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BV STELLAR PHOTOMETRY OF 23 GALACTIC GLOBULAR CLUSTERS

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ABSTRACT

We report V-$(B-V)$ CCD Color Magnitude Diagrams (CMDs) for 23 southern Galactic globular clusters. Limiting magnitudes for each cluster are between 18 and 20 magnitudes in V. Most CMDs show subgiant stars, red giant stars, and horizontal branch stars. From the CMDs, we have determined the horizontal branch magnitudes, $V(HB)$, reddenings, $E(B-V)$, and distances of each cluster.

1. INTRODUCTION

Stellar photometry of globular clusters provides a potentially powerful means for studying stellar evolution. Dynamical evolutionary status of a globular cluster system can be examined from the analysis of stellar population distribution within a globular cluter. Moreover, color distributions within a globular cluster are affected by the results of dynamical processes, which relocate stars in the system according to their masses (Bailyn *et al.* 1988, Djorgovski *et al.* 1988, Djorgovski *et al.* 1991, Djorgovski & Piotto 1993).

This is in a series of papers studying the photometry of Galactic globular clusters. From the surface photometry of 29 Galactic glubular clusters, Sohn *et al.* (1997) showed that 22 clusters have flat-core King (1966) type surface profile and 7 clusters show power law cusps. Sohn *et al.* (1996, 1998) claimed that the color gradients within globular clusters are not unique to the post core collapse (PCC) clusters, but also exist in some King type clusters. In this paper, we report V-$(B-V)$ Color Magnitude Diagrams (CMDs) for 23 Galactic globular clusters observed with the 1-m telescope at Siding Spring Observatory.

2. OBSERVATIONS AND DATA REDUCTIONS

BV CCD images for 23 Galactic globular clusters were recorded at the $f/8$ focus of the 1-m telescope at Siding Spring Observatory in May and August 1991. The detector was a EEV P8063A CCD in a 576×380 format. The image scale is $0.56''$/pixel, so that each image covers $5.4' \times 3.5'$ centered on the culster center. Details of observations and observational journals can be found in Sohn *et al.* (1998).

A median bias frame was subtracted from the raw exposures, and the results were divided by the twilight sky flat field image. Full widths at half maximum of stars in the images are typically between $2''$ and $3.5''$. The brightnesses of individual stars were measured with the point spread function fitting routine DAOPHOT/ALLSTAR (Stetson & Harris 1988) in IRAF. A preliminary set of stellar brightnesses was estimated from the original frames, and the detected stars were then subtracted from the data. Unresolved hidden stars on the original images appear on the subtracted image. With the coordinates of these stars, ALLSTAR was re-run on the original images. The photometric calibration was defined by observations of standard stars in Graham (1982). Details of the calibration are given in Sohn *et al.* (1996).

3. COLOR MAGNITUDE DIAGRAMS AND DISTANCES

3.1 Color Magnitude Diagrams

V-$(B-V)$ CMDs for 23 Galactic globular clusters have been obtained. Limiting magnitudes for each cluster, which depend on the sky brightnesses and seeing conditions, are between 18 and 20 magnitudes in V. Most CMDs show stars brighter than subgiant stars, including red giant stars, and horizontal branch stars. No field star removal process was applied, so that CMDs of globular clusters near the Galactic plane are contaminated by some field stars. Because crowding effect would be more serious in the cluster center, only brightest red giants and horizontal branch stars were resolved in the very central area with larger scatters. Figure 1 shows V-$(B-V)$ CMDs for stars located at outer region of each cluster. Core radii for King type clusters were adopted from Sohn *et al.* (1997), while we used the values in Table 1 of Trager *et al.* (1993) for the PCC clusters.

CMDs for each cluster, which were divided to four different areas with the core radius unit, are shown in Sohn (1994). Tabular values of V and $(B-V)$ for each star in a cluster can be also found in Sohn (1994).

3.2 V Magnitude of Horizontal Branch

A mean magnitude of horizontal branch stars has been used as a standard candle to determine the distance to a globular cluster (Peterson 1993). Apparent magnitude of a horizontal branch ($V(HB)$) could be assigned either by a mean magnitude of red or blue horizontal branch stars on the CMDs, by which we determined $V(HB)$s in this paper, or by a mean magnitude of RR Lyrae variable stars (Harris 1976, 1980, Webbink 1985). We have derived $V(HB)$ for each cluster using CMDs of Figure 1. In the case of a CMD with a blue horizontal branch morphology, we adopted the mean magnitude of stars located around the bluest part of the RR Lyrae gap as $V(HB)$. For a cluster with only red horizontal branch stars, we adopted their mean magnitude as $V(HB)$.

The determined V magnitudes of horizontal branches are shown in column 3 of Table 1, and are plotted on Figure 1. $V(HB)$ in this study has been compared with those of Webbink (1985) and Peterson (1993) as shown in Figure 2. The agreement among different determinations is excellent.

