The Globular Cluster M54 and the Star Formation History of the Sagittarius Dwarf Galaxy

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Accepted for publication in Astrophysical Journal Letters.

ABSTRACT

We present a deep color-magnitude diagram in the $VI$ passbands of the globular cluster M54, a member of the Sagittarius dwarf galaxy. The data extend below the cluster’s main sequence turn-off, allowing us to estimate the cluster’s age. We find that M54 is 0.5–1.5 gigayears older than the Galactic globulars M68 and M5. In absolute terms, the age is comparable to the published age estimates of the other member clusters Arp 2 and Terzan 8, but is significantly older than the member cluster Terzan 7. An age estimate of the Sagittarius field population relative to M54 suggests that M54 is $>3$ Gyr older than the field. We discuss briefly the star formation history of the Sagittarius dwarf galaxy.

Subject headings: galaxies: individual (Sagittarius) — galaxies: star clusters — galaxies: stellar content — globular clusters: individual (NGC 6715) — stars: Population II

1. Introduction

Ibata, Gilmore, & Irwin (1994, hereafter referred to as IGI) announced the discovery of a gas-poor galaxy lying behind the bulge of the Milky Way at a distance of $\sim24$ kpc. They estimated the overall stellar content of this galaxy (hereafter referred to as the Sagittarius dwarf galaxy, or Sgr)

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\textsuperscript{2}Observations obtained while a staff member of the Cerro Tololo Inter-American Observatory, one of the National Optical Astronomy Observatories (NOAO). NOAO is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
to be similar in age, metallicity, and total luminosity to the Fornax dwarf spheroidal galaxy. They also noted that four previously-known globular clusters (M54, Arp 2, Ter 7, and Ter 8) had roughly the correct distances, positions on the sky, and radial velocities to be members of this galaxy.

The presence of a galaxy so nearby provides an unparalleled opportunity for detailed study of stellar populations, chemical enrichment history, and galaxy formation and evolution. Ibata et al. (1997) provide an excellent review of the ensuing research on Sgr. The results of several of these studies have increased the likelihood that the four globular clusters are members of Sgr. In particular, Da Costa & Armandroff (1995) presented new abundances and radial velocities for the four globular cluster candidates; their velocities agree well with the systemic velocity of Sgr (IGI). The new isodensity map of Ibata et al. (1997) confirms that Sgr extends over the three outlying clusters, Arp 2, Ter 7, and Ter 8.

Table 1 summarizes our current knowledge concerning the ages of Sgr and its globular clusters. The difficulties in comparing absolute ages of stellar systems are well-known (e.g., Chaboyer 1995), so we have used ages, when available, from the self-consistent work of Chaboyer et al. (1996, hereafter referred to as CDS). We use the ages from column 2 of their Table 3, which employ an $M_V(\text{RR}) - [\text{Fe/H}]$ relation nearly identical to that of Lee et al. (1990, hereafter referred to as LDZ). CDS do not include ages for the Sgr field population, so the estimates for Sgr listed in Table 1 are less homogeneous. The confusion is compounded by the uncertainty in the metallicity of Sgr; the dependence of derived age on assumed metallicity is well known (e.g., CDS). Still, the studies agree on an age between 10 and 14 Gyr for the dominant population of Sgr.

The only Sgr globular cluster candidate currently without accurate main sequence turn-off (MSTO) photometry and an age estimate is M54 (NGC 6715). Sarajedini & Layden (1995, hereafter referred to as SL95) presented a CCD color-magnitude diagram (CMD) of the bright stars in M54 ($M_V \approx +2.0$). They found M54 to be metal poor ($[\text{Fe/H}] = -1.79$ dex) and to have a blue horizontal branch typical of old Galactic globular clusters. The recent photometry of M54 by Marconi et al. (1997) goes deeper, but the photometric errors and incompleteness at the magnitude of the MSTO preclude an accurate age analysis.

M54 is by far the most luminous of the four Sgr clusters (SL95), and perhaps the most secure candidate for membership in Sgr, since it lies in the highest density region of that galaxy (IGI) and has a distance (SL95) and radial velocity (Da Costa & Armandroff 1995) which correspond very well with those of Sgr. SL95 have speculated that M54 is the “nucleus” of Sgr, akin to the nuclei found in many dwarf elliptical galaxies. Clearly, we cannot have a complete understanding of the star formation history of Sgr without information about the age of M54.

2. Observations, Reductions, and the CMD

In order to obtain photometry to the MSTO, we secured deep images of M54 using the CTIO 4.0-m telescope at prime focus during the nights of 1995 June 28 and 29. We employed the Tek#4
2048 pixel CCD, which provided a scale of 0.43 arcsec pixel$^{-1}$. The median seeing was 1.2 arcsec.

