

REDDENINGS, METALLICITIES, AND POSSIBLE ABUNDANCE ANOMALIES IN YOUNG GLOBULAR CLUSTERS

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ABSTRACT

We present new photometry in the *VI* passbands for the “young” globular clusters Rup 106, Ter 7, and Arp 2. After formulating the simultaneous reddening and metallicity (SRM) method of Sarajedini [AJ, 107, 618 (1994)] in the *BV* passbands, we apply it, along with the SRM method in *VI*, to the red giant branches (RGBs) of these clusters using *B–V* photometry from the literature and the *V–I* data presented herein. We find $[\text{Fe}/\text{H}] = -1.90 \pm 0.10$, $E(B-V) = 0.18 \pm 0.02$ for Rup 106, $[\text{Fe}/\text{H}] = -0.82 \pm 0.15$, $E(B-V) = 0.07 \pm 0.03$ for Ter 7, and $[\text{Fe}/\text{H}] = -1.84 \pm 0.09$, $E(B-V) = 0.10 \pm 0.02$ for Arp 2. Furthermore, in light of this new abundance for Ter 7 and recent work on the luminosity of the red horizontal branch, we rederive the age of Ter 7 finding it to be some 6 Gyr younger than 47 Tuc. We show that the SRM method is insensitive to age for clusters with purely red HBs and ages as young as ~ 5 Gyr; for clusters with bluer HBs, the SRM method is only mildly sensitive to age differences between such clusters and the calibrating (standard) clusters. From these metallicity estimates, we conclude that the photometric abundances of the program clusters based on the properties of the RGB are systematically lower ($\Delta[\text{Fe}/\text{H}] = 0.1\text{--}0.4$ dex) than those derived using other indicators, in particular the Ca II triplet method. We note that the young globular cluster Palomar 12 also exhibits this behavior. We suggest that this discrepancy is due to systematic differences in the $[\alpha/\text{Fe}]$ ratios between the young clusters and the “normal” Galactic globulars used to calibrate the abundance determination methods. However, we are unable to completely reconcile all the observations of Rup 106 using this approach. Systematic differences in $[\alpha/\text{Fe}]$ between the young clusters and the rest of the Galactic globulars may indicate differences in their chemical enrichment histories, perhaps due to differing environments at the times of their formation. Interestingly, both Ter 7 and Arp 2 are believed to be members of the Sagittarius dwarf galaxy. © 1997 American Astronomical Society. [S0004-6256(97)00601-8]

1. INTRODUCTION

Over the past several years, it has become increasingly clear that there are a number of exceptionally young globular clusters located in the Galactic halo. The first object to be so identified was the sparse globular cluster Palomar 12; Stetson *et al.* (1989) found Pal 12 to be 25% to 30% younger than the average of 47 Tuc and M5. Then, Buonanno *et al.* (1990) and Buonanno *et al.* (1993) studied Ruprecht 106 and claimed that, based upon a derived metallicity of $[\text{Fe}/\text{H}] = -1.9 \pm 0.2$, it is 4 to 5 gigayears (Gyr) younger than other metal-poor clusters such as M68 and NGC 6397. Two globular clusters that appear to be members of the Sagittarius dwarf galaxy, Ter 7 and Arp 2, have been studied by

Buonanno *et al.* (1995a; hereafter BCPFRF) and Buonanno *et al.* (1995b; hereafter BCFRF), respectively. They find that Ter 7, with $[\text{Fe}/\text{H}] = -1.00 \pm 0.13$, is 4 to 5 Gyr younger than 47 Tuc, and Arp 2, with $[\text{Fe}/\text{H}] = -1.84 \pm 0.25$, is ≈ 3 Gyr younger than a group of metal-poor clusters. Most recently, Ferraro *et al.* (1995) have shown that IC 4499, at $[\text{Fe}/\text{H}] = -1.75 \pm 0.20$, is 3 to 4 Gyr younger than globular clusters of similar metallicity. We note in passing that these metal abundances are all based, in one way or another, on the color of the red giant branch.

In each case, the derived relative age of each cluster depends sensitively on the adopted metal abundance. Furthermore, the interpretation of the age and abundance of the cluster in the context of the formation and evolution of the Galactic halo is affected by our knowledge of the cluster horizontal branch (HB) morphology. As a result, the motivation behind the present study is to improve our knowledge of the characteristics of these young clusters. In particular, we are interested in the metallicities, reddenings (hence distances), HB morphologies, and ages of Rup 106, Ter 7, and

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TABLE 1. Observing log.

Cluster	Date	Telescope	CCD	Field	Exposure Time	Filter	(Airmass)	(FWHM)	Phot?
Rup 106	5 Dec 1993	0.9-m	Tek1K	Center	600s, 100s 400s, 80s	V I	1.75 1.66	1.5 1.5	N
Rup 106	6 Dec 1993	0.9-m	Tek1K	Center	700s, 100s 500s, 80s	V I	1.67 1.55	1.9 1.6	Y
Rup 106	6 Dec 1993	0.9-m	Tek1K	3.8' SW	100s 80s	V I	1.53 1.53	1.9 1.9	Y
Rup 106	6 Dec 1993	0.9-m	Tek1K	3.8' NW	100s 80s	V I	1.51 1.51	1.9 1.9	Y
Rup 106	6 Dec 1993	0.9-m	Tek1K	3.8' NE	100s 80s	V I	1.46 1.46	2.2 1.9	Y
Rup 106	5 Feb 1994	0.9-m	Tek1K	Center	2×300 2×200	V I	1.10 1.10	1.6 1.7	N
Rup 106	13 Mar 1994	0.9-m	Tek1K	Center	2×300 2×200	V I	1.23 1.23	2.0 2.1	N
Rup 106	8 Apr 1994	1.5-m	Tek2K	Center	2×150s 2×100s	V I	1.10 1.10	1.5 1.4	N
Rup 106	8 Apr 1994	1.5-m	Tek2K	20' E	2×150s 2×100s	V I	1.09 1.09	1.6 1.4	N
Rup 106	9 Apr 1994	1.5-m	Tek2K	Center	150s 100s	V I	1.14 1.14	1.8 1.5	N
Rup 106	9 Apr 1994	1.5-m	Tek2K	20' E	150s 100s	V I	1.13 1.13	1.7 1.4	N
Rup 106	10 Apr 1994	1.5-m	Tek2K	Center	150s 100s	V I	1.13 1.12	1.4 1.3	Y
Rup 106	10 Apr 1994	1.5-m	Tek2K	20' E	150s 100s	V I	1.12 1.12	1.3 1.3	Y
Rup 106	17 Jun 1994	0.9-m	Tek1K	Center	2×300s 2×200s	V I	1.08 1.09	1.7 1.6	Y
Rup 106	17 Jun 1994	0.9-m	Tek1K	20' E	300s 200s	V I	1.09 1.09	1.7 1.6	Y
Ter 7	17 Jun 1994	0.9-m	Tek1K	Center	4×300s 4×220s	V I	1.5 1.5	1.9 1.9	Y
Ter 7	18 Jun 1994	0.9-m	Tek1K	Center	3×300s 3×220s	V I	1.02 1.02	1.4 1.3	Y
Ter 7	18 Jun 1994	0.9-m	Tek1K	6.5' S	3×300s 3×220s	V I	1.12 1.12	1.5 1.3	Y
Arp 2	17 Jun 1994	0.9-m	Tek1K	Center	3×450s 3×350s	V I	1.10 1.10	1.8 1.8	Y
Arp 2	18 Jun 1994	0.9-m	Tek1K	Center	3×450s 3×350s	V I	1.00 1.00	1.4 1.3	Y
Arp 2	18 Jun 1994	0.9-m	Tek1K	11' N	3×450s 3×350s	V I	1.02 1.03	1.5 1.4	Y

Arp 2 in order to better understand their place in the formation and evolution of the Milky Way.

The next section describes the observations and how they were reduced. Section 3 presents the resulting color-magnitude diagrams and Sec. 4 compares the photometry with previous studies. We then go on to present the cluster characteristics derived from these data and to discuss the implications of the results.

2. OBSERVATIONS AND REDUCTIONS

The observations used in this study were obtained with the 0.9-m and 1.5-m telescopes at Cerro Tololo Inter-American Observatory (CTIO). For each run, we used the standard CTIO *V* and *I* filters matched to the CCD. Table 1 shows the dates of the observations, the telescope and CCD, the position of the CCD field relative to the cluster center, the exposure time, and the filter. The effective airmass of the

exposure and the full-width at half maximum of the stellar images, in arcsec, are recorded, along with a flag (“Y” or “N”) indicating whether or not the sky conditions were photometric at the time of observation.

Figures 1(a), 1(b), and 1(c) (Plates 10–12) show the observed cluster fields. For each cluster, off-cluster “field” frames were obtained to allow us to quantify the field star contamination. These field frames were centered 20 arcmin east of Rup 106, 11 arcmin north of Arp 2, and 6.5 arcmin south of Ter 7. Profile-fitting photometry was performed using DAOPHOT II (Stetson 1994) on all of the cluster and field frames. Details of this procedure, and of the transformation to the standard photometric system (see below), can be found in Sec. 3 of Sarajedini & Layden (1995).

On each photometric night, we observed between 14 and 30 standard stars, in 4–11 independent fields, from the list of Landolt (1992). They were chosen to cover a large range in

color, airmass, and universal time, allowing us to solve for up to five coefficients in the instrumental-to-standard photometry transformation.

The large number of standard stars allowed us to treat each night as an independent photometric solution. Thus the photometry presented here for Rup 106 is based on three independent photometric calibrations, and the photometry of Ter 7 and Arp 2 are based on two independent calibrations. The off-cluster field frames are based on 2 independent calibrations for Rup 106, and a single calibration for Arp 2 and Ter 7. The night-to-night agreement of our photometry suggests that it is of high external precision.

3. COLOR-MAGNITUDE DIAGRAMS

Figures 2, 3, and 4 show the CMDs for Rup 106 (3123 stars), Ter 7 (699 stars), and Arp 2 (896 stars), respectively, along with the CMDs for the off-cluster regions. These diagrams contain only stars that have been detected on at least 3 frame pairs and have $\sigma_V \leq 0.050$ mag and $\sigma_{V-I} \leq 0.071$ mag. Tables 2, 3, and 4 list the photometry for the stars in each cluster. It is clear from the cluster CMDs that there is a significant contribution from non-cluster stars, especially in the case of Rup 106 where the CCD images cover a field of view of 14.8×14.8 arcmin as compared to 6.8×6.8 arcmin for Ter 7 and Arp 2. In order to minimize the effects of contamination from non-cluster stars, the three panels of Fig. 5 are the CMDs for stars inside 2 arcmin of the cluster center.

Several features of these diagrams are worth noting. The RGB of Ter 7 is not as steep as those of Rup 106 and Arp 2 indicative of the more metal-rich nature of the former. The HBs of Rup 106 ($V \approx 18$, $V-I \approx 0.9$) and Ter 7 ($V \approx 18$, $V-I \approx 1.0$) are predominantly redward of the RR Lyrae instability strip whereas that of Arp 2 ($V \approx 18$, $V-I \approx 0.2$) is mostly blueward. In addition, all three clusters seem to exhibit significant blue straggler star sequences. The off-cluster CMDs contain very few stars with colors in this range; thus it appears that the majority of these blue straggler candidates are cluster members. The blue straggler content of Rup 106, Ter 7, and Arp 2 are discussed in more detail by Kaluzny *et al.* (1995, hereafter KKM), BCPFRF, and BCFRF, respectively.

