are quoted from the given references. The redshift axis uses the age–redshift relation appropriate to the sequence stars. The age of 47 Tucanae is determined here, while those of NGC 6397, Messier 4, and the open cluster NGC 6791 are taken from the literature. The age of the thin disk is taken from an analysis of the white-dwarf population in the solar neighbourhood and the metallicity error bar is determined from the range of metallicities measured for nearby stars. The age uncertainties for all populations are quoted from the given references. The redshift axis uses the age–redshift relation appropriate to the WMAP (currently accepted) cosmology. This demonstrates that the age difference derived here corresponds to the difference between $z = 3$ and $z = 2$.

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Supplementary Information is available in the online version of the paper.

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