We measured instrumental stellar magnitudes on each frame using the DoPHOT photometry program (Schechter, Mateo, & Saha 1993), and transformed them directly to the $VI$ magnitude system of SL95 using the large number of stars common to both data sets. Photometry from the five $VI$ frame pairs with the best seeing were assembled, and mean magnitudes and errors (standard errors of the mean) were computed for each star detected in three or more frame pairs. The details of the reduction procedure and the photometric data for the resulting 26,485 stars are presented in Layden & Sarajedini (1997). Comparisons show that these data are accurately tied to the SL95 photometric system.

Figure 1 presents the $VI$ CMDs for (a) all the M54 stars with high quality data, and (b) all the high quality M54 stars located between 2.5 and 4.3 arcmin from the cluster center. In these panels, the curves are the fiducial red giant branches (RGBs) of M54 and Sgr derived by SL95. These curves, together with the CMDs of Sgr and a foreground bulge control field by Mateo et al. (1995, hereafter referred to as MUSKKK), facilitate the interpretation of our CMD.

The curve on the left is the M54 RGB fiducial; it guides the eye faintward to where the M54 RGB becomes well populated. The M54 RGB turns blueward onto the subgiant branch (SGB) at $(V - I, V) = (0.9, 20.9)$ mag, and merges with a column of points $\sim$0.2 mag blueward of this. As we will see, this column represents the superimposed MSTO regions of M54 and Sgr.

The curve on the right is the Sgr RGB fiducial. The lower RGB of Sgr is not as well populated as that of M54 in this figure, but there appears to be an excess of points roughly parallel to the M54 RGB which terminates at $(V - I, V) = (1.0, 20.9)$ mag, and which presumably turns blueward onto the SGB at this point (see MUSKKK). The MSTO of Sgr in the MUSKKK field occurs at $(V - I, V) \approx (0.75, 21.4)$ mag, the same region as the MSTO of M54 in our data. The plume of stars at $V - I = 0.75$ and $20.2 < V < 20.9$ mag corresponds to the young (4 Gyr) Sgr population discovered by MUSKKK.

Other prominent sequences in Figure 1a include the M54 blue HB (SL95), the Sgr red HB clump (MUSKKK, SL95), and a population of blue stragglers or very young stars belonging either to M54 or Sgr $(0.2 < V - I < 0.6, 19 < V < 21$ mag). The MUSKKK bulge control field coincides well with the column of stars at $V - I \approx 0.9$ and $V < 19.5$ mag which sweeps redward at fainter magnitudes across the M54 and Sgr lower RGBs. Thus most of the scatter with $V > 20$ and $V - I > 1.0$ mag is attributed to the foreground bulge.

One important qualitative statement about the relative ages of M54 and Sgr can be made at this point. The MSTOs of these populations appear to be coincident at $V - I \approx 0.75$ mag. The reddenings are identical since the populations lie in the same field. Yet the metallicity of M54 is at least 0.5 dex lower than that of Sgr, so for the MSTOs to coincide, M54 must be older than Sgr.
3. Comparison with Cluster Fiducial Sequences

A simple estimate of the age of M54 can be made by directly comparing our photometry with the fiducial sequences of other clusters. High quality $VI$ CCD photometry exists in the literature for M68 ($[Fe/H] = -2.09$) and M5 ($[Fe/H] = -1.40$), which bracket M54 in metallicity. Figure 2 shows our data plotted with the fiducial sequence of M68 from Walker (1994, dashed line) and the fiducial of M5 from Sandquist et al. (1996, solid line). All the cluster data were registered to the observational HR Diagram using the $V(\text{HB})$, $[Fe/H]$, and $E(V-I)$ values given in Table 2 along with the relation $M_V(\text{RR}) = 0.17[Fe/H] + 0.82$ (LDZ).

The fiducial sequence comparison reveals that the age of M54 is comparable to those of M68 and M5. Since M54 is almost exactly between M68 and M5 in metallicity, one expects the data for M54 to lie midway between the M68 and M5 fiducials. However, the M54 data, particularly for the SGB, appears to be skewed slightly toward the M5 fiducial. This suggests that M54 may be slightly older than M68 or M5. In the next section, we will quantify this age difference.

4. Isochrone Fitting

Another method for measuring globular cluster ages is isochrone fitting. Figure 3 shows the Revised Yale Isochrones (RYI; Green, Demarque, & King 1987) for $Y = 0.23$, $[Fe/H] = -1.50$, and ages of 10–18 Gyr, superimposed on the data from Figure 1b. The isochrones were shifted to the observed plane using the $V(\text{HB})$ and $E(V-I)$ values listed in Table 2, and the LDZ relation between $M_V(\text{RR})$ and $[Fe/H]$ (assumed for consistency with the RYI, see King et al. 1988). The ridge-line of M54 SGB stars suggests an age of 13–14 Gyr. The 12 Gyr isochrone forms an envelope about the MSTO points, setting a hard lower limit for the age of M54 under the stated assumptions.

