White Paper for the COPAG – Input for Large Astrophysics Missions

Precision Ages for Milky Way Star Clusters

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Age Dating Star Clusters and Associated Uncertainties

Our knowledge of the fundamental properties of the Milky Way globular cluster system establishes a foundation for testing several aspects of the formation time and assembly of galaxies. These systems are not only among the oldest objects in the Universe, but they accompany most major star formation episodes in galaxies (e.g., Brodie & Strader 2006). Significant improvements in the ages of the Milky Way globular cluster population would immediately impact several astrophysical studies. For example,

- The *absolute* age determination of the Milky Way population represents one of the most reliable measures of when baryonic structure formation occurred in the Universe (Spergel et al. 2003). If it can be established that the oldest, metal-poor clusters indeed formed >13 Gyr ago with sub-Gyr precision, then they *must* have formed in very low mass halos and been affected by reionization (Bullock & Johnston 2005; Gnedin 2010).

- A robust slope in the globular cluster age-metallicity relation can also anchor high-resolution N-body simulations of galaxy formation, by informing the subsequent mass-merger history (Mackey & Gilmore 2004; Font et al. 2011; Beers et al. 2012). As an example, recent discoveries of outer halo GCs in M31 reveal a striking correlation between their positions and that of tidal debris streams (Mackey et al. 2010).

- The *relative* age difference between clusters associated with distinct structural components establishes the formation and assembly timescales of these parent populations (e.g., the bulge, halo, and substructure). For example, the ages of the metal-rich bulge clusters is the best method to place the formation time of the bulge within the landscape of galaxy formation models.

Modern derivations of globular cluster ages have primarily involved reproducing visible-light color-magnitude diagrams (CMDs) and the main-sequence turnoff feature with stellar evolution models. These studies have been greatly impacted by the Hubble Space Telescope, which has been used to uniquely explore dense cluster environments with high-resolution and high-precision imaging. For example, the Advanced Camera for Surveys Treasury Survey of globular clusters provides homogeneous and accurate photometry for thousands of individual stars in each of 60 systems, and is the current state-of-the-art study of both relative and absolute ages (Sarajedini et al. 2007). Recent analysis of these data, based on a uniform set of stellar evolution models with updated physics (Marin Franch et al. 2009; Dotter et al. 2010, 2011), suggests that the bulk of the Milky Way's globular clusters formed more than 12.0 Gyr ago, the oldest of which formed just a few hundred Myr after the Big Bang (Dotter et al. 2010; see also VandenBerg et al. 1996; Gratton et al. 1997; Chaboyer et al. 1998).

Despite the many advances in establishing high-precision globular cluster CMDs, the current state-of-the-art analysis of the main-sequence turnoff feature still leads to large errors in the derived absolute age of any given Milky Way cluster. For example, stellar models on the hydrogen-burning main sequence are impacted by uncertainties in nuclear reaction rates, chemical composition (e.g., [α/Fe]), the equation of state, and several second order effects including diffusion, rotation, and turbulence. Comparisons between fixed observational data sets and families of models that make different assumptions on the micro- and macrophysics of stellar structure lead to $\sim$0.5 Gyr differences in the derived age alone (Chaboyer & Krauss 2002). In addition to these uncertainties from stellar models, an additional 0.5 Gyr uncertainty results from uncertainties in the globular cluster metallicity. The *largest* uncertainty impacting this technique comes from simultaneously "fitting" the age at a given distance and reddening (σ = 1.0 to 1.5 Gyr – Dotter et al. 2011; Chaboyer 2008). For the latter, future GAIA distances to clusters will be very useful.

White Dwarf Cooling

After the hydrogen-burning main-sequence and post main-sequence evolutionary stages, the end product of 98% of all stars will be the white dwarf stage of stellar evolution. As white dwarfs, stars have no nuclear energy sources and have a very simple structure with a thin hydrogen envelope. Over time, the stars simply cool and become dimmer. On the CMD of a co-eval population, the white dwarfs will pile up on the faint-blue end and form a distinct sequence. The fainter stars are those that have been cooling longer, representing the remnants of more massive progenitors that exhausted their hydrogen supply faster.

Given their '"simple" evolution, a detection of the white dwarf cooling sequence and its limiting luminosity can enable a sensitive measurement of the age of the parent population. Over an age range of 10 – 13 Gyr, this limiting luminosity will vary by >1 magnitude in a visible-light CMD, many times larger than the luminosity or color difference of similar age models at the hydrogen-burning main sequence. The challenge is to measure these faint stars within a dense population such as a globular cluster; the faintest white dwarfs have $M_{\rm V}$ =

16.5, implying $V > 29$ in the *nearest* Milky Way globular clusters.

Over the past decade, three very large programs on the Hubble Space Telescope have successfully measured the complete white dwarf cooling sequences in the three nearest Milky Way globular clusters (Hansen et al. 2004; 2007; 2013; also Bedin et al. 2009). These studies each required 100+ orbits. For a given set of white dwarf models, sub-Gyr ages are published for each cluster. Although white dwarf models are not free of uncertainties (e.g., the onset of core-crystallization), most of the systematics are well understood and are also completely independent to the main-sequence turnoff physics.

As an example of the power of the white dwarf technique, Figure 1 illustrates the superimposed CMD of two of the globular clusters, NGC 6397 and 47 Tuc, after removing differences in distance and reddening. Whereas the locus of the stellar main-sequence is very different in the two CMDs (e.g., due to differences in metallicity), the white dwarf cooling sequences overlap almost perfectly, thereby affirming the simple nature of these stars. In this specific example, the white dwarf cooling sequence in the metal-rich cluster 47 Tuc is clearly truncated at a brighter luminosity than the metal-poor cluster NGC 6397, thereby indicating that the cluster is younger (Hansen et al. 2013).

