ANOTHER NONSEGREGATED BLUE STRAGGLER POPULATION
IN A GLOBULAR CLUSTER: THE CASE OF NGC 2419

E. DALESSANDRO, B. LANZONI, F. R. FERRARO, F. VESPE, M. BELLAZZINI, AND R. T. ROOD

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ABSTRACT

We have used a combination of ACS HST high-resolution and wide-field Subaru data in order to study the blue straggler star (BSS) population over the entire extent of the remote Galactic globular cluster NGC 2419. The BSS population presented here is among the largest ever observed in any stellar system, with more than 230 BSSs in the brightest portion of the sequence. The radial distribution of the selected BSSs is essentially the same as that of the other cluster stars. In this sense the BSS radial distribution is similar to that of ω Centauri and unlike that of all Galactic globular clusters studied to date, which have highly centrally segregated distributions and, in most cases, a pronounced upturn in the external regions. As in the case of ω Centauri, this evidence indicates that NGC 2419 is not yet relaxed even in the central regions. This observational fact is in agreement with estimated half-mass relaxation time, which is of the order of the cluster age.

Subject headings: binaries: general — blue stragglers — globular clusters: individual (NGC 2419) — stars: evolution — stars: horizontal-branch

Online material: machine-readable table

1. INTRODUCTION

This paper is part of a series aimed at studying the complex interplay between dynamics and stellar evolution in a sample of globular clusters (GCs) with different structural properties. To this purpose we are using the so-called blue stragglers star (BSS) population as a probe. BSSs are the most abundant and common population of stars which significantly deviates from the evolutionary path defined by a simple, old stellar population. In the color-magnitude diagram (CMD), BSSs define a sparsely populated sequence that is more luminous and bluer than the turn-off point (TO) of a normal hydrogen-burning main sequence (MS). Hence they appear as stars that are more massive (see also Shara et al. 1997) and younger than the bulk of the cluster population. They are thought to form from the evolution of binary systems, either via mass-transfer/coalescence phenomena in primordial binaries (PB-BSS; McCrea 1964; Zinn & Searle 1976), or by stellar mergers induced by collisions (COL-BSS; Hills & Day 1976). Since collisional stellar systems like GCs dynamically evolve over a timescale significantly shorter than their age, BSSs are expected to have sunk into the cluster core, as have the majority of the most massive objects (such as binaries and other binary by-products) harbored in the system.

In many GCs the projected radial distribution of BSSs has been found to be bimodal: highly peaked in the center, with a clear-cut dip at intermediate radii, and with an upturn in the external regions. Such behavior has been confirmed in at least seven GCs: M3, 47 Tuc, NGC 6752, M5, M55, and NGC 6388 (all references in Dalessandro et al. 2008), and M53 (Beccari et al. 2008). Dynamical simulations (Mapelli et al. 2006; Lanzoni et al. 2007a, 2007b) suggest that the observed central peak is mainly due to COL-BSSs formed in the core and/or PB-BSSs sunk into the center because of dynamical friction, while the external rising branch is made of PB-BSSs evolving in isolation in the cluster outskirts. Even in those GCs that do not show any bimodality the BSSs always appear to be significantly more segregated in the central regions than the reference cluster stars. The only exception to these general observational features is ω Centauri (hereafter ω Cen); the large population of BSSs discovered by Ferraro et al. (2006, hereafter F06) in this giant stellar system has the same radial distribution of the normal cluster stars. This is clear evidence that ω Cen is not fully relaxed, even in the central regions, and therefore, the dynamical evolution of the cluster has not significantly altered the radial distribution of these stars. It is likely that the vast majority of BSSs observed in this cluster are the progeny of primordial binaries evolved in isolation (see also Mapelli et al. 2006).