3.3 Reddening

Reddening values, $E(B-V)$, toward our clusters have been determined by the comparison of apparent and intrinsic subgiant color indecies, i.e. $(B-V)_g$ and $(B-V)_{o,g}$. Subgiant color index is defined by the color of subgiant branch having the same brightness of a horizontal branch on CMDs. Third order polynomial fit was applied to derive the fiducial lines of giant branch stars, which are

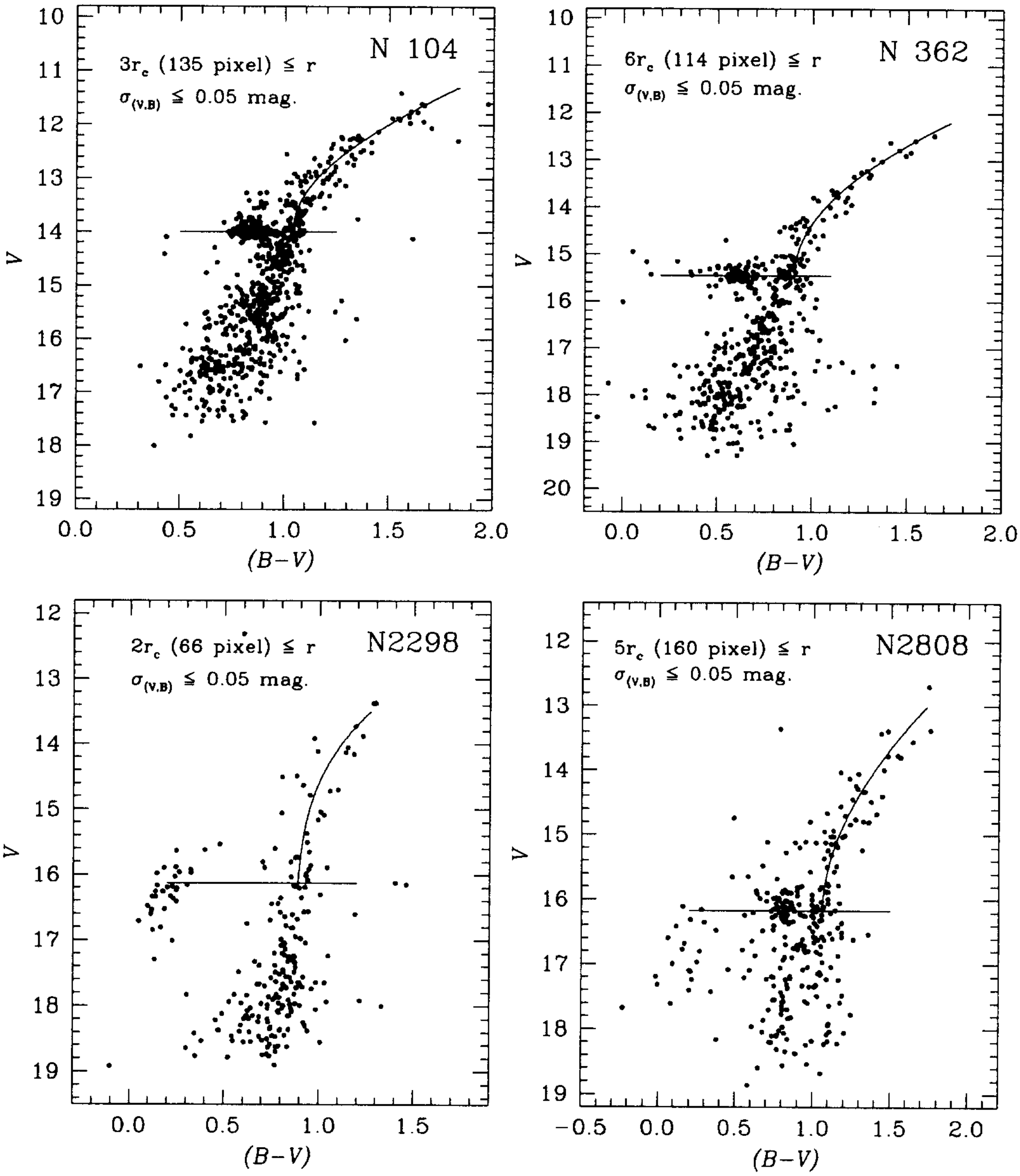


Figure 1. $(B-V)$ and V CMDs for 23 Galactic globular clusters. $V(HB)$ and third order polynomial fit to the red giant stars are plotted.

