10 Milky Way Stars and Stellar Populations

Guy Worthey (Washington State University)

ABSTRACT

SIM Lite will revolutionize the study of almost every category of star (Chapter 7). However, a few stellar types are especially applicable to the study of galaxies. These include classical Cepheid variable stars and Population II stars. The former are reliable standard candles, which, given improved calibration, will help establish distance scales, both to external galaxies and within our own. Cepheids are also interesting because of their (poorly understood) pulsation mechanism and what it may reveal about the physics of stars in general. Population II stars — older, less luminous, and in general metal-poor — comprise a fossil record, the preserved remains of the Milky Way's remote past. Their study will help establish a Galactic time scale and the evolutionary path leading from formation to the present day.

In the study of extragalactic stellar populations, a plethora of questions remain: field versus cluster environment, chemical evolution, morphological evolution, emergence from the dark ages, and the overall scheme of galaxy assembly. The isochrone-based ages of these populations are currently uncertain at the level of 30 percent. The Galactic clusters studied by SIM Lite, rich in Population II stars, will help reduce this to about 5 percent, leading to increased precision and better understanding of galaxy evolution at all redshifts. By targeting the distance scale, we will complement the more direct studies of dynamics and the role of dark matter in galaxy assembly and evolution (Chapter 4). Better distances, filtered through stellar evolution models and models for the integrated light of stellar populations, translate to better understanding of the chemical and age structure of the various stellar populations that make up the Milky Way and external galaxies. The age-measurement tools can also be applied to data from the James Webb Space Telescope and from the new generation of adaptive-optics ground-based telescopes. They will play a vital role in their studies of galaxy formation.

10.1 Galactic Distances and Age Scales

Cepheid variable stars are reliable standard candles, which, given improved calibration, will help establish the distance scale to external galaxies. SIM Lite will dramatically improve calibration of the period-luminosity relationship. At the same time, it will yield a wealth of Cepheid science. An accurate distance calibration will allow for an accurate determination of extinction and (currently mysterious) metallicity effects on the inferred absolute luminosity. The physics of the pulsation mechanism (including the mysterious amplitude decline of Polaris) can be studied in great detail for those nearby Cepheids where the extinction is small or well measured (such as in clusters), as well as for Cepheids that are members of binary systems where accurate mass measurements can be made. In addition, SIM Lite will use star clusters to determine accurate ages for metal-poor (Population II) stars by identifying the various evolutionary sequences in a stellar color-magnitude diagram. This will provide a firm lower limit on the age of the Universe and probe the early formation history of the Milky Way, including the interplay between age, abundance pattern, and dynamics.

10.1.1 Classical Cepheid Variable Stars

A SIM Lite program will yield a plethora of Cepheid science, even with a successful all the distances Gaia determines, since SIM Lite maintains the same high astrometric precision for stars that are brighter than Gaia’s magnitude range and for fainter stars for which Gaia’s precision decreases:

(1) Variable stars identified as Cepheids would be useful for inertial frame Galactic rotation dynamical studies if sufficiently precise proper motions are available.
(2) An accurate distance calibration allows for an accurate determination of extinction and (currently mysterious) metallicity effects on the inferred absolute luminosity.
(3) The physics of the pulsation mechanism (including the mysterious amplitude decline of Polaris) can be studied in great detail for those nearby Cepheids where the extinction is small and/or well measured (such as in clusters), and for Cepheids that are members of binary systems where accurate mass measurements can be made.

The second and third points are essential for our understanding and usage of Cepheids as tools. From the deeper physics comes the deeper understanding. Currently, our lack of detailed understanding of the physics of the pulsation mechanism (i.e., the calibration of the period-luminosity-color relation) yields galaxy distances that carry systematic uncertainties of order plus or minus 5 percent (Pietrzynski et al. 2006; Macri et al. 2006). A better understanding of the physics would likely result in smaller systematic errors, and hence, in an easier method for determining accurate distances to a large number of galaxies. For example, it has been claimed that "bump Cepheids" can be used to determine distances below the 2 percent level. This method is based on a detailed analysis of the light-profile and nonlinear pulsation models (e.g., Keller and Wood 2006).

