THE ASTRONOMICAL JOURNAL, 116:1295–1300, 1998 September

VI PHOTOMETRY OF THE POST–CORE-COLLAPSE GLOBULAR CLUSTER NGC 6558 AND THE ADJACENT BULGE FIELD POPULATION[1]

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Received 1998 March 10; revised 1998 April 21

ABSTRACT

We present *VI* color-magnitude diagrams (CMDs) of the globular cluster NGC 6558 and its surrounding field, obtaining cluster parameters. The cluster has a blue extended horizontal branch and a depleted red giant branch, characteristics already observed in other post–core-collapse clusters in the bulge, such as NGC 6522, NGC 6540, and HP 1. These clusters do not belong to the metal-rich stellar population, and they may define a distinct class in the bulge. We derive a reddening of $E(B-V) = 0.50$ and a distance $d_\odot \approx 6.3$ kpc. The CMD morphology is consistent with a metallicity range of $-1.6 < [\mathrm{Fe/H}] < -1.2$. We also report photometry of the bulge field population ($b = -6°$ on the minor axis) in which NGC 6558 is imbedded. As is the case for other bulge fields, there is a prominent red clump and a strong descending red giant branch, similar to that seen in lower latitude bulge fields; we estimate the metallicity of the bulge population to lie between that of 47 Tuc and the nearly solar-metallicity cluster NGC 6553 (i.e., approximately −0.3 dex).

Key words: globular clusters: individual (NGC 6558)

1. INTRODUCTION

In the course of a study of ages and metallicities of field stars in the Galactic bulge (Ortolani, Rich, & Renzini 1998), we imaged the globular cluster NGC 6558 and its surrounding field at −6° on the minor axis. Very deep photometry of the bulge field population is also being obtained from a *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) observation made near the cluster (Rich et al. 1998) and will be reported in a separate paper.

Several factors have contributed to a renewed interest in the globular clusters of the bulge. First, high-resolution imaging from the ground and space has made age determinations and secure distance measurements possible. This body of work has identified a separate population of globular clusters associated with the Galactic bulge (Barbuy, Bica, & Ortolani 1998). *HST* imaging of the metal-rich globular cluster NGC 6553 with WFPC2 shows that it is as old as 47 Tuc (Ortolani et al. 1995), and the analysis of the same data shows that the bulge field population is the same age as the metal-rich clusters. The second factor contributing to a renewal of interest in the bulge clusters is the large number of clusters with collapsed cores and other indications of being dynamically evolved. These include the metal-rich clusters NGC 6388 and NGC 6441 (Rich et al. 1997), which have anomalous blue horizontal branches, and NGC 6522 (Shara et al. 1998), which is depleted of red giants. In this paper, we report on another bulge globular cluster with a depleted red giant branch and other anomalies in its color-magnitude diagram (CMD). We suggest that the frequent shocking experienced by bulge clusters may contribute to or accelerate dynamical evolution in these globular clusters.

NGC 6558 is also designated as GCl B1807−3146, GCl 89 (Alter, Ruprecht, & Vanysek 1970), and ESO 456-SC62. The coordinates are (B1950.0) $\alpha = 18^{\mathrm{h}}07^{\mathrm{m}}03\overset{\mathrm{s}}{.}3$, $\delta = -31°46'27''$, or (J2000.0) $\alpha = 18^{\mathrm{h}}10^{\mathrm{m}}18\overset{\mathrm{s}}{.}4$, $\delta = -31°45'49''$. The Galactic coordinates are $l = 0\overset{\circ}{.}201$, $b = -6\overset{\circ}{.}025$ a relatively low absorption bulge region (Blanco 1988).

