

# Anchoring the Population II Distance Scale: Accurate Ages for Globular Clusters and Field Halo Stars

## Abstract

As the oldest objects whose ages can be accurately determined, Galactic globular clusters can be used to establish the minimum age of the universe (and hence, to constrain cosmological models) and to study the early formation history of the Milky Way. The largest uncertainty in the determination of globular cluster ages is the distance scale. SIM will be able to determine distances to globular clusters and other stars in the halo with unprecedented accuracy, thereby significantly reducing the uncertainty in the derived ages of metal-poor stars. We are proposing a SIM key project to determine the distance scale to globular clusters (i.e. the Population II distance scale) which will allow us to determine the ages of globular clusters and field halo stars with unprecedented accuracy. To establish the Population II distance scale and the ages of the metal-poor stars in our galaxy, three different observing strategies will be utilized: (1) direct parallax distances to 21 nearby globular clusters; (2) calibration of the luminosity of RR Lyrae stars in the field and in globular clusters; and (3) parallax distances to a sample of Population II main sequence turn-off and subgiant branch stars. The parallax observations of field turn-off and subgiant stars will lead to an accurate determination of the ages of these stars. The direct parallax distances to the nearest globular cluster will be the cornerstone of the observing strategy allowing us to set a firm lower limit to the age of the universe accurate to  $\pm 5\%$  and to investigate the early formation history of the Milky Way. The calibration of the Population II distance scale will allow accurate distances to be obtained to a number of distant globular clusters and nearby galaxies (such as the Large Magellanic Cloud and Andromeda) and will help calibrate the zero point of the extragalactic distance scale. To maximally exploit the SIM observations in the determinations of cluster ages, we propose to initiate a wide spectrum of ground-based observational programs to improve the photometry of the clusters, their reddening estimates, the helium mass fraction, and the abundances of the heavy elements, especially oxygen.

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## Executive Summary

The metal-poor stars in the halo of the Milky Way galaxy were among the first objects formed in our Galaxy. These Population II stars are the oldest objects in the universe whose ages can be accurately determined. Age determinations for these 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. The age of the universe determined from studies of Population II stars may be compared to the expansion age of the universe and used to constrain cosmological models. The largest uncertainty in estimates for the ages of stars in our halo is due to the uncertainty in the distance scale to Population II objects. We propose to obtain accurate parallaxes to a number of Population II objects (globular clusters and field stars in the halo) resulting in a significant improvement in the Population II distance scale and greatly reducing the uncertainty in the estimated ages of the oldest stars in our galaxy. At the present time, the oldest stars are estimated to be 12.8 Gyr old, with an uncertainty of  $\pm 15\%$  ( $1\sigma$ , see section 1). The SIM observations we are proposing combined with the supporting theoretical research (section 2.2) and ground based observations (section 2.3) outlined in this proposal will reduce the estimated uncertainty in the age estimates to  $\pm 5\%$ .

The expansion age of the universe is determined by the present expansion rate of the universe (given by the Hubble constant,  $H_o$ ), the matter density of the universe (parameterized by  $\Omega_M$ ) and the vacuum energy density of the universe ( $\Omega_\Lambda$ ). Astronomy is entering into an era of precision cosmology where these fundamental cosmological constants will soon be determined to an unprecedented accuracy from a variety of ground and space based observations (such as HST and MAP). The proposed SIM observations and resultant age determination for the universe will provide an important, independent check of the preferred cosmological model.

The ages we determine will also be used to probe the early formation history of the Milky Way. Understanding the process of galaxy formation is a key quest in astrophysics and is one of the long term goals of NASA's Origins Program. The Milky Way plays a unique role in furthering our understanding of galaxy formation as it is the only large galaxy for which we can obtain detailed chemical, kinematic, and chronology information. The Milky Way provides us with a fossil record of its formation period, which yields unique insights into the process of galaxy formation.

RR Lyrae variable stars are Population II standard candles and can be used to determine the distances to globular clusters and nearby galaxies beyond the reach of SIM. An important part of this proposal will be to determine the luminosity of the RR Lyrae stars (section 3). This will be done via distance determinations to globular clusters rich in RR Lyrae stars and a selected sample of RR Lyrae stars in the field. This calibration of the luminosity of RR Lyrae stars will allow accurate distances to be obtained to a number of distant globular clusters and nearby galaxies (such as the Large and Small Magellanic Clouds). Refining the distance estimates to nearby galaxies will help calibrate the zero point of the extragalactic distance scale.

In order to achieve these goals, we propose the following SIM observations

1. parallax and proper motion measurements to 5 stars in each of 21 different globular clusters. These clusters have been chosen to span a range in metallicities, horizontal branch types, number of RR Lyrae stars and Oosterhoff types (section 2)
2. parallax measurements to a selected sample of 60 field RR Lyrae stars, chosen to complement the RR Lyrae star observations taken by FAME (section 3).
3. parallax and proper motion measurements to 60 metal-poor main sequence turn-off and subgiant branch stars in the field, allowing us to determine the age of the halo stars and directly compare this to the globular clusters ages (section 4).

Field stars make up  $\approx 99\%$  of the halo, and are an important population to study in our quest to understand the early formation history of the Milky Way. The parallaxes we obtain for a large sample of main sequence turn-off and subgiant branch stars in the halo of the Milky Way will allow us to accurately determine the ages of these stars and will complement our globular cluster age estimates in providing a firm lower limit to the age of the universe.

To take full advantage of the SIM parallax results will require a concentrated effort to reduce other uncertainties associated with the age determination process. Accurate photometry and heavy element abundances will be obtained for all of the target stars and globular clusters. Helium abundances will be determined through studies of eclipsing binaries in the nearest globular clusters and double-lined spectroscopic binaries in the halo. We will also undertake detailed spectroscopic studies for stars in selected globular clusters to establish a very high quality set of  $gf$  values, and apply those results to determine the atmospheric parameters and  $[\text{Fe}/\text{H}]$  values for all of our program clusters and field stars. We will obtain the even more crucial abundances of oxygen and other  $\alpha$  elements for all of our targets. We will seek to reduce possible systematic errors by using a variety of oxygen lines in stars in selected clusters. The resultant high-precision chemical compositions will be used as input parameters to the stellar models and isochrones. The input physics used to construct the theoretical stellar models and isochrones will be improved through a continuing investigation of the fundamental physics which governs the evolution of stars. These ground based observations and theoretical work are key to substantially reducing the error in age estimates for the oldest stars in the Galaxy.

This key project is estimated to cost \$6.1M over the next 11 years and require 1330 SIM mission hours. This investment will lead to an improved understanding of the galaxy formation process, a substantially improved Population II distance scale and an determination of the minimum age of the universe to an accuracy of  $\pm 5\%$ . This key project will address questions of great general interest such as how old the universe is, and how our galaxy came to form. These exciting topics can form the basis of educational efforts for students and the public, and our team is eager to contribute to such efforts.

# 1 Introduction

Studies of the ages of the metal-poor stars in the halo of the Milky Way (Population II stars) address two problems of fundamental importance in astronomy: (1) they provide a stringent lower limit to the age of the universe and as such, provide a fundamental constraint on cosmological models and (2) they provide unique information regarding the early formation history of the Milky Way which is important to understanding the process of galaxy formation.

In a standard Friedmann-Walker universe, the evolution of the universe is completely specified by three of the following four quantities: the present age of the universe  $t_o$ ; the present expansion rate of the universe  $H_o$ ; the matter density of the universe  $\Omega_M$ ; and the vacuum energy density  $\Omega_\Lambda$ . Recent observations favor a universe with  $H_o \simeq 70$  km/s/Mpc (e.g. Mould et al. 2000),  $\Omega_M \simeq 0.3$  and  $\Omega_\Lambda \simeq 0.7$  (Perlmutter et al. 1999; Lange et al. 2000). These parameters imply  $t_o = 13.5$  Gyr. One of goals of this proposal will be to obtain an independent estimate of  $t_o$  from stellar ages and to see if this estimate is compatible with the accepted values of the cosmological parameters.

Another major goal of this proposal will be to obtain precise relative ages for a number of globular clusters (GCs) and field halo stars which vary in metallicity and kinematics. This will allow us to address a number of questions related to the formation of the Milky Way, and galaxy formation in general. For example, did the more metal-rich stars in the halo form at a significantly later time than the metal-poor stars? Did the thick disk GCs form at the same time as the GCs in the halo? Is there a significant age range among the Galactic GCs and/or field halo stars? These are open questions which have been a subject of considerable debate (see the contrasting reviews by Stetson et al. 1996 and Sarajedini et al. 1997). By obtaining accurate distances to a large number of metal-poor stars and GCs, the primary source of uncertainty in the age estimates will be sig-

nificantly reduced leading to much more accurate age estimates. This will allow us to make definitive statements regarding the chronology of the formation of the halo and thick disk of the Milky Way.

Globular clusters provide the best opportunity to determine ages of Population II (hereafter Pop II) stars, as it is easy to identify the various evolutionary sequences in a GC color-magnitude diagram. The main sequence turnoff (MSTO) luminosity is the best stellar ‘clock’ which can be used to determine the absolute ages of GCs (e.g. Demarque 1980; Rood 1990; Vandenberg 1990; Renzini 1991). A 1% error in the distance leads to a  $\approx 2\%$  error in the derived age.

The distance scale to GCs (and Pop II stars in general) is still subject to a great deal of uncertainty. RR Lyrae stars (RRL) are the standard candle typically used to set the Pop II distance scale. The publication of the Hipparcos database led to a heightened interest in the Pop II distance scale. The book ‘Post-Hipparcos Cosmic Candles’ contains four review papers (Chaboyer 1999; Gratton et al. 1999; Layden 1999; Popowski & Gould 1999) which discuss the state of the Pop II distance scale. The absolute magnitude calibrations of the RRL stars published by these authors had a range of over 0.30 mag.