4. COMPARISON WITH PREVIOUS PHOTOMETRY

All three of the program clusters have previously published CCD photometry in the BV system. Figures 6(a), 6(b), and 6(c) show comparisons of our V magnitudes with those of the most recently published studies for Rup 106 (KKM), Ter 7 (BCPFRF), and Arp 2 (BCFRF), respectively, as a function of V from the present study. The mean differences (others - us) in the range $15 < V < 19$ are $\langle \Delta V \rangle = 0.003 \pm 0.004$ for Rup 106, $\langle \Delta V \rangle = -0.035 \pm 0.011$ for Ter 7, and $\langle \Delta V \rangle = 0.074 \pm 0.002$ for Arp 2. The differences in the latter two cases are probably due to the difficulty of obtaining accurate aperture corrections in the densely crowded fields near the bulge.

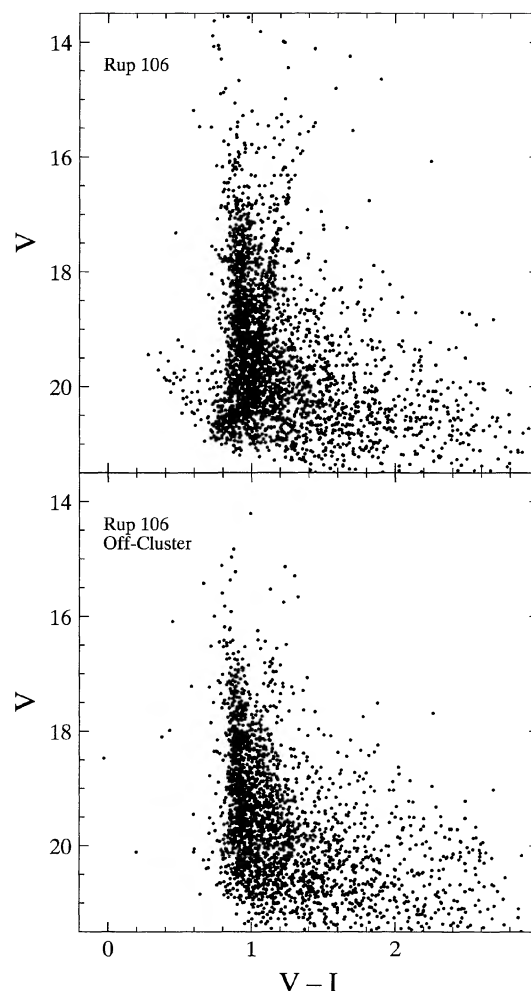


FIG. 2. Color-magnitude diagrams of Rup 106 stars with $\sigma_V \leq 0.050$ mag, $\sigma_{V-I} \leq 0.071$, and at least three detections. The upper panel shows photometry for the cluster field and the lower panel shows the off-cluster field.

5. SRM METHOD IN $B-V$

We are primarily interested in applying the simultaneous reddening and metallicity (SRM) method of Sarajedini (1994a) to CCD photometry of the program clusters. This method uses the V mag of the horizontal branch (HB), the apparent color of the red giant branch (RGB) at the level of the HB, and the shape of the RGB, along with an empirical calibration of the RGB position and shape with metal abundance to derive the cluster reddening and metallicity in a self-consistent manner. Sarajedini (1994a, see also Sarajedini & Milone 1995) formulated the SRM method in the $V, V-I$ filter passbands thus making the application of this method to our data straightforward. However, as noted in the previous section, $V, B-V$ data also exist for these clusters, and we would like to formulate the SRM method in these filter passbands as well. In this way, we can obtain two largely independent measures of the reddening and metallicity of each cluster.

To calibrate the SRM method in $B-V$, we rely upon high quality CCD photometry from the literature for well-studied

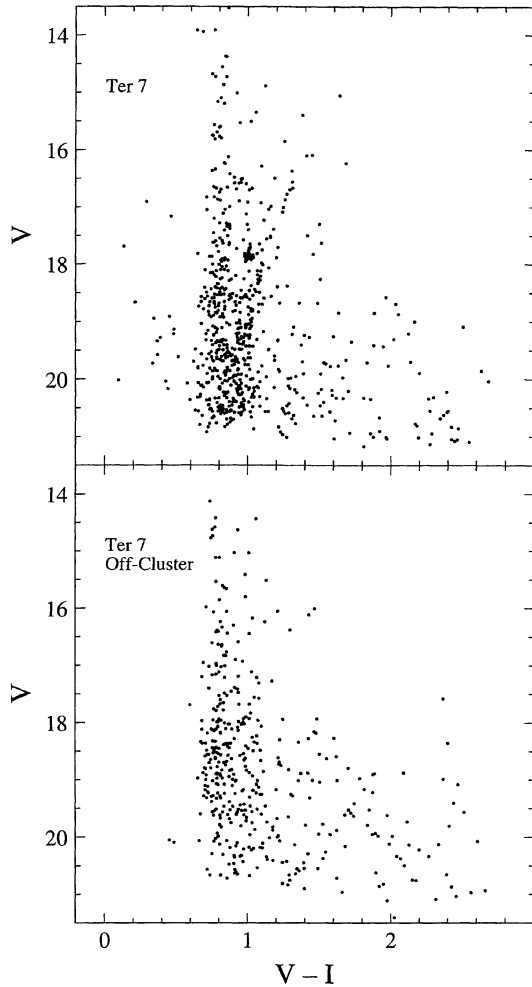


FIG. 3. Same as Fig. 2, except for Ter 7.

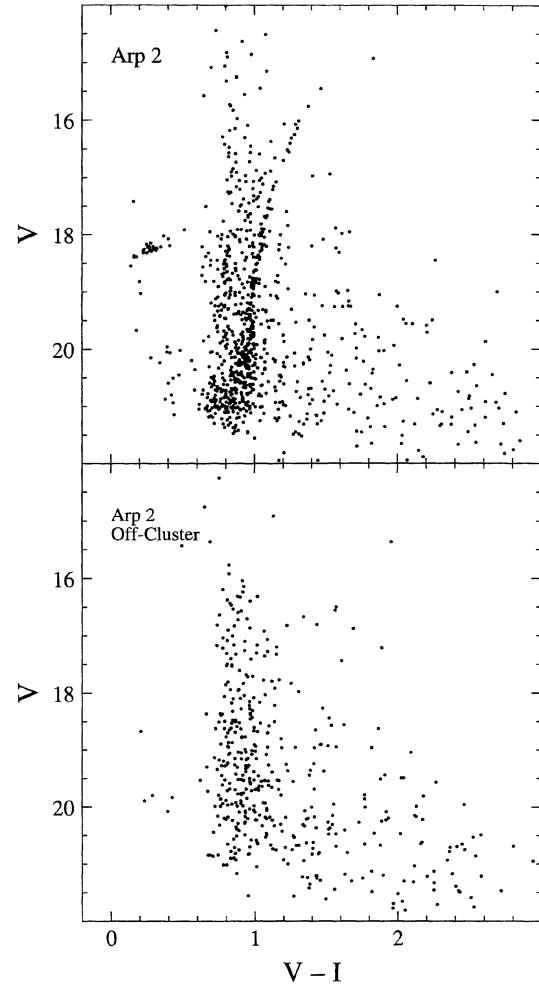


FIG. 4. Same as Fig. 2, except for Arp 2.

Galactic globular clusters. These six clusters are listed in the first part of Table 5. They are identical to those used by Sarajedini (1994a) and Sarajedini & Milone (1995) except that we have substituted M68 for NGC 6397 and omitted M2. The metallicities of 47 Tuc, NGC 6752, and M68 are taken from Zinn & West (1984), those of NGC 1851 and M15 are those adopted by Da Costa & Armandroff (1990), and the metallicity of NGC 5053 comes from Armandroff *et al.* (1992). The reddenings and $V(\text{HB})$ values of 47 Tuc, NGC 1851, NGC 6752, and M15 are taken from Da Costa & Armandroff (1990), while those of M68 and NGC 5053 come from the CMD studies referenced in Table 5.

The BV photometry for each cluster is taken from the reference given in the last column of Table 5. In order to facilitate the measurement of the RGB parameters, a polynomial was fitted to the RGB stars using the 2σ rejection algorithm of Sarajedini & Norris (1994). These fits are shown in Fig. 7 and four of them, those that approximately span our metallicity range, are listed in Table 6. From these fits and the adopted cluster reddenings, we measure the color of the RGB at the level of the HB $[(B-V)_{0,g}]$ and the difference in V mag between the HB and the RGB at $(B-V)_0=1.2$ ($\Delta V_{1,2}$) and at $(B-V)_0=1.1$ ($\Delta V_{1,1}$). In addition, utilizing

the distance scale of Lee *et al.* (1990), $M_V(\text{RR})=0.82 + 0.17[\text{Fe}/\text{H}]$, and the reddenings in Table 5, we have measured the color of each RGB at $M_V=-2$ $[(B-V)_{0,-2}]$. The calibrations of these photometric quantities with metallicity for the six primary calibrating clusters are shown as filled circles in the four panels of Fig. 8. The solid lines are weighted least squares fits to these data and have the following form:

$$[\text{Fe}/\text{H}] = -5.763 + 5.236(B-V)_{0,g}, \quad \text{rms}=0.07 \text{ dex}, \quad (1)$$

$$[\text{Fe}/\text{H}] = 0.3492 - 0.8618\Delta V_{1,2}, \quad \text{rms}=0.06 \text{ dex}, \quad (2)$$

$$[\text{Fe}/\text{H}] = -0.0735 - 0.8149\Delta V_{1,1}, \quad \text{rms}=0.05 \text{ dex}, \quad (3)$$

$$[\text{Fe}/\text{H}] = -5.318 + 3.547(B-V)_{0,-2} - 0.5586(B-V)_{0,-2}^2, \quad \text{rms}=0.08 \text{ dex}. \quad (4)$$

The open circles represent the secondary calibrating clusters listed in the lower part of Table 5. The metallicities, reddenings, and $V(\text{HB})$ values for these are generally taken from the studies referenced in the last column of Table 5, except in the case of NGC 6352 where the metal abundance and

TABLE 2. CCD photometry for Ruprecht 106.^a

#	X (pixels)	Y (pixels)	V	σ_V	V-I	σ_{V-I}	N
1	1378.85	869.83	12.90	0.003	1.53	0.003	9
2	1110.76	1571.48	12.93	0.008	0.71	0.008	4
3	708.95	1009.82	13.05	0.003	0.66	0.006	10
4	1381.42	1188.69	13.06	0.003	1.57	0.005	9
5	923.01	1212.40	13.13	0.004	0.72	0.003	10
6	876.87	850.75	13.27	0.004	0.74	0.002	10
7	1272.67	1207.80	13.29	0.004	1.19	0.003	6
8	1071.02	1850.71	13.30	0.002	1.36	0.005	3
9	1428.93	732.97	13.30	0.002	1.23	0.004	8
10	1323.23	1328.77	13.45	0.002	1.21	0.003	10
11	837.80	1659.03	13.55	0.018	0.83	0.004	3
12	1168.24	1126.60	13.57	0.004	0.98	0.002	13
13	897.27	632.46	13.63	0.007	0.74	0.004	6
14	1090.68	120.24	13.82	0.003	1.06	0.005	4
15	642.81	1716.26	13.89	0.027	0.73	0.004	3
16	1160.22	1184.99	13.99	0.008	1.22	0.012	10
17	1132.83	228.19	14.01	0.005	1.23	0.014	3
18	1072.70	548.62	14.07	0.014	0.77	0.003	4
19	980.18	187.07	14.08	0.004	0.73	0.009	4
20	749.60	1310.54	14.12	0.001	1.44	0.003	11
21	1304.35	1468.94	14.12	0.006	0.77	0.004	9
22	951.87	1550.29	14.25	0.006	1.68	0.003	3
23	1862.87	1623.06	14.29	0.016	0.78	0.025	3
24	872.77	1324.96	14.45	0.002	1.25	0.003	11
25	849.84	1367.87	14.65	0.004	1.90	0.003	11
26	981.78	1010.15	14.67	0.011	0.91	0.004	13
27	1035.06	1103.94	14.81	0.011	0.82	0.010	14
28	968.84	1037.32	14.81	0.005	1.58	0.013	10
29	1374.21	1329.86	14.88	0.005	0.80	0.004	8
30	746.07	958.80	14.90	0.006	0.78	0.007	13

Notes to TABLE 2

^aTable 2 is to be presented in its complete form in the ApJ/AJ CD-ROM Series. The first page of this table is presented here for guidance regarding its form and content.

reddening comes from the work of Fullton *et al.* (1995). The RGB parameters of the secondary clusters have been measured in precisely the same manner as for the primary calibrators. These secondary calibrators have not been used in the determination of the above mentioned fitted relations. They only serve to corroborate these relations.

