7 Formation History of the Milky Way

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ABSTRACT

Globular clusters and Population II stars are fossil remnants of the first major epoch of star formation in the Milky Way. SIM Lite will determine precise distances to selected Pop II objects to define a reliable distance scale, and establish reliable absolute and relative ages. Those ages set a minimum age for the Universe and map the early formation history of the Milky Way. The resultant ages will be accurate to better than 1.0 Gyr, resolving the detailed chronology of the first epoch of star formation in the Milky Way Galaxy.

7.1 RR Lyrae Stars As Population II Distance Indicators

RR Lyrae stars are solar-mass stars that have exhausted core hydrogen burning on the main sequence (MS); they have evolved through the hydrogen shell-burning phase and, after experiencing the helium flash at the tip of the red giant branch (RGB), have settled onto the helium core-burning phase at ~ 10 × $L_{\odot}$. Metal-rich stars show little evolution in color over the few × 10^8 year lifetime of this phase of evolution, and form the "red clump" close to the RGB, but metal-poor stars evolve blueward, forming the horizontal branch (HB). At a certain point, when the surface temperature is ~5,700 K, the star becomes unstable and pulsates; this behavior persists until the surface temperature reaches ~7,000 K, and recurs during the (faster) redward evolution back across the instability strip. The pulsations have periods from 0.3 to 1.5 days and produce luminosity variations with amplitudes up to a factor of 3, rendering these stars easily recognizable not only in the field, but also in globular clusters (Pickering and Bailey 1895) and nearby galaxies such as the Large Magellanic Cloud (LMC) (Thackeray and Wesselin 1953) and M31 (Pritchett and van den Bergh 1987).

These characteristic photometric variations, coupled with their ubiquity, have led to RR Lyrae stars playing a key role as secondary indicators to Local Group systems in the extragalactic distance ladder. However, different calibration techniques lead to different absolute zero points for RR Lyrae luminosities (Figure 7-1). As a result, there remain significant uncertainties in both the absolute magnitudes of RR Lyrae stars and the extent to which those luminosities depend on metallicity (Figure 7-2). There are also (metallicity-based?) inconsistencies between the RR Lyrae results and other distance indicators: for example, RR Lyrae stars give a relative distance modulus δm ~ 6.2 magnitudes between the LMC and M31 (Reid 1999), while Cepheids give δm ~ 5.9 magnitudes (Freedman and Madore 1990), and red clump stars give δm ~ 6.4 magnitudes (Reid 1999).

The first step towards reconciling those differences is to establish the absolute-magnitude calibration, and its dependence on metallicity, of RR Lyrae stars in the Galactic field. The nearest variables, including RR Lyrae itself, lie at distances of 100 to 200 pc, barely within reach of the Hipparcos astrometric satellite. The Hubble Space Telescope has measured submilliarcsecond accuracy parallaxes for a handful of nearby variables (Benedict et al. 2002 and 2007), but the formal uncertainties in the distances remain in excess of 15 percent and therefore do not break the degeneracies evident in Figures 7-1 and 7-2.