The impact that the current uncertainty in the Pop II distance scale has on GC age estimates was evaluated with a Monte Carlo simulation. In this simulation, the uncertainties in the composition parameters and various input physics used to construct stellar models and isochrones (such as  $[\alpha/\text{Fe}]$ , helium abundance, nuclear reaction rates, etc) were varied within their presently known uncertainties (Chaboyer et al. 1998). The results of the simulation are shown in Figure 1. The value of  $M_V(\text{RR})$  was chosen randomly from a distribution which encompasses the current uncertainties in measuring  $M_V(\text{RR})$  and reflects the values discussed by Chaboyer (1999), Gratton et al. (1999), Lay-

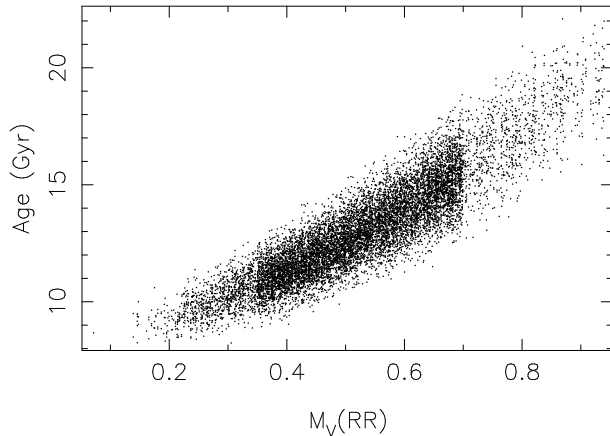


Figure 1: The estimated age of the oldest GCs, as a function of the assumed absolute magnitude of the RRL stars (at  $[\text{Fe}/\text{H}] = -1.90$ ). The vertical extent of the points at a given  $M_V(\text{RR})$  illustrates the current theoretical and observational uncertainties of the age dating process, assuming that the distances to the GCs are known exactly.

den (1999) and Popowski & Gould (1999).

It is clear from Figure 1 that the current uncertainties in the calibration of the Pop II distance scale imply an allowed range for the age of the oldest GCs from 10 to 17 Gyr. The large error in current estimates for the absolute age of the oldest GCs makes them a weak test of cosmological models.

SIM will be able to measure accurate parallaxes to objects within 10 kpc of the Sun. This excludes a large number of GCs in the halo of our Galaxy along with a number of satellite galaxies, such as the Large Magellanic Cloud. For these objects, astronomers will have to continue to use standard candles (such as RRL stars) to determine their distances. For this reason, a third major goal of this key project proposal is to improve the Pop II distance scale through an accurate calibration of the magnitude of the RRL stars, as a function of their metallicity and evolutionary status. The Full-sky Astrometric Mapping Explorer (FAME) will determine the zero-point of the  $M_V(\text{RR})$ - $[\text{Fe}/\text{H}]$  relation, but will not be

able to accurately determine  $M_V(\text{RR})$  as a function of metallicity and evolutionary state. We propose to determine the distances to a large number of RRL stars in order to significantly reduce the uncertainty in the Pop II distance scale. This effort will allow accurate distances, and hence ages to be determined for a large number of GCs in the halo of our galaxy which are too distant for parallax measurements by SIM.

## 2 Globular Cluster Distances and Ages

Obtaining accurate parallaxes to GCs will allow us to (1) determine the ages of the GCs and (2) determine the luminosity of the RRL stars in each cluster. We are interested in two different types of ages (a) absolute ages for the most metal-poor GCs (yielding a lower limit to the age of the universe) and (b) relative ages among GCs of a range of properties in order to probe the early formation history of the Milky Way. These science goals require that we pick a diverse sample of GCs. In particular, we would like a sample of GCs which span a range in metallicities (to look for age-metallicity relations) but which include a significant number of the most metal-poor GCs; a range in kinematics (old halo, young halo and disk, allowing us to look for correlations between kinematics and age) and a range in Oosterhoff types (see section 3) allowing us to check for systematic trends in the luminosity of RRL stars.

To achieve our science goals requires us to observe GCs which will have the smallest possible errors in their age determinations and in their derived luminosity of the RRL stars. Our age determination method will use the absolute magnitude of the stars on the main sequence turn-off ( $M_V(\text{TO})$ ) and/or sub-giant branch ( $M_V(\text{SGB})$ ) (Chaboyer et al. 1996) as the stellar clock. SIM will obtain parallaxes, and hence, direct distances to the GCs.

**Reddening:** In order to convert this dis-

tance to a determination of the absolute magnitude of the stars in the GC will also require a knowledge of the reddening to the cluster ( $A_V = 3.2 E(B - V)$ ). Thus, we need to pick GCs which have small reddenings. We will rely on five methods to determine reddening to each cluster. First, we plan to utilize the DIRBE/IRAS dust maps of Schlegel et al. (1998); these maps produce reddenings with an accuracy of 16% leading to a typical error of  $\sigma_{E(B-V)} = 0.02$  mag in the reddening of clusters in our sample.

We will supplement these reddenings with those determined via the simultaneous reddening and metallicity (SRM) method of Sarajedini (1994). The SRM method takes advantage of the fact that the position and shape of the red giant branch (RGB) in the CMD is influenced by reddening and metallicity in different ways. Judging from the work of Sarajedini (1994) and Sarajedini & Layden (1997), the typical reddening error yielded by the SRM method is expected to be  $\sigma_{E(B-V)} = 0.02$  mag.

Spectroscopic temperatures for the red giants and observed colors for low-reddening GCs will be used to empirically determine a color-temperature relationship. In the more heavily reddened GCs, the spectroscopic temperatures will be converted to a color and compared to the observed colors in order to estimate the reddening. In addition, we will look for variations in the strength of the interstellar lines (Ca K and Na D) from our observations of several stars within each cluster. This will allow us to check for possible variations in reddening within a GC.

Clusters which contain blue horizontal branches will have their reddenings estimated from color-color data. Lastly, we will use the RRL colors to estimate the cluster reddenings. The minimum-light colors of ab-type RRL are nearly identical after small corrections for metallicity and period (Sturch 1966; Mateo et al. 1995). We estimate an error of  $\sigma_{E(B-V)} = 0.02$  mag in these determinations.

The zero points of each determination will be checked through an analysis of the well-observed GCs in our sample such as M92 and M3. The reddenings yielded by all of these methods will then be combined to obtain a mean reddening for each GC with an estimated error of  $\sigma_{E(B-V)} \leq 10\%$ . It is likely that a zero-point uncertainty of  $\pm 0.01$  in  $E(B - V)$  will exist in our reddening determinations.

**Target Selection:** With the constraints imposed by the estimated distances and reddenings to known GCs, along with our desire to pick a diverse sample of GCs we have selected 21 nearby GCs as our targets for parallax determinations by SIM. The properties of this sample, along with the expected accuracy in distance determinations, derived absolute magnitudes and age determinations are listed in Table 1. The clusters we have chosen contain a large number of RRL stars which will allow us to compare the absolute magnitude of RRL stars in the clusters to those in the field (see section 3). They span a range in metallicity, kinematic type and Oosterhoff type. A large number of metal-poor clusters have been selected allowing an accurate determination of the age of the oldest GCs.

## 2.1 Error Budget in the Ages

The final error in our derived ages for the globular clusters will consist of two components: a random component which values from cluster to cluster and a systematic component which affects the age determinations of all of the GCs. The random error is of importance when discussing relative ages and the formation of the Milky Way. The systematic errors are of importance when one averages together the ages of the most metal-poor GCs in order to determine the minimum age of the universe.

Table 1: Target Globular Clusters

NGC	Name	$R_{\odot}$	$E(B - V)$	$V_{\text{HB}}$	[Fe/H]	KT	Nrr	Oo	$\sigma_{\pi}$ (%)	$\sigma_{M_V}$ (mag)	$\sigma_{M_K}$ (mag)	$\sigma_{\text{age}}$ (%)
[Fe/H] < -1.80												
6397	–	2.2	0.18	12.87	-1.95	OH	–	–	1	0.06	0.02	6
6809	M55	5.3	0.07	14.40	-1.81	OH	10	–	2	0.05	0.04	5
6541	–	7.4	0.12	15.30	-1.83	OH	–	–	3	0.07	0.06	6
7099	M30	7.9	0.03	15.10	-2.12	OH	10	II	3	0.07	0.06	6
6341	M92	8.1	0.02	15.10	-2.29	OH	25	II	3	0.07	0.07	6
4590	M68	10.1	0.04	15.68	-2.06	YH	41	II	4	0.08	0.08	7
-1.80 < [Fe/H] < -1.45												
6752	–	3.9	0.04	13.70	-1.55	OH	–	–	2	0.04	0.03	5
6218	M12	4.7	0.19	14.60	-1.48	OH	–	–	2	0.07	0.04	7
3201	–	5.1	0.21	14.80	-1.48	YH	85	I	2	0.08	0.04	8
5139	$\omega$ Cen	5.1	0.12	14.53	-1.62	OH	152	II	2	0.06	0.04	9
6205	M13	7.0	0.02	14.90	-1.54	OH	3	–	3	0.06	0.06	6
5272	M3	10.0	0.01	15.65	-1.57	YH	260	II	4	0.08	0.08	8
-1.45 < [Fe/H] < -1.00												
5904	M5	7.3	0.03	15.07	-1.29	OH	123	I	3	0.06	0.06	6
6362	–	7.5	0.09	15.34	-1.06	OH	33	I	3	0.07	0.06	7
288	–	8.1	0.03	15.30	-1.24	OH	–	–	3	0.07	0.07	7
362	–	8.3	0.05	15.43	-1.16	YH	13	I	3	0.07	0.07	7
6723	–	8.6	0.05	15.50	-1.12	OH	29	I	3	0.07	0.07	7
[Fe/H] > -1.00												
6838	M71	3.8	0.25	14.44	-0.73	D	–	–	2	0.09	0.03	6
104	47 Tuc	4.3	0.05	14.06	-0.76	D	1	–	2	0.04	0.04	6
6352	–	5.6	0.21	15.13	-0.70	D	–	–	2	0.08	0.05	8
6652	–	9.4	0.09	15.85	-0.85	YH	–	–	4	0.08	0.08	8

Values taken from the Harris (1996) compilation, unless otherwise noted.

Notes on individual columns:

$R_{\odot}$  – distance from the Sun these values are uncertain by  $\pm 10\%$ .

$E(B - V)$  – reddening

$V_{\text{HB}}$  – V magnitude of the horizontal branch. SIM target stars will have similar magnitudes.