Equations (1) and (2) are used in the application of the SRM method. In cases where the upper portion of the cluster RGB is poorly populated, Eq. (3) can be substituted for Eq. (2). Furthermore, in situations where $V(\text{HB})$ cannot be measured reliably, and the distance modulus and reddening are both known, Eq. (4) can be used to derive the metal abundance.

The variation of RR Lyrae absolute magnitude with metallicity is built into the SRM method. Thus, the absolute magnitude-metallicity relation need not be known *a priori* to apply the SRM method [i.e., when using Eqs. (1), (2), and (3)]. In addition, Sarajedini *et al.* (1995, hereafter SLL) note that, for clusters with purely red HB morphologies, the magnitude of the HB [$M_V(\text{RHB})$] depends not only on $[\text{Fe}/\text{H}]$ but also on the cluster age. As a result, inasmuch as the calibrating clusters reflect it, the variation of $M_V(\text{RHB})$ with metallicity and age is also built into the relations which define the SRM method.

Why then do the points for ESO121-SC03 (hereafter ESO121) and Lindsay 1 (hereafter L1), which are exception-

ally young globular clusters in the LMC and SMC, respectively, lie so close to the plotted relations in Fig. 8? That is to say, these Magellanic Cloud clusters are believed to be much younger than their Galactic counterparts (see SLL and references therein), and we know that decreasing age has an effect, albeit small, on the color and slope of the RGB, making the former smaller and the latter larger. Why then do the $(B-V)_{0,g}$ and $\Delta V_{1,2}$ values for L1 and ESO121 appear to follow the same relation as those of the older Galactic globular clusters?

To answer this question, we need to adjust the $(B-V)_{0,g}$ and $\Delta V_{1,2}$ values of L1 and ESO121 to match the older ages of the Galactic globulars. In particular, we have chosen 47 Tuc, which we assume to be 13 Gyr old, as our reference cluster. We begin by noting that, in the case of clusters with purely red HBs, as the age of the cluster increases, the magnitude of its HB becomes fainter; the amount of this change is roughly 0.02 mag/Gyr but depends on metallicity (see Fig. 5 of SLL). In performing this adjustment, we have adopted the ages and $M_V(\text{RHB})$ values derived by SLL for these clusters. Based on the difference between the $M_V(\text{RHB})$ of each cluster and that of 47 Tuc, we have adjusted the measured $V(\text{HB})$ values of ESO121 and L1 by 0.18 and 0.16 mag, respectively, yielding $V(\text{HB})=19.14$ for the former and 19.50 for the latter. This

TABLE 3. CCD photometry for Terzan 7.^a

#	X (pixels)	Y (pixels)	V	σ_V	V-I	σ_{V-I}	N
1	643.32	606.93	12.20	0.003	1.27	0.011	4
2	806.38	829.82	13.38	0.002	1.25	0.003	4
3	134.60	259.60	13.52	0.002	0.86	0.004	4
4	37.48	212.73	13.91	0.001	0.77	0.004	4
5	730.65	690.90	13.91	0.002	0.64	0.002	5
6	882.06	562.92	13.94	0.020	0.69	0.013	7
7	482.51	330.02	14.37	0.002	0.84	0.002	7
8	846.91	27.34	14.37	0.001	0.85	0.013	3
9	162.84	1013.75	14.55	0.004	0.82	0.007	7
10	389.45	847.99	14.68	0.003	0.75	0.001	7
11	511.15	391.12	14.72	0.003	0.85	0.003	7
12	1025.66	626.19	14.72	0.025	0.77	0.028	7
13	11.41	715.25	14.86	0.003	0.83	0.007	4
14	835.14	322.81	14.88	0.002	1.12	0.002	7
15	1025.50	235.95	15.01	0.027	0.93	0.023	6
16	505.37	484.72	15.05	0.001	1.64	0.002	7
17	1008.69	102.45	15.09	0.002	0.81	0.002	7
18	669.97	219.28	15.16	0.002	0.79	0.002	7
19	539.24	175.99	15.19	0.002	0.83	0.002	7
20	724.62	987.82	15.34	0.004	1.06	0.006	7
21	435.67	538.94	15.39	0.003	1.38	0.003	7
22	200.83	340.61	15.50	0.002	1.02	0.002	7
23	495.23	806.35	15.53	0.011	0.94	0.012	7
24	378.58	891.88	15.57	0.002	0.76	0.003	6
25	191.60	165.29	15.59	0.001	0.81	0.004	6
26	718.80	604.49	15.60	0.004	0.80	0.004	6
27	299.08	298.04	15.69	0.003	0.78	0.005	7
28	160.30	741.08	15.74	0.003	0.75	0.004	7
29	694.60	198.38	15.75	0.010	0.76	0.010	6
30	298.51	544.94	15.76	0.001	0.80	0.003	6

Notes to TABLE 3

^aTable 3 is to be presented in its complete form in the ApJ/AJ CD-ROM Series. The first page of this table is presented here for guidance regarding its form and content.

correction accounts for the age differences between 47 Tuc and the two younger clusters.

We then measure $(B-V)_{0,g}'$ [i.e., the $B-V$ color of the RGB at this *adjusted* value of $V(\text{HB})$] for each cluster using the RGB fit. These RGB colors are then reddened by 0.003 mag for each Gyr of age difference relative to 47 Tuc, to account for the slight age-sensitivity of the RGB color, and are plotted as crosses in Fig. 8(a). Similarly, as noted above, the slope of the RGB also changes with age; thus, we must adjust the V magnitude at $(B-V)_0 = 1.2$ ($V_{1,2}$) for ESO121 and L1 to account for their younger ages relative to 47 Tuc. As a result, the $V_{1,2}$ is made fainter (effectively decreasing the slope of the RGB as measured by $\Delta V_{1,2}$) by 0.026 mag for each Gyr age difference relative to 47 Tuc. This age-adjusted value of $V_{1,2}$ is subtracted from the age-adjusted $V(\text{HB})$ to form $\Delta V_{1,2}$, and plotted as crosses in Fig. 8(c). The quoted RGB color offsets in units of mag/Gyr have been derived from the Straniero & Chieffi (1991) isochrones.

It is clear from the locations of the crosses in Fig. 8 that correcting for the effects of age has moved the points for ESO121 and L1 a negligible amount. This is because as we move to older ages, $V(\text{HB})$ becomes fainter causing $(B-V)_{0,g}$ to be bluer, but it is made redder again by adjusting the RGB colors to account for the older ages, leaving the actual value of $(B-V)_{0,g}$ essentially unchanged. In the case of $\Delta V_{1,2}$, the amount by which the HB becomes fainter as

the cluster ages is almost identical to the amount by which $V_{1,2}$ becomes fainter leaving $\Delta V_{1,2}$ basically unchanged. This is also true for $\Delta V_{1,1}$ and for the VI SRM method. Thus, we have a method to determine reddening and metallicity simultaneously which is largely insensitive to the effects of age for predominantly-red HB clusters with ages as young as ≈ 5 Gyr and with $[\text{Fe}/\text{H}] \lesssim -0.3$.

The “self-correcting” property of the SRM method described above applies *only* to clusters with predominantly red HBs so that the mean level of the HB is measured as the mean level of the *red* HB stars; thus, clusters such as Arp 2 and IC 4499 (and perhaps Rup 106) do not benefit from this property. This is because, while the value of $M_V(\text{RHB})$ is dependent on age, the value of $M_V(\text{RR})$ is generally not. In the next section, we assess the effect of Arp 2’s younger-than-average age on the derived reddening and metallicity from the SRM method.

6. RESULTS OF SRM METHOD

The first step in applying the SRM method to Rup 106, Ter 7, and Arp 2 is to measure $V(\text{HB})$ for each cluster. Since our photometric scale agrees with that of KKM for Rup 106, we have averaged their photometry for the RR Lyrae stars in Rup 106 and found $\langle V(\text{HB}) \rangle = 17.80 \pm 0.02$, where the error is composed of the standard error of the mean and an esti-

TABLE 4. CCD photometry for Arp 2.^a

#	X (pixels)	Y (pixels)	V	σ_V	V-I	σ_{V-I}	N
1	779.42	779.41	14.01	0.006	0.80	0.005	4
2	1041.55	860.98	14.44	0.001	0.73	0.003	3
3	162.10	384.73	14.51	0.004	1.08	0.003	5
4	864.79	362.94	14.63	0.002	0.92	0.002	6
5	379.08	814.59	14.82	0.001	0.81	0.002	6
6	768.52	1016.39	14.85	0.004	0.98	0.003	6
7	285.53	235.61	14.89	0.001	0.81	0.002	6
8	558.71	924.85	14.92	0.001	1.83	0.002	5
9	547.66	273.67	15.06	0.003	0.80	0.001	6
10	621.25	941.52	15.08	0.004	0.70	0.002	6
11	504.14	557.35	15.15	0.005	1.09	0.003	5
12	9.74	455.19	15.25	0.008	0.88	0.007	3
13	390.93	3.62	15.26	0.003	0.88	0.006	3
14	770.05	920.10	15.31	0.003	0.80	0.002	6
15	660.35	723.78	15.44	0.002	1.04	0.003	6
16	553.44	591.17	15.45	0.003	1.47	0.002	6
17	156.19	852.72	15.55	0.002	0.93	0.004	6
18	104.39	636.61	15.57	0.006	0.65	0.006	6
19	339.56	233.63	15.72	0.002	0.83	0.002	6
20	685.23	1023.77	15.74	0.007	0.83	0.006	4
21	472.86	602.63	15.76	0.002	1.38	0.002	6
22	433.70	37.37	15.82	0.004	0.85	0.007	6
23	683.35	755.73	15.97	0.002	0.88	0.002	6
24	513.53	564.52	16.01	0.006	1.31	0.006	4
25	523.97	256.23	16.06	0.002	1.21	0.003	6
26	445.36	628.99	16.07	0.002	1.29	0.003	6
27	303.14	504.29	16.09	0.004	0.95	0.002	6
28	88.49	728.81	16.14	0.003	1.30	0.002	5
29	444.75	207.40	16.15	0.003	0.87	0.001	6
30	385.34	568.11	16.18	0.004	0.83	0.005	5

Notes to TABLE 4

^aTable 4 is to be presented in its complete form in the ApJ/AJ CD-ROM Series. The first page of this table is presented here for guidance regarding its form and content.

mated uncertainty of 0.02 mag in the photometric zeropoint. For Ter 7, we consider all stars in Fig. 5 with $0.97 < V-I < 1.05$ and $17.75 < V < 18.00$. The mean magnitude of these stars is $\langle V(\text{HB}) \rangle = 17.86 \pm 0.02$. For the *BV* photometry of Ter 7, we adopt the value of $\langle V(\text{HB}) \rangle = 17.76 \pm 0.07$ from BCFRF. In the case of Arp 2, we follow the method described in Sarajedini & Layden (1995); we fitted the fiducial HB of the metal-poor globular cluster M68 (Walker 1994) to the blue HB stars in Arp 2. The fitted fiducial at the position of the RR Lyrae instability strip corresponds to $\langle V(\text{HB}) \rangle = 18.13 \pm 0.04$ mag using our *VI* CMD, and to $V(\text{HB}) = 18.23 \pm 0.05$ using the *BV* photometry of BCFRF. Both of the uncertainties in these values include an estimated error of 0.02 mag in the photometric zeropoint.