We used isochrones with $[Fe/H] = -1.50$ because the RYI employ scaled-solar abundance ratios, whereas observations suggest that Galactic globular clusters have an enhancement of $\alpha$-elements of $[\alpha/Fe] \approx +0.4$ dex (e.g., Pagel & Tautvaisienė 1995). Salaris et al. (1993) showed that for a given iron abundance, scaled-solar isochrones 0.29 dex more metal-rich in $[Fe/H]$ closely mimic $\alpha$-enhanced isochrones with $[\alpha/Fe] = +0.4$ dex. RYI with $[Fe/H] = -1.79$ indicate ages 1–2 Gyr older than those shown here.

Analogous RYI fits to the data of M68 (Walker 1994) and M5 (Sandquist et al. 1996), again using the parameters from Table 2 and the “$\alpha$-enhanced” metallicities, produced ages of $\sim 13$ Gyr for M68 and $\sim 12$ Gyr for M5. As in Sec. 3, M54 appears to be comparable in age to these clusters, or perhaps slightly older.

We are concerned by the tendency for the isochrones to be bluer than the data at $V \gtrsim 22$. This could be due to (1) differential incompleteness in our data as a function of color, (2) a tendency for Sgr stars to dominate the red side of the lower main sequence and thus to bias the data redward, or (3) inadequacies in the isochrones or adopted reddening and distance modulus. Though adopting
a larger reddening (e.g., by 0.05 mag ≈ 2σ) corrects the main sequence color problem and makes the derived age younger (∼2 Gyr), it degrades the fit to the lower RGB. Adjusting the reddening and distance modulus in concert enables us to obtain a better overall fit; the age obtained is 15 Gyr for E(V − I) = 0.18 and a distance modulus 0.15 mag smaller than employed in Figure 3.

Our isochrone age estimates are supported by estimates based on the luminosity of the subgiant branch. The difference between the magnitude of the subgiants at a well defined color and that of the horizontal branch is similar for M54, M68, and M5. When calibrated using the RYI, we find that M54 is 1–2 Gyr older than M68 and 0–1 Gyr older than M5. Details of this procedure are presented in Layden & Sarajedini (1997).

Given the uncertainties in determining absolute ages, we would like to compare our age for M54 to that of the Sgr field population in a relative sense. In Figure 1, the lower RGB of the Sgr field population appears to terminate abruptly at V ≈ 20.9 mag. RYI with metallicities and ages with lower RGBs terminating at this magnitude can be used to place an upper limit on the age of the Sgr field. For [Fe/H] = −0.50 (SL95), we find a maximum age of 6 Gyr. For [Fe/H] = −1.2 and [α/Fe] = +0.4, we find an age of 9 Gyr. For [Fe/H] = −1.2 and [α/Fe] = +0.0, we find an age of 11 Gyr. The latter is the oldest age obtainable for Sgr which is consistent with currently quoted abundance estimates. This age is also in good agreement with the Sgr ages listed in Table 1. Clearly, M54 must be older than the Sgr field stars by ≥3 Gyr.

5. Discussion

All three of the methods discussed above suggest that M54 is 0.5–1.5 Gyr older than the comparison clusters M68 and M5. CDS find the age of M5 to be typical of Galactic globular clusters of its metallicity, while M68 may be somewhat younger than average. Thus, M54 has an age typical of Galactic globulars of its metallicity (see Figure 1 of CDS).

The absolute age estimates discussed in Sec. 4, using the LDZ relation between $M_V(RR)$ and [Fe/H] and [α/Fe] = +0.4, suggest that M54 has an age of ∼14 Gyr. Comparing this with the ages of the other Sgr globulars shown in Table 1 indicates that M54, Ter 8, and Arp 2 are all comparably old (for more details, see Layden & Sarajedini 1997), while Ter 7 is significantly younger. Given the uncertainties in the existing photometry, we cannot rule out the possibility that the three old clusters in Sgr are coeval.

Comparing our absolute age for M54 with the age estimates for the dominant Sgr field population shown in Table 1 suggests that M54 is older than the metal-rich field population in which it is embedded. This result is supported by our analysis in Sec. 4, where we estimated the maximum age of the Sgr field as a function of assumed [Fe/H], and found that M54 is at least 3 Gyr older than Sgr.

