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# Parallaxes of metal-poor main-sequence stars

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**Abstract.** Our team was awarded 108 orbits of *Hubble Space Telescope* time to obtain parallaxes and photometry of nine metal-poor stars with [Fe/H] $< -1.5$ dex. The parallaxes are obtained from observations with the Fine Guidance Sensor (FGS 1r; 11 orbits per star) and photometry was obtained with the Advanced Camera for Surveys (one orbit per star). The first data were obtained in October 2008, and the data collection is ongoing. It is anticipated that the observations will be complete in June 2013. Preliminary data reduction has been completed for five of our target stars. The parallax errors vary from 0.12 to 0.16 milli-arcseconds, and the parallaxes are at least an order of magnitude more accurate than existing *Hipparcos* parallaxes for these stars. The errors in the true distance modulus range from 0.02 to 0.03 mag. Ground-based high-resolution spectra have been analyzed to obtain accurate abundances for three stars. The properties of the two stars with accurate abundances and parallaxes are in excellent agreement with those predicted by stellar evolution models.

**Keywords.** stars: Population II, stars: distances, astrometry, globular clusters: general

## 1. Introduction

Globular clusters (GCs) are the oldest objects in our Galaxy whose ages may be accurately determined. Age determinations of GCs provide information about the early formation epoch of the Milky Way, thereby providing important constraints on galaxy formation theories and cosmology. If one assumes a ΛCDM cosmology, then the *WMAP* data's best-fitting value for the age of the Universe is $t_0 = 13.75 \pm 0.13$ Gyr (Larson *et al.* 2011). An independent estimate of the minimum age of the Universe provides a test of the preferred ΛCDM cosmological model. Using the absolute magnitude of the main-sequence turn-off, the absolute age of the oldest GCs is estimated at 12.6 ± 1.6 Gyr. The error in the absolute age of the oldest GCs is dominated by the uncertainty in the distance scale to GCs (e.g., Krauss & Chaboyer 2003). The distance-scale uncertainty is also the dominant uncertainty in determining relative ages for GCs of different metallicity. Our *Hubble Space Telescope (HST)* parallax program of metal-poor stars will significantly reduce the error in current distance estimates to metal-poor GCs, resulting in much improved age determinations.

When our program is complete, we will obtain parallaxes of nine unevolved, metal-poor ([Fe/H] $< -1.5$ dex) field stars The *HST* parallaxes will have an accuracy of $< 0.2$

milliarcsec (mas), leading to absolute-magnitude uncertainties between $\sim 0.02$ and 0.05 mag for a given star. These stars will be used to determine main-sequence-fitting distances to 24 low-metallicity GCs. Including uncertainties in the GC reddening values and metallicities, the resultant GC distance determinations will be accurate to $\pm 0.05$ mag. This will lead to absolute age determinations with an accuracy of $\sim 5\%$, more than a factor of two improvement over current estimates.

Extremely high-quality GC color–magnitude diagrams which are now available for 65 GCs from the *HST*/Advanced Camera for Surveys (ACS) Treasury Project on Galactic Globular Clusters (Sarajedini *et al.* 2007) form the basis for the main-sequence fitting. We have obtained photometry for our parallax target stars using *HST*/ACS with the same filters as the GC survey of Sarajedini *et al.* (2007). This uniform photometric data set removes one source of systematic error which has hampered previous efforts to obtain main-sequence-fitting distances to GCs.

Determinations of accurate distances to a large number of low-metallicity GCs will lead to an improved Population II distance scale. In particular, many of the GCs contain RR Lyrae stars, which are a popular Population II distance indicator. RR Lyrae stars are the low-mass, low-metallicity analogues of Cepheid variable stars and allow one to determine distances to old stellar populations. There is still considerable debate about the RR Lyrae distance scale, in particular as regards the exact sensitivity of the absolute magnitude of RR Lyrae stars to metallicity and evolutionary status (e.g., Clementini *et al.* 2003; Catelan *et al.* 2004; Feast *et al.* 2008). We will obtain accurate distances to 11 GCs that host RR Lyrae stars. These GCs contain over 500 known RR Lyrae stars, with metallicities in the range $-1.5 \leqslant [\mathrm{Fe/H}] \leqslant -2.3$ dex.

