THE ASTROPHYSICAL JOURNAL, 671:380-401, 2007 December 10

ABSTRACT

We present the results of a deep Hubble Space Telescope (HST) exposure of the nearby globular cluster NGC 6397, focussing attention on the cluster’s white dwarf cooling sequence. This sequence is shown to extend over 5 mag in depth, with an apparent cutoff at magnitude F814W ~ 27.6. We demonstrate, using both artificial star tests and the detectability of background galaxies at fainter magnitudes, that the cutoff is real and represents the truncation of the white dwarf luminosity function in this cluster. We perform a detailed comparison between cooling models and the observed distribution of white dwarfs in color and magnitude, taking into account uncertainties in distance, extinction, white dwarf mass, progenitor lifetimes, binarity, and cooling model uncertainties. After marginalizing over these variables, we obtain values for the cluster distance modulus and age of \( \mu_0 = 12.02 \pm 0.06 \) and \( T_c = 11.47 \pm 0.47 \) Gyr (95% confidence limits). Our inferred distance and white dwarf initial-final mass relations are in good agreement with other independent determinations, and the cluster age is consistent with, but more precise than, prior determinations made using the main-sequence turnoff method. In particular, within the context of the currently accepted \( \Lambda \)CDM cosmological model, this age places the formation of NGC 6397 at a redshift \( z \approx 3 \), at a time when the cosmological star formation rate was approaching its peak.

Subject headings: Galaxy: halo — globular clusters: individual (NGC 6397) — stars: luminosity function, mass function — stars: Population II — white dwarfs

1. INTRODUCTION

The oldest known stellar systems in the Milky Way are the globular clusters. As such, their nature reflects the conditions under which our Galaxy first formed and offers a unique window into the high-redshift universe. Age determination of globular clusters by fitting models to the main-sequence turnoff (MSTO) has a long and venerable history (Sandage 1953; Janes & Demarque 1983; Fahlman et al. 1985; Chieffi & Straniero 1989; Vandenberg et al. 1996 and references therein). For a long period of time, the results of these studies led to a so-called cosmological crisis, in which the estimated cluster ages (~16–20 Gyr) were larger than the age of the universe, based on a variety of cosmological tests (e.g., Bolte & Hogan 1995). However, over the last decade, improvements in the distance measurements to globular clusters, particularly using the Hipparcos satellite, have resulted in a lower estimate for the mean age of the metal-poor (hence oldest) globular clusters (>10.4 Gyr at 95% confidence; Krauss & Chaboyer 2003), which is now consistent with the age of the universe estimated from microwave background measurements (Spergel et al. et al. 1996 and references therein). This method has been carried as far as it can go with current technology and further significant improvements must await technical advances, such as improvements in distance measurement using the Space Interferometry Mission (Chaboyer et al. 2002).

In the past several years, we have embarked on a program to measure the ages of globular clusters by an entirely different method—measuring the white dwarf cooling sequence (WDCS) and determining the age by modeling the rate at which they cool (Hansen et al. 2002, 2004). This method also has a distinguished history when applied to the stellar population in the solar neighborhood (Girardi et al. 1996; Wood 1992; Hernandez et al. 1994; Oswalt et al. 1996; Leggett et al. 1998; Hansen 1999; Harris et al. 2006), but it has only recently become possible to apply the same method to globular clusters because of the extreme requirements such measurements place on both resolution and photometric depth.

Our initial measurements of the age of Messier 4 (M4), the closest globular cluster to the Sun, yielded a best-fit age of 12.1 Gyr, with a 95% lower bound of 10.3 Gyr. This is similar to the accuracy achieved by the latest MSTO analysis (12.6±3.2 Gyr) by Krauss & Chaboyer (2003). The M4 measurement was performed using the
Fig. 1.—ACS color-magnitude diagram for our field in NGC 6397. All real point sources are shown (so the extended galaxy population is not shown). Prominent features include a cluster main sequence, a clear main-sequence turnoff, and a clear white dwarf cooling sequence. Most important is the clear evidence for a sharp decline in the number of white dwarfs at magnitudes greater than $F814W = 27.6$. The detectability of sources at fainter magnitudes is evident from the fainter, bluer population of background galaxies that survive the point source cuts.
tests to predict the final distribution of colors expected after accounting for observational scatter. We may then characterize how well this fits with the true observed color distribution using the $\chi^2$ statistic. By varying the value of the true underlying color until we find the minimum of $\chi^2$ at each magnitude, we may then derive the best-fit color as a function of magnitude—an empirical cooling sequence.

This is shown in Figure 6. This may seem superfluous given that, in subsequent sections we fit model atmosphere colors to the data. However, there are still several issues outstanding in the chemical evolution and atmospheric modeling of white dwarfs, which means that there is some uncertainty in the final model colors (Bergeron et al. 1997; Bergeron & Leggett 2002). So, it is of interest to see what kind of relationship between color and magnitude fits the data independent of theoretical models. In particular we see evidence in Figure 6 (in the form of a turn toward the blue) for the deviation from blackbody trends (Hansen 1998; Saumon & Jacobsen 1999) expected due to collisionally induced absorption by molecular hydrogen in hydrogen-rich white dwarf atmospheres (Mould & Liebert 1978; Bergeron et al. 1995a; Borysow et al. 1997). Below we will see that this empirical relationship is similar to that found from theoretical hydrogen atmosphere models, suggesting that our sample is dominated by hydrogen atmosphere dwarfs.