KT – Kinematic Type: OH = Old Halo; YH = Young Halo; D = Thick Disk, from DaCosta & Armandroff (1995)

Nrr – Number of RR Lyrae stars in the cluster (from compilation by Carney)

Oo – Oosterhoff Type (from compilation by Carney)

$\sigma_{\pi}$  – percent uncertainty in the parallax, assuming  $4\mu$  as accuracy

$\sigma_{M_V}$  – uncertainty in  $M_V$  including contributions due to uncertainties in the distance determination, reddening and photometric zero-point

$\sigma_{M_K}$  – uncertainty in  $M_K$  including the same sources of error as in the  $M_V$  error

$\sigma_{\text{age}}$  – percent uncertainty in the age estimate, see text for further details.



The errors quoted in Table 1 are the random errors only. This error represents the error in the *relative* abundances and ages. The error in the absolute ages is discussed in section 2.2. The size of the relative age errors is of interest when considering questions related to the formation of the Milky Way. The age uncertainty was calculated using new isochrones constructed by Chaboyer specifically for this proposal. These isochrones include infrared (JHK) colors, allowing us to evaluate the relative merits of observations in the optical and infrared wavelengths. As a rough guide, the amount the various sources of error contribute to the uncertainty in the age estimates are given below.

- **Parallax uncertainty:** A 1% uncertainty in the parallax will translate into a 2% uncertainty in the age for observations in the  $V$  band and to a 4% uncertainty in the  $K$  band.

- **Reddening Uncertainty:** An uncertainty in  $E(B - V)$  of  $\pm 0.01$  mag will lead to an error in the age of 3% in the  $V$  band and to 0.3% in the  $K$  band. A zero-point uncertainty in the reddening determination of  $\pm 0.01$  mag along with a random uncertainty in the reddening equal to 10% of the value of the reddening has been assumed in Table 1.

- **Photometric Accuracy:** High quality color-magnitude diagrams will allow the determination of  $M_V(\text{SGB})$  or  $M_K(\text{SGB})$  to an uncertainty of  $\pm 0.01$  mag, implying an error in the derived age of  $\pm 1\%$  ( $V$  band) and  $\pm 2\%$  ( $K$  band).

- **Heavy Element Composition:** Our determinations of  $[\text{Fe}/\text{H}]$  and  $[\text{O}/\text{Fe}]$  will have a random uncertainty of  $\pm 0.03$  dex per cluster (see section 2.3). The  $[\text{O}/\text{Fe}]$  uncertainty will lead to an error in the derived age of  $\pm 1\%$ . The  $[\text{Fe}/\text{H}]$  uncertainty will lead to an error in the derived age of  $\pm 0.6\%$ .

- **Helium Abundance:** It is estimated that the helium abundance will be known to a 5% accuracy (see section 2.4). This will lead to an error in the derived ages of  $\pm 3\%$ .

In order to minimize the total error in our age estimates, ages will be derived from optical photometry for all but three or four GCs (NGC 6397, M71, NGC 3201 and possibly NGC 6752). The stars in the massive GC  $\omega$  Cen have a range of metallicities, and it has been assumed that this will lead to a significant increase in the error on the derived age of this cluster.

These precise age determinations require that the photometry be accurate to  $\pm 0.01$  mag and that we can measure  $M_V(\text{SGB})$  to a similar accuracy. Many of the clusters in this list do not have such precise photometry. We will obtain new, accurate optical and/or infrared photometry to ensure that all of the clusters listed in Table 1 have accurate photometry. These observations will be taken using telescopes at MDM (north), LCO (south) and SOAR (south) for which we have guaranteed access.

Our target GC sample includes 5 metal-poor ( $[\text{Fe}/\text{H}] < -1.8$ ) clusters which belong to the ‘old halo’ (Da Costa & Armandroff 1995). The error in the mean age of this group will be  $\pm 2.6\%$ . At a similar metallicity, M68 has been suggested to be a ‘young’ halo GC (based upon its horizontal branch morphology). Thus, one question which this project will seek to answer is if an age difference exists between M68 and other clusters with a similar metallicity. Given the expected uncertainties in our age determinations, we will be able to make a strong ( $2\sigma$ ) statement regarding the age difference if M68 is 14% ( $\approx 2$  Gyr) younger than the other clusters.

The error in the mean age of the old halo clusters (or disk clusters) in each of our metallicity bins will range from  $\pm 2.6\%$  at the metal poor end to  $\pm 3.8\%$  at the metal-rich end. Thus, differences in the mean ages of the different metallicity groups greater than  $\approx 10\%$  (1.4 Gyr) will be easily determined using the data we obtain. These precise relative ages will allow us to investigate the chronology of the formation of the halo and thick disk in the Milky Way. Our radial velocity work (see below) will yield precise ( $\pm 0.5$  km/s) radial velocities which will

be combined with the proper motions obtained by SIM to determine the orbit of each cluster and to search for systematic trends between kinematics, metallicity and age.

## 2.2 Improved Stellar Models and Isochrones

Ultimately, the absolute accuracy of the ages derived by this project will rest upon the reliability of the stellar models and isochrones which are used to determine the ages. In the construction of stellar models and isochrones, a large number of input parameters (such as nuclear reaction rates, opacities and diffusion coefficients) are required, along with a number of simplifying assumptions (for example, how convection is treated). In order to obtain ages of the highest accuracy, a concentrated effort will be made over the lifetime of this key project to improve the physics used in the stellar models. Research will be conducted in a number of areas and combined to produce stellar models and isochrones which accurately reflect the true evolution of low mass ( $M \lesssim 1.0 M_{\odot}$ ) stars.

We anticipate that our studies, along with results from other groups, will lead to a significant improvement in the absolute accuracy of stellar models and isochrones over the next decade. Currently, uncertainties in the stellar models and isochrones imply that even if the heavy element composition and distance to a GC are known exactly, then the error in the estimated age of the cluster is  $\pm 4\%$  ( $1\sigma$ , Chaboyer et al. 1998). Our goal will be to reduce this uncertainty associated with stellar models by a factor of 2 or more over the lifetime of the SIM mission. Doing so will require a number of improvements in the stellar models. Here, we briefly outline five areas of research which should allow us to achieve our goal of reducing the theoretical uncertainty in the models by at least a factor of two.

1. The study of solar oscillations (helioseismology) has led to a detailed understanding of

the interior structure of the Sun (e.g. Gough et al. 1996). This has included the realization that the gravitational settling of helium and other heavy elements must be included in order to obtain accurate solar models. Chaboyer has been involved in helioseismic research for a number of years (e.g. Chaboyer et al. 1995; a member of the GONG modeling and inversions team) and will continue to utilize helioseismic observations to constrain the physics used in the construction of stellar models.

2. In the near future, observations of non-radial (solar type) oscillations on other stars will be used to investigate the structure of stars other than the Sun. For example, Buzasi et al. (2000) have recently reported a detection of 10 solar type oscillation modes on a KO III star with  $M \approx 4.0 M_{\odot}$ . Buzasi has also observed Procyon A ( $M = 1.5 M_{\odot}$ ). Chaboyer et al. (1999) calculated oscillation modes of Procyon A based upon a number of stellar models. The calculated oscillation frequencies are uncertain by 1%, due to known uncertainties in the stellar models. As such, observations of  $p$ -mode frequencies on Procyon A will serve as a robust test of stellar evolution models. Chaboyer will continue this work on astro-seismology in order to test and improve stellar evolution models. He is currently involved in an HST project to detect solar-type oscillations on an F5 star, and has recently been asked to join the MONS modeling and analysis team (MONS is a Danish satellite dedicated to the measurement of solar-type oscillation in other stars, scheduled for launch in 2003).

3. One of the principal uncertainties in constructing models for the evolution of stars is the treatment of convection. This leads to a significant uncertainty in GC age estimates (Chaboyer 1995). The standard mixing length treatment of convection is commonly used, but is clearly inadequate. Helioseismic observations of clearly shown that mixing length theory does **not** correctly predict the super-adiabatic gradient at the surface of the Sun (e.g. Demar-

que et al. 1999). There is a considerable effort among a number of groups (Chaboyer is associated with one of these groups) to improve the treatment of convection in stellar models, and it is anticipated that by the time accurate parallaxes from SIM are available, the current uncertainty in treating convection in stars will be considerably reduced.

4. As Chaboyer et al. (1996) noted, the  $^{14}\text{N}(p,\gamma)^{15}\text{O}$  reaction rate is a significant source of uncertainty in GC ages. Work now underway by Dr. Art Champagne and his collaborators at UNC, working at the Triangle Universities Nuclear Lab, will soon provide a much more accurate value for this reaction.

5. Luminosity functions (number of stars as a function of their luminosity) of GCs can be used to test the *relative* evolutionary time scales predicted by the stellar models. The evolution from the main sequence turn-off to the tip of the red giant branch is very quick, implying only a small difference in initial mass between stars at the turn-off and those at the tip. As such, the number of stars as a function of luminosity from the turn-off to the tip of the red giant branch does not depend on the initial mass function and simply reflects the relative evolutionary timescale for the stars. We will use ground based and HST observations of a number of clusters in our SIM target lists to construct luminosity functions containing  $\gtrsim 10^5$  stars. These luminosity functions will be used to test the relative evolutionary timescales predicted by the stellar models.

We are confident that these ongoing research projects will reduce the theoretical uncertainties in the age estimates of GCs to  $\pm 2\%$ . This will be one of our primary sources of error in the estimate for the absolute age of the oldest GCs (used to determine the minimum age of the universe). The estimated uncertainty in the ages of the individual clusters shown in Table 1 includes the random uncertainties in the distance determinations and abundance analysis, but does not include the systematic uncertainty

associated with the stellar models, or a systematic uncertainty in the abundance scale. If we average the age of the 5 old, most metal-poor clusters in our sample (NGC 6397, 6809, 6541, 7099 and 6341), then the random error in the mean age will be 2.6%. Assuming a systematic uncertainty in our total heavy element abundance scale of  $\pm 0.07$  dex (see section 2.3) will lead to an error in our mean estimated age of 2.2%. The error in the helium abundance will lead to an error of 3% in the age. Thus, the estimated total uncertainty in our absolute age of the oldest GCs is  $\pm 4\%$  (adding the errors due to the models, the heavy element composition, the helium abundance and the mean age in quadrature). Our final age estimate and associated error estimate will be calculated using a Monte Carlo analysis similar to that done by Chaboyer et al. (1998).