Sub-Gyr Ages for the Milky Way Globular Cluster Population

The Hubble Space Telescope imaging projects in M4, NGC 6397, and 47 Tuc provide a strong "proof of concept" for measuring and characterizing the white dwarf populations of dense globular clusters. However, it is difficult to use these three measurements alone to address the global goals introduced above, and further Hubble observations of more clusters are unfeasible given their large foreground extinctions and/or larger distances.

A transformative breakthrough in establishing sub-Gyr ages for a family of Milky Way globular clusters, each with their own metallicity, orbit, galaxy component association, and dynamical state, will require a large aperture and high-resolution telescope, with excellent visible-light throughput. The LUVOIR telescope from the NASA Astrophysics 30-year Roadmap[1] is perfectly suited for this science goal. For example, for a $\sim$10-m space telescope, the 10σ depth in a 10-hour integration is AB $\gtrsim 32$. This would enable a robust detection of the faintest white dwarfs that could have cooled over the age of the Universe, out to 10 kpc. More than 30 Galactic globular clusters are located within this distance, and therefore a LUVOIR Large Program of a few hundred orbits would achieve high-precision ages for all of them.

[1] http://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap/

A LUVOIR study of white dwarfs in globular clusters is synergistic to both GAIA and LSST. GAIA will target the brightest giants in star clusters to establish much better distances, while LSST will study the periphery of these systems for population studies and dynamics. JWST can also establish high-resolution deep images of cores of globular clusters, but the infrared photometry is not ideally suited for white dwarf studies.

A LUVOIR imaging survey of 30+ globular clusters in the Milky Way will yield the most accurate measurement of the formation time of stars in our Galaxy, and establish a high-fidelity age-metallicity relation based on a method that is independent of stellar chemistry. In addition to the new white dwarf technique, such a survey would *also* provide the highest-precision photometry of the main-sequence population in each cluster to date. If stretched over a wider wavelength baseline from the blue to the red, large gains in the the precision of the main-sequence turnoff could be simultaneously achieved by reducing the error contribution from "fitting" the turnoff feature with stellar models. Therefore, for the first time, two completely independent methods for age-dating stellar populations could be tested over a wide range of metallicity. Not only would this provide *even* more accurate age estimates, but such a uniform comparison of the two methods would yield powerful insights on the validity of stellar evolution models in different parameter space.

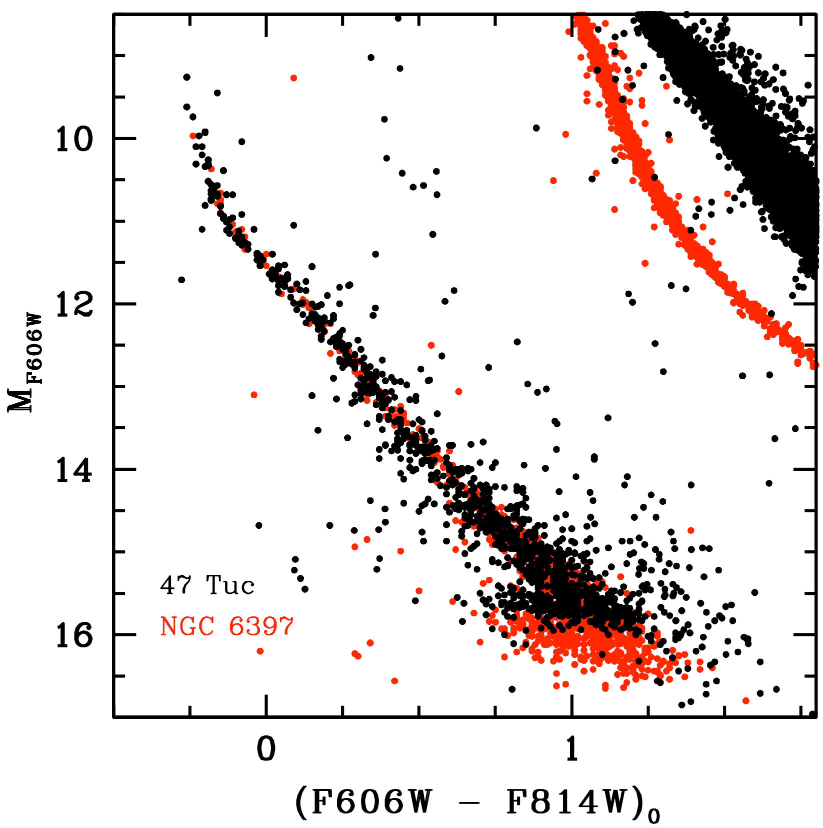

Fig. 1.— The CMD of two nearby globular clusters, NGC 6397 (red) and 47 Tuc (black), as observed in large Hubble Space Telescope imaging projects (Richer et al. 2008 and Kalirai et al. 2012), are superimposed after accounting for differences in distance and reddening. Whereas the stellar main-sequence in the two clusters looks very different due to the different chemical composition (right hand side of Figure), the remnant white dwarf populations sit right on top of another. If imaged with high-precision, these cooling dwarfs provide a very accurate and metallicity-independent age measurement for the cluster. In this case, the NGC 6397 white dwarfs have cooled to a luminosity that is ∼0.5 mag fainter than the 47 Tuc white dwarfs, indicating that NGC 6397 is much older.

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