Taken at face value, these ages suggest that the metal-poor clusters represent the earliest epoch
of significant star formation in Sgr. Vigorous star formation in the field appears to have begun several Gyr later. Given this age difference, it seems reasonable to expect that gas expelled from evolving metal-poor cluster stars enriched the interstellar medium and thus the first generation of Sgr field stars. This explains, at least in part, why the Sgr field is so much more metal-rich than the old clusters. As was the case for many of the Galactic satellite dwarf spheroidals (e.g., Smecker-Hane et al. 1994), Sgr managed to retain a significant portion of its gas for many Gyr, enabling the formation of Ter 7, and of the $\sim$4 Gyr field population discussed by MUSKKK and represented by the blue plume of stars above the MSTO in Figure 1. Given the age and abundance of Ter 7, it is perhaps more appropriate to compare this cluster with the “populous clusters” of the SMC or ESO121-SC03 in the LMC (Da Costa 1991) than with traditional globular clusters. Finally, we note that the HB morphologies of the three old Sgr globulars are quite blue for their metallicity (SL95, Buonanno et al. 1995, Ortolani & Gratton 1990), in better agreement with the Galactic globular clusters than those of the Fornax dwarf galaxy. In this respect, Sgr may be a better example of a surviving “building block” of the Galactic halo than Fornax (see Zinn 1993).

We thank Mario Mateo for his thoughtful comments. A.C.L. was supported by NASA grant number HF-01082.01-96A, and A.S. was supported by NASA grant number HF-01077.01-94A, from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS5-26555.

REFERENCES

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This preprint was prepared with the AAS L\TeX macros v4.0.
Table 1. The Ages of Sgr and its Clusters.

<table>
<thead>
<tr>
<th>Object</th>
<th>$[Fe/H]$</th>
<th>Age</th>
<th>Source$^a$</th>
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<tr>
<td>Sgr</td>
<td>-1.2</td>
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<td>1</td>
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<tr>
<td>Sgr</td>
<td>-0.5</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
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<td>3</td>
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<tr>
<td>Sgr</td>
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<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Arp 2</td>
<td>-1.70</td>
<td>12.3 ± 0.8</td>
<td>5</td>
</tr>
<tr>
<td>Ter 7</td>
<td>-0.36</td>
<td>7.2 ± 0.5</td>
<td>5</td>
</tr>
<tr>
<td>Ter 8</td>
<td>-1.99</td>
<td>16.9 ± 1.5</td>
<td>5</td>
</tr>
</tbody>
</table>

$^a$Sources: (1) MUSKKK, (2) Mateo et al. (1996), (3) Fahlman et al. (1996), (4) Marconi et al. (1997), (5) CDS.

Table 2. Adopted Cluster Parameters.

<table>
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<tr>
<th>Cluster</th>
<th>$V(HB)$</th>
<th>$(V – I)_g$</th>
<th>$[Fe/H]$</th>
<th>$E(V – I)^a$</th>
</tr>
</thead>
<tbody>
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<td>M68</td>
<td>15.64 ± 0.01</td>
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<td>-2.09 ± 0.11</td>
<td>0.09</td>
</tr>
<tr>
<td>M54</td>
<td>18.17 ± 0.05</td>
<td>1.095</td>
<td>-1.79 ± 0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>M5</td>
<td>15.09 ± 0.02</td>
<td>0.966</td>
<td>-1.40 ± 0.06</td>
<td>0.04</td>
</tr>
</tbody>
</table>

$^a$computed from $E(B – V)$ using the relation of Dean et al. (1978).
Fig. 1.— (a) Color-magnitude diagram of 18,796 stars in the direction of M54. Only stars with at least three detections, $\sigma_V < 0.050$ mag, and $\sigma_{V-I} < 0.071$ mag are shown. (b) As for (a), but only the 7551 stars located between 2.5 and 4.3 arcmin from the cluster center are shown. The curves are the red giant branch fiducials of M54 (left) and Sgr (right) from SL95.
Fig. 2.— As for Figure 1b, but the observed data have been shifted to the theoretical plane as discussed in Sec. 3. The solid line is the fiducial for M5 ([Fe/H] = −1.40, Walker 1994) and the dashed line is the fiducial for M68 ([Fe/H] = −2.09, Sandquist et al. 1996).
Fig. 3.— The data from Figure 1b are plotted with Revised Yale Isochrones shifted to the observed plane (see Sec. 4). The isochrones are for 10, 12, 14, 16, and 18 Gyr (left to right) and $[\text{Fe/H}] = -1.50$. The latter is equivalent to an isochrone with $[\text{Fe/H}] = -1.79$ and $[\alpha/\text{Fe}] = +0.4$. 