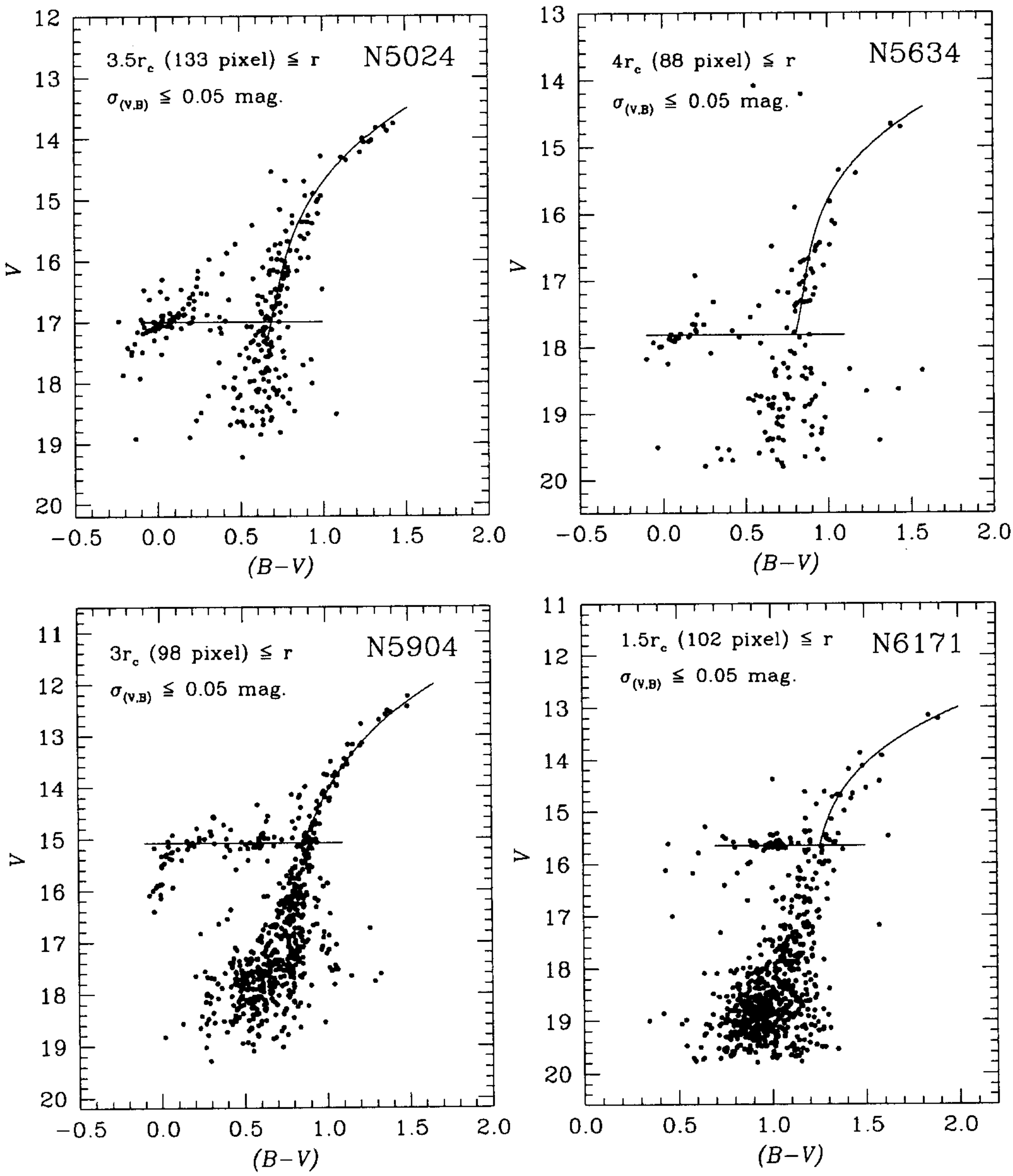


Figure 1. *continued*