On the subject of disk dynamics, the Milky Way is the only galaxy for which we can perform detailed three-dimensional dynamical studies because all six phase-space parameters can be determined for a number of tracers of the gravitational potential. Young stars like Cepheids (age ~50 Myr) are very sensitive to small- and large-scale perturbations of the potential (Mayor 1974), and are thus very useful to study the dynamical effects of the bar, spiral structure, the Gould Belt, and the warp. For such studies, the apparent magnitude is not important, just the distance and space velocity. Cepheids are useful for these kinds of studies because they can be identified based on their light curve (Metzger, Caldwell, and Schechter 1998). A total of about 900 Galactic Cepheids are currently known (Welch 1998), while only the 200-odd nearest of these stars are typically used in studies of Galactic dynamics (Zhu 2000; Metzger, Caldwell, and Schechter 1998; Feast and Whitelock 1997; Pont et al. 1997; Pont, Mayor, and Burki 1994; Caldwell and Coulson 1987). The Cepheid sample provides a unique opportunity to perform very detailed studies of the dynamics of disk galaxies. Many of these Cepheids will have Gaia data, and these could have refined distances and much better proper motions with SIM Lite. Because the binarity rate amongst Cepheids is large (≈80 percent; Szabados 2003), it is crucial to monitor the Cepheids astrometrically throughout the SIM Lite mission.

Cepheids in the Milky Way typically suffer a significant amount of dust extinction. For example, the nearest 180 stars in the sample of Pont and collaborators (Pont, Mayor, and Burki 1994; Pont et al. 1997) have $A_V = 1.7\pm1$ mag. In general, it is hard to determine extinction better than about 0.05 mag for stars with Cepheid colors, even with the Gaia instrument suite (Jordi et al. 2006). Currently, the extinction is estimated from an intrinsic period-color relation (e.g., Laney and Stobie 1994; Caldwell and Coulson 1986) that is calibrated on Cepheids in open clusters. Future work to measure extinction promises to nail the currently fuzzy relations between period, luminosity, color, and abundance for bright, local stars.

Independent measurements of the period-distance-metallicity-extinction calibration would be available via the Cepheids in galaxies with rotational-parallax distances (see Chapter 6): M31 and M33 (employing SIM Lite) and the LMC (employing Gaia).

A final point is that Cepheids are pulsating variable stars and it is through this dynamic that we can learn much more about the internal structure and atmospheric physics than for normal stars. The ultimate goal is to usher in the age of precision stellar physics and hence stellar population studies.

10.1.2 Population II Ages and Chemistries

Age determinations for metal-poor (Population II) stars allow us to set a firm lower limit to the age of the Universe and to probe the early formation history of the Milky Way with the interplay between age, abundance pattern, and dynamics. Star clusters provide the best opportunity to determine ages of Population II stars, as it is easy to identify the various evolutionary sequences in a stellar color-magnitude diagram. The main sequence turnoff (MSTO) luminosity is the best stellar "clock" that can be used to determine the absolute ages of globular clusters (e.g., Demarque 1980; Rood 1990; VandenBerg 1990; Renzini 1991; Chaboyer et al. 1996). However, the main sequence turnoff becomes redder as well as fainter as a cluster of stars gets older. Thus, ages can be derived from the color of the turnoff, independent of distance, and this fact is exploited in the application of integrated-light models to extragalactic stellar populations.