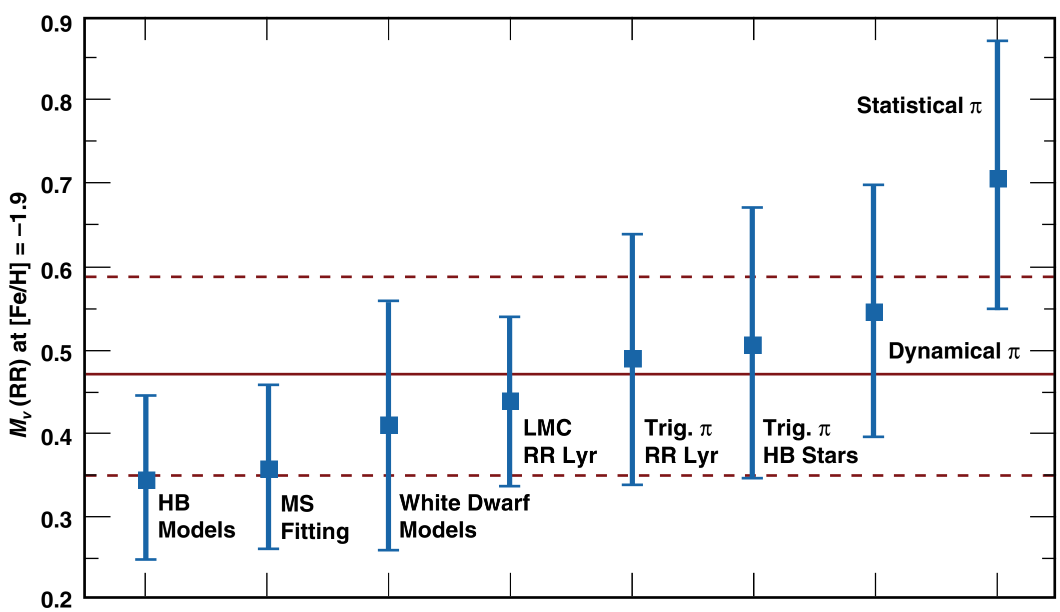

Figure 7-1. The absolute magnitude of metal-poor RR Lyrae stars as determined through a variety of techniques; averaging all techniques gives a formal uncertainty of ±0.12 mag or ±6 percent in distance. SIM Lite will make high-accuracy distance measurements for a small sample of field RR Lyrae stars.

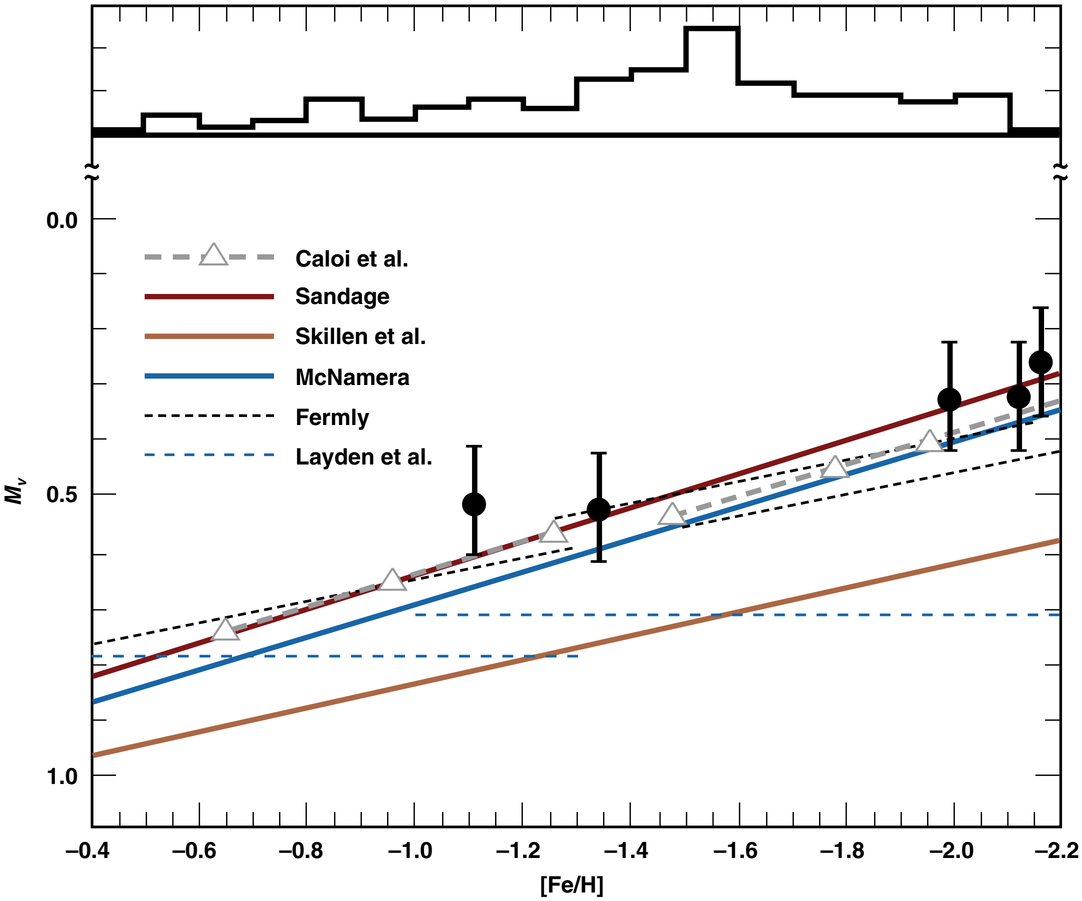

Figure 7-2. A summary of the various RR Lyrae (M_V, [Fe/H]) relations from six different reports. In addition, five solid points mark ⟨ M_V ⟩ for M5, M13, M15, M68, and M92 variables, using Hipparcos-based distance moduli. The upper histogram plots the abundance distribution of the field (from Reid 1999). SIM Lite will target about 20 field RR Lyrae stars, chosen to span a range in distance and metallicity. This will establish the slope and brightness zero point, providing an independent check on Gaia.