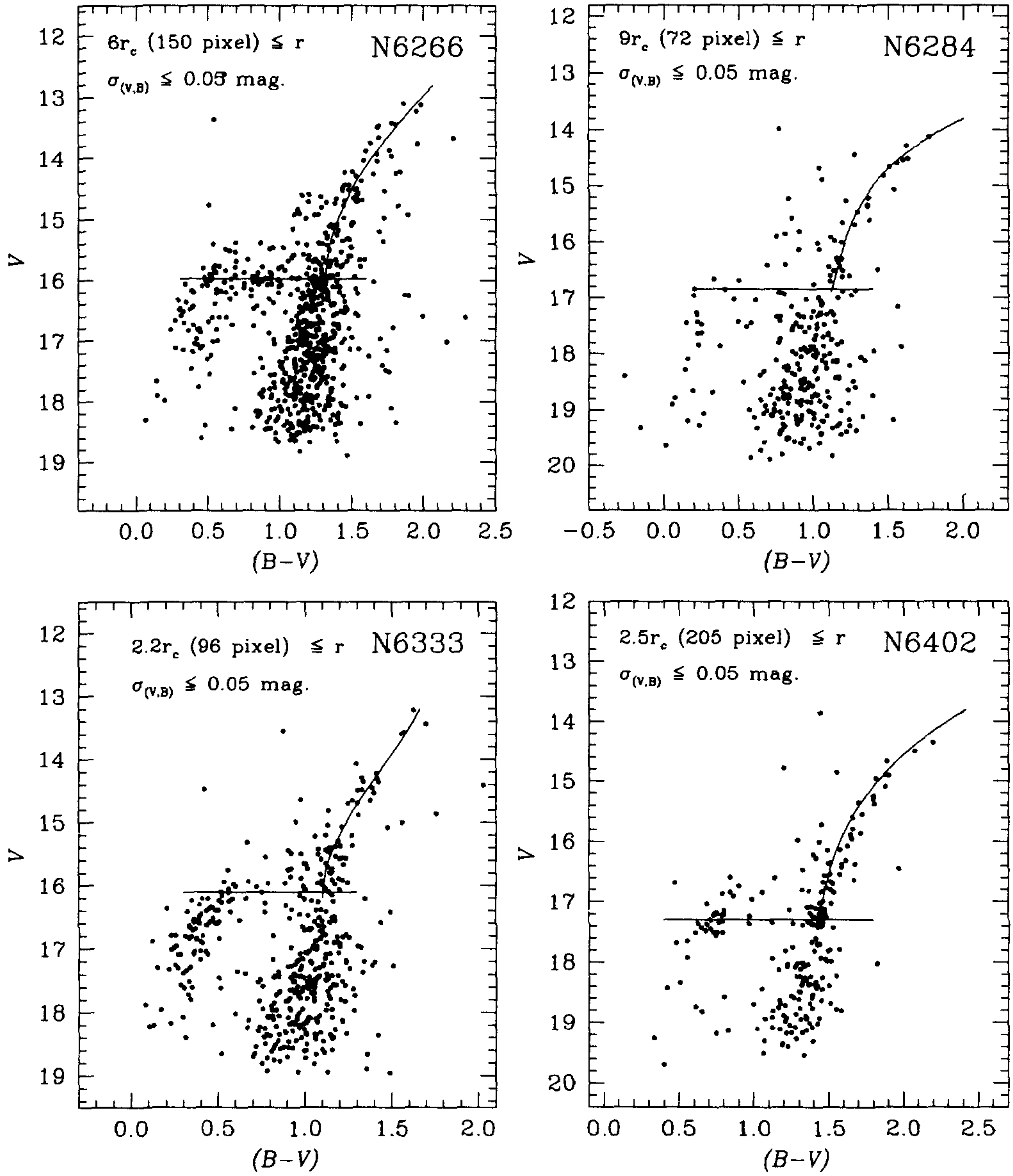
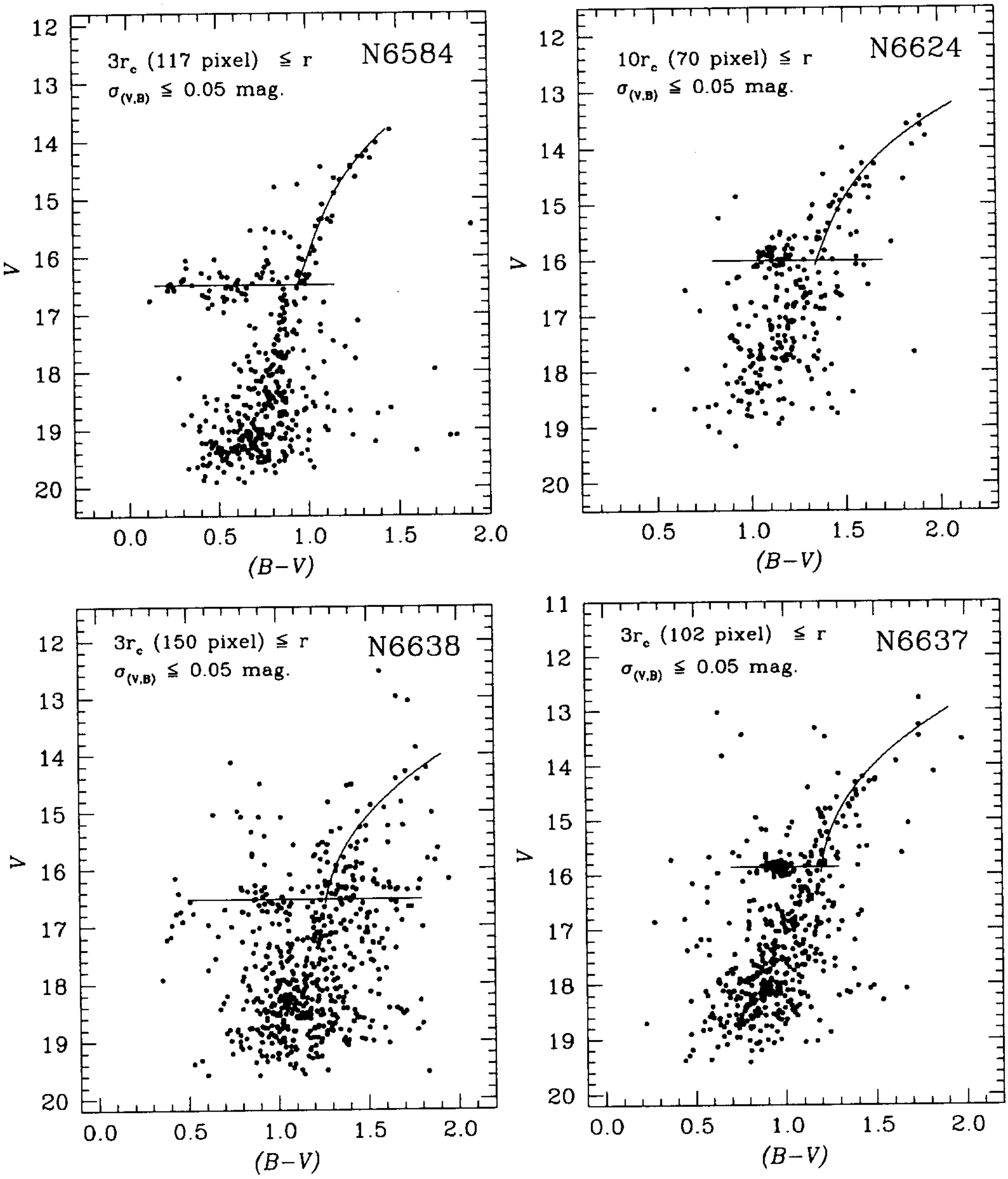