## 2.3 Heavy Element Abundances

Since the structure and evolution of GC stars is dependent on the interior opacities, it is essential to measure the chemical composition as precisely as possible; metallicity errors of order 0.1 dex will lead to uncertainties comparable to those arising from the parallaxes ( $\geq 3\%$ ). This suggests that in order to eliminate the composition as a significant source of error we require metallicity measurements to an accuracy of 0.05 dex.

**Iron Abundance Scale:** In our opinion the chemical abundances of GCs is not determined to the required precision. For example, Carretta & Gratton (1997) provide a useful source for high resolution  $[\text{Fe}/\text{H}]$  values for some, but not all of our clusters; but the data are highly inhomogeneous, based mostly on a re-analysis of literature equivalent widths from spectra with a variety of wavelength regions, S/N and resolving powers, for a set of randomly selected stars. Regrettably, these issues leave the data set insufficient for our purposes, particularly as the Fe I equivalent widths values

are not all on the same system, and systematic differences between  $gf$  values used for lines in metal-poor and metal-rich stars could exist.

In our experience, the scatter in measured iron abundances for red giant stars comes from photon noise, continuum placement uncertainty, blending with weak contaminant lines, uncertain  $gf$  values, incorrect (or inappropriate) model atmosphere parameters, and deficiencies in the model atmosphere physics. In order to reduce errors introduced by photon noise, uncertain continuum placement, and line blending we will acquire spectra with the maximum resolving power available to us ( $R \simeq 60,000$  at Magellan and the MMT), with  $S/N \geq 100$  per pixel for our field and cluster stars. We will place appropriately greater weight on abundances derived from lines on the linear portion of the curve of growth, which have the maximum sensitivity to abundance and minimum dependence on micro-turbulent velocity. Errors due to uncertain  $gf$  values, line blends, and any non-LTE effects can be greatly reduced by computing line-by-line relative abundances.

Given the large range in cluster  $[Fe/H]$  it is necessary to ensure that the  $gf$  scale for weak and strong Fe I lines yields the same results. This will be accomplished by: (1) Comparison of iron abundances from cool and warm stars within two or three of our target clusters with a wide range of temperatures. In the cooler stars the low- $gf$  lines dominate the iron abundance, whilst in the hotter stars only the high- $gf$  lines will be usable. If the  $gf$  scale is internally consistent then one would obtain the same  $[Fe/H]$  for warm and cool stars. (2) A similar approach is to measure the iron abundance in RR Lyrae stars at cool and warm phases; although shocks may influence the results. Such multiple observations of the field RRL will be necessary to assure us that metallicities derived for them do not have systematically different abundances from the GCs for which we and others will determine distances using this crucial standard candle. (3) With sufficiently high  $S/N$  spec-

tra (300-500) for the most metal-poor GC stars it will be possible to derive iron abundances from lines which are on the linear portion of the curve of growth in the most metal-rich GC stars; for example these lines will be  $\simeq 1$  mÅ in NGC 6397 ( $[Fe/H]=-2$ ) and  $\simeq 30$  mÅ in 47 Tuc ( $[Fe/H]=-0.8$ ). *Thus we may use the same set of weak lines in all GC stars*, and derive relative iron abundances independent of  $gf$  value. If the high  $S/N$  spectra do not give a satisfactory result we can use a GC of intermediate metallicity (e.g. M5  $[Fe/H]=-1.3$ ) to link the  $gf$  scales in the most metal-poor and metal rich GCs.

In order to further reduce  $[Fe/H]$  errors for all of our clusters, we will concentrate on stars in clusters within a narrow temperature window. The temperature windows will vary, depending on a cluster's metallicity, so that the lines employed from one cluster to the next lie roughly on the same part of the curve of growth. Due to the metallicity-dependence of the giant branch, this means that stars in the metal-rich clusters will be somewhat hotter and fainter than those in metal-poor clusters.

The sample will be selected based on photometric temperatures, then the Fe I lines will enable the most appropriate model  $T_{\text{eff}}$  to be determined, by forcing the abundance to be independent of line excitation. We have achieved  $T_{\text{eff}}$  of 40 to 50 K by this method. This spectroscopic method is powerful because it selects the model atmosphere which best represents the conditions responsible for the spectrum and gives the smallest dispersion in derived abundances, even if systematic errors exist in the atmosphere grid. Our temperatures will be compared with photometric values from the relations of Alonso et al. (1996, 1999) and will provide useful constraints on the cluster reddenings. For atmospheric gravities we will rely on both spectroscopic and photometric measures; previously we found agreement to within 0.04 dex in  $\log g$  for stars with good Hipparcos parallaxes.

### Oxygen and $\alpha$ Element Abundances:

Because oxygen typically provides more than 60% of the total mass fraction of metals in halo stars the [O/Fe] ratio is critical to the final derived ages (note that together  $\alpha$ -elements comprise roughly 80% of the metals by mass in halo stars). Since non-uniform enhancements of oxygen and other  $\alpha$  elements (e.g Mg, Si, Ca, Ti) relative to iron is seen for many halo objects (e.g. Brown et al 1997; Carney et al. 1997; Nissen & Schuster 1997), it is not safe to simply infer the oxygen abundance of our program stars from [Fe/H]. Our objective requires that we measure both iron and oxygen, or an oxygen proxy. The requirement for oxygen abundance measurements is made more compelling given a current controversy over the trend of [O/Fe] with [Fe/H] in the halo. The important oxygen abundances will be based primarily on the forbidden lines at 6300, 6363 Å, which are arguably the most reliable lines accessible. Oxygen depletion (due to mixing down to levels where the ON cycle is operating) is a well-recognized phenomenon in clusters (e.g. Kraft et al. 1993). Oxygen destruction requires high temperatures, and cluster sodium abundances are an excellent indicator of the degree of the mixing (Kraft 1994; Carney 1996). As mixing begins to alter photospheric abundances, sodium is seen to increase in abundance, with no change in oxygen until the sodium abundance has increased significantly. Thus, our determinations of sodium abundances will reveal which stars have experienced lesser degrees of mixing. We can use other elements as a proxy for the oxygen abundance; in particular Mg and O are thought to be formed in the most massive type II supernovae. Although Mg can be slightly affected by hot-bottom envelope burning in evolved red giants, this is accompanied by large Al enhancements. The  $\alpha$  elements Si, Ca and Ti, (not affected by envelope burning) are also thought to be formed mostly by type II supernovae, and could be used to infer O abundance.

Prior to acquisition of full-coverage,  $R \simeq 60,000$ , spectra we will obtain restricted-wavelength fiber spectra of  $\approx 50$  RGB stars per cluster, in order to identify stars affected by envelope processing of O, as indicated by Na and Al. Given the small number of [O I] and good Mg I lines available the fiber spectra will also permit improved accuracy of the cluster O and Mg abundances, despite the expected lower resolution.

Recently Israelian et al. (1998) and Boesgaard et al. (1999) found evidence for a 0.5 dex upward revision in halo [O/Fe] ratios; this is not universally accepted (e.g. Fulbright & Kraft 1999), and we are skeptical of the new claim. Even though the oxygen issue is likely to be resolved by forthcoming studies of IR OH lines (e.g. see Balachandran & Carney 1996), the situation probably requires us to exercise caution. We will adopt two approaches for independent measurement of the oxygen abundances derived from the [O I] lines: First, we will acquire near-IR spectra of OH lines for a small sample of stars in one or two of our clusters, using Gemini or SOAR telescopes with the Phoenix IR spectrograph or any improved instrumentation. Coverage of the OH features near 1.6  $\mu\text{m}$  and the CO features near 2.2  $\mu\text{m}$  will help determine both carbon and oxygen abundances. The red giant branch tips for NGC 6397, NGC 6752, and 47 Tuc, which span our metallicity range, all lie at  $K \approx 7.2$  mag. A 4-meter telescope can easily achieve  $S/N > 100$  in reasonable exposure times at resolving powers of 40,000 for stars with  $K \approx 10$ . Second, we will also utilize O I lines near 9260 Å in clusters with blue horizontal branch stars (e.g. see Lambert, McWilliam & Smith 1992). Due to their high excitation potential these lines are useful only in such relatively hot stars. In these stars the region also contains C I lines at 9061–9095 Å and N I lines at  $\lambda\lambda 8185$ –8718 Å; thus we can measure C+N+O which is constant in the CNO cycle. In the red giants we will measure carbon abundances from the CH G-band lines;

nitrogen will be measured from the red CN lines in metal-rich clusters and the CN band lines at 3883Å for metal-poor giants. We note that for red giants it is necessary to measure the carbon and oxygen abundances simultaneously, to account for formation of the CO molecule; failure to include CO equilibrium results in O under-abundances, by typically 0.05 dex.

**Improved Computational Treatment:**

We plan to undertake the abundance analyses using ATLAS12 (supplied by Dr. R. L. Kurucz), which employs opacity sampling rather than opacity distribution functions (ATLAS9) to compute the model atmospheres to check the importance of opacity in the models.

We will also estimate the magnitude of non-LTE effects on our Fe abundances. Model Fe atoms for non-LTE calculations in hot stars have already been constructed (e.g. Thévenin & Idiart 1999), and we already have experience with Ca non-LTE calculations in red giants, using the program MULTI (Carlsson 1986).

**Error Budget:** Our previous experience with spectroscopic temperatures and gravities derived from high S/N Keck data suggests that we can constrain model atmosphere parameters  $T_{\text{eff}}$  and  $\log g$  to 50K and 0.04 dex respectively. For RGB stars 100K uncertainties in  $T_{\text{eff}}$  lead to typical abundance errors of  $\approx 0.12$  dex for Fe I lines; for gravity-sensitive species, such as Fe II or [O I], the sensitivity is approximately 0.07 dex in abundance per 0.3 dex change in  $\log g$  (see McWilliam et al 1995). This suggests uncertainties on the order of 0.06 dex per star arising from the atmosphere parameters. We can reduce this random component to 0.03 dex by taking samples of 4, or more, stars per cluster.