Here we direct our attention to another massive cluster (NGC 2419) which shares a number of properties with ω Cen. This remote object (d ~ 81 kpc; Harris et al. 1997) is one of the most luminous clusters in the Galaxy ($M_V = -9.4$; see Bellazzini 2007, hereafter B07), similar to ω Cen and M54 (NGC 6715). It has been suggested that both of the latter clusters are the remnants of stripped cores of dwarf spheroidals (see, e.g., Layden & Sarajedini 2000; Bekki & Freeman 2003). With its high luminosity and half-light radius ($r_h \approx 25$ pc; B07), NGC 2419 lies (together with ω Cen and M54) in the $(r_h, M_V)$ plane well above the locus defined by all the other Galactic GCs. Indeed, it is the most significant outlier, thus suggesting that it also might be the stripped core of a former dwarf galaxy (van den Bergh & Mackey 2004; Mackey & van den Bergh 2005). Further, Newberg et al. (2003) suggested that NGC 2419 could be somehow connected with the Sagittarius (Sgr) dwarf spheroidal, since it seems to be located in a region with an overdensity of type-A stars that is in the same plane as the tidal tails of Sgr. However, the high-quality CMDs of NGC 2419 recently published by Ripepi et al. (2007, hereafter R07; see also B07) do not show any evidence of multiple stellar
populations, in contrast to ω Cen (Lee et al. 1999; Pancino et al. 2000; Bedin et al. 2004; Rey et al. 2004; Sollima et al. 2005) and possibly M54 (Layden & Sarajedini 2000; see also Monaco et al. 2005). It is possible, however, that for such a metal-poor cluster (Fe/H) = −1.97; Ferraro et al. 1999a) the range in metallicities for the subpopulation components is so small that different sequences cannot be seen in the CMD (Mackey & van den Bergh 2005; Federici et al. 2007).

In order to further investigate the dynamical status and stellar populations of this remote cluster, we present here a multiwavelength study of BSSs in NGC 2419. By combining HST high-resolution data with wide-field Subaru images, we sampled the total radial extension of the cluster. This allowed us to study and compare the projected radial distributions of BSSs and other cluster stars in different evolutionary stages. The data and photometric reductions are described in §2. A general overview of the CMD is discussed in §3. The BSS population is described in §4, and the discussion is presented in §5.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. The Data Sets

To study the crowded cores of high-density systems and simultaneously cover the total cluster extensions, a combination of high-resolution observations of the central regions and complementary wide-field images is needed.

1. High-resolution set.—This is composed of a series of public images obtained with the Wide Field Channel of the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST): two F435W (∼B filter) images with texp = 800 s each, two F555W (∼V filter) images with texp = 720 s, and two F814W (∼I filter) images with texp = 676 s (proposal GO9666, P.I. Gilliland). These are the highest resolution (∼0.05′′ pixel−1) observations available to date for NGC 2419. Unfortunately the ACS images are off-center (see Fig. 1), and they do not completely sample the most central region of the cluster. As in previous works (see, e.g., Dalessandro et al. 2008), average ACS images were obtained in each filter, and they were corrected for geometric distortion and effective flux (Sirianni et al. 2005). The data reduction has been performed using the ROMAFOT package (Buonanno et al. 1983), specifically developed to perform accurate photometry in crowded regions (Buonanno & Iannicola 1989).

2. Wide field set.—We have used a set of public F and I images obtained with the Subaru Prime Focus Camera (Suprime-Cam) of the 8.2 m Subaru telescope at the Hawaii National Astronomical Observatory of Japan. The Suprime-Cam is a mosaic of 10 2048 × 4096 CCDs, which covers a 34′ × 27′ field of view (FOV) with a pixel scale of 0.2″. A combination of long-exposure (texp = 180 s) and median-exposure (texp = 30 s) images has been retrieved from the Subaru Archive Web site (SMOKA). As shown in Figure 2, the cluster is centered in chip 2 and it is totally included in the five adjacent chips; therefore only these six chips have been considered in the present study. We have applied standard prereduction procedures (correction for bias, flat-field, and overscan) using IRAF6 tools. The reduction was performed independently for each image using the PSF fitting software DoPhot (Schechter et al. 1993).

2.2. Astrometry, Center of Gravity, and Photometric Calibration

The ACS and Subaru data have been placed on the absolute astrometric system by using the stars in common between each single chip and the SDSS data set used by B07, that, in turn, was astrometrized on the GSC-II astrometric reference star catalog. Hundreds of stars have been matched in each chip, thus allowing a very precise determination of the stellar absolute positions. The resulting rms residuals (a measure of the internal astrometric accuracy) were of the order of ∼0.3″ both in right ascension (α) and declination (δ).