Early investigators were uncertain as to whether NGC 6558 was an open or a true globular cluster (Rosino 1962 and references therein). Rosino (1962) discovered several RR Lyrae stars in the cluster, which, along with its central concentration, clearly confirmed its classification as a globular cluster. CCD photometry reveals NGC 6558 to be very concentrated, with a post–core-collapse structure with a core radius of $r_c = 2''$ and a half-light radius $r_h = 129''$ (Trager, King, & Djorgovski 1995).

Because of the difficult crowded field and sparse population of this cluster, no CMD has been reported in the literature up to now. Globular clusters in the direction of the bulge have often revealed surprising CMD morphologies when they are studied with modern CCD detectors in good seeing. For example, a recent case is the cluster HP 1, previously thought to be metal-rich but now shown (Ortolani, Bica, & Barbuy 1997) to have an extreme blue horizontal branch (HB). In the latter study and in Barbuy et al. (1998), the properties of these clusters are reviewed.

While no CMD is available for NGC 6558, several studies report integrated properties. Zinn's (1980) photometry yields $E(B-V) = 0.41$ and $[\mathrm{Fe/H}] = -1.63$, and that of Bica & Pastoriza (1983) yields $E(B-V) = 0.54$ and $[\mathrm{Fe/H}] = -1.11$. The spectroscopy of Zinn & West (1984) derives a revised metallicity of $[\mathrm{Fe/H}] = -1.44$. They also derive a radial velocity $v_r = -135$ km s^{-1}. In the course of constructing a grid of star cluster spectra, Bica & Alloin (1986a, 1986b) ranked the line strengths of NGC 6558 relative to a large sample. They concluded that the spectral properties are consistent with $E(B-V) = 0.40$ and $[\mathrm{Fe/H}] = -1.3$. Webbink's (1985) compilation reported $E(B-V) = 0.43$, $V_{\mathrm{HB}} = 16.7$, a distance $d_\odot = 8.8$ kpc, and a

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TABLE 1
LOG OF OBSERVATIONS

Filter	Exposure Time (s)	Seeing (arcsec)
V	10	1.1
	3 × 180	1.1
I	7	1.35
	2 × 120	1.25

NOTE.—All observations taken 1993 June 15 with the NTT and EMMI instrument.

metallicity [Fe/H] = −1.51, whereas that of Harris (1996) gives $E(B-V) = 0.42$, $V_{\rm HB} = 16.7$, $d_{\odot} = 8.7$ kpc, and [Fe/H] = −1.44.

Recently, Hazen (1996) identified some new variables within the cluster tidal radius. From the five RR Lyrae stars, which are probable members, she deduces $B_{\rm HB} = 16.8 \pm 0.08$ and a cluster distance of 6.6 kpc, this latter distance being considerably lower than the catalog values.

In the present study, we report new *VI* photometry for NGC 6558 obtained at the ESO New Technology Telescope (NTT), and from the CMD we derive the cluster distance and reddening. We also discuss other CMD properties of this cluster, which is in the direction of the bulge but not metal-rich. We describe our observations in § 2 and discuss the cluster and field CMDs in § 3. We derive reddening and metallicity from our CMDs in § 4 and present a case for a new family of bulge globular clusters in § 5. Our concluding remarks are given in § 6.

2. OBSERVATIONS AND REDUCTIONS

NGC 6558 was observed with the NTT at the European Southern Observatory using the ESO Multi-Mode Intrument (EMMI) in the imaging/focal reducer mode. Images were obtained through the red arm, equipped with the 2024 × 2024 pixel Loral antireflection-coated CCD No. 34 detector. The pixel size is 15 μm, corresponding to 0".35 on the sky, and the array gives a full field of 11'.8 × 11'.8. The log of observations is provided in Table 1.

The data were trimmed, bias-subtracted, and flat-fielded using MIDAS routines. Details of the reduction procedure for these crowded, often differentially reddened fields are described for the clusters NGC 6553, NGC 6528, and Liller 1 by Ortolani, Barbuy, & Bica (1990) and Ortolani, Bica, & Barbuy (1992, 1996), respectively.