## 2. Subdwarf Target Stars

In constructing our target list for *HST*, we attempted to find stars which are single, unevolved, and have a metallicity lower than $[\mathrm{Fe/H}] = -1.5$ dex (using data from Carretta *et al.* 2000; Latham *et al.* 2002; Gratton *et al.* 2003). Latham *et al.* (2002) conducted a long-term radial-velocity monitoring program of high-proper-motion stars. These data are used to ensure that the *HST* target stars are not members of multiple-star systems. Binary stars are not suitable for use in main-sequence fitting, since one needs to know the absolute magnitude of a single star to compare to the GC main sequences.

To ensure that a star has not evolved off the main sequence, we required that the star be faint ($M_V < 5.5$ mag) and/or have a high surface gravity ($\log g > 4.4$), and be fairly red, $(B - V) > 0.55$ mag. Stars with low surface gravities and/or blue colors are likely main-sequence turn-off or subgiant stars. They are not suitable for use in main-sequence fitting. The color and surface-gravity constraints were needed, because many potential target stars have fairly large *Hipparcos* parallax errors, leading to large uncertainties in $M_V$. The *Hipparcos* parallax errors for our target stars range from 1.3 to 2.8 mas, leading to $\Delta M_V$ ranging from $\pm 0.18$ to $\pm 0.63$ mag. The *HST* parallaxes obtained by this program will lead to $\Delta M_V$ of approximately 0.02 to 0.04 mag. For all of these stars with *HST* parallaxes, $\sigma_\pi/\pi < 0.04$, resulting in negligible Lutz–Kelker corrections.

## 3. Ground-based Observations

Astrometry with the Fine Guidance Sensors on *HST* provides positions relative to a set of six nearby reference stars. Absolute parallaxes are obtained from the data in a quasi-Bayesian approach, whereby prior information about the target stars is used in the data reduction process (Benedict *et al.* 2011). The prior information consists of photometry

**Table 1.** Abundance analysis

| HIP | [Fe/H] (dex) | $T_{\rm eff}$ (K) |
|---|---|---|
| 106924 | −2.13 | 5270 |
| 103269 | −1.83 | 5370 |
| 87062 | −1.65 | 6000 |

and spectroscopy of all reference stars. The photometry consists of $UBVRIJHK$, DDO 51, and Washington M and T2 filters. The $JHK$ photometry comes from 2MASS, while the optical photometry was obtained at the MDM, Apache Point, and Fan Mountain Observatories. The DDO and Washington-filter photometry assists in obtaining an accurate dwarf/giant classification. Low-resolution spectra from Apache Point Observatory were obtained for all reference stars and used to determine accurate spectral types for all stars.

The luminosity of a star depends upon its composition. Thus, it is important to obtain accurate abundances for our parallax stars. The [Fe/H] values we used to construct our target sample are from a variety of sources, some of which are estimated [Fe/H] values based upon very low signal-to-noise data. In addition, the abundance of elements such as oxygen and calcium can affect stellar structure. Therefore, we obtained high-dispersion spectroscopy for our target stars using the *Keck*/HiRES and *Magellan*/MIKE spectrographs. Preliminary analysis has been completed for three of the stars and is reported in Table 1. The abundance of oxygen in these low-metallicity stars was found to be $[\mathrm{O/Fe}] = +0.60$ dex.