We can check the $\langle V(\text{HB}) \rangle$ value for Arp 2 by using the four RR Lyrae stars detected in our photometric data, found using the variability index (I_{WS}) of Welch & Stetson (1993). As illustrated in Fig. 9, there are four stars with $I_{WS} > 30$, which we have chosen as the threshold criterion for intrinsic variability. The (X, Y) positions and intensity-mean magnitudes and colors of these stars are given in Table 7. Their locations in the CMD (lower panel of Fig. 5) suggest that they are likely to be RR Lyrae members of Arp 2. The mean V mag of these stars, weighted by the number of observations per star, gives $\langle V(\text{HB}) \rangle = 18.14 \pm 0.08$. The small num-

ber of observations per star and the unknown phase distribution of the observations means that the quoted intensity-means may be poor representations of their true values. Monte Carlo simulations using the 40 well-sampled RR Lyrae light curves from the cluster M68 (Walker 1994) showed that 67% of the time, a random sampling of data mimicking that in Table 7 produces a $\langle V(\text{HB}) \rangle$ estimate within 0.06 mag of the true value. Thus, the uncertainty of 0.08 mag quoted above is consistent with our expectations, and the value of $\langle V(\text{HB}) \rangle$ derived from the RR Lyrae stars corroborates the $\langle V(\text{HB}) \rangle$ value derived from the BHB stars.

As an aside, since we have detected 4 RR Lyrae variables in Arp 2, we can calculate the HB morphology index of Lee *et al.* (1988), $(B-R)/(B+V+R)$, where B , V , and R are the numbers of HB stars located blueward, within, and redward of the instability strip, respectively. Under the assumption that $R=0$ in Arp 2, we calculate $(B-R)/(B+V+R) = 0.86$, which is identical to the value estimated by BCFRF from a smaller sample of stars. We note in passing that this value of $(B-R)/(B+V+R)$ is actually an upper limit and would therefore be lower if $R > 0$.

The next step involves fitting polynomials to the RGBs of the program clusters. Figure 10 shows these fits to the $V, V-I$ photometry presented in this study and $V, B-V$ data taken from the literature. The RGB fits have been performed using the 2σ rejection technique mentioned above. These fits

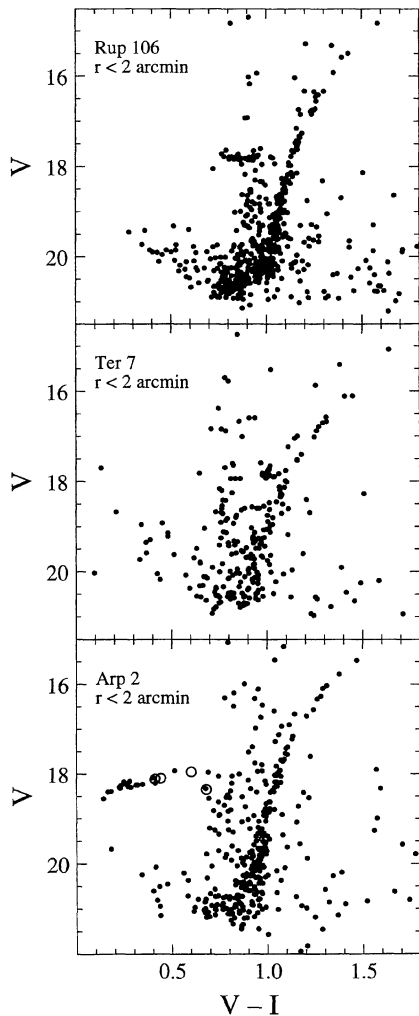


FIG. 5. Color-magnitude diagrams of Rup 106, Ter 7, and Arp 2 for stars inside 2 arcmin of the clusters' centers. The open circles in the lower panel are the four suspected RR Lyraes in Arp 2.

then allow the determination of the apparent color of the RGB at the level of the HB. The errors in these colors are derived by combining the RMS deviation of the fitted values from the RGB fits and an estimated uncertainty in the photometric zeropoint of ± 0.02 mag. These RGB colors along with the adopted $V(\text{HB})$ levels are listed in Table 8.

With the required input parameters in hand, we can proceed with the application of the SRM method. The 'numerical method' outlined in Sarajedini (1994a) yields the reddenings and metallicities given in columns 2 through 5 of Table 9. Taking the weighted mean of these values, we arrive at the reddenings and metallicities listed in the last two columns of Table 9. The conversion between $E(V-I)$ and $E(B-V)$ has been accomplished using the relations published by Dean *et al.* (1978).

As mentioned in the previous section, the estimated reddening and metallicity of Arp 2 may be affected by the fact that it is believed to be ≈ 3 Gyr younger than other "normal" clusters at its metallicity (BCFRF). To assess the importance of this fact on the results of the SRM method, we

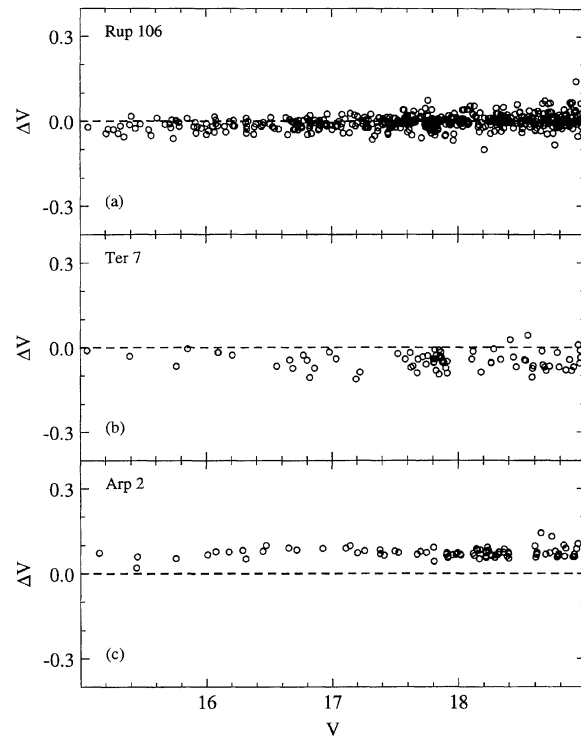


FIG. 6. Comparisons of our V magnitudes with those of the most recently published values for Rup 106, Ter 7, and Arp 2. The sources of the photometry are as follows: Rup 106-KKM, Ter 7-BCPFRF, Arp 2-BCFRF. The differences are in the sense (others-us).

have performed the following test. We would like to adjust the shape of the Arp 2 RGB so as to simulate a cluster that is 3 Gyr older. In other words, we need to make the Arp 2 RGB redder (horizontal shift) and decrease its slope (differential vertical shift).

Beginning with the $B-V$ RGB fit shown in the lower left panel of Fig. 10, we adjust the color of the entire RGB redward by 0.003 mag/Gyr (Straniero & Chieffi 1991). Then, to simulate the slight decrease in the RGB slope with age, the RGB is shifted in the magnitude direction using the following prescription. At the level of the HB, $V(\text{HB})$, the RGB is left unchanged; at $V_{1.2}$, the RGB is shifted to fainter mags by 0.023 mag/Gyr, and everywhere else along the RGB, the magnitude shift is computed as a linear interpolation/extrapolation of these two points. The result of this differential vertical shift of the Arp 2 RGB is to make the RGB slightly fainter and the slope shallower. The result of the entire procedure is to simulate the RGB of Arp 2 if it were 3 Gyr older than it is believed to be.

Once we have this simulated RGB, it is a simple matter to apply the SRM method to it. When we do this, we find a reddening value that is within 0.001 mag of that quoted in column 5 of Table 9, but the metallicity value is 0.038 dex higher. However, we believe that this difference is almost certainly an upper limit and that the effect of age on the derived metallicities via the SRM method is actually somewhat smaller. This is because we have exaggerated the decrease in the slope of the RGB by assuming that its vertical location remains unchanged at $V(\text{HB})$. It is difficult to assess

TABLE 5. Primary and secondary calibration clusters.

Cluster	[Fe/H]	$E(B-V)$	$V(\text{HB})$	$(B-V)_{0,g}$	$\Delta V_{1,2}$	$\Delta V_{1,1}$	$(B-V)_{0,-2}$	Reference ^a
47 Tuc	-0.71 ± 0.07	0.04	14.06	0.958	1.275	0.798	1.806	1,2
NGC 1851	-1.29 ± 0.07	0.02	16.05	0.873	1.806	1.433	1.525	3
NGC 6752	-1.54 ± 0.09	0.04	13.75	0.781	2.264	1.873	1.294	4
M68	-2.09 ± 0.11	0.07	15.64	0.694	2.810	2.508	1.087	5
M15	-2.17 ± 0.07	0.10	15.86	0.691	2.972	2.601	1.063	6
NGC 5053	-2.41 ± 0.12	0.06	16.65	0.647	3.101	2.741	1.016	7
NGC 6352	-0.60 ± 0.08	0.21	15.28	0.994	0.953	0.591	1.971	2
ESO121-SC03	-0.93 ± 0.10	0.03	18.96	0.907	1.507	1.101	1.575	8
Lindsay 1	-1.10 ± 0.10	0.04	19.34	0.864	1.888	1.522	1.539	8
NGC 362	-1.27 ± 0.07	0.03	15.44	0.832	2.050	1.741	1.449	9
NGC 1261	-1.31 ± 0.09	0.00	16.65	0.860	2.095	1.735	1.402	10
NGC 288	-1.40 ± 0.12	0.02	15.38	0.852	1.884	1.503	1.448	11
Eridanus	-1.41 ± 0.11	0.03	20.24	0.838	1.897	1.569	1.461	8
Pal 14	-1.60 ± 0.18	0.05	20.04	0.803	2.288	1.939	1.303	8
NGC 1904	-1.69 ± 0.09	0.01	16.15	0.801	2.332	2.001	1.275	12
NGC 6535	-1.75 ± 0.15	0.44	15.73	0.745	2.537	2.134	1.196	13
NGC 6397	-1.91 ± 0.14	0.18	12.90	0.717	2.842	2.483	1.103	14

Notes to TABLE 5

^a(1) Hesser *et al.* 1987; (2) Sarajedini & Norris 1994; (3) Walker 1992; (4) Penny & Dickens 1986; (5) Walker 1994; (6) Durrell & Harris 1993; (7) Sarajedini & Milone 1995; (8) Sarajedini *et al.* 1995; (9) Harris 1982; (10) Ferraro *et al.* 1993; (11) Bergbusch 1993; (12) Ferraro *et al.* 1992; (13) Sarajedini 1994b; (14) Kaluzny 1996.

the degree of this change using theoretical isochrones because the morphology of the RGB is itself nearly vertical in this magnitude range. However, it appears from the shapes of the RGBs that the vertical shift at $V(\text{HB})$ is small, though

not identically zero. Furthermore, the effect of age on the RGB color and slope in $V-I$ is even smaller than it is in $B-V$ (Da Costa & Armandroff 1990). Therefore, we estimate that the final derived abundance of Arp 2 should be ≈ 0.02 dex more metal rich than that quoted in Table 9. We have chosen not to correct the metallicity for this effect because of the uncertainties inherent in deriving the correction itself and because the correction is within the quoted errors in reddening and metallicity.