Gaia is expected to have a major impact in this area. At $M_V \approx 0.5$, RR Lyrae stars within 5 kpc have apparent magnitudes V < 14, and, over its mission, Gaia should achieve trigonometric parallaxes accurate to ~10 to 20 µas for those stars (Lindegren et al. 2007), corresponding to uncertainties of 1 to 2 percent at 1 kpc ($\sigma(M_V) \approx 0.05$ magnitudes) and 5 to 10 percent at 5 kpc. With a space density of 5/kpc^3, several hundred RR Lyrae stars fall within Gaia's reach, and the resultant data will map the (M_V, [Fe/H]) relation and define the absolute magnitude zero point to a potential accuracy of a few percent.

SIM Lite, with a mission accuracy of 3 to 5 µas — three to four times better than Gaia — can play a crucial role by providing an independent check of the calibration for key stars. We anticipate targeting ~20 field RR Lyrae stars, chosen to span an appropriate range in distance and metallicity. Acquiring those observations will require only 14 to 15 SIM Lite mission hours.

7.2 Ages of Globular Clusters

Globular clusters are the archetypical Population II systems. These metal-poor systems, with total masses between 10^5 and 10^6 $M_\odot$, are generally held to date back to the earliest stages of the formation of the Milky Way. Consequently, an absolute determination of cluster ages sets a lower limit for both the age of the Milky Way and the Universe. Moreover, the distribution of globular cluster ages can probe the overall modus operandi: Did the oldest stars in spiral galaxies form in a rapid burst, or was there a more protracted process, perhaps involving accretion of satellite systems (as in the Searle and Zinn model discussed in Chapter 4)? SIM Lite can illuminate this question by setting cluster distances on a more reliable foundation.

Traditionally, globular clusters are characterized as mini-starbursts, with a single-age stellar population. Recent observations indicate that a handful of the most massive systems (e.g., NGC2808, Piotto et al. 2007) have more complex star formation histories, possibly indicative of their origin as cores of stripped dwarf galaxies. Even those systems, however, have relatively simple color-magnitude diagrams (CMD), with a well-defined main sequence turnoff (MSTO) at $M_V \approx 4$ or ~ 0.85 $M_\odot$. Relative ages for globular clusters can be derived using a variety of techniques, including measuring the (vertical) offset between the MSTO and the HB or the (horizontal) offset between the MSTO and the base of the RGB. Those analyses show that most clusters are coeval, within the uncertainties (~±1.5 Gyr), with a handful of clusters that are a few Gyr younger (De Angeli et al. 2005).

Absolute age estimates, however, require matching the observed color-magnitude diagram against theoretical models (Figure 7-3), and therefore demand reliable distance estimates. Specifically, a change of $\delta m \approx 0.1$ magnitude in the absolute magnitude of the MSTO corresponds to $\delta\tau \approx 1.5$ Gyr.