Systematic errors are harder to estimate, but our use of several very different approaches to obtain the abundances of the key element, oxygen, should enable us to understand their importance and how to reduce them to below the desired precision level of 0.07 dex.

## 2.4 Helium Abundance

The construction of stellar models requires that the helium abundance be specified. A 10% uncertainty in the helium mass fraction leads to a 6% uncertainty in the derived age (Chaboyer et al. 1996). It is generally assumed that the helium abundance in halo stars is equal to the value found in low metallicity extragalactic H II regions (e.g. Pagel et al. 1992). However, the determination of the helium abundance in these regions is subject to a number of systematic uncertainties (e.g. Skillman et al. 1998; Viegas et al. 2000). Methods to directly estimate the helium abundance in GC stars (such as the ratio of stars on the RGB and HB) suffer from large systematic uncertainties (e.g. Sandquist 2000).

The study of double-lined spectroscopic binaries in the field, and eclipsing binaries in GCs over the next 10 years will likely lead to an accurate determination of the helium abundance in metal-poor stars. The studies of these system enables one to determine the mass-luminosity relation, and hence to determine the helium abundance through a comparison with the stellar models (e.g. Metcalf et al. 1996). Latham is involved in a long term program to determine orbital parameters and masses of 34 low metallicity double-lined spectroscopic binaries (Goldberg et al. 2000) from the Carney-Latham survey. For example, G24-18p is an interesting system which has a proper motion companion, G24-18f. This star's radial velocity is the same as the systemic velocity of the G24-18p pair, so it is safe to assume that all three stars have the same chemical abundances. G24-18f can be analyzed using standard procedures since we have found it to be sharp-lined and not a velocity variable (based on 61 radial velocities spanning 3334 days). A preliminary analysis of an echelle spectrum indicates  $[\text{Fe}/\text{H}] = -0.9$ . FAME will be able to determine accurate distances and orbital parameters for many of the double-lined spectroscopic binaries being studied by Latham. SIM observations may be required for some of the more

distant and/or tight systems. This research initiative promises to make a major contribution to our understanding of the helium abundances in metal-poor stars.

In tandem with this effort on field stars, we plan to undertake an intensive observational campaign to search eclipsing binaries in the nearest GCs in our target list. The identification of these systems, and follow up spectroscopic observations by various groups will serve as a test of stellar models and to estimate the helium abundance directly in a few of the GCs whose ages will be determined by this project. Together, we anticipate that these two different methods will allow us to determine the mass fraction of helium in our models ( $Y$ ) to  $\pm 0.01$ .

### 3 RR Lyrae Calibration

This proposal will result in direct trigonometric parallaxes for 21 of the  $\approx 150$  Galactic GCs. We wish to employ this new distance calibration to map out the distances to all of the other GCs, to the Galactic center, and to nearby galaxies using their RR Lyrae variables (RRL). For heavily reddened clusters in particular, the best age estimator for clusters spanning a range of metallicities is the reddening-independent gap between the horizontal branch and the main sequence turn-off. Knowledge of the horizontal branch luminosity then opens the way for much improved age estimation throughout the Galaxy. Over the years, our views of the absolute magnitudes of RRL,  $M_V(\text{RR})$ , have evolved from a constant value to one that may be a linear function of metallicity. It now appears it is not that simple, either, and we propose to exploit SIM's capabilities to put this issue to rest.

**Metallicity:** A major part of our calibration will come from the 11 clusters in Table 1 that contain significant numbers of RRL. These clusters are spread in  $[\text{Fe}/\text{H}]$  from  $-2.3$  to  $-1.1$ , so will help define the metallicity dependence of  $M_V(\text{RR})$ , and hence to determine RRL-based

distances to the halo clusters beyond the range of SIM. Within a given cluster, the magnitudes of the individual RRL variables at mean light are observed to have an intrinsic scatter with  $\sigma = 0.05$  to  $0.10$  mag. By averaging the magnitudes of 20–100 RRL in each cluster, we can reduce the affect of this scatter on the derived  $M_V(\text{RR})$  of the cluster to a negligible amount. Figure 2c shows simulated results of the proposed program (circles) generated from the assumed relation between  $M_V(\text{RR})$  and  $[\text{Fe}/\text{H}]$  (solid line). But metallicity may not be the only effect relevant to luminosity.

**Evolutionary status:** The 11 clusters are also equally divided between the two Oosterhoff groups. Clusters with longer period RRL ( $\langle P_{ab} \rangle \approx 0.65$  days) are known as Oosterhoff II clusters (OoII), and clusters with shorter period RRL ( $\langle P_{ab} \rangle \approx 0.55$  days) are known as Oosterhoff I clusters (OoI). The OoII clusters have  $[\text{Fe}/\text{H}] < -1.6$  while the OoI clusters have  $-1.6 < [\text{Fe}/\text{H}] < -1.0$  dex. From a theoretical standpoint, a star's period is related to its average density through the pulsation condition,  $P \propto \langle \rho \rangle^{-1/2}$ ; since a more luminous star has a larger radius, it is reasonable to expect the OoII RRL to be more luminous than OoI stars, as may be the case (e.g., Carney, Storm, & Jones 1992). Clement & Shelton (1999) and Lee & Carney (1999) have argued that at equal metallicities, OoI and OoII clusters' RRL have differing luminosities. This may be due to an age effect, with OoII RRL being post-blue horizontal branch stars compared to OoI RRL being near the zero-age horizontal branch. This in turn suggests that the OoII and OoI clusters have different ages. If this is true, we expect to see a discontinuity in the cluster  $M_V(\text{RR})$  values at  $[\text{Fe}/\text{H}] \approx -1.6$  dex. Figure 2b shows simulated results of the proposed program generated from the stepped relation between  $M_V(\text{RR})$  and  $[\text{Fe}/\text{H}]$  indicated by the line. The clusters alone are not enough to distinguish between the sloped and stepped  $M_V(\text{RR})$  scenarios, and so we must use field

stars to investigate further (see below). Determining which scenario is correct is important when determining the distances and ages of clusters with  $[\text{Fe}/\text{H}]$  near  $-1.6$  dex; a  $0.1$  mag error in the assumed  $M_V(\text{RR})$  implies *systematic* errors in distance and age of  $5\%$  and  $9\%$ , respectively, at this important boundary between known populations.

**Field RRL:** Additional RRL are required for a final calibration, and we propose to select them from the field. Figure 2c shows how the field RRL are distributed in metallicity (data from Fernley et al. 1998). There are a considerable number of field RRL with  $[\text{Fe}/\text{H}] > -1.0$  which are not represented in our globular cluster sample. Nonetheless, they are a crucial component of the Galactic Bulge and its clusters (e.g., Lee 1992). We will observe with SIM  $\approx 10$  of these metal-rich RRL in order to extend the  $M_V(\text{RR})$ – $[\text{Fe}/\text{H}]$  calibration up to solar metallicity. We will also observe  $\approx 5$  field RRL with  $[\text{Fe}/\text{H}] < -2.0$  to further constrain the metallicity dependence.

A study of the period distribution of the field RRL suggests the presence of a period discontinuity among the field stars at  $[\text{Fe}/\text{H}] \approx -1.6$ , with RRL at lower metallicity having longer periods. This parallels the Oosterhoff dichotomy seen among GCs (Suntzeff et al. 1991). We propose to compare the mean  $M_V(\text{RR})$  of a sample of  $\approx 10$  RRL with  $[\text{Fe}/\text{H}] \approx -1.7$  with the  $M_V(\text{RR})$  of a similar sample at  $[\text{Fe}/\text{H}] \approx -1.5$  to search for a luminosity discontinuity among the field stars. Assuming a cosmic  $M_V(\text{RR})$  dispersion at fixed metallicity of  $0.08$  mag, we should be able to detect a  $0.2$  mag jump (Lee & Carney 1999) at the  $5\text{-}\sigma$  level.

There appears to be another period discontinuity in at  $[\text{Fe}/\text{H}] \approx -1.0$ , the transition between halo and disk RRL (Layden 1995). Could there be another luminosity discontinuity at this important population boundary? We will test this hypothesis using another pair of 10 field stars above and below the metallicity break.

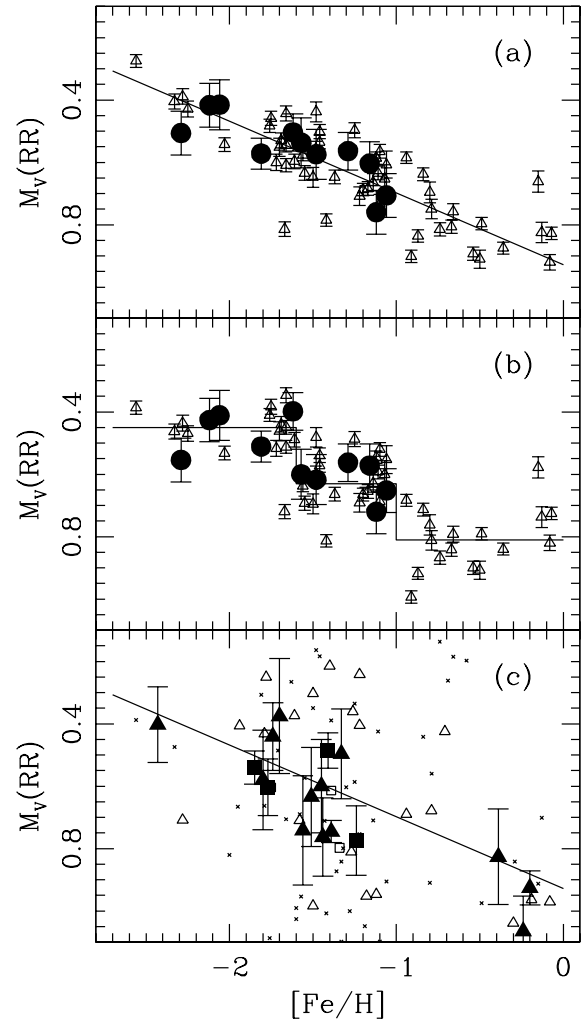


Figure 2: **(a)** Simulated results of the SIM RR Lyrae absolute magnitude calibration as a function of metallicity. Circles indicate the 11 target globular clusters. Triangles indicate  $\approx 60$  field RRL. The line is the input, sloping  $M_V(\text{RR})$ – $[\text{Fe}/\text{H}]$  relation. **(b)** As for (a) except a step-like  $M_V(\text{RR})$ – $[\text{Fe}/\text{H}]$  relation was used (line). The steps correspond to (left to right) OoII, OoI, and Disk populations. **(c)** Simulated results of the  $M_V(\text{RR})$  calibration to be produced by FAME. Solid points have simulated errors in  $M_V < 0.2$  mag, crosses have errors  $> 0.4$  mag, and open symbols have errors between these values. Triangles mark RRab and squares mark RRc. The line is the input  $M_V(\text{RR})$ – $[\text{Fe}/\text{H}]$  relation from (a).