7. DISCUSSION OF RESULTS

7.1 Rup 106

We begin by comparing our metallicity and reddening estimates for Rup 106 with those of previous investigations. Buonanno *et al.* (1990) obtained BV photometry of the cluster, and by adopting a reddening of $E(B-V) = 0.24 \pm 0.06$ from Burstein & Heiles (1982), they derived $(B-V)_{0,g} = 0.72 \pm 0.06$. When coupled with the Zinn & West (1984) calibration between $(B-V)_{0,g}$ and $[\text{Fe}/\text{H}]$, this yielded a metallicity of $[\text{Fe}/\text{H}] = -1.9 \pm 0.2$. Comparing their main sequence turn-off photometry with clusters of similar metallicity, they determined that Rup 106 is 4–5 Gyr younger than the other clusters. Buonanno *et al.* (1993) obtained a similar abundance from their VI CMD when they adopted $E(B-V) = 0.19$ mag.

More recently, Da Costa *et al.* (1992) obtained Ca II triplet spectra of seven stars in Rup 106. They measured $[\text{Fe}/\text{H}] = -1.69 \pm 0.05$. When transformed to the standard calibration system of Da Costa & Armandroff (1995, hereafter DCA95), this abundance becomes $[\text{Fe}/\text{H}] = -1.75 \pm 0.08$ (see footnote in DCA95). Interpreted in the context of this higher abundance (higher than $[\text{Fe}/\text{H}] = -1.9 \pm 0.2$ from Buonanno *et al.* 1990), Rup 106 is only ~ 3 Gyr younger than clusters of comparable metallicity.

This metallicity was corroborated by Sarajedini (1994a) who applied the SRM method to the VI photometry published by Buonanno *et al.* (1993), and obtained

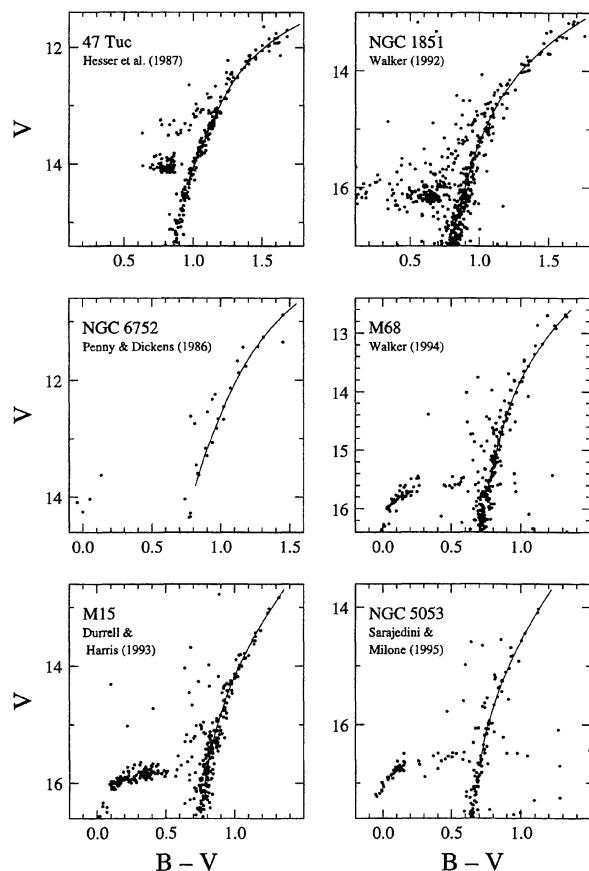


FIG. 7. Polynomial fits to the red giant branches of the primary calibrating clusters of the BV simultaneous reddening and metallicity method.

TABLE 6. Fiducial red giant branches for selected clusters.

M15		NGC 6752		NGC 1851		47 Tuc	
V	B - V	V	B - V	V	B - V	V	B - V
12.7	1.354	10.7	1.545	13.1	1.760	11.6	1.770
12.8	1.325	10.8	1.495	13.2	1.693	11.7	1.694
12.9	1.297	10.9	1.449	13.3	1.630	11.8	1.626
13.0	1.269	11.0	1.407	13.4	1.572	11.9	1.565
13.1	1.242	11.1	1.367	13.5	1.518	12.0	1.511
13.2	1.215	11.2	1.331	13.6	1.468	12.1	1.463
13.3	1.190	11.3	1.297	13.7	1.421	12.2	1.420
13.4	1.165	11.4	1.266	13.8	1.378	12.3	1.381
13.5	1.141	11.5	1.236	13.9	1.338	12.4	1.347
13.6	1.118	11.6	1.209	14.0	1.301	12.5	1.315
13.7	1.095	11.7	1.183	14.1	1.266	12.6	1.287
13.8	1.074	11.8	1.158	14.2	1.233	12.7	1.261
13.9	1.053	11.9	1.135	14.3	1.203	12.8	1.236
14.0	1.033	12.0	1.113	14.4	1.175	12.9	1.214
14.1	1.013	12.1	1.092	14.5	1.149	13.0	1.192
14.2	0.995	12.2	1.071	14.6	1.124	13.1	1.172
14.3	0.977	12.3	1.052	14.7	1.101	13.2	1.152
14.4	0.960	12.4	1.033	14.8	1.079	13.3	1.133
14.5	0.944	12.5	1.014	14.9	1.059	13.4	1.114
14.6	0.929	12.6	0.996	15.0	1.040	13.5	1.096
14.7	0.914	12.7	0.979	15.1	1.021	13.6	1.077
14.8	0.900	12.8	0.962	15.2	1.004	13.7	1.060
14.9	0.887	12.9	0.945	15.3	0.988	13.8	1.042
15.0	0.874	13.0	0.929	15.4	0.973	13.9	1.025
15.1	0.862	13.1	0.913	15.5	0.958	14.0	1.008
15.2	0.851	13.2	0.897	15.6	0.944	14.1	0.992
15.3	0.841	13.3	0.882	15.7	0.932	14.2	0.977
15.4	0.831	13.4	0.867	15.8	0.919	14.3	0.963
15.5	0.821	13.5	0.853	15.9	0.908	...	...
15.6	0.812	13.6	0.840	16.0	0.898	...	...
15.7	0.804	13.7	0.827	16.1	0.888	...	...
15.8	0.796	13.8	0.816	16.2	0.880	...	...
15.9	0.788	...	...	...	...	...	...
16.0	0.781	...	...	...	...	...	...

$[\text{Fe}/\text{H}] = -1.61 \pm 0.20$ and $E(B - V) = 0.13 \pm 0.03$. For comparison, the RGB fit used by Sarajedini (1994a) is shown as the dashed line in Fig. 10. It is different from the solid line for two reasons. First, there is a distortion in the color scale of the Buonanno *et al.* (1993) photometry for Rup 106 relative to the data presented herein. In addition, the RGB of Buonanno *et al.* is not as well defined as that in the present study resulting in a poorly constrained best-fit line. The RGB shown as the solid line in Fig. 10 is based on three independent photometric scales (Sec. 2) and appears better defined, so the SRM results in the present paper supercede those in Sarajedini (1994a).

The BV photometry of KKM, which we have used in the present SRM study, also includes light curves for 12 RR Lyrae variables in Rup 106. Using a relation between metallicity, reddening, and color at minimum light along with the Zinn & West (1984) calibration between $(B - V)_{0,g}$ and $[\text{Fe}/\text{H}]$, KKM were able to solve simultaneously for the metallicity and reddening. They found that $E(B - V) = 0.198 \pm 0.002$ and $[\text{Fe}/\text{H}] = -1.87 \pm 0.23$, which compare favorably with the values we have measured from their RGB photometry (see Table 9).

On the other hand, KKM also examined the period-amplitude and period-rise-time diagrams for the Rup 106

RR Lyraes, and from them concluded that the metal abundance of Rup 106 is closer to that of M3 (i.e., $[\text{Fe}/\text{H}] \approx -1.6$) than M15 (i.e., $[\text{Fe}/\text{H}] \approx -2.1$).

Finally, Brown *et al.* (1996) have determined preliminary high dispersion abundances for two stars in Rup 106. They found that $[\text{Fe}/\text{H}] = -1.50$, and that the α -process elements except oxygen (i.e., Mg, Si, and Ca) are deficient relative to the solar values: $[\text{Mg}/\text{Fe}] \approx -0.1$, $[\text{Si}/\text{Fe}] \leq -0.1$, $[\text{Ca}/\text{Fe}] \approx -0.2$ dex. Oxygen is slightly enhanced relative to solar, $[\text{O}/\text{Fe}] = 0.0$ – 0.1 dex. However, the internal errors due to line-to-line variations in equivalent width measurements were large, ~ 0.2 dex in abundance, and no external errors were given.

Our SRM abundance, $[\text{Fe}/\text{H}] = -1.90 \pm 0.10$, and our reddening value, $E(B - V) = 0.18 \pm 0.02$ agree well with the values obtained by Buonanno *et al.* (1990, 1993) and KKM, both of which are based on the position and shape of the RGB. However, the Ca II triplet observations, high dispersion abundances, and RR Lyrae light curves indicate that Rup 106 is ~ 0.2 dex more abundant in metals. Specifically, our result differs from the Ca II triplet observations by 0.15 ± 0.13 dex (1.26). We shall consider this discrepancy in more detail in Sec. 7.4.

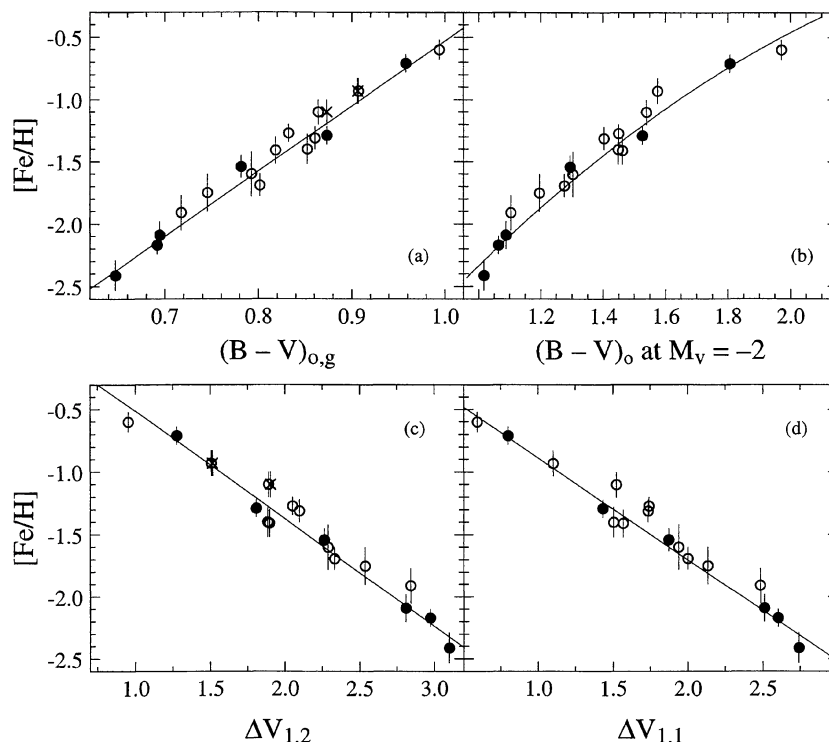


FIG. 8. Calibration of various photometric parameters of the red giant branch as a function of $[\text{Fe}/\text{H}]$ using CCD photometry taken from the literature. The lines are fitted to the filled circles, which are the primary calibrators. The open circles are the secondary calibrators and are plotted to corroborate the primary fit.