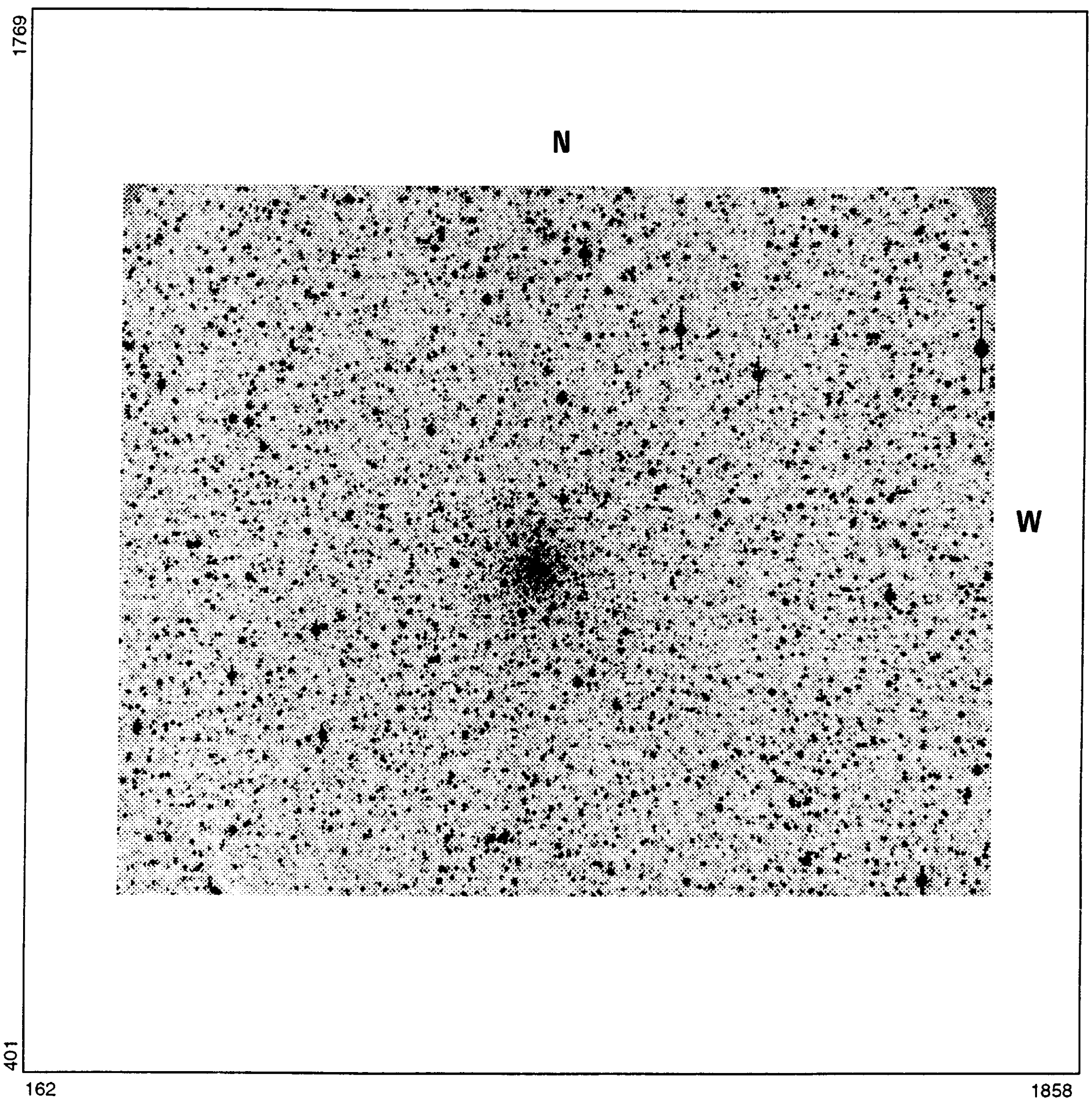

FIG. 1.—*I* image of NGC 6558 obtained with the NTT equipped with EMMI. Dimensions are 10'.7 × 10'.7. North is at the top and east is to the left.