Figure 2b shows simulated results for the proposed program based on the step-like relation between  $M_V(\text{RR})$  and  $[\text{Fe}/\text{H}]$  shown by the line. Allowing for small uncertainties in the exact locations of the population boundaries near  $[\text{Fe}/\text{H}] \approx -1.6$  and  $-1.0$ , we expect to be able to distinguish between the sloped and stepped hypotheses with  $>95\%$  confidence.

The inclusion of field RRL in our program is crucial for another reason. The long-standing discrepancy between the “long” and “short” RRL distance scales has led some astronomers to consider whether the field and cluster RRL obey systematically different  $M_V(\text{RR})$  relations (e.g., Gratton 1998). Other evidence, from period shift analysis (Catelan 1998), suggests that field and cluster RRL have the same luminosities at a given metallicity. The direct parallaxes of field and cluster RRL obtained in the course of the proposed program will settle this crucial point.

**Other Absolute Magnitude Calibrations:** Roughly half of the Galactic globulars do not contain (m)any RRL, so an  $M_V(\text{RR})$  calibration would be of limited value in determining their distances and ages. However, these clusters *do* have stable horizontal branch stars that lie blueward and/or redward of the instability strip (BHB and RHB stars, respectively). We will derive  $M_V(\text{BHB})$  and/or  $M_V(\text{RHB})$  relations from all 21 SIM target GCs listed in Table 1. These clusters span a large range in metallicity, in particular the metal-rich extreme where few clusters contain RRL. The clusters also represent both Oosterhoff groups, and the full range of horizontal branch morphologies. Thus, they will provide an important check and extension of the more traditional RRL luminosity calibration. Similarly, we will use the parallax distances to our 21 clusters to calibrate the  $I$ -band absolute magnitude of the red giant branch tip (e.g., Sakai et al. 2000), and the absolute magnitudes of other pulsating variable stars in the clusters (e.g., Type-II Cepheids and Miras).

**SIM versus FAME:** NASA’s Full-sky Astrometric Mapping Explorer satellite (FAME) is scheduled to fly ahead of SIM. FAME will provide moderate-precision astrometry for  $\approx 4 \times 10^7$  stars. The FAME Concept Study Report (1999, hereafter FCSR) indicates that FAME will yield parallax errors of  $<10\%$  for about 22 field RR Lyrae stars, and that the resulting calibration of  $M_V(\text{RR})$  will be accurate to 0.04 mag (2% in distance). Why, then, should SIM continue to work on this problem?

One answer is target selection. FAME will achieve precise results for the nearest RRL ( $R_\odot < 0.7$  kpc). But the demands of high quality distances for all clusters and field variables demands a broader study of RRL as a function of metallicity and evolutionary state, and we are therefore required to expand the FAME study beyond its reach using SIM. Unfortunately, the best observed FAME stars will not fully represent the period distributions of the metal-rich RRab stars and the RRc stars.<sup>1</sup>

Figure 2c shows a simulation of the expected FAME results, based on a model combining the predicted astrometric precision of the FAME satellite (FCSR) with the observed apparent magnitudes, reddenings, and metallicities of 144 nearby RR Lyrae from Fernley et al. (1998). Our model predictions match those in FCSR. Clearly, the proposed SIM observations (Figure 2a) will result in an RR Lyrae distance scale that is more precise, bias-free, and rigorously tested. Such a scale is crucial in determining the ages of distant Galactic globulars.

**Pre-launch Observations:** Most of the candidate field RRL already have high quality light curves in Johnson  $B$  and  $V$ . Most will soon have light curves in the  $I$ -band as well. We therefore require only  $K$ -band photometry for

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<sup>1</sup>We will observe with SIM an additional 3–5 RRc stars to improve their representation in period-metallicity space. It is important to look for any systematic differences in  $M_V(\text{RR})$  between the RRc stars and the more common RRab stars.

most of the  $\approx 60$  field RRL on our program. In contrast, only a few of the globulars have high quality RRL light curves, particularly in the  $K$ -band (e.g., M5 and M92). We will obtain the required data over the coming years from the MDM, SOAR, and Las Campanas Observatories, to which we have direct access. Layden and Carney are both highly experienced in this field. We will carefully coordinate the calibration of the field and cluster RRL photometry with those of the MSTO photometry to ensure internal consistency.

## 4 Ages of Halo Field Stars

The primary thrust of this proposal involves the GCs as tracers of the Galactic halo; they provide distinct data points in age and abundance space from which we can reconstruct the formation chronology of the halo as well as set a lower limit on the age of the Universe. However, the ensemble of Galactic GCs represents only  $\approx 1\%$  of the luminous mass of the halo. The field halo stars comprise the remaining  $\approx 99\%$  and, as such, are an important constituent of the halo. Comparisons between the age distributions of the GCs and field halo stars will shed light on the relative status of each component in the temporal evolution of the Galactic halo.

As in the case of GC stars, we can measure the ages of field halo stars by knowing their helium abundances, heavy element compositions, reddenings, and distances. Using knowledge of these quantities, we can compare the locations of main sequence turnoff and subgiant stars (MSTO/SGB) in the halo with the predictions of theoretical isochrones in the color-magnitude plane in order to measure the ages of the stars. We restrict our attention to MSTO/SGB stars because the locations of these stars in the color-magnitude diagram (CMD) are especially sensitive to age.

FAME will obtain accurate (5%) parallaxes for a large sample ( $\approx 250$ ) of metal-poor stars (FCSR). MSTO/SGB stars are not as com-

mon as main sequence stars, and the local stellar density drops quickly as one goes to lower metallicities (there are no single MSTO/SGB stars with  $[\text{Fe}/\text{H}] < -1.1$  which had parallaxes accurate to 5% in the Hipparcos catalogue). Thus, FAME will not obtain accurate parallaxes for a significant number of single MSTO/SGB stars with  $[\text{Fe}/\text{H}] < -1.1$ . Our study of field halo stars will complement the FAME effort by concentrating on MSTO/SGB stars with  $[\text{Fe}/\text{H}] < -1.1$ . Of particular interest will be stars with extremely low metal abundances ( $[\text{Fe}/\text{H}] < -2.3$ ). The large majority of these stars have  $13 < V < 15$ . A MSTO star has  $M_V \simeq 4$ , and hence with  $V = 13$ , will be at a distance of  $d \sim 600$  pc implying  $\pi = 1.6$  mas. At  $V = 13$  FAME parallaxes will have an error of  $\sigma_\pi = 0.15$  mas (FCSR), implying a distance uncertainty of  $\sim 10\%$ . This will translate into an error in the derived age estimate of  $\sim 20\%$  for the metal-poor stars in the FAME database. SIM will be able to determine the distances to such stars with an accuracy of better than 0.25%, resulting in a negligible contribution to the error budget in our derived ages.

We will select our target stars from the catalogs of Carney et al. (1996, and references therein), Nissen & Schuster (1991, and references therein), and Anthony-Twarog et al. (2000 and references therein) along with additional stars that we will observe over the next several years in preparation for the launch of SIM. All of the target stars possess well-determined ( $\sigma_{mag} = 0.01$  mag) photometric measurements. The majority of these are in the Strömgen  $uvby-H\beta-Ca$  system with the remainder being in the Johnson-Kron-Cousins UBVRI system. From these catalogs, we will select MSTO/SGB target stars with well-determined reddenings ( $\sigma_{E(B-V)} = 0.01$  mag). Their evolutionary states will be deduced from the reddening corrected Strömgen luminosity class index ( $c_0$ ). A large fraction of these stars are already part of radial velocity programs led by Carney or Latham. We will eliminate radial

velocity binaries from this group. Additional high-resolution spectroscopic data will provide precision metal abundances for these stars with  $\sigma = 0.05$  dex. We will also obtain near-infrared photometry of these MSTO/SGB stars in the JHK filter passbands so that the uncertainties introduced by our knowledge of the reddenings and metallicities are further reduced (cf. section 2).

Once these MSTO/SGB stars have been corrected for reddening and distance using parallaxes measured by SIM, their colors and magnitudes will be compared with GC color-magnitude diagrams (from Table 1) to search for an age difference between the cluster and field stars. If an age difference does exist, its size will be determined via a comparison to the predictions of the theoretical isochrones discussed in Section 2.2. The ages for field stars with  $[\text{Fe}/\text{H}] < -2.3$  will be determined directly from the theoretical isochrones. Given the above-mentioned observational errors and the astrometric capabilities of SIM, we estimate an error of 1.4 Gyr (11%) in the age of an individual halo star. This error assumes that the uncertainty in the colors predicted by the stellar models will have been reduced by a factor 3 due to our efforts at improving the physics used in stellar models (section 2.2).

The sample will be divided into four metallicity bins (the lowest metallicity bin will contain stars with  $[\text{Fe}/\text{H}] < -2.3$ ) and look for differences in ages between the subsamples. Assuming that the age ranges in each subsample are dominated by measurements errors then observations of 15 field stars in each metallicity bin will enable us to detect an age difference between two subsamples as small as 1 Gyr with better than a 95% confidence level. The proper motions provided by SIM will be combined with our precise radial velocities to determine the orbits of the individual halo stars and to search for correlations between kinematics and ages in order to deepen our understanding of the early formation history of the Milky Way.