Furthermore, this empirical sequence should allow other groups to compare their models to the data. Table 2 gives the best-fit colors as a function of magnitude.

2.6. Distance and Extinction

In both the MSTO and WDCS methods, the determination of the distance to the cluster is a fundamental aspect of the age measurement. The traditional method for globular clusters is to compare the main sequence with local, metal-poor subdwarfs with known parallaxes to determine the distance. We take our default distance to NGC 6397 to be $\mu_0 = 12.13 \pm 0.15$ by Reid & Gizis (1998), who used Hipparcos distances for the subdwarfs in $V$ and $I$ for their main-sequence fit. This also assumes a reddening $E(B-V) = 0.18$ for this line of sight. We chose this determination because most other main-sequence distance determinations to NGC 6397 use the $B$ and $V$ bandpasses, so that the Reid & Gizis work is a more direct comparison to the bandpasses used here. We examine this further in § 4.2.

Although we shall later compare to the distance and extinction derived from the main sequence, we prefer to initially determine...
Fig. 11.—**Left:** The observed cooling sequence, after removal of the majority of background galaxies using CENXS cuts. **Middle:** Comparison of the data (plotted now as small crosses) with the theoretical cooling sequence for the best-fit model, before any photometric scatter is applied. **Right:** Monte Carlo realization of the white dwarf population derived from the best-fit cooling sequence, adopting the best-fit age of 11.61 Gyr, and modeling the photometric scatter in accordance with the artificial star tests.

Fig. 12.—Filled circles are the observed luminosity function. The solid histogram shows the model population, which includes both model white dwarfs and our estimate of the residual galaxy contamination per bin. The fitting region is delineated by the vertical dashed lines.

Fig. 13.—Solid contours are the confidence intervals for the Hess diagram fit but now using the [Fe/H] = −2 models from Dotter & Chaboyer. The dotted contours indicate the same but using the luminosity function.
White dwarf cooling

Independent limit on age of galactic disk

Once nuclear burning stops a star forms a white dwarf, physics of its cooling is relatively simple

disk age = 9.3 ± 2 Gyr

Galaxy formation model needed to make this into an estimate of age of Universe

Fig. 1.—The white dwarf luminosity distribution. The circles represent the observed number of white dwarfs in each luminosity bin; the solid line shows the theoretical distribution. The vertical axis, \( \Phi \), is \( \log N \) (pc\(^{-2}\)M\(_{\odot}\)).
Fig. 26.—Solid curve indicates the relationship between cosmological redshift $z$ and look-back time for the best-fit flat universe model from Spergel et al. (2003). The shaded regions indicate white dwarf cooling ages ($2\sigma$ range) for the Galactic disk (Hansen et al. 2002) and NGC 6397 (this paper), and the arrow indicates the lower limit on the age for M4 (Hansen et al. 2004). Above the plot we show two 95% lower limits. The limit marked KC indicates the lower limit for the age of the globular cluster system as whole, taken from Krauss & Chaboyer (2003). The limit marked G03 is the 2 $\sigma$ lower limit on the age of NGC 6397, based on the results of Gratton et al. (2003). The comparison indicates that our age determination is consistent with, but also more accurate than, the best measurements using the MSTO method.
Fig. 17.—The hatched area represents a frequency histogram of Rich (1988) solution 1 [Fe/H], corrected for the regression relation found here. The solid histogram outline represents the solar neighborhood GK giant distribution found by McWilliam (1990), smoothed by a Gaussian of $\sigma = 0.25$ dex. Note that the bulge giants have a similar mean [Fe/H] but a slightly broader distribution and more very metal-poor stars.
Fig. 26. Distribution of metallicities for the volume complete sample of single stars (full histogram). For comparison the dotted curve shows the reconstructed distribution for G dwarfs from Jørgensen (2000) which is corrected for scale height effects and measurement errors.

However, as pointed out by Edvardsson et al. (1993) themselves, the restriction of their sample to F-type dwarfs automatically excluded any old, metal-rich stars if such existed, a fact that has been overlooked in several later discussions. Th
Mapping the Galaxy with star counts

Herschel used counts of stars in different directions to make a map of the Galaxy (he got it quite wrong).

Q. What sort of assumptions would you need to make, in order to work out the density distribution of the Galaxy using star counts?

→ magnitude → distance, BUT:
→ stars vary in luminosity → assume all on main sequence
→ there may be dust in the way (gets lots of colors)

This works well when you can isolate a part of the HR diagram which gives a unique luminosity to a color.

Q. What would work?

→ color range just a runoff of old pop.
The numbers for disk scale height from star counts and integrated IR photometry are worryingly different:

250 pc vs 300-350

What are strengths & weaknesses of each technique?

What might be going on here?
Thick disk

Thick disks first detected in other galaxies — surface photometry of edge on systems by van der Kruit and Searle (1981).

Suggestions for origin: early stages of disk formation or heating from accretion of small satellite galaxy.

Soon after, star count data (Gilmore & Reid) suggested that the Milky Way also had a thick disk.

Q: What problems might arise in mapping the spatial distribution of the Galaxy using star counts? (especially for ‘minority’ populations)
Figure 10.22 The space density as a function of distance $z$ from the plane of MS stars with absolute magnitudes $4 \leq M_V \leq 5$. The full lines are exponentials with scale heights $z_0 = 300 \text{ pc}$ (at left) and $z_0 = 1350 \text{ pc}$ (at right). The dashed curve shows the sum of these two exponentials.