DAOPHOT II was used to extract the instrumental magnitudes. These magnitudes have been calibrated using Landolt (1983, 1992) stars and the same calibration equations described in Ortolani, Barbuy, & Bica (1994):

$$V = v + 0.02(V-I) + 23.88 \pm 0.015 \text{ mag} ,$$

$$I = i + 0.015(V-I) + 23.61 \pm 0.015 \text{ mag} ,$$

reduced to 1 s exposure time and 1.2 air masses. Because of crowding effects arising in the transfer of the aperture magnitudes from standards to the field stars, the zero-point calibration errors are dominant, estimated to be about ± 0.03 mag. The CCD shutter time uncertainty (0.7 s), for a typical 20 s exposure time for the standard stars, produces an additional 3% uncertainty, which is propagated to the calibrations of the long-exposure cluster frames. The final magnitude zero-point uncertainty amounts to ± 0.04. The atmospheric extinction was corrected with the standard La Silla coefficients ($C_V = 0.20$, $C_I = 0.12$ mag per air mass). We measured 12 Landolt stars during the two photometric nights used to define the calibration transformations. Some of them were observed repeatedly, giving a total of 23 independent measurements. Having accounted for the different average transparency between the two nights, the 1 σ spread of the standards around the linear interpolation is about 0.02 mag, and all of them are within 0.05 mag in V. In the I band, the spread is around 30% less important. This means that the errors associated with the calibration equations are negligible when compared with crowding effects in the aperture corrections.

As a check of the calibration, we compared nine photoelectric stars published by Hazen-Liller (1984) with our measurements. The difference is $\Delta V = 0.02 \pm 0.06$ (present paper minus Hazen-Liller), which shows an excellent agreement in the V zero point.

Figure 1 shows the I image of NGC 6558, corresponding to a field size of 10'.7 × 10'.7. The small physical size of the cluster, the compact core, and the dominance of field crowding are clearly evident.

3. COLOR-MAGNITUDE DIAGRAMS

In Figure 2, we show a V versus $V-I$ diagram for the whole frame. The mean locus of the metal-rich cluster NGC 6553 is also plotted. The CMD has a blue disk main sequence (MS) and a strong metal-rich bulge component, denoted by the prominent red HB, a descending red giant branch (RGB), and a populated turnoff. A blue extended HB, located blueward of the disk MS, is seen.

In Figure 3, we present the V versus $V-I$ diagram for a smaller region centered on the cluster ($R < 42'$). After some experimentation by varying the extraction radius, we chose this value to maximize the number of cluster members relative to contaminating field stars.

The cluster RGB is sparsely populated and there is a blue extended HB, properties common to other bulge clusters; we return to this issue in § 5. The contamination by field stars at the bright cluster giant branch is negligible. Our tests in the field surrounding the cluster at a distance of about 7' around the cluster center show that there are no red giant field stars brighter than $V = 15$ in an area equivalent to that used for the extraction of Figure 3. The CMD is deep, but it appears to fall just short of the cluster turnoff, likely because of our I limiting magnitude and strong field population.