## 5 Technical Issues

**Globular Cluster Stars:** A number of stars will be selected for SIM observation in each of the 21 target clusters listed in Table 1. Several issues are to be considered when deciding just what the optimal number of stars per cluster is, with the goal of determining the most accurate cluster parallax at a reasonable expenditure of SIM mission time. While measures of multiple stars may be averaged to improve the overall cluster astrometry, one cannot reduce the uncertainty below the  $\approx 3 \mu\text{as}$  floor set by the uncertainty in the tie-in to the nearby grid stars. On the other hand, due to the likelihood of crowding and binarity and the possible loss of some fraction of the target stars to these effects, it is best to have some redundancy. The finite extent of the larger, more nearby clusters may lead to a distance discrepancy between the cluster center and a member near the tidal radius that amounts to at most 2%, but is less than 1% for most of the target clusters. Averaging measures of at least several stars per cluster will ensure this source of error is negligible. Finally, multiple measures within the same cluster allow an internal consistency check and uncertainty estimate.

With these factors in mind, as well as the estimated mission time per target as outlined in the SIM AO Support Wide-Angle Astrometry Timeline, we feel a strategy of observing 5 stars per cluster, at a somewhat reduced individual accuracy per star, namely the  $5 \mu\text{as}$  level, provides the most efficient use of observing time. Assuming target stars with magnitudes roughly equal to that of the cluster HB, the 21 clusters will require from 3 to 10 hours of mission time per star, per cluster. The total estimated mission time for each cluster is  $\approx 29$  hours, or 609 total hours for the 21 clusters listed in Table 1.

In addition, we feel it would be beneficial to examine one cluster in more detail, in order to allow a more thorough analysis of the parallax data as a function of color and magnitude and position (relative to the defining grid

stars). NGC 6752 is an ideal choice for this assignment, as it is nearby and relatively bright, thus lessening the required observing time per star. It is also the subject of an ongoing HST study of its internal velocity distribution as derived from proper-motion measures based on scores of Planetary Camera exposures obtained over a seven-year baseline, (Girard et al. 1995). These exposures, including many of which are offset from the crowded cluster center by five to ten core radii, may also provide the preparatory imaging needed to select isolated SIM targets. And as an added benefit, the SIM observations will provide proper-motion data which will complement that of the HST study. To this end, we propose to observe an additional 10 stars in NGC 6752, selected to cover a range in color, magnitude, and position, as permitted. This will require an additional 50 hours of mission time.

Nearly by definition, GCs have high stellar densities. If there is a significant possibility that a 2nd star is in the  $1.6''$  field of SIM, the standard data products from the Interferometry Science Data Center (ISDC) will not provide correct positional data. The 2nd star can be up to 8 magnitudes fainter than the target and produce an error  $> 4\mu$  as.

In order to minimize the crowding of the SIM target stars, we will pick isolated stars which are fairly bright (approximately the level of the horizontal branch<sup>2</sup>) and which are near the outskirts of each GCs. This will require that we have good photometry (to 2 magnitudes below the level of the horizontal branch) over the entire cluster. We will compile these photometric databases from existing photometry, and new observations which we will carry out in the next few years.

Radial velocity measurements by Latham will be used to determine membership of potential target stars. The radial velocity mea-

surements will be done several times in order to remove binaries from the proposed target lists. Even with these precautions, it is likely that some of the target stars will turn out to have nearby neighbors, requiring that the team work with the fringe visibilities and delays.

SIM itself is quite capable of identifying multiple objects in the  $1.6''$  field. If a star is not at zero delay, the Fourier transform of the visibility vs  $1/\lambda$  data will show a delta function at that non-zero delay. If two stars (more than  $\approx 40$  mas apart) are in the  $1.6''$  field, the Fourier transform of visibility vs  $(1/\lambda)$  will show two delta functions, one for each star. In most cases the two orthogonal orientations of the baseline, will reveal the 2nd star (or 3rd star), because it won't be  $< 40$  mas away in both baseline orientations. Our SIM observations will be taken in such a manner as to ensure that two orthogonal orientations of the baseline are taken for all of our GC target stars.

We have conducted a simulation on the accuracy of the astrometry. If we know about the existence of nearby neighbors, then a least squares fit can solve explicitly for the position of the nearby stars and these nearby stars do not cause an error in the solution of the target star. Without "rotational" synthesis, the area of confusion is an area of  $\approx 60 \text{ mas} \times 60 \text{ mas}$ . By picking stars in relatively uncrowded regions of each cluster, we are confident that a significant fraction of our target stars will not have neighbors in the area of confusion. Choosing five stars per cluster will provide us with a redundancy such that we will not need to make rotational synthesis images of each target star field. It is likely that some of our target stars will have multiple objects in the  $1.6''$  field. In this case our team will work with the fringe visibilities and delays rather than just use the positions and parallax solutions provided by the ISDC. If the SIM data indicate that there are a small number (one – ten) stars in the  $1.6''$  field, we can solve for the positions of all the objects simultaneously. This requires that we take enough

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<sup>2</sup>Stars near the tip of the giant branch tend to be irregular variables, and so would not make good targets for SIM

measurements to solve for all the unknowns. If we were limited to fringe measurements at 1 wavelength, then we would need to measure the fringe visibility/phase at more than 2 baseline orientations. In these cases, we would work with the complex fringe visibility ( $v_s \lambda$ ) data directly, not relying on the ISDC's position solutions. Shao will manage the project's effort to determine the level of data processing needed (depending on how crowded the fields are) for the chosen targets. Our team will develop the software necessary to correctly obtain the parallax and proper motions of stars which have a small number of neighbors in the 1.6" SIM field of view.

In the event SIM only achieves parallaxes with  $30 \mu\text{as}$  accuracy then the goal of obtaining precise distances and ages to a number of GCs will be significantly compromised. In this case, we would only wish to observe the clusters for which SIM could achieve a 10% accuracy in the parallax. In this scenario, our determination of precise distances and ages to GCs would rely upon the RRL field star calibration.

**Field RR Lyrae Stars:** The field RRL to be observed by SIM all have been observed with Hipparcos, and so have very accurate positions and proper motions. This and the low crowding of the fields ensures that SIM will have no difficulty acquiring the stars. The field RRL selected will all have  $10.5 < V_{min} < 13.0$ , implying distances in the range  $1.0 \text{ kpc} \lesssim d \lesssim 3.2 \text{ kpc}$  and parallaxes  $300 \mu\text{as} \lesssim \pi \lesssim 1000 \mu\text{as}$ . We will obtain parallaxes with  $4 \mu\text{as}$  accuracy from SIM which will require between 2.7 to 4.3 hours per star over the mission lifetime and a total of approximately 200 mission hours for the entire sample of 60 field RR Lyrae stars. In the event SIM only achieves parallaxes with  $30 \mu\text{as}$  accuracy, the error bars in Figure 2a will expand by a factor of  $\approx 2.5$ , giving an average error in  $M_V$  for each field RRL of  $\approx 0.09$  mag. This will not significantly affect the science derived from the field RRL

**Field Halo Stars:** The main sequence

turn-off and subgiant branch stars to be observed with SIM have accurate positions and are in uncrowded fields. Ground-based spectroscopic observations will be used to eliminate radial velocity binaries from the target list before the launch of SIM. The field stars selected will have  $10 < V < 15$ . The brightest subgiant branch stars for which we will be able to determine accurate ages will have  $M_V > 3$ , implying that the most distant stars in our sample will have  $d \sim 2.5 \text{ kpc}$  and  $\pi \sim 400 \mu\text{as}$ . Thus distances accurate to 1% will require parallaxes with  $4 \mu\text{as}$  accuracy for the fainter stars in our sample. As there is only a small increase in mission time to get parallaxes of a similar accuracy for the brighter stars in our sample,  $4 \mu\text{as}$  parallaxes will be obtained for all of the field stars in our sample. This will require between 2.6 and 10.8 mission hours per star, with an average time of approximately 8 hours per star. Observing 60 stars will require approximately 480 mission hours.

In the event SIM only achieves parallaxes with  $30 \mu\text{as}$  accuracy, we will concentrate our efforts on the nearer stars in our sample (within  $\sim 1.7 \text{ kpc}$  for which SIM would yield distances accurate to 5% (and hence, ages accurate to 10%) and we would be able to achieve our science goals, albeit with a somewhat reduced accuracy in the age determination. To compensate for this reduced accuracy, we would request observations of two to three times as many field stars. The overall mission time allocated to this key project would not be significantly effected, as we would be observing a much smaller sample of GCs.

## Education/Public Outreach Statement of Participation

Our Key Project team is very supportive of SIM E/PO activities and we are committed to participate in E/PO activities at a level of 5% of our supported time as part of our normal, ongoing involvement with SIM. Our backgrounds in teaching and outreach demonstrate that this has been a long-term commitment for many of us and that we have the experience to carry it out effectively. For example, PI Brian Chaboyer is a recipient of a major NSF grant to improve the introductory astronomy courses and labs offered to non-science majors at Dartmouth. Dartmouth itself is known for excellence in and commitment to education, so the support here will be long-lasting. Team member Duncan serves as Education Coordinator of the American Astronomical Society and has run many programs which support K-12 teachers. Team member Carney has served as President of the Astronomical Society of the Pacific, planning a wide range of programs for the public, for teachers, and for amateur astronomers.

In general, we would expect our science team members to play a variety of educational roles, harnessing their varied backgrounds and interests. These could range from working directly with teachers and/or students, to behind-the-scenes support activities in areas such as curriculum development, creation of WWW pages which explain our science or suggest educational activities, or supporting teachers by answering their questions or those of students. We will cooperate closely with the SIM E/PO scientist and JPL Offices of Educational Activities and Public Affairs in planning and conducting these activities.

We believe that the science investigated by SIM is extremely interesting. Topics such as how the Galaxy came to form, how many stars have planets, the size and scale of the universe, and the age of the universe will capture the interest of many students (and the public) if well-presented. Our Key Project investigation can contribute to lessons based on these topics, especially the ones concerned with sizes, scales, and ages.