7.2 Ter 7

In the Introduction, we mentioned the work of BCFRF in which they derive a photometric abundance of $[\text{Fe}/\text{H}] = -1.00 \pm 0.13$ for Ter 7 based on an adopted reddening of $E(B-V)=0.06$ and $(B-V)_g=0.99 \pm 0.03$ along with the Zinn & West (1984) calibration between $[\text{Fe}/\text{H}]$ and $(B-V)_{0,g}$. There have been two previous studies which measured the abundance of Ter 7. Both used the Ca II triplet method. Da Costa & Armandroff (1995, hereafter DCA95) obtained $[\text{Fe}/\text{H}] = -0.36 \pm 0.09$ from four stars, and Suntzeff *et al.* (1996) obtained $[\text{Fe}/\text{H}] = -0.49 \pm 0.05$ from 5 stars. The weighted mean of these values, $\langle [\text{Fe}/\text{H}] \rangle = -0.46 \pm 0.04$, differs from our value, $[\text{Fe}/\text{H}] = -0.82 \pm 0.15$, by 0.36 ± 0.16 dex (2.3σ). As in the case of Rup 106, the Ca II triplet value is more metal rich than the SRM value.

7.3 Arp 2

BCFRF measured a photometric metallicity of $[\text{Fe}/\text{H}] = -1.84 \pm 0.25$ for Arp 2 based on a reddening of $E(B-V)=0.11$ and $(B-V)_g=0.84 \pm 0.04$. Two previous studies of Arp 2, both using the Ca II triplet method, found $[\text{Fe}/\text{H}] = -1.70 \pm 0.11$ from three stars (DCA95), and $[\text{Fe}/\text{H}] = -1.73 \pm 0.03$ from 8 stars (Suntzeff *et al.* 1996). The weighted mean of these values, $\langle [\text{Fe}/\text{H}] \rangle = -1.73 \pm 0.03$, is 0.11 ± 0.09 dex (1.2σ) more metal rich than the value we obtained herein using the SRM method, $[\text{Fe}/\text{H}] = -1.84 \pm 0.09$.

7.4 Systematic Differences in $[\text{Fe}/\text{H}]$ Estimates

For each of the three clusters considered herein, we find a small (0.1 – 0.4 dex) and possibly significant (1.2 – 2.3σ) difference between the $[\text{Fe}/\text{H}]$ values derived from the Ca II triplet and SRM methods, in the sense that the latter gives lower abundances. The pattern is also present for the young cluster Pal 12: $[\text{Fe}/\text{H}] = -0.64 \pm 0.09$ from the Ca II triplet (DCA95; Da Costa & Armandroff 1991), and $[\text{Fe}/\text{H}] = -0.98 \pm 0.14$ from the SRM method (Sarajedini

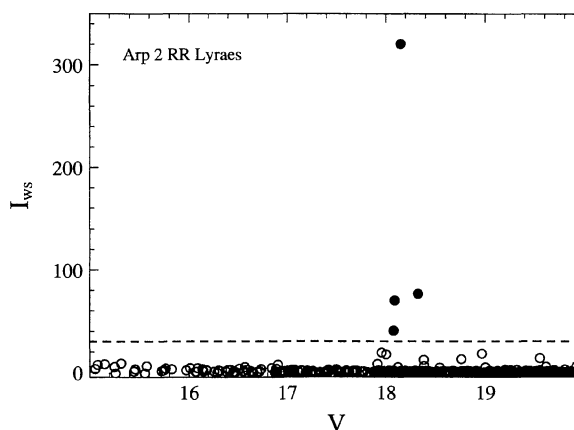


FIG. 9. The Welch & Stetson (1993) variability index (I_{ws}) is plotted against V mag for the bright stars in Arp 2. There are four stars with V magnitudes similar to the horizontal branch of Arp 2 that appear to be RR Lyrae variables.

TABLE 7. Arp 2 RR Lyrae stars.

#	X	Y	$\langle V \rangle$	$\langle V-I \rangle$	N	I_{WS}
1	538.96	161.14	17.95	0.58	5	320.4
2	463.77	842.11	18.35	0.68	6	76.7
3	448.96	8.37	18.09	0.44	3	70.3
4	608.55	557.00	18.11	0.40	6	40.7

1994a, see also Da Costa & Armandroff 1990), a difference of 0.34 ± 0.17 dex (2.0σ). In fact, Da Costa & Armandroff (1991) point out that, in the case Pal 12, there is a systematic difference between the photometric and various spectroscopically derived $[\text{Fe}/\text{H}]$ values, not just those that utilize the Ca II triplet. Furthermore, Ferraro *et al.* (1995) claim that the young cluster IC 4499 is also afflicted with this condition (see Walker 1996 for a contrasting view). However, this is not certain as yet since a published spectroscopic metallicity is not available for IC 4499.

Statistically speaking, the abundance differences cited for Arp 2 and Rup 106, both metal-poor clusters ($[\text{Fe}/\text{H}] \sim -1.9$), are not significant, whereas those found for Pal 12 and Ter 7, which are more abundant in metals ($[\text{Fe}/\text{H}] \sim -0.9$), do appear to be significant. Another way of stating this is that, for the young clusters considered herein, the difference between the photometric and spectroscopic metallicities are larger for more metal-rich clusters. Indeed, the mean difference is 0.13 dex for Rup 106 and Arp 2 whereas it is 0.35 dex for Ter 7 and Pal 12. This may be a clue to understanding the cause of these anomalies. Regardless, further work is required to better establish these metallicity trends, especially in Arp 2, Rup 106, and IC 4499, but we will proceed under the assumption that they do exist and investigate the consequences.

These abundance trends have been pointed out and discussed by Fusi Pecci *et al.* (1995, see their Table 1). However, in the present paper, we have improved the foundation upon which the photometric abundances are based by largely removing uncertainties due to the adopted reddenings and the calibration of $[\text{Fe}/\text{H}]$ in terms of the photometric properties of the RGB (see the next paragraph). Fusi Pecci *et al.* (1995) also indicate that the effect of a younger age on the RGB color- $[\text{Fe}/\text{H}]$ calibrations is not enough to account for the difference between the photometric and spectroscopic abundances, in agreement with the analysis presented herein (see Secs. 5 and 6).

These abundance differences cannot be due to a systematic difference between the Ca II triplet and SRM calibrations, since the two methods use many of the same clusters to calibrate their relations (the seven clusters in common are M68, NGC 6397, NGC 6752, NGC 1851, M15, M2, and 47 Tuc), and the Zinn & West (1984) $[\text{Fe}/\text{H}]$ values were used in both calibrations.

Perhaps the differences are a result of different light element ratios in the young clusters, relative to the clusters used to define the Ca II triplet and the SRM methods (see BCFPRF, BCFRF, and Fusi Pecci *et al.* 1995). For example, if the young clusters are enhanced in α -elements relative to the calibrating clusters, the Ca II lines would appear uncharacteristically strong for the iron abundance, and the Ca II

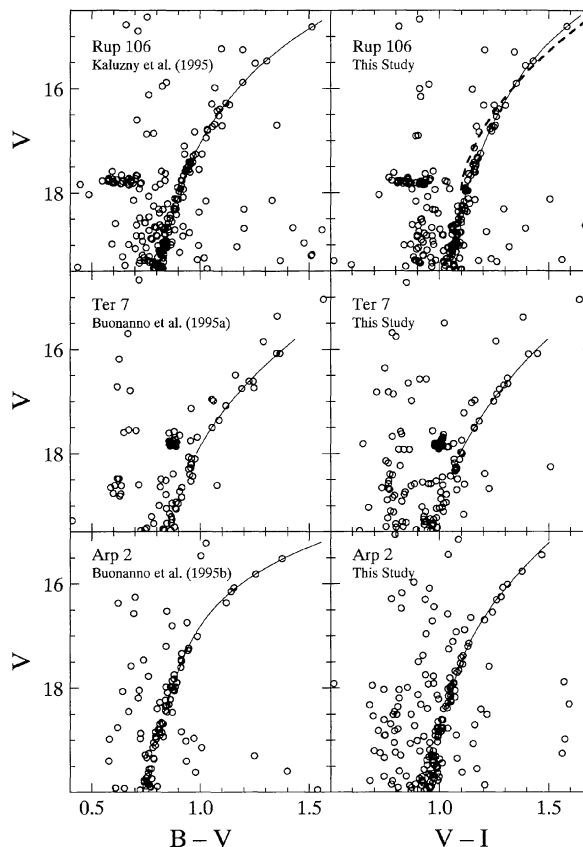


FIG. 10. Polynomial fits to the red giant branches of the program clusters. The dashed line for Rup 106 is the fit used by Sarajedini (1994a).

triplet method would find these clusters to be more metal rich than their true $[\text{Fe}/\text{H}]$. The SRM method would suffer a similar effect; the young cluster RGBs would appear uncharacteristically red for their iron abundances, due to the added opacity produced by the enhanced α -elements, and the abundance measured for these clusters would be overestimated. However, the abundance overestimate would be smaller for the SRM method because both the α -element and iron abundances determine the color and shape of the RGB (Salaris *et al.* 1993). This produces the pattern of observed abundances seen among the young clusters; the Ca II triplet abundances are slightly more metal rich than the SRM abundances. A consequence of this effect is that the true $[\text{Fe}/\text{H}]$ values of the young clusters would be lower than those predicted by *either* method, e.g., $[\text{Fe}/\text{H}] < -1.9$ for Rup 106.

We can estimate the magnitude of this effect on metallicities derived using the SRM method, $[\text{Fe}/\text{H}]_{\text{SRM}}$, using the isochrones of Salaris *et al.* (1993). They show that isochrones having enhanced α -elements closely follow those having scaled solar abundances, after the latter are corrected to the overall metallicity of the former. Specifically, their Table 2 indicates that isochrones for a scaled solar abundance Z_0 , to which an α -enhancement of $+0.6$ dex has been added, can be closely approximated with scaled solar isochrones having an overall abundance fZ_0 , where $f=2.91$. Thus, $[M/H] = [\text{Fe}/\text{H}] + \log(2.91)$ for an enhancement of

TABLE 8. Observed cluster parameters.

Cluster	$V(\text{HB})_{V-I}$	$(V-I)_g$	$V(\text{HB})_{B-V}$	$(B-V)_g$
Rup 106	17.80 ± 0.023	1.14 ± 0.020	17.80 ± 0.023	0.92 ± 0.020
Ter 7	17.86 ± 0.021	1.11 ± 0.020	17.76 ± 0.07	1.01 ± 0.020
Arp 2	18.13 ± 0.04	1.05 ± 0.020	18.23 ± 0.05	0.85 ± 0.025

$[\alpha/\text{Fe}] = +0.6$ dex, where $[M/H]$ is the effective metallicity controlling the RGB locus of an α -enhanced model, and $[\text{Fe}/H]$ is the true iron abundance of the model. From their Table 2, we compute that a cluster of identical $[\text{Fe}/H]$ but with $[\alpha/\text{Fe}] = +0.4$ dex will have $f = 1.96$, and thus $[M/H] = [\text{Fe}/H] + \log(1.96)$. The difference between the values, $\Delta[M/H]$, thus reflects the metallicity difference estimated by the SRM method for the two clusters of identical $[\text{Fe}/H]$, due solely to their different $[\alpha/\text{Fe}]$ values. In this example, if the young clusters have $\Delta[\alpha/\text{Fe}] = +0.2$ relative to the calibrating clusters (at $[\alpha/\text{Fe}] = +0.40$), then $\Delta[\text{Fe}/H]_{\text{SRM}} = +0.17$ dex.