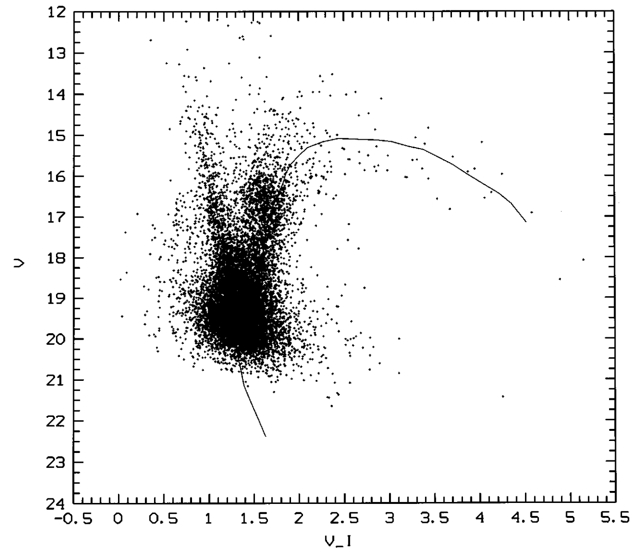

FIG. 2.—V vs. $V-I$ CMD for the whole NTT frame (11'.8 × 11'.8). The mean locus of NGC 6553 is overplotted.

The mean locus of NGC 6752 is overplotted in Figure 3, as a good example of a well-populated blue extended HB in a post–core-collapse cluster (Rosino et al. 1997). The brightest part of the blue HB level of NGC 6558 is located at $V = 16.05 \pm 0.15$ (around $V-I \approx 0.95$). The RGB slope and extent are almost coincident with those of NGC 6752, suggesting that NGC 6558 should have a comparable intermediate metallicity, i.e., [Fe/H] ≈ -1.5, given that [Fe/H] $= -1.54$ for NGC 6752 is reported by Zinn & West (1984).

A mean locus for 47 Tuc (Bica, Ortolani, & Barbuy 1994a) of [Fe/H] $= -0.71$ (see Zinn 1985) is a poor fit; however, one may not exclude intermediate metallicity as high as [Fe/H] ≈ -1, particularly if the three brightest, reddest giants are cluster members. In fact, the dominance of blue HB stars should, in principle, weaken the measured line strengths (except for hydrogen lines) of the integrated

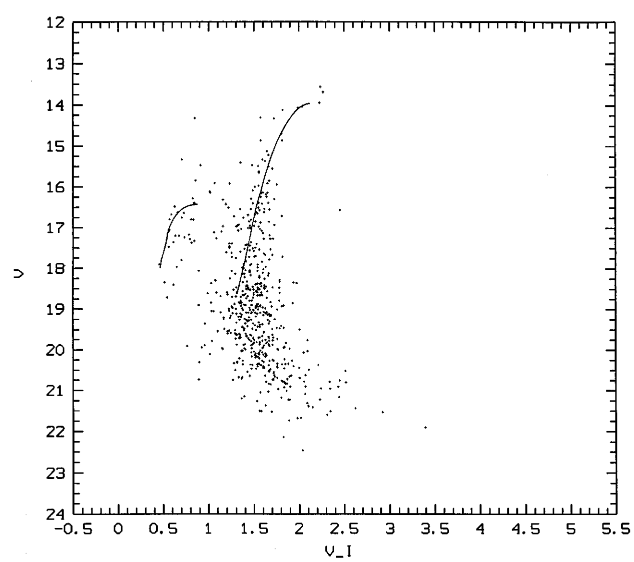

FIG. 3.—V vs. $V-I$ CMD for an extraction of $R < 42''$ centered on NGC 6558. This CMD is a combination of deep and short exposures. The mean locus of the post–core-collapse, blue extended HB cluster NGC 6752 is superposed.

spectrum (Bica & Alloin 1986b), causing systematically lower derived metallicity. (See also the discussion of the integrated spectrum and CMD of the very similar post–core-collapse cluster NGC 6540 in Bica, Ortolani, & Barbuy 1994b.)

3.1. *Surrounding Field*

We present the field CMD in Figure 2, together with the mean locus of NGC 6553. The CMD has a strong blue sequence, which is the result of foreground disk stars at varying distance and reddening (Kiraga, Paczyński, & Stanek 1997). The bulge field population has a strong red clump and clear descending red giant branch. These are both clear indicators of a metal-rich population, and their presence shows that the field population has roughly the same age and metallicity as that in Baade's window, $-4°$ on the minor axis.