A particularly interesting possibility for cooperation which would leverage NASA's educational dollars is available in New Hampshire, the PI's home state. New Hampshire is relatively rural, and not every school can afford state-of-the art science equipment. The New Hampshire Science Instrumentation Project (NHSIP) was formed to procure and share such equipment among schools, and to instruct teachers and students. It is supported by the New Hampshire Space Grant Consortium, University of New Hampshire, and a number of charitable foundations. The NHSIP Director, Barbara Hopkins, has discussed SIM with us and would very much like to work with the science and technology of SIM. NHSIP, supported by the Governor of New Hampshire, is currently in the process of obtaining a van to carry around scientific equipment. If SIM could furnish lessons based on some of the SIM technology, such as precision measurement, interferometry, properties of light, lightweight and strong structures, etc. NHSIP is within easy driving distance of Boston, and that is another natural site for us to conduct any education activities which would take place in person, such as workshops.

## Individual Duties and Responsibilities

### DUTIES AND RESPONSIBILITIES: BRIAN CHABOYER

B. Chaboyer has overall management responsibility for the project. This will include coordinating the ground based observing efforts and preparatory research efforts. Chaboyer will be a member of the SIM science team and will represent the interests and requirements of this key project. With the aid of M. Shao, Chaboyer will oversee the development (by a post-doc) of project specific data analysis software necessary for the globular cluster star observations.

Chaboyer will lead the efforts to improve the stellar models and isochrones. This will include on-going research efforts in helioseismology and astro-seismology; studies of the luminosity functions of GCs; and efforts to improve the treatment of mixing and convection in halo and thick disk stars. At the end of the project, Chaboyer will lead the efforts to determine the ages of the globular clusters and the MSTO/SGB field stars. This will include a detailed examination of the error budget in the derived age.

Chaboyer will assist Sarajedini in obtaining and analyzing the precise optical and infrared color-magnitude diagrams and luminosity functions necessary for this key project. Part of this data will be taken with the MDM 2.4m and 1.3m telescopes. Chaboyer is guaranteed 25 nights/year on each of these telescopes.

### DUTIES AND RESPONSIBILITIES: BRUCE CARNEY

Bruce W. Carney will work at the University of North Carolina at Chapel Hill under a subcontract from Dartmouth College. His contributions will be to several areas of the proposed research. First, using the 4.2-meter SOAR Telescope in Chile, which will begin science operations in 2003 (UNC will receive over 60 nights per year on this telescope) he will undertake much of the infrared photometry proposed for field stars and clusters. He will also obtain the high-resolution infrared spectra for the carbon and oxygen abundances in globular cluster red giant branch stars. He will help obtain and reduce long-term photometry of the target field and cluster RR Lyrae variable stars. This work will be done in conjunction with Andy Layden. Carney will help compute new model atmospheres with ATLAS12 and analyze the high-resolution optical spectra obtained from Magellan and the MMT (and possibly Gemini) outlined in the proposal. This work will be done in collaboration with Andy McWilliam and Doug Duncan. Carney will host a postdoc throughout almost all of the contract period to help with the data acquisitions, reductions, analyses, and publication of the results and related scientific outcomes from our work.

## DUTIES AND RESPONSIBILITIES: DOUG DUNCAN

Doug Duncan will obtain and analyze ground based spectra to derive temperatures and abundances for proposed targets, compute ATLAS synthetic spectra to aid those determinations, and make use of SIM parallaxes as described in the text. Some of the observations will be done with the Univ. of Chicago's Apache Pt. Observatory and ARC echelle spectrograph. D. Duncan has worked on that spectrograph extensively in the past.

Duncan will also be responsible for coordinating the team's participation in education and public outreach activities of the SIM mission.

## DUTIES AND RESPONSIBILITIES: TERRY GIRARD

Terry Girard will provide astrometric expertise as needed during the target selection and preparation phase of the project, and, most importantly, during the analysis and interpretation of the final SIM-delivered data. Activities prior to SIM launch will include a search of existing proper-motion databases to assist in evaluating cluster membership in those cases where adequate radial velocity data are not available, and providing optimal, uniform astrometric data, adequate to assure acquisition by SIM, for all targets associated with this Key Project.

Upon release of the intermediate and final SIM data, approximately 2.5 and 5 years after launch, Girard will perform tests of the delivered astrometric data, to verify the estimates of uncertainty in the data and search for any possible systematic errors that may have escaped detection during the SIM internal reduction process. A full understanding of the limits of the data will be critical to their interpretation and statistical analysis.

## DUTIES AND RESPONSIBILITIES: ANDREW LAYDEN

- Compile existing RR Lyrae light curves from the literature and determine which targets require further observations.
- Obtain  $K$ -band light curves (and any optical light curves not available in the literature) for  $\sim 60$  field RR Lyrae. Requires observing at MDM, LCO, CTIO, and/or BGSU observatories. Write paper presenting data obtained.
- Obtain light curves for RR Lyrae in globular clusters. We expect  $\sim 6$  clusters will require optical ( $B, V, I$ ) light curves, and  $\sim 8$  will require infrared ( $K$ ) light curves. Requires observing at MDM, LCO, and/or SOAR/CTIO observatories. Write papers (one per cluster) presenting data and analysis of variable star properties as appropriate.
- If astrometric corrections require magnitude or color information, Layden will photometrically monitor  $\sim 60$  field RR Lyrae using BGSU 0.5-meter and LCO 40-inch telescopes.
- Lead or contribute to the RR Lyrae, BHB, and RHB star absolute magnitude calibrations. Write paper.



## DUTIES AND RESPONSIBILITIES: ANDREW MCWILLIAM

Andrew McWilliam will obtain and the analyze high resolution spectrum outlined in this proposal. This data will be used to determine accurate abundances for the target stars and globular clusters. He has direct access to the Magallen telescopes along with the Dupont telescope at LCO and much of the data will be obtained at these telescopes. This work will be done in conjunction with Bruce Carney and Doug Duncan. McWilliam will coordinate the publication of the results and will help oversee the efforts of the postdoc stationed at UNC.

## DUTIES AND RESPONSIBILITIES: ATA SARAJEDINI

- Obtain optical *BVI* photometry for the globular clusters in the target list. These data will be used to construct color-magnitude diagrams and luminosity functions for the clusters. This requires obtaining accurate and precise as well as statistically complete photometry well below the main sequence turnoff and providing a well-defined unevolved main sequence. This in turn means that multiple images per filter on several photometric nights are required for each cluster. The data will be gathered using guaranteed time at the MDM observatory in the north with the 8k x 8k optical CCD mosaic and a similar mosaic array at CTIO in the south. Papers will be written presenting the data obtained.
- Obtain infrared *JHK*-band photometry for the globular cluster targets. These data will also be used to construct cluster color-magnitude diagrams and luminosity functions. Like the optical observations, this requires accurate and precise photometry providing a well-defined unevolved main sequence and turnoff. Multiple images per filter on several photometric nights are required for each cluster. The data will be gathered using guaranteed time at the MDM observatory in the north and CTIO in the south. Papers will be written presenting the data obtained.
- Maintain overall responsibility for the integrity of the observing and reduction effort related to the cluster photometry. This includes leading the effort as well as supervising and training others, such as post docs and students.

## DUTIES AND RESPONSIBILITIES: MIKE SHAO

M. Shao will help the key project team in areas where knowledge of the SIM instrument or operations is important. This will include: help plan SIM observations in crowded fields, help define the data types needed by the key project team from the ISDC, define any on orbit calibrations needed specifically by this key project's science observations, and define project specific data analysis software.

If there is a significant possibility that a 2nd star is in the 1.6 arcsec field of SIM, the standard data products from the ISDC will not provide correct positional data. (The 2nd star can be up to 8 magnitudes fainter than the target and produce an error  $> 4 \mu\text{as}$ .) In this case the team needs to work with the fringe visibilities and delays rather than just use the positions and parallax solutions provided by the ISDC. Part of my task would be to help the project determine the level of data processing needed (depending on how crowded the fields are) for the chosen targets, as well as optimize the observing scenario.

## DUTIES AND RESPONSIBILITIES: DAVID W. LATHAM

Dr. David W. Latham of the Smithsonian Astrophysical Observatory (SAO) will lead the effort to use radial-velocity observations from ground-based telescopes to finalize the selection of optimum targets. The goal is to confirm the membership of globular cluster candidate target stars and to identify those candidates which should not be SIM targets because they are members of binaries. Radial velocities will also be used to identify binaries among the halo field-star candidate targets as needed.

Dr. Latham is a world leader in the field of stellar radial-velocity observations and their applications to studies of the frequency and characteristics of binaries in a variety of stellar populations, including the disk and halo populations of the galaxy, and in star clusters. Dr. Latham led the effort that identified the first spectroscopic binary in a globular cluster (Pryor, Latham & Hazen 1988). He also led the long-term effort to monitor the radial velocities of the stars in the Carney-Latham proper-motion sample and has shown that the frequency and characteristics of stellar companions orbiting halo field stars is remarkably similar to that for the companions orbiting sun-like stars in the solar neighborhood (e.g. Latham et al. 1988), contrary to the traditional view that halo binaries are rare. Dr. Latham has also worked on the problem of RR Lyra distances (e.g. Jones et al. 1992).

As a member of the FAME Science Team, Dr. Latham will have early access to the FAME results for candidate targets for this project.

Throughout the duration of this project, both before and after launch, Dr. Latham will participate in the refinement of the scientific ideas, the detailed formulations of the experiments to be performed, and the interpretation and publication of the results. He will participate in team meetings and communicate electronically as needed.

For new radial-velocity observations that are needed, Dr. Latham has access to the HEC-TOCHELLE multi-fiber echelle spectrometer on the 6.5-m MMT at SAO's Whipple Observatory on Mt. Hopkins, Arizona and to the CfA Digital Speedometers on the 1.5-m Tillinghast and Wyeth reflectors located in Arizona and Massachusetts. These facilities can be used to observe targets north of declinations about  $-32$  degrees. During the pre-launch phase funding is needed to support these ground-based observations, both at the telescopes and for data reduction and analysis. Dr. Latham is a senior astronomer at SAO, and his time is provided at not cost to Dartmouth or NASA.

Dr. Latham's time commitment:

2001 – 2006 10%

2007 – 2011 5%

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