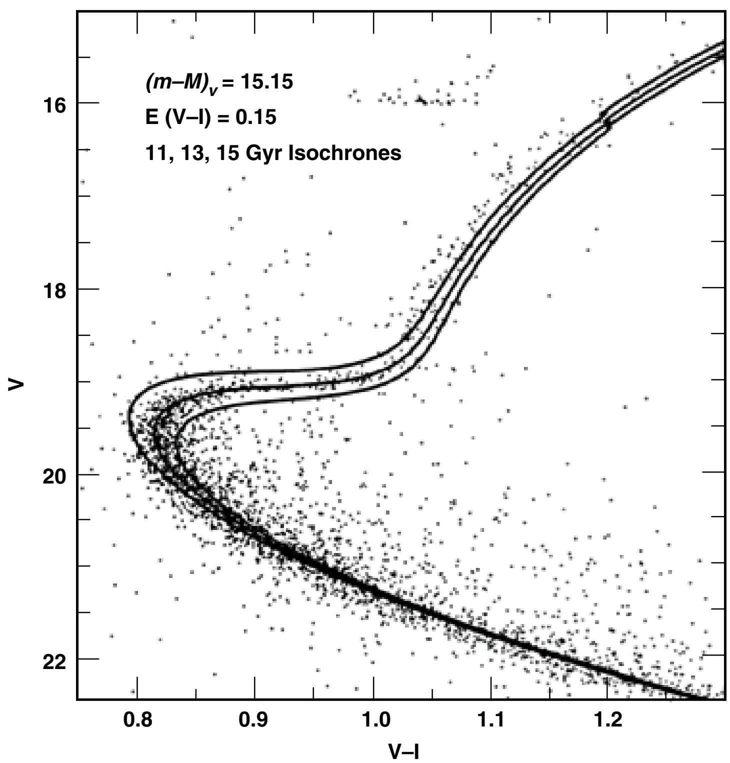

Figure 7-3. Theoretical isochrones matched against ground-based photometry of the inner halo globular cluster NGC6652. (From Chaboyer et al. 2000). Cluster age is estimated by adjusting distance and reddening to attain a best fit. However, the near-degeneracy of these complicates this method. SIM Lite will circumvent this problem by directly measuring distance via trigonometric parallax.

Expressed generally, if ε_τ is the fractional uncertainty in age, σ_τ/τ, and ε_d is the fractional uncertainty in distance, σ_d/d, then $\varepsilon_\tau \sim 2\varepsilon_d$.

It is clear that we will need to resolve age differences of 1 Gyr ($\varepsilon_\tau \approx 7$ percent) to obtain a better understanding of the early star-formation history of the Milky Way. That requirement in age resolution demands that we determine cluster distances to an accuracy of ~4 percent or better.

In the past, cluster distances have been estimated based on (M_V, [Fe/H]) relations derived for HB stars or RR Lyrae stars. Figures 7-1 and 7-2 show that those methods have formal random uncertainties of ~6 percent in distance, with potential systematic errors at comparable levels. Current estimates of cluster distances are therefore based primarily on the main sequence fitting technique, matching the observed

CMD either against local subdwarfs with known trigonometric parallax or directly against theoretical isochrones. Each variant has its own particular set of drawbacks.

Theoretical models offer a precise definition of the CMD from the RGB through the MSTO to the lower main sequence. However, the luminosities and effective temperatures generated in the computations need to be transformed to the observational plane via stellar atmosphere models, and inconsistencies in opacities or temperature distributions can lead to mismatches. Moreover, the exact treatment adopted for processes such as convective overshoot and heavy-element diffusion, as well as the adopted nuclear reaction rates, can lead to systematic errors in the isochrone predictions. As an example, theoretical isochrone fitting consistently predicted globular cluster ages of 14 to 17 Gyr in the mid-1990s (e.g., Vandenberg, Stetson, and Bolte 1996). In more recent years, following Hipparcos and the Wilkinson Microwave Anisotropy Probe (WMAP) estimate of 13.7 Gyr for the age of the Universe (Spergel et al. 2007), the models have been equally consistent in converging on an average age of ~12 Gyr (11.7 ±1.5 Gyr, Chaboyer 2001). In part, this change reflects improvements in our understanding of the physics of stellar interiors, yet these results also strongly suggest that this is one field where observations can drive the theory.

Empirical main sequence fitting has its own problems. Hipparcos provided improved parallaxes for the nearest subdwarfs, and laid the foundation for an extensive reexamination of cluster ages and distances (Reid 1997, 1998; Gratton et al. 1997, 2003). Those analyses provided much of the basis for the recent downward revision in mean age for the cluster system. However, the Hipparcos sample includes fewer than 20 subdwarfs with parallaxes measured to better than 10 percent. Those stars provide sparse coverage in (M_V, color, [Fe/H]), with the result that many clusters are calibrated against only three or four local subdwarfs. This leads to uncertainties of ±0.1 to 0.15 magnitudes in the distance modulus and ±1.5 to 2 Gyr in the age.