The field CMD appears to show a range in metallicity, from that of 47 Tuc (Bica et al. 1994a; Desidera & Ortolani 1997) up to that of the nearly solar-metallicity globular cluster NGC 6553 (or Baade's window; see Ortolani et al. 1995). Preliminary analysis of deep NTT and *HST* images indicates that the field population is also as old as that in Baade's window; these findings will be reported later.

Several factors appear to contribute to broaden the principal sequences in the field CMD; combined depth and reddening effects are illustrated in the recent simulations by Kiraga et al. (1997). The most important effects in the present field are due to the intrinsic spread in abundance (see Bica, Barbuy, & Ortolani 1993 for metallicity effects on CMDs) and differential reddening (see, e.g., Fig. 8 of Ortolani et al. 1990), which broaden the sequences. A visual inspection of the field on the ESO(B) sky survey (plate 456) reveals some clear elongated patches of absorption in the vicinity of the cluster, especially noticeable toward the northwest and west and likely extending to cover the cluster itself. These effects, along with the spatial distribution of the bulge along the line of sight, also broaden the sequences in V magnitude. We will consider the field CMDs in detail in Ortolani, Rich, & Renzini (1998).

4. REDDENING AND DISTANCE

We calculate the cluster reddening taking NGC 6752 as reference. The $V-I$ color of the RGB at the HB level for NGC 6558 is 1.55 ± 0.03, whereas for NGC 6752 it is $V-I = 1.00 \pm 0.04$ (Rosino et al. 1997), and the difference is $\Delta(V-I) = 0.55$. Adopting $E(B-V) = 0.04$ for NGC 6752 (Zinn 1980) and $E(V-I)/E(B-V) = 1.31$ (Dean, Warren, & Cousins 1978), we get $E(V-I) = 0.60$ and $E(B-V) = 0.46 \pm 0.05$ for NGC 6558.

The magnitude of the brightest part of blue HB level at the RR Lyrae position of NGC 6752 is located at $V = 13.55 \pm 0.1$ (Rosino et al. 1997). The magnitude difference between the HB levels of NGC 6558 and NGC 6752 is then $\Delta V = 2.5 \pm 0.15$. The absolute V absorption for NGC 6558 is $A_V = 1.42$ $[R = A_V/E(B-V) = 3.1$; Savage & Mathis 1979]. The absolute distance modulus of NGC 6752 is $(m-M)_0 = 13.05$ according to Renzini et al. (1996), based on the white dwarf cooling sequence, which leads to $(m-M)_0 = 14.13 \pm 0.2$ and a distance from the Sun $d_\odot = 6.7 \pm 0.6$ kpc for NGC 6558. An alternative method is the use of the absolute magnitude of the HB for [Fe/H] = -1.5, of $M_V = 0.7$ (Buonanno, Corsi, & Fusi Pecci 1989; Lee, Demarque, & Zinn 1990; Sandage & Cacciari 1990). In this case, the distance would be $d_\odot = 6.1$ kpc ($R = 3.1$). We adopt the average from the two methods, $d_\odot = 6.4 \pm 0.5$ kpc. This result agrees well with the value derived from RR Lyrae stars by Hazen (1996) but is somewhat closer to the Sun than previously reported in compilations (Webbink 1985; Harris 1996). The Galactocentric coordinates of the cluster, assuming a distance from the Sun to the Galactic center of $R_\odot = 8.0$ kpc (Reid 1993), are $X = -1.64$ ($X < 0$ refers to our side of the Galaxy), $Y = 0.0$, and $Z = -0.67$ kpc. The Galactic center distance $R_G = 1.8$ kpc. Therefore, NGC 6558 is located in the bulge but does not belong to the metal-rich population (§ 5).