Presumably, the same α -enhancement would produce a larger $\Delta[\text{Fe}/H]_{\text{Ca}}$ (the metallicity measured from the Ca II triplet), since the effects of the enhancement are not “diluted” by iron, as is the case for the SRM method. In principle, we could make similar arguments to quantify this effect. In practice, however, the details of the Ca II triplet method require us to do a more in-depth analysis. We are planning a series of experiments using synthetic spectra to quantify this effect, but such work is outside the scope of the current paper.

The previous explanation for the discrepant $[\text{Fe}/H]_{\text{Ca}}$ and $[\text{Fe}/H]_{\text{SRM}}$ observations requires an α -enhancement relative to the calibrating clusters. Buonanno *et al.* (1993) favor such an enhancement, as it improves the self-consistency of their Rup 106 age analysis, and helps to explain why a metal-poor cluster possesses an HB that is so red. However, the clusters used to calibrate the Ca II triplet and SRM methods are already significantly enhanced relative to the Sun, $[\alpha/\text{Fe}] \approx +0.4$ (Lambert 1989; Pagel & Tautvaišienė 1995). A value of $[\alpha/\text{Fe}] > +0.4$ for Rup 106 is in conflict with the low preliminary $[\alpha/\text{Fe}]$ estimates of Brown *et al.* (1996).

If we consider the opposite effect, i.e., that of α -element deficiencies relative to the calibrating clusters, we see different elements of the puzzle fitting together. Inverting the previous argument concerning the effects of α -element enhancements, we see that the high $[\text{Fe}/H]$ value of -1.50 obtained for Rup 106 by Brown *et al.* (1996), together with their observed deficiencies of α -elements relative to the calibrating clusters, is qualitatively consistent with the lower abundance estimates (-1.7 to -1.9) obtained by the Ca II triplet and SRM methods. In this scenario, however, we would expect the SRM abundance estimates to be *higher*

than the Ca II triplet estimates, again owing to the diluting effect iron has on $[\alpha/\text{Fe}]$ variations.

Clearly, there are inconsistencies in the detailed element abundances that remain unsolved, and it is too early to say whether α -element enhancements are responsible for the metallicity discrepancies discussed above. More high dispersion abundance analyses of α -element ratios in “young clusters” would clarify this situation.

7.5 The Age of Terzan 7

Recent work on several fronts indicates that a re-examination of the age of Ter 7 is in order. The relevant works include, (1) our new metal abundance estimate for Ter 7; (2) the work of SLL, which showed that $M_V(\text{RHB})$ depends not only on $[\text{Fe}/H]$ but also on the cluster age; and (3) the work of Chaboyer *et al.* (1996, hereafter CDS), which presents, for the first time, relations between cluster age, $[\text{Fe}/H]$, and the mag difference between the main sequence turnoff and the red HB.

Since our metallicity for Ter 7 is similar to that of 47 Tuc ($[\text{Fe}/H] = -0.71 \pm 0.08$, Zinn & West 1984), we will use 47 Tuc as a comparison cluster. Based on the magnitude difference between the main sequence turnoff (TO) and the HB, $\Delta V = 3.61$ for 47 Tuc (Fulton *et al.* 1995) and $\Delta V = 3.20$ for Ter 7 (BCPFRF), the theoretical models of CDS predict that Ter 7 is 6 Gyr younger than 47 Tuc regardless of the adopted relation between $M_V(\text{RR})$ and $[\text{Fe}/H]$. Since both of these clusters possess red HBs, the models of SLL (see their Fig. 5) must be used to derive $M_V(\text{RHB})$. These yield $M_V(\text{RHB}) = 0.64$ for 47 Tuc and $M_V(\text{RHB}) = 0.50$ for Ter 7. These values, along with the median $V(\text{HB})$ magnitudes and the reddenings listed in Tables 5 and 9, can be used to place 47 Tuc and Ter 7 in the absolute magnitude–intrinsic color plane as shown in Fig. 11. The arrows indicate the absolute magnitudes of a 7 Gyr and 13 Gyr turnoff as tabulated in the CDS isochrones for $[\text{Fe}/H] = -0.7$, and $Y = 0.23$. Figure 11 illustrates the remarkable consistency between the HB models of SLL; the theoretical calibration between $M_V(\text{TO})$, $[\text{Fe}/H]$, and age presented by CDS; and the various observational parameters measured for 47 Tuc and Ter 7.

TABLE 9. Derived cluster parameters.

Cluster	$[\text{Fe}/H]_{V-I}$	$E(B-V)_{V-I}$	$[\text{Fe}/H]_{B-V}$	$E(B-V)_{B-V}$	$\langle[\text{Fe}/H]\rangle$	$\langle E(B-V) \rangle$
Rup 106	-2.006 ± 0.183	0.181 ± 0.029	-1.845 ± 0.122	0.172 ± 0.042	-1.90 ± 0.10	0.18 ± 0.02
Ter 7	-0.845 ± 0.186	0.074 ± 0.028	-0.769 ± 0.259	0.059 ± 0.064	-0.82 ± 0.15	0.07 ± 0.03
Arp 2	-1.787 ± 0.187	0.098 ± 0.029	-1.856 ± 0.096	0.106 ± 0.035	-1.84 ± 0.09	0.10 ± 0.02

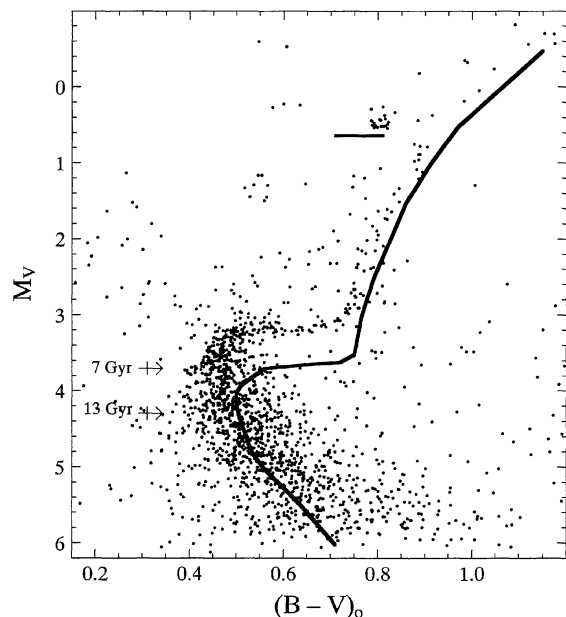


FIG. 11. The Ter 7 photometry of BCPFRF, corrected for distance modulus and reddening as described in Sec. 7.5, is compared with the fiducial sequence of 47 Tuc (Hesser *et al.* 1987). The turnoff magnitudes of a 7 Gyr and 13 Gyr isochrone (Chaboyer *et al.* 1996) are indicated.

8. SUMMARY AND CONCLUSIONS

We present new photometry in the *VI* passbands for the Galactic globular clusters Rup 106, Ter 7, and Arp 2. Application of the SRM method in *B-V* and *V-I* yields estimates of their reddenings and metallicities, which are based on the shapes and positions of the red giant branches of these clusters. We find $[\text{Fe}/\text{H}] = -1.90 \pm 0.10$, $E(B-V) = 0.18 \pm 0.02$ for Rup 106, $[\text{Fe}/\text{H}] = -0.82 \pm 0.15$, $E(B-V) = 0.07 \pm 0.03$ for Ter 7, and $[\text{Fe}/\text{H}] = -1.84 \pm 0.09$, $E(B-V) = 0.10 \pm 0.02$ for Arp 2. Based on the new abundances and recent progress in cluster age determinations, we have derived a new relative age for Ter 7. It is estimated to be 6 Gyr younger than 47 Tuc, where 47 Tuc is assumed to be 13 Gyr old. Using the young Magellanic Cloud clusters ESO121-SC03 and Lindsay 1, we show that the SRM method is insensitive to age for clusters with purely red HBs and ages as young as ~ 5 Gyr; for clusters with bluer HBs, the SRM method is only mildly sensitive to age, yielding a $[\text{Fe}/\text{H}]$ which is ~ 0.02 dex too low for Arp 2, which we assume to be ~ 3 Gyr younger than calibrating clusters at its metallicity.

It appears that the photometric abundances of Rup 106, Ter 7, and Arp 2 based on the position and shape of the RGB are systematically lower ($\Delta[\text{Fe}/\text{H}] = 0.1\text{--}0.4$ dex) than those derived using other indicators, in particular the Ca II triplet method (e.g., DCA95). We note that the young globular cluster, Pal 12, suffers from the same malady (Sarajedini 1994a, DCA95), and there is suggestive evidence that IC 4499 may as well (Ferraro *et al.* 1995). In addition, while the correct photometric $[\text{Fe}/\text{H}]$ value for Arp 2 (and perhaps IC 4499) might be ~ 0.02 dex higher, this is not enough to fully

account for the systematic 0.1–0.4 dex difference between the Ca II triplet and SRM $[\text{Fe}/\text{H}]$ estimates.

We suggested that this discrepancy is due to systematic differences in the $[\alpha/\text{Fe}]$ ratios between the young clusters and the “normal” Galactic globulars used to calibrate the Ca II triplet and SRM methods. We showed that an $[\alpha/\text{Fe}]$ enhancement of +0.2 dex relative to the calibrating cluster results in an $[\text{Fe}/\text{H}]$ estimate for the program cluster that is ~ 0.17 dex higher than its true value, when the SRM method is used and when $[\alpha/\text{Fe}] = +0.4$ is assumed for the calibrating clusters. However, we were unable to completely reconcile all the observations of Rup 106 using this approach. We presented several suggestions for future work which would help to solve this problem.

