A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Distances and ages of globular clusters

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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. The current uncertainty in the distances to globular clusters is $\sim 6\%$, which leads to a 13% uncertainty in the absolute ages of globular clusters. I am the PI on a SIM-Planetquest key project to determine the distances of 21 globular clusters with an accuracy of ranging from 1 to 4%. This will lead to age determinations accurate to $5 - 9\%$. The mean age of the oldest, most metal-poor globular clusters will be determined with an accuracy of $\pm 3\%$.

Keywords. globular clusters: general

1. Introduction

A typical globular cluster contains several hundred thousand stars, all with the same age and composition. As a result, globular clusters provide an excellent test of stellar evolution models and represent the oldest objects in our galaxy for which accurate ages can be obtained. There is still considerable uncertainty about the distance scale to globular clusters, and Population II stars in general. For example, the review by Krauss & Chaboyer (2003) reviews 8 different methods to determine the distances to globular clusters, and concludes that these various methods imply an uncertainty in the distance modulus to globular clusters of ± 0.12 mag, or $\pm 6\%$ in the distance. The nearest globular cluster is approximately 2 kpc distant, and there are only a few globular clusters within 5 kpc of the Sun. Significant progress in refining the distance scale to globular clusters will require parallaxes accurate at the micro-arcsecond level.

2. Globular cluster ages

The ages of globular clusters are determined by comparing the results of stellar evolution calculations to the observed properties of stars within a globular cluster. There has been some recent progress in using white dwarfs to determine the age of the nearest globular cluster (Hansen *et al.* 2007), but white dwarfs are faint and it is extremly difficult to observe the entire white dwarf cooling sequence in a globular cluster. As a result, the main sequence turn-off region is the diagnostic which is usually used to determine globular cluster ages.

The calculations of stellar evolution models require a knowledge of the physical processes which occur in high temperature plasma. This includes such things as nuclear reaction rates, opacities, the equation of state and turbulent convection. These input ingredients to stellar evolution calculations are not known exactly, but the uncertainty in this calculations can be quantified, which in turn allows for a reliable estimate in the uncertainty in the determination of globular cluster ages. The stellar evolution Monte Carlo simulation of Krauss & Chaboyer (2003) demonstrated that, for absolute ages, the absolute magnitude of the main sequence turn-off region was the best diagnostic of the absolute age of globular clusters. Of course, determining the absolute magnitude of the turn-off requires a knowledge of the distance to a globular cluster. Krauss & Chaboyer (2003) show that the current uncertainties in the distance scale to globular clusters and in the stellar evolution calculations leads to an uncertainty of $\pm 13\%$ in the determination of absolute age of the oldest globular clusters.

3. Globular cluster distances with SIM-Planetquest

NASA had an open call for proposals for SIM key science projects in 2000, and as a result 10 key projects were selected. The importance of improving our knowledge of the globular cluster distance scale lead to the selection of our proposal to NASA for a SIM key science project to determine parallaxes to a number of globular clusters. The design goal of SIM-Planetquest is the determination of stellar parallaxes with an accuracy of ± 4 micro-arcsecond. As the current distance scale to globular clusters is accurate to $\pm 6\%$, one would like to have individual parallaxes accurate to $\pm 4\%$ in order to make a significant improvement in our knowledge of the globular cluster distance scale. This implies observing globular clusters which are within 10 kpc of the Sun.

There are of order 90 globular clusters within 10 kpc of the Sun (Harris 1996). However, many of these globular clusters are located in the bulge of the Milky Way, and are highly reddened. Determination of the absolute magnitude of the turn-off requires a knowledge of the absorption along the line of sight in addition to the parallax. Going to the infrared can significantly reduce the uncertainty in the absorption along the line sight. However, age determinations which use the absolute magnitude of the main sequence turn-off in the K band are a factor of two more sensitive to distance uncertainties than those ages determined in the V band. For example, an uncertainty of ± 0.06 mag in the K band leads to a 12% uncertainty in the age determination, while an uncertainty of ± 0.06 mag in the V band leads to a $\pm 6\%$ uncertainty in the age determination. As a result, for accurate age determination, one needs to use globular clusters which have low interstellar absorptions.

Our SIM key project 'Anchoring the Population II Distance Scale: Distances and Ages of Globular Clusters' selected 21 globular clusters within 10 kpc of the Sun for observation by SIM. These clusters are listed in Table 1. In this table, the distance from the Sun ($R_{\odot}$), reddening ($E(B-V)$), metallicity ([Fe/H]), and magnitude of the horizontal branch (V_{HB}) are taken from the 2003 online version of the Harris (1996) catalog of Milky Way globular clusters. The estimated percent uncertainty in the parallax to each cluster is listed under σ_{π}, while σ_{age} gives the percent uncertainty in the age. The uncertainty in the age includes uncertainties in the distance, reddening, composition and stellar evolution models. It is based upon a Monte Carlo simulation which takes into account all known errors in globular cluster age determination, as discussed by Krauss & Chaboyer (2003).

Of key interest to cosmology is the absolute age of the oldest globular clusters. There are 5 metal-poor globular clusters which are believed to be among the first objects formed in the halo of the Milky Way. Given that these clusters are scattered over the sky, the error in the distance uncertainty will not be correlated, allowing one to average together the age determinations and determine the mean age with a lower uncertainty. Of course, the possible errors in stellar evolution models are the same for all clusters, so one must take into account this correlated error when determining the mean age of the oldest, most metal-poor globular clusters. Taking this into account, parallaxes from SIM-Planetquest will allow our key project to determine the absolute age of the oldest globular clusters with an uncertainty of $\pm 3\%$.

Table 1: Target Globular Clusters

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

This significant reduction in the uncertainty in the absolute age of the oldest globular clusters will provide a strong consistency check on cosmological models. For example, an age of 15.5 ± 0.4 Gyr for the oldest clusters would be inconsistent at the $4\,\sigma$ with the currently favored cosmological model, which implies an age of $13.7{\pm}0.2$ Gyr (Spergel *et al.* 2003). Alternatively, if the absolute globular cluster ages are consistent with cosmology, then one can use the absolute ages to infer the redshift of formation for the oldest stars in the Milky Way. For example, an age determination of 11.3 ± 0.3 Gyr for the oldest globular clusters would imply that these clusters formed at a redshift of $z \simeq 3$.

The launch of SIM-Planetquest has been delayed a number of times, and currently there is no firm launch date. The earliest possible launch date is 2012. Parallaxes accurate to 4 micro-arcseconds will require 5 years of observing by SIM-Planetquest. Thus, it will be some time before we will obtain accurate parallaxes to globular clusters. When the data do arrive, they will lead to an important advance in our understanding of globular cluster ages, and provide new constraints on galaxy formation and cosmological models.

References

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