To briefly recap Chapter 7 material, the largest uncertainty in the determination of globular cluster ages based upon the MSTO luminosity is the distance scale for Pop II objects. A 1 percent error in the distance leads to a ≈2 percent error in the derived age (e.g., Chaboyer et al. 1996). SIM Lite will be able to determine distances to the bulk of the Milky Way globular cluster system and other distant stars in the halo. To illustrate the expected accuracy of our relative age determinations for the field halo stars and the globular clusters in our SIM program, Unwin et al. (2008) ran a Monte Carlo simulation that allowed for the true distance to the object to vary within its current estimated uncertainties, and which took into account the uncertainties in the SIM distance determination, reddening determinations, and in the chemical composition of the stars. They found that the field stars will have a typical age uncertainty of about 0.6 Gyr, while the globular cluster ages will have an error of about 0.9 Gyr (column 8 in Table 5 of Unwin et al.).

Only SIM Lite can get parallax distances to the bulk of the Milky Way globular cluster population.

10.1.3 Local Group Rotational Parallax Calibrators

In Chapter 6 we saw that local galaxies will have 1 percent rotational parallax distances from SIM Lite. Thus, with additional photometry, most of which is already available, stellar groups such as Cepheid variables, Miras, post-planetary nebula objects, red giants, and hot main sequence stars can all be compared with Milky Way equivalents with essentially zero error due to luminosity uncertainty.

10.2 All-Redshift Galaxy Evolution

10.2.1 Galactic Evolution at All Redshifts

In the study of extragalactic stellar populations, many questions remain. These regard field versus cluster environment, chemical evolution, morphological evolution, emergence from the dark ages, and the overall scheme of galaxy assembly. The error in the isochrone-based ages of these populations — currently 30 percent — is the principal limitation on our ability to address these questions. Improved age determination, combined with an improved distance scale, will complement the direct studies of dynamics and the role of dark matter in galaxy assembly and evolution (Chapter 4). Better ages and distances, filtered through stellar evolution models and models for the integrated light of stellar populations, translate to better understanding of the chemical and age structure of the various stellar populations that make up the Milky Way and external galaxies. The age measurement tools can also be applied to data from the James Webb Space Telescope and from the new generation of adaptive-optics ground-based telescopes and play a vital role in their studies of galaxy formation.

10.2.2 Extragalactic Stellar Populations

The study of normal galaxy evolution will be greatly enhanced by SIM projects that target dynamics and dark matter, naturally. But those that target the distance scale provide a crucial, complementary strategy that mushrooms into much more than just distance knowledge. Better distances, filtered through stellar evolution models and models for the integrated light of stellar populations, translate to much more precise information on the chemical and age structure of the various stellar populations that make up the Galaxy and external galaxies.

With odd irony, the key for deriving ages throughout the universe is the humble and ubiquitous main sequence turnoff star. In the integrated light of galaxies, the game is to use spectroscopy to measure the chemical makeup of a galaxy and then uncover the temperature of the main sequence turnoff stars. Advanced phases of evolution (e.g., asymptotic giant branch stars) and the effects of binarism (e.g., blue straggler stars) and other physical effects (initial mass function [IMF], dust, rotation) serve, at this point, as complications, although they may turn into opportunities as our knowledge increases.

In the study of extragalactic stellar populations, a plethora of questions regarding field versus cluster environment, chemical evolution, morphological evolution, emergence from the dark ages, and the overall scheme of galaxy assembly remain, and are likely to remain for many years. Present age errors intrinsic to isochrone-based models are of order 30 percent (Charlot et al. 1996), but the clusters studied by SIM Lite should allow for increased precision for better understanding of galaxy evolution at all redshifts. A reasonable goal in this regard is 5 percent age precision for favorable, well-observed extragalactic stellar populations from the next generation of large, ground-based spectroscopic telescopes.