4.1. *Parameters for the Field*

The field is of interest since it is along the bulge minor axis, apparently in a window with a lower reddening than Baade's window (Terndrup 1988; Barbuy, Ortolani, & Bica 1994). The metal-rich population has $V_{HB} = 16.6 \pm 0.25$, and $(V-I)_{HB} = 1.60 \pm 0.12$. The difference between the metal-rich population (bulge) and the metal-rich reference cluster NGC 6553 (Ortolani et al. 1995) is $\Delta(V-I)^{6553}_{bulge} = 0.40$; given that, from *HST* data, the revised value $E(V-I) = 0.95$ for NGC 6553 (Guarnieri et al. 1998), this leads to $E(V-I)_{bulge} = 0.55$ and $E(B-V) = 0.41$. Assuming $R = 3.1$, we obtain $A_V = 1.27$; if $R = 3.6$, suitable for red stars, is adopted (Terndrup 1988; Grebel & Roberts 1995), we obtain $A_V = 1.48$. Assuming that the absolute magnitude of the HB for a metallicity of about [Fe/H] ≈ -0.2 is 0.80 (Chaboyer et al. 1996), and applying a 0.14 mag blanketing correction that matches bolometric magnitudes (see discussion in Guarnieri et al. 1998), we derive $M_V^{HB} = 0.94$. The distances are $d_\odot = 7.5$ kpc ($R = 3.1$) and $d_\odot = 6.8$ kpc ($R = 3.6$).

Note that the field reddening is somewhat lower than that of the cluster, and slightly more distant. This marginal difference in reddening might be explained by the patchy dust distribution in the cluster area.

4.2. *Variables*

Rosino (1962) found RR Lyrae stars (likely members) in this cluster. Hazen (1996) presented average magnitudes and periods for these variables. Six of these variables are present in our frames: V1, V3, V4, V5, V6, and V8; according to Hazen, they are within the half-tidal radius. We checked the membership of these variables on our CMD, by comparing their $\langle V \rangle$ magnitudes (transformed from Hazen's $\langle B \rangle$ magnitudes) with the vertical width of our HB.

Following Hazen, in the transformation from $\langle B \rangle$ to $\langle V \rangle$, an intrinsic color for the RR Lyrae stars of $(B-V)_0 = 0.35$ and our reddening of $E(B-V) = 0.43$ were adopted (§ 4). We considered members those variables found within the HB vertical width in the range $15.85 < V < 16.25$ (Fig. 3). We confirmed Hazen's results that V3, V4, V6, and V8 are members and that V5 is too faint and not a member. V1 is slightly too bright, but as mentioned by Hazen, it is in the center of the cluster and could be contaminated. Checking our photometric tables, we find that V1 has $V = 15.94$ (and $V-I = 0.92$), consistent with membership.

5. A NEW FAMILY OF CLUSTERS IN THE BULGE?

The striking feature of the CMD of NGC 6558 is the predominance of HB stars and a seeming absence of bright giants. Very similar CMD morphology occurs in other intermediate-metallicity, post–core-collapse bulge clusters,

TABLE 2

PROPOSED MEMBERS OF THE NGC 6522 CLASS

ID (1)	c (2)	r_c (3)	r_h (4)	ρ_0 (5)	n(HB)/n(BRG) (6)
HP 1	2.50[a]	0.03	3.10	4.80	47/20
NGC 6522......	2.50[a]	0.05	1.04	5.40	85/29
NGC 6540......	2.50[a]	0.03	0.24:	5.96	21/0(?)
NGC 6558......	2.50[a]	0.03	1.61:	5.01	60/19

NOTE.—Columns (2)-(5) are from Harris 1996.

[a] Core-collapsed.

e.g., HP 1 (Ortolani et al. 1997), NGC 6522 (Barbuy et al. 1994; Terndrup & Walker 1994; Shara et al. 1998), and NGC 6540 (Bica et al. 1994b); Table 2 gives a summary of their properties. These clusters have the maximum concentration parameter of 2.50 and are all classified as post–core-collapse candidate clusters. NGC 6522, in particular, has been observed with *HST* and has a highly significant depletion of bright red giants (Shara et al. 1998).