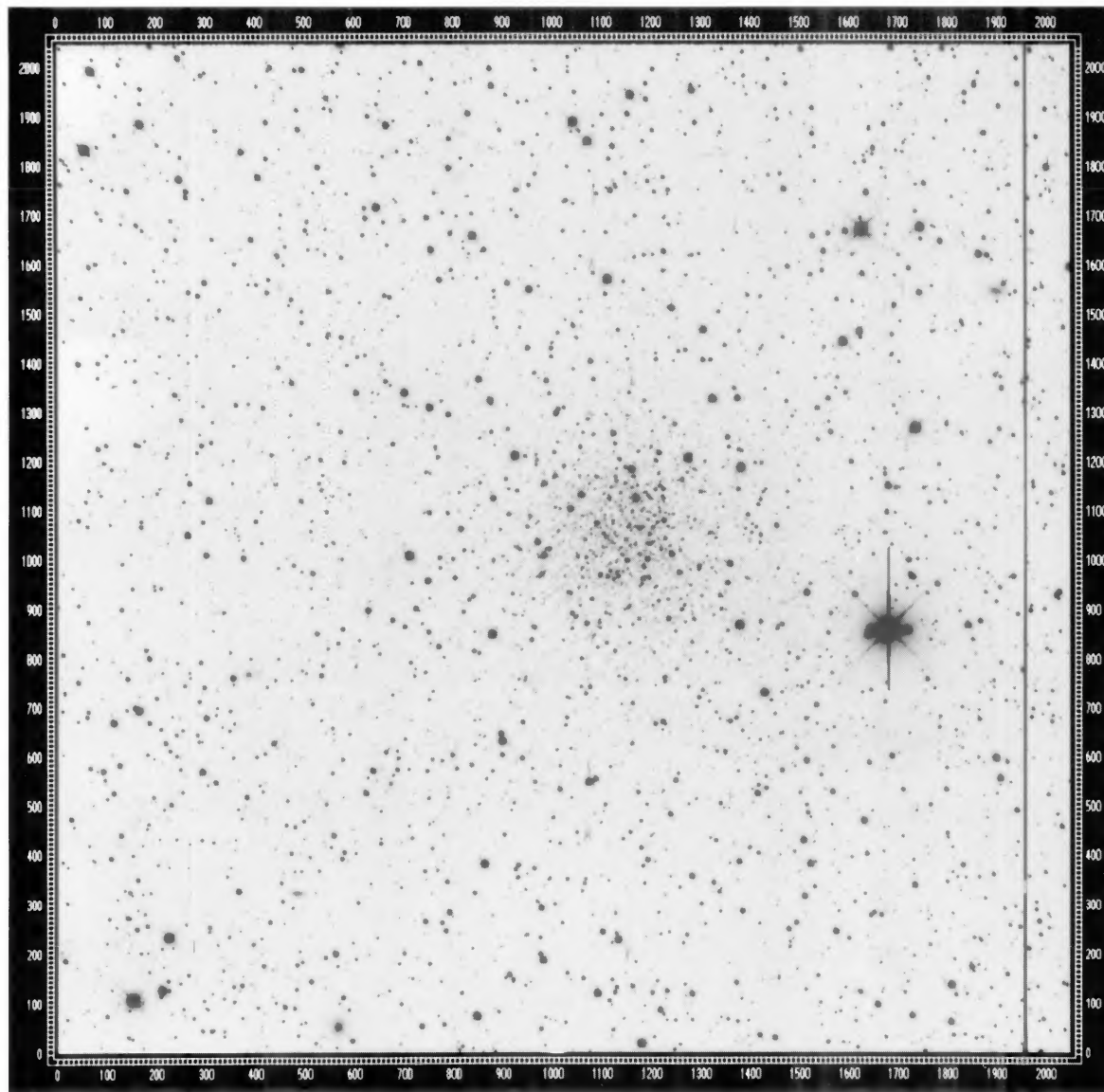
The notion that these clusters may have formed in an environment with a different chemical enrichment history than the majority of Galactic globular clusters has been proposed previously by Buonanno *et al.* (1994) and Fusi Pecci *et al.* (1995). In fact, both Ter 7 and Arp 2 are believed to be members of the Sagittarius dwarf galaxy, thus supporting this theory. In addition, Lin & Richer (1992) have claimed that Rup 106 and Pal 12 may have been captured by the Milky Way from the Magellanic Clouds (MCs). One way this hypothesis can be investigated is by measuring the Ca II triplet $[\text{Fe}/\text{H}]$ values (on the standard system of DCA95) of young Pop II clusters in the MCs, such as ESO121 and L1, and comparing this with their SRM values which should be derived using high quality well-calibrated photometry. If these young Pop II clusters in the MCs have photometric abundances that are lower than their spectroscopic ones, then this may be evidence supporting the suggestion that Pal 12 and Rup 106 originated in the MCs. In principle, this can be done for ESO121 and L1 with the data already available, since these clusters are in our SRM calibration, but their Ca II triplet abundances are not on the system of DCA95 and their photometric calibration needs to be placed on a firmer foundation.

We note, in passing, that Rup 106, Ter 7, Arp 2, Pal 12, and IC 4499 (i.e., the clusters that exhibit the abundance anomaly discussed herein) are presently located within a relatively small range of Galactocentric distance (between 14 and 21 kpc). Whether this is related to the environment in which they formed is an open question.

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(a)

FIG. 1. Finder charts for the observed program cluster fields. North is to the left and east is down. (a) Rup 106: image scale is 0.44 arcsec/pixel.

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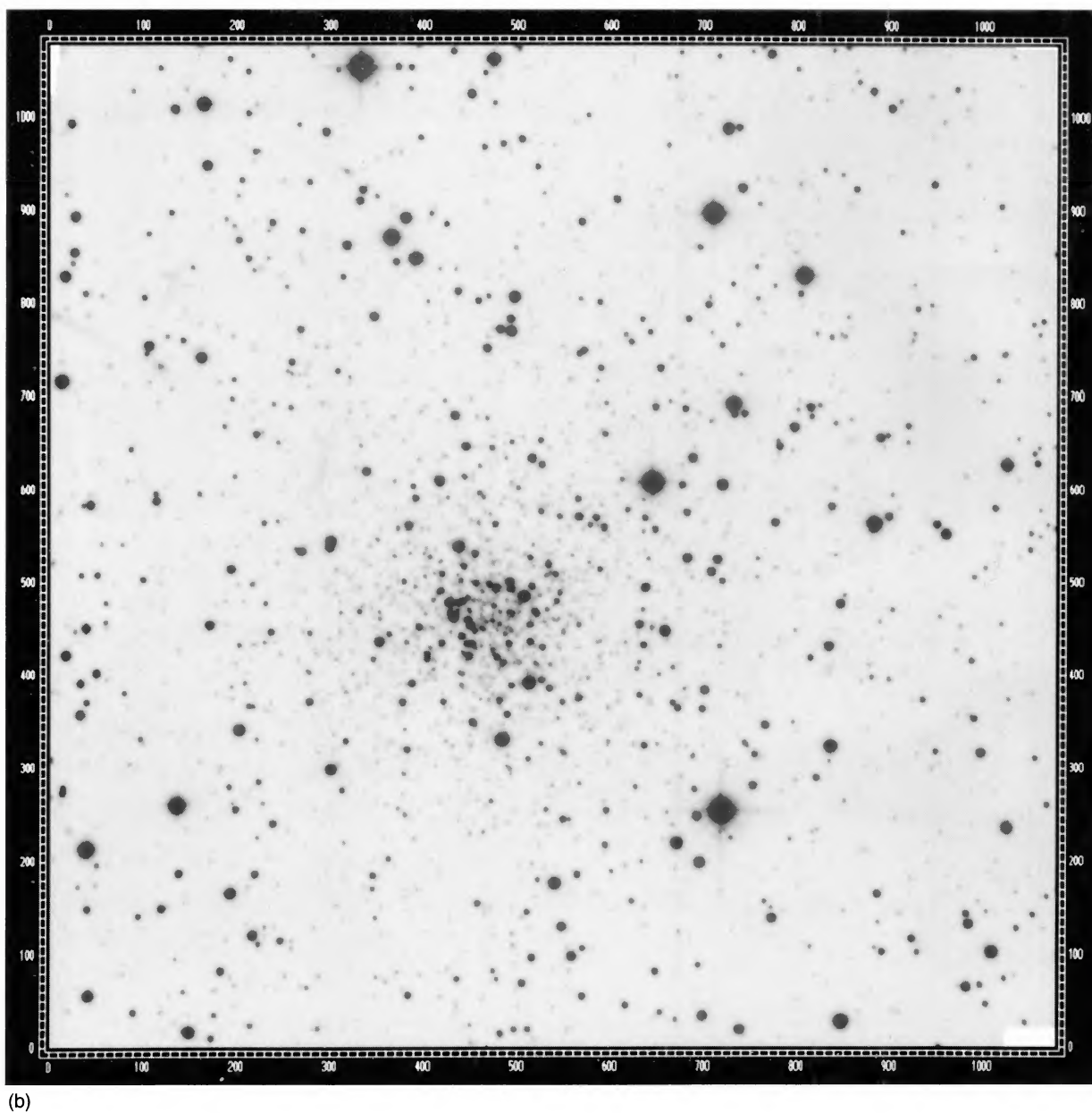
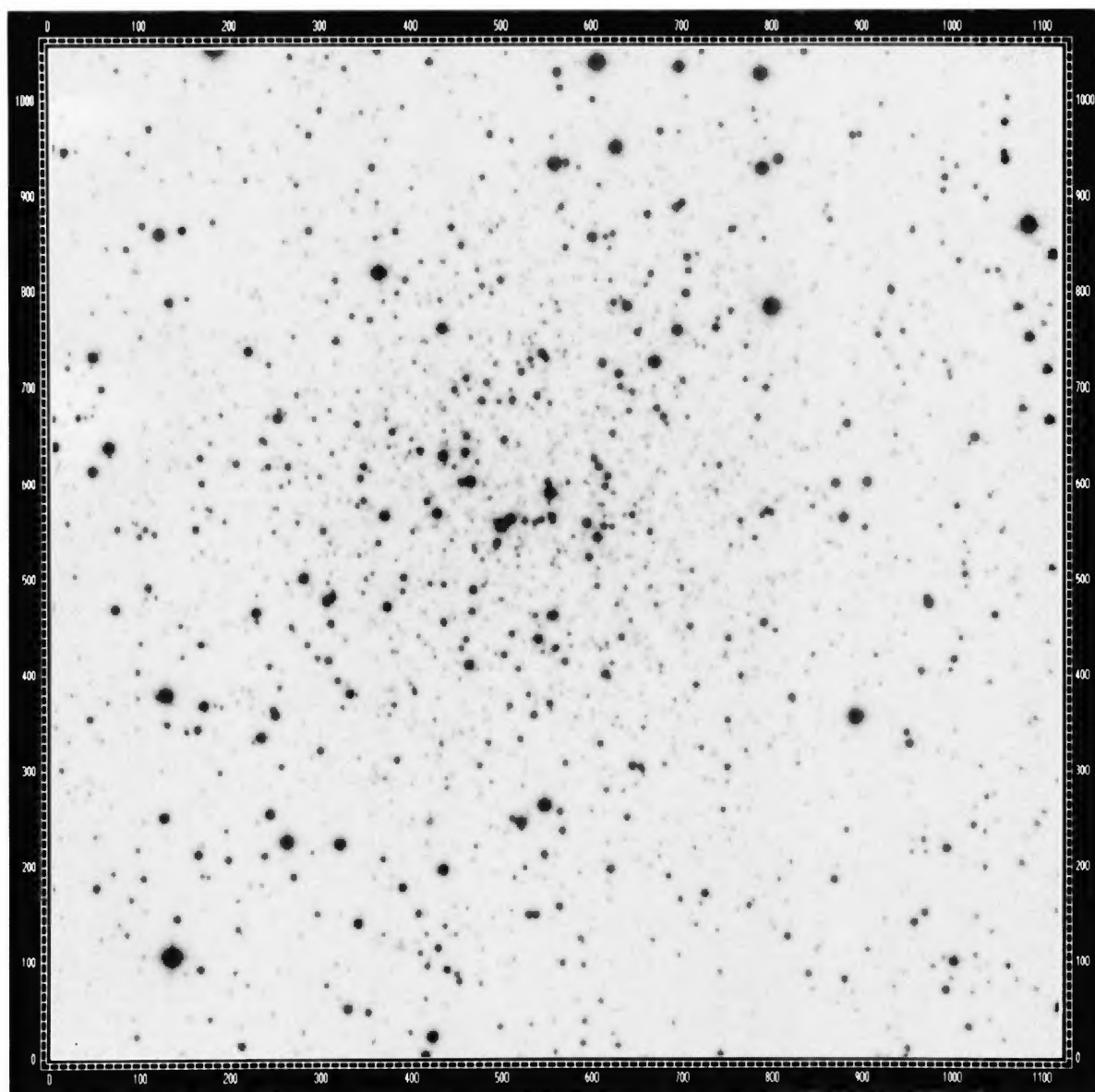


FIG. 1. (b) Ter 7: image scale is 0.40 arcsec/pixel.

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(c)

FIG. 1. (c) Arp 2: image scale is 0.40 arcsec/pixel.

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