Figure 1. *continued*



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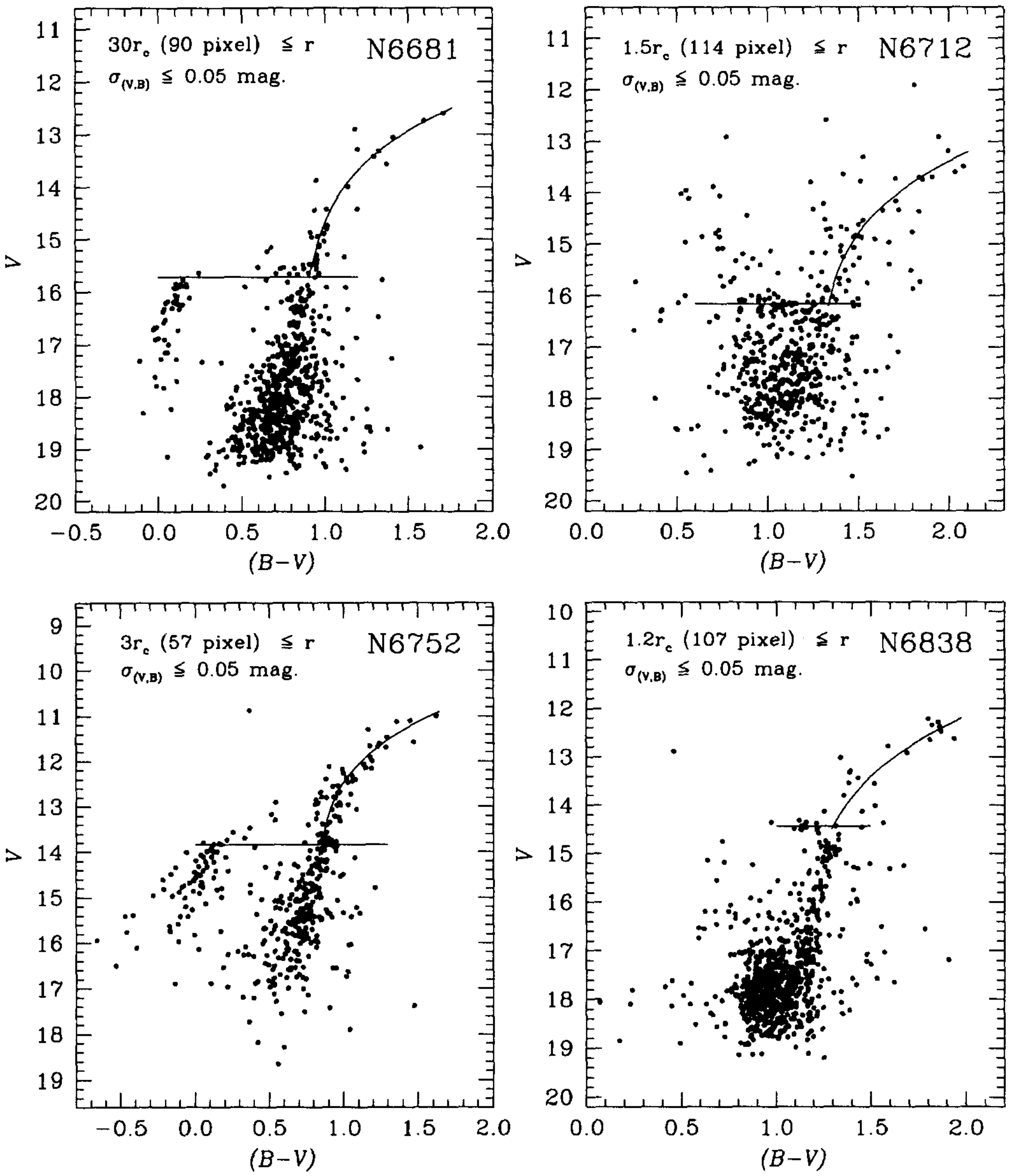