We have measured the ratio of HB to bright red giants (BRGs) in the "NGC 6522" clusters by counting only those giants lying brighter than the HB locus. For other test clusters with similar crowding in the Galactic center region, this ratio is usually less than 2:1. The clusters in Table 2 exceed this ratio, and all share extended blue HBs. We emphasize that, given the crowding-induced photometric errors (and, in some cases, differential reddening), the present data should serve as an inspiration to undertake the necessary confirmation, rather than as the certain identification of a new class of globular clusters.

A number of observations in recent years have hinted at a link between the dynamical state of globular clusters and the morphology of the CMD. Djorgovski et al. (1991) measured radial color gradients in some high-concentration clusters, while Fusi Pecci et al. (1993) found a strong correlation between the presence of blue HB tails and strong central concentration. Rich et al. (1997) find extended-blue HB tails in two metal-rich clusters with extraordinarily high central surface brightnesses; HB tails are absent in all other metal-rich clusters of lower central concentration. While none of these cases prove the dynamical connection beyond doubt, they clearly argue for the value of further investigations in this direction. On the other hand, theoretical efforts to explain how red giants might be converted to HB stars in the extended blue tail have not succeeded, starting with Djorgovski et al. (1991) and continuing to the present day (Rich et al. 1997).

Efforts to explain unusual CMD morphology and red giant depletion have always emphasized the correlation of the CMD with intrinsic cluster properties such as central concentration. To first order, this must be the case. However, clusters in the bulge experience considerable shocking from the bar and inner disk, which may have an additional effect. Gnedin & Ostriker (1997) calculate that clusters with concentration parameter $c \equiv \log(R_t/R_c) > 1.5$ are most resistant to destruction. The dense stellar population of the bulge may also favor encounters between cluster members and bulge field stars (Bica et al. 1997), which could harden a core population of binaries. The space motion of NGC 6522 relative to the bulge has recently been determined; the cluster is nearly on a plunging orbit toward the Galactic center (Terndrup et al. 1998) with a period of $\approx 10^7$ yr. NGC 6522 may have experienced 10^3 bar/disk passages in a Hubble time. Our suggestion of a new class of post–core-collapse, perhaps highly dynamically evolved, clusters in the bulge is based currently on only relatively thin evidence; however, *HST* observations are capable of confirming or refuting our hypothesis.

6. CONCLUSIONS

We have used the EMMI on the ESO New Technology Telescope to image the globular cluster NGC 6558 in *V* and *I*. We have measured color-magnitude diagrams for the cluster and surrounding field, deriving their reddenings and distances. From the CMD morphology, we conclude that the cluster is metal-poor, in the range -1.5 to -1 dex, which covers a considerable fraction of bulge globular clusters. The cluster has a clear blue extended horizontal branch and a poorly populated giant branch. These properties, along with the post–core-collapse structure, have been observed in several bulge clusters, which may suggest the existence of a distinct class of clusters in that region. The adjacent bulge field population has a strong red clump and descending red giant branch, which are consistent with a metallicity between that of 47 Tuc and solar.

The globular clusters of the bulge may correspond to red populations of globular clusters associated with the spheroids of elliptical galaxies. The measurement of precise main-sequence turnoff points and metallicities for these clusters will provide an important constraint on bulge formation theories. We believe that those clusters that have survived in the bulge may have unusually interesting stellar populations in their cores, and we recommend that a survey using the *Hubble Space Telescope* be undertaken to explore this hypothesis.

We acknowledge partial financial support from the Conselho Nacional de Pesquisas and the Fundação de Amparo à Pesquisa do Estado de São Paulo. R. M. R. acknowledges *HST* Guest Observer program 6820.

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