Morphological look-back studies (e.g., Galaxy Evolution from Morphology and Spectra, [GEMS], Rix et al. 2004) and spectroscopic surveys (e.g., Classifying Objects by Medium-Band Observations — a spectrophotometric 17-filter survey [COMBO-17], Wolf et al. 2004) dovetail nicely with stellar populations studies that earlier predicted in a broad way what the direct observations are finding. That is, spiral galaxies look as if they have had quasi-continuous star formation for long epochs, as expected, but elliptical galaxies, while largely quiescent today, have also had much more complex star formation histories than one would suppose, not too drastically different from spirals (Worthey 1998). The charting of galaxy assembly is a major scientific thrust of the James Webb Space Telescope and much of extragalactic astrophysics today.

SIM Lite will contribute toward this push by providing the foundation of age measurement tools that will be applied to JWST data. It can be used to obtain parallax distances to Galactic (disk; Population I) clusters. This will complement SIM Lite's Population II (halo and thick-disk) distance scale investigations described in Section 7.1. A critical step in studying ages and chemical compositions of stellar populations is to establish a collection of standard clusters, mostly Galactic clusters, for which distances, reddenings, abundances, and ages will be derived with unprecedented accuracy. SIM Lite is critical to this task by providing accurate parallax distances. These standard clusters can then be used to tightly constrain theoretical isochrone sets more stringently than ever before. The isochrones, in turn, give ages for clusters and also for galaxies via integrated-light models. Precision studies of galaxy evolution are the ultimate aims enabled by this SIM study.

Figure 10-1 illustrates this concept by parceling the universe of galaxies and clusters into age and metallicity bins. Galaxies that are not actively forming stars — leaving aside extreme post-starburst objects — will have ages of order 100 Myr, rather like the Pleiades star cluster, or older. Upper limits are imposed by the redshift of the galaxy, being younger at high redshift and, by the age of Milky Way globular clusters, at zero redshift. This age range is marked on the figure as "Red Envelope" Galaxies: those galaxies that are ready for the highest-quality spectral analysis, that is, their starlight is not too severely affected by internal dust and gaseous nebular emission.

The second dimension of Figure 10-1 is abundance. It is already crystal clear that metal-poor populations are a very minor component of the mass and the light output of any chemically mature galaxy (less than 5 percent contribution from stars less than a tenth of the solar abundance: Worthey, Dorman, and Jones 1996), so the parameter range of most interest is from somewhat subsolar to the supersolar regime of the most massive elliptical galaxies. Finally, a sprinkling of target clusters in the Milky Way has been overlaid on the figure, showing how Milky Way calibrators can indeed unlock the high-redshift Universe. The goal is to be able to age-date any stellar population at any redshift to 5 percent precision, given high-quality data.