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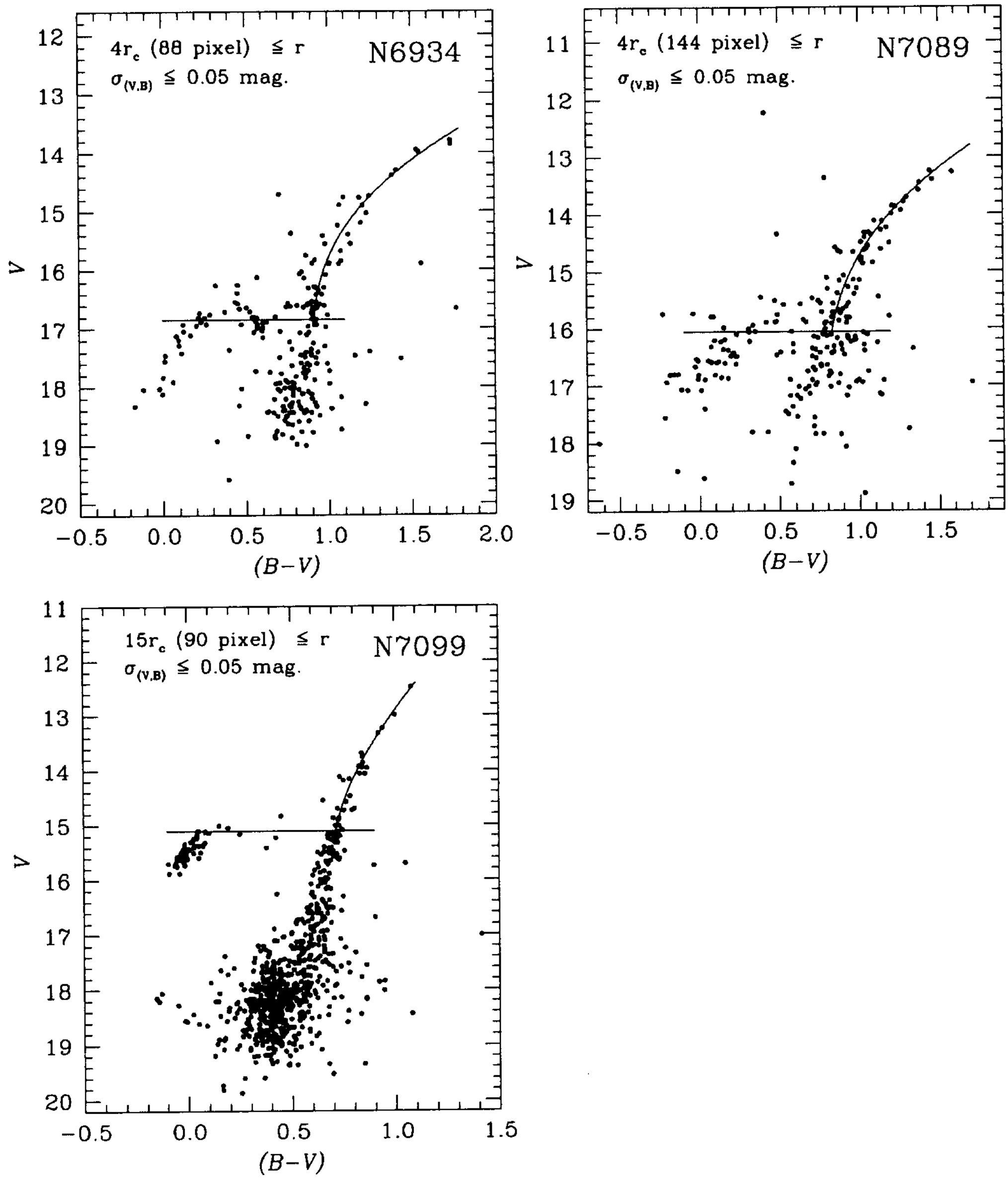