Both Gaia and SIM Lite offer means of addressing this problem. Gaia is well suited to supplementing and refining the sample of local subdwarf calibrators. With a formal mission accuracy of 8 to 21 µas for 6 < V < 15, Gaia can determine parallaxes accurate to better than 1 percent for K-type subdwarfs within 300 pc of the Sun, potentially increasing the census to include 1,000+ stars. As with RR Lyrae stars, SIM Lite has the capability to obtain higher accuracy parallaxes for a small subset of this sample, verifying the Gaia calibration. While these observations will lead to a much improved sample of local calibrators, a number of issues will remain. For example, local subdwarfs show a range of detailed elemental abundances, notably [α/Fe] ratios, and this could lead to a mismatch between calibrators and cluster. Moreover, any main sequence fitting technique requires that the cluster photometry be corrected for foreground reddening; this is a significant correction for many globular clusters, including M4 and NGC6397, the two nearest systems.

The best method of circumventing these complications would be to directly measure the trigonometric parallax of a star (or stars) in the globular cluster. The brightest stars in the nearer globular clusters, RGB stars and HB stars, have visual magnitudes in the range 12 < V < 14, and are therefore readily accessible to SIM Lite and even Gaia. Both missions plan to capitalize on this, measuring multiple stars in the accessible systems, and averaging the individual parallax measurements to derive higher-accuracy measurements for the parent clusters. Gaia expects to achieve parallax accuracies of 10 to 20 µas for the individual (mainly RGB) stars, corresponding to uncertainties of 10 to 20 percent in distance for a globular cluster at 10 kpc. In principle, one can combine observations of 5 to10 stars to derive cluster distances with improved accuracy, and Gaia aims to achieve ~8 µas accuracy, corresponding to 8 percent at 10 kpc. In practice, Hipparcos offers some vital lessons in this type of analysis: specifically, the parallax of 8.45 ±0.25 mas derived for the Pleiades (van Leeuwen 1999) is based on combining 1 to 2 mas accuracy Hipparcos astrometry of 55 cluster members; that result is at odds with other measurements (see also Section 6.3), and poses severe problems for stellar evolution theory. Soderblom et al.

(2005) have demonstrated that astrometry of three cluster members with the fine-guidance sensors on the Hubble Space Telescope yields a mean parallax of 7.43 ±0.17 mas, consistent with the distances derived from orbital parallaxes (of Pleiades binaries [Pan, Shao, and Kulkarni 2004]) and from conventional main sequence fitting (Pinsonneault et al. 1998).

This Hipparcos Pleiades problem emphasizes the vital importance of understanding and controlling systematic errors before attempting to achieve gains in accuracy by combining separate measurements. SIM Lite has a clear advantage over Gaia in this respect. Not only are the measurements of individual stars more accurate, but those measurements are tied to the reference grid, providing a stringent test for hidden systematic errors.

SIM Lite will be used to measure parallaxes for six 14th-magnitude stars in each of the 35 globular clusters that lie within 12 kpc of the Sun. These observations, which require ~6.6 mission hours per cluster, will yield parallaxes accurate to 5 to 6 μas over the mission lifetime. The individual parallaxes can be combined to yield a mean cluster parallax matching the projected accuracy of the SIM Lite grid, ≈3.6 μas, or ~4 percent accuracy at 12 kpc. Thus, with an investment of ~230 hours over the course of its mission, SIM Lite can significantly tighten the constraints on the age distribution of the cluster system and set a new, improved benchmark for the oldest stars in the Milky Way.

7.3 Summary

A strong synergy exists between Gaia and SIM Lite for investigations of key characteristics of Population II and the early star-formation history of the Milky Way. Gaia will conduct an exhaustive census of local halo stars, specifically RR Lyrae stars and field subdwarfs, providing parallaxes accurate to 1 to 2 percent for stars within 1 kpc. Gaia also has the potential to measure distances to ~5 percent, and ages to ~10 percent, for the nearest globular clusters, given that the systematic errors can be well controlled. SIM Lite, in contrast, will enable high-accuracy measurements for a small, but representative, sample of field RR Lyrae stars and subdwarfs, verifying and refining the Gaia-based (M_V, [Fe/H]) calibration for those stars. SIM Lite offers the most reliable route to direct distance measurements for 30 to 40 globular clusters within ~12 kpc. The resultant ages will be accurate to better than 1.0 Gyr, resolving the detailed chronology of the first epoch of star formation in the Milky Way Galaxy.

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