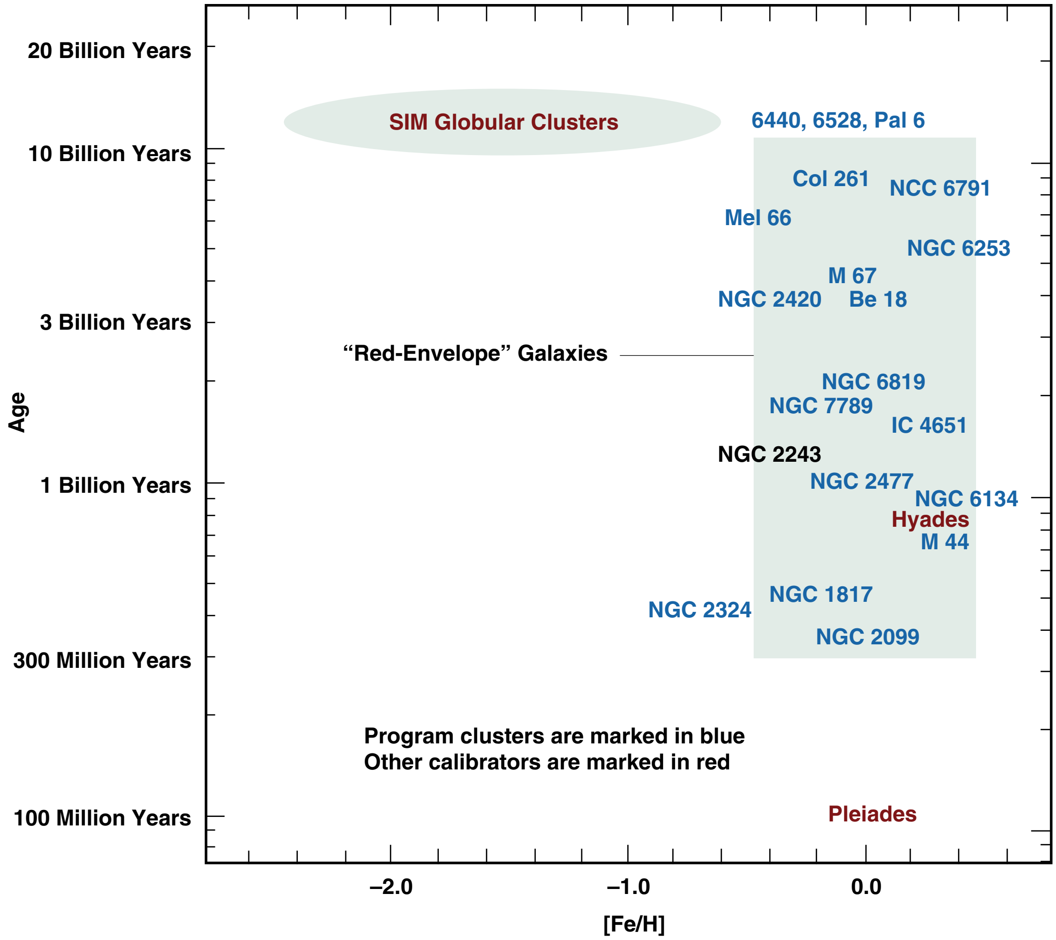

Figure 10-1. Clusters in the Milky Way studied by SIM Lite can be used to investigate distant galaxies.

10.2.3 Understanding the Systematics of Stellar Populations

An absolute 5 percent age precision requires a better grip on the systematics of stellar populations than presently exists. With precise distances from SIM Lite, distance will no longer contribute significantly to the uncertainties and, instead, other effects will dominate. For example, the uncertainty in heavy element abundance (Z) propagates approximately as $\delta \log(age) = -3/2\, \delta \log(Z)$ (Worthey 1994) using stellar temperatures as age indicators, as one is forced to do for integrated-light applications. This implies that overall heavy element abundance uncertainty be less than 0.02 dex, a goal reached only rarely at present, but which should be very common in the near future.

The detailed, element-by-element composition also matters. Worthey (1998) estimates that abundance ratio effects need to be tracked and calibrated if they induce more than a 7 K shift in stellar temperature. Progress on such detailed effects is underway (Dotter et al. 2007) and should be available in a few years. Progress on bolometric corrections, absolute flux scale, and stellar color-T_{eff} relations can also be expected over time.

A standard cluster set ties down points for stellar modelers, which relate intimately to the interpretation of high-redshift stellar population studies. SIM Lite will measure parallax distances to distant Galactic and globular clusters unreachable by Gaia, including the crucial old, metal-rich NGC6791 (see Figure 10-1 and the target list in Unwin et al. 2008). The luminosity of the main sequence turnoff in the color-magnitude diagram is the best age indicator: the one with the smallest errors (Chaboyer 1995) and the one that ties most directly to the “fusion clock” of the hydrogen-burning star.

Distance uncertainty is currently the dominant uncertainty, and that will be removed by SIM Lite (to less than 1 percent for most individual Galactic clusters, and perhaps 1 percent for the globular clusters in aggregate). After abundance effects, the remaining uncertainties are those of interstellar extinction, which may prove to be the dominant uncertainty in the end, along with the practical difficulty of extracting the main sequence turnoff temperatures amid the light of less well-understood phases of stellar evolution, notably the asymptotic giant branch that becomes quite important in the near infrared.

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