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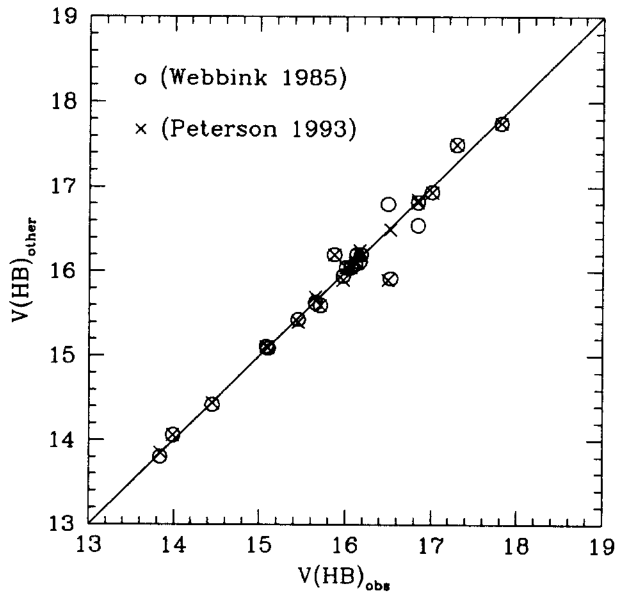

Figure 2. Comparison of the $V(HB)$

plotted on CMDs of Figure 1. The intersection of this fiducial line and the line of horizontal branch magnitude is to be defined as the apparent subgiant color index, $(B - V)_g$. On the other hand, the intrinsic subgiant color index has been derived from the relation to the metallicity, $[Fe/H] = -5.0 + 4.3(B - V)_{o,g}$ (Zinn & West 1984).

[Fe/H] for each cluster is listed in column 2 of Table 1. The $E(B - V)$ values derived from the subgiant color index method are shown in column 5 of Table 1. The estimated $E(B - V)$s for each cluster are also compared with those of Webbink (1985) and Peterson (1993) in Figure 3. Again the agreement is quite good.

3.4 Absolute Magnitude of Horizontal Branch and Cluster Distance

It has been reported that there is a linear relation between absolute magnitude of a horizontal branch and metallicity. Using the [Fe/H] values of Zinn & West (1984), we estimated mean absolute magnitudes of horizontal branches from the relations given by several authors (Sandage 1982, Iben & Renzini 1984, Buonanno *et al.* 1986, 1989, Fusi-Pecci *et al.* 1990, Lee 1990, Longmore *et al.* 1990, Sandage & Cacciari 1990, Carney *et al.* 1992, Clementini *et al.* 1992, Rees 1993). We have derived a mean relation from them (Figure 4): $M_V(HB) = 0.26(\pm0.10)[Fe/H] + 1.06(\pm0.15)$. Using this relation we have estimated the absolute magnitudes of the horizontal branch, which are listed in column 7 of Table 1.

We determined the distance modulus, $(m - M)_o$, to each cluster using the $V(HB)$ and absolute magnitude of horizontal branches, after applying corrections for the interstellar absorption, $A_V = 3.2E(B - V)$. The derived distance modulus of each cluster is listed in column 9 of Table 1. Error

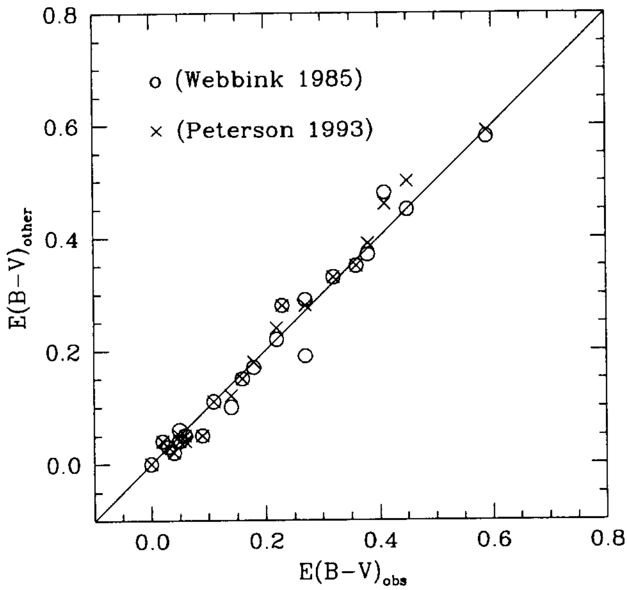

Figure 3. Comparison of the $E(B-V)$

budget includes errors of measuring horizontal branches magnitudes, interstellar reddenings, and zero point calibration errors of the relation between [Fe/H] and absolute magnitudes of horizontal branches. Column 11 and 12 of Table 1 are cluster distances from the Sun and the Galactic center. We assume the distance from the Galactic center to the Sun is 8 kpc (Reid 1993).

4. SUMMARY

We present V-$(B-V)$ CMDs for 23 southern Galactic globular clusters observed with the 1-m telescope at Siding Spring Observatory, Australia. Limiting magnitudes for each cluster lies between 18 and 20 magnitudes in V. Most CMDs show stars brighter than subgiant stars, including red giant stars, and horizontal branch stars. Apparent magnitudes of horizontal branches, $V(HB)$, and reddenings, $E(B-V)$, have been determined from the outermost CMDs of each cluster field. Using the absolute magnitude of a horizontal branch, we also determined the distances to those clusters.