The spectra of HIP 87062 contained detectable interstellar Na D lines, indicating that the star lies behind an interstellar gas/dust cloud. The measured equivalent width of the D1 line was 163 mÅ. Referring to Poznanski *et al.* (2012), this corresponds to a reddening of $E(B-V) = 0.05$ mag. Furthermore, the excitation effective temperature was many hundreds of degrees hotter than indicted from photometry. This star was observed at both *Keck* and *Magellan*, and line equivalent widths are almost all identical between the two spectra, over a large range in excitation parameters. However, this star turned out to be a velocity variable; the *Keck* and *Magellan* radial velocities differ by 37 km $\mathrm{s}^{-1}$. This star is likely a single-lined spectroscopic binary. This is unfortunate, since we cannot quantify the amount of light emitted by each component, thus leading to a systematic uncertainty in our photometry. As a result of its relatively high reddening and binary status, HIP 87062 is not a suitable reference star for main-sequence fitting.

## 4. Results

*HST* observations are complete for eight of our target stars. At the time of this conference, we had completed the preliminary data reduction and high-dispersion abundance analysis for five stars, including HIP 106924 and HIP 103269. Fig. 1 compares the loci of these stars in the observed color–magnitude diagram to the Dartmouth stellar evolution models (Dotter *et al.* 2008). This is the first time very metal-poor stellar isochrones have been tested with accurate parallax data. The agreement between the models and observations is excellent.

A main-sequence-fitting distance to M53 ([Fe/H] = −2.1 dex) has been determined using HIP 106924 as comparison star. We find $(m-M)_0 = 16.25 \pm 0.02$ mag, or $(m-M)_V = 16.31 \pm 0.04$ mag. Using time-series photometry, Arellano Ferro *et al.* (2011) found an apparent magnitude of RR Lyrae stars in M53 of $m_V(\mathrm{RR}) = 16.88$ mag,

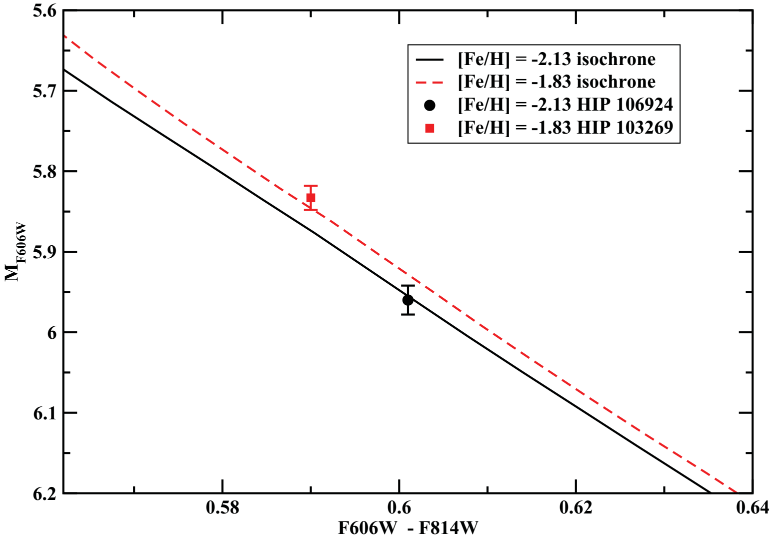

**Figure 1.** Comparison between theoretical isochrones and our two stars which have well-determined parallaxes and abundances.

which—with our distance modulus—implies $M_V\,(\mathrm{RR}) = 0.57 \pm 0.04$ mag. This absolute magnitude agrees to within 0.05 mag with the value Arellano Ferro *et al.* (2011) derived from Fourier decomposition of the RR Lyrae light curves. However, it is considerably brighter than the absolute magnitude obtained from the commonly used relation of Clementini *et al.* (2003), which implies $M_V\,(\mathrm{RR}) = 0.38$ mag at $[\mathrm{Fe/H}] = -2.1$ dex. The full implications of this result will be determined once we have completed our analysis of the remaining six stars in our parallax program and determined main-sequence-fitting distances to the 11 metal-poor GCs which contain RR Lyrae stars and have ACS photometry available in the literature.

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