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TABLE 1. Photometric parameters of 23 globular clusters

Cluster	[Fe/H]†	$V(HB)$	$\sigma_{V(HB)}$	$E(B-V)$	$\sigma_{E(B-V)}$	$M_V(HB)$	$\sigma_{M_V(HB)}$	$(m-M)_o$	$\sigma_{(m-M)_o}$	$R_o(kpc)$	R_{GC}‡
NGC0104	-0.71	13.99	0.12	0.05	0.03	0.88	0.24	12.97	0.41	3.9	7.3
NGC0362	-1.27	15.45	0.21	0.02	0.01	0.73	0.19	14.67	0.41	8.6	9.4
NGC2298	-1.85	16.13	0.25	0.16	0.05	0.58	0.16	15.06	0.43	10.3	15.3
NGC2808	-1.37	16.18	0.10	0.22	0.02	0.70	0.18	14.78	0.37	9.1	10.8
NGC5024	-2.04	17.00	0.12	0.00	0.02	0.53	0.16	16.47	0.36	19.7	20.0
NGC5634	-1.82	17.81	0.15	0.06	0.03	0.58	0.16	17.03	0.38	25.5	21.5
NGC5904	-1.40	15.08	0.07	0.03	0.01	0.69	0.18	14.29	0.36	7.2	6.1
NGC6171	-0.99	15.65	0.16	0.32	0.03	0.80	0.22	13.81	0.40	5.8	3.5
NGC6266	-1.28	15.97	0.17	0.45	0.03	0.73	0.19	13.80	0.40	5.7	2.4
NGC6284	-1.40	16.84	0.23	0.23	0.03	0.69	0.18	15.42	0.42	12.1	4.5
NGC6333	-1.78	16.11	0.12	0.36	0.03	0.60	0.16	14.37	0.37	7.5	1.7
NGC6402	-1.39	17.29	0.09	0.59	0.04	0.70	0.18	14.70	0.37	8.7	3.8
NGC6584	-1.54	16.49	0.22	0.14	0.03	0.66	0.17	15.38	0.42	11.9	5.6
NGC6624	-0.35	16.01	0.12	0.27	0.04	0.97	0.28	14.17	0.43	6.8	1.6
NGC6638	-1.15	16.52	0.09	0.38	0.03	0.76	0.20	14.56	0.38	8.2	1.5
NGC6637	-0.59	15.87	0.06	0.18	0.03	0.91	0.26	14.40	0.40	7.6	1.5
NGC6681	-1.51	15.71	0.15	0.09	0.02	0.67	0.18	14.75	0.38	8.9	2.1
NGC6712	-1.01	16.16	0.07	0.41	0.02	0.80	0.21	14.04	0.38	6.4	3.6
NGC6752	-1.54	13.84	0.11	0.06	0.01	0.66	0.17	12.99	0.36	4.0	5.2
NGC6838	-0.58	14.45	0.07	0.27	0.02	0.91	0.26	12.67	0.40	3.4	6.8
NGC6934	-1.54	16.84	0.08	0.11	0.02	0.66	0.17	15.84	0.36	14.7	12.0
NGC7089	-1.62	16.06	0.11	0.04	0.01	0.64	0.17	15.28	0.36	11.4	10.3
NGC7099	-2.13	15.10	0.06	0.05	0.01	0.50	0.16	14.45	0.35	7.7	7.0

†Zinn & West (1984)

‡It is assumed that the galactocentric distance to the Sun as 8 kpc.

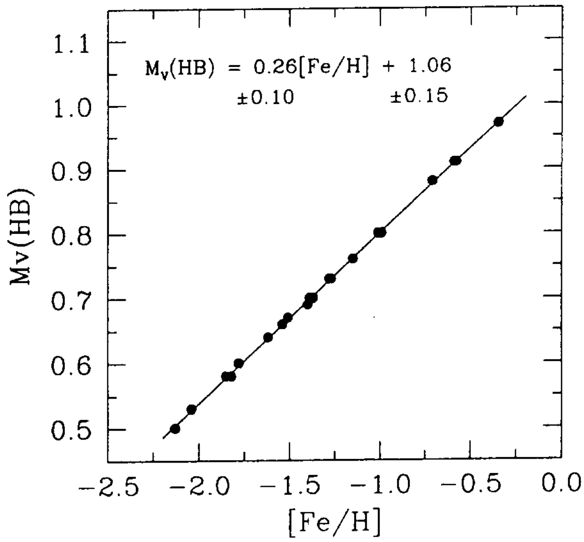

Figure 4. Relation between the absolute magnitudes of horizontal branches and metallicities.

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