The photometric calibration of the ACS catalog has been performed in the VEGAMAG system using the relations and zero points described in Sirianni et al. (2005). Then the Subaru catalog was homogenized to the ACS one. In order to transfer the

6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the national Science Foundation.
instrumental Subaru magnitudes into the ACS VEGAMAG system, a subsample of a few hundred stars in common between the Subaru and the ACS FOVs has been selected, and the following relations have been obtained:

\[
I_{\text{ACS}} - i_{\text{Subaru}} = -0.55(V - I)_{\text{ACS}} + 27.41, \quad (1)
\]

\[
V_{\text{ACS}} - v_{\text{Subaru}} = -0.20(V - I)_{\text{ACS}} + 27.46, \quad (2)
\]

where \(i_{\text{Subaru}}\) and \(v_{\text{Subaru}}\) are the instrumental \(I\) and \(V\) magnitudes in the Subaru sample referred to 1 s exposure. In this way a final list of absolute positions and homogeneous (VEGAMAG) magnitudes for all of the stars in the two catalogs was obtained.

In order to determine the center of gravity \((C_{\text{grav}})\) of the cluster, we computed the barycenter of all the stars found in the ACS catalog at a distance \(r < 10''\) from the center, as quoted by Harris (1996). A circular region of 10'' radius is the maximum available area that is completely covered by the ACS observations (see Fig. 1). The absolute positions \((\alpha, \delta)\) of the stars have been averaged using an iterative technique described in previous works (e.g., Montegriffo et al. 1995; Ferraro et al. 2003). We have excluded stars brighter than \(V = 19.5\) since they are saturated in the ACS images. The same procedure has been repeated for three different magnitude cuts \((V < 24, V < 23.5, \text{and } V < 23)\) in order to check for any possible statistical or spurious fluctuations. The three measures agree within \(\sim 1''\) and their mean value has been adopted as best estimate of \(C_{\text{grav}}, \alpha = 7^h 38^m 4.47^s\) and \(\delta = 38^\circ 52'55.0''\), with an uncertainty of 0.5'' in both \(\alpha\) and \(\delta\). This new determination is in agreement with that listed by Harris (1996).

Given the coordinates of \(C_{\text{grav}}\), we have divided the data set in two main samples: the HST sample, which includes all the stars found in the ACS catalog, and the Subaru sample, which consists of stars not included in the ACS FOV and lying at \(r > 60''\) from the cluster center. The latter choice implies that a small region (a segment of a circle located \(\sim 20''\) north from the cluster center) is covered neither by the HST sample nor by the Subaru sample (see Fig. 2). This conservative choice is made to avoid incompleteness effects of the ground-based observations in the most crowded central regions of the cluster.\(^7\)

3. CMD OVERALL CHARACTERISTICS AND THE HB MORPHOLOGY

The CMD of stars in the HST sample is shown in Figure 3. This is the deepest CMD ever published for NGC 2419, reaching down to \(B \sim 27\). All the main cluster evolutionary sequences are clearly defined and well populated. The stars in the brightest \((B < 19.5)\) portion of the red giant branch (RGB) are not shown in the figure, because they are heavily saturated in these exposures. The MS-TO of the cluster is located at \(B_{\text{TO}} = 24.5 \pm 0.1\). Particularly notable is the horizontal-branch (HB) morphology, which looks quite complex, with a long HB blue tail (BT) extending well below the cluster MS-TO. The peak of the HB population is located at \(B \sim 20.7\) and \((B - I) \sim 0.2\). The HB population significantly decreases with decreasing luminosity along the BT. A poorly populated region (a gap?) is visible at \(B \sim 23.4\), separating the extreme extension of the BT and a clump of stars extending down to \(B \sim 25\). Following the nomenclature adopted in Dalessandro et al. (2008), these are extreme HB (EHB) stars with the faintest ones being blue hook (BHK) stars. Definitive assignment to these groups will require UV photometry.

In Figure 4 we show a direct comparison between the HB of NGC 2419 and that of \(\omega\) Cen (from Ferraro et al. 2004), suitably shifted (by \(\sim 5.6\) mag) in order to match the HB level of NGC 2419. The two HBs show very similar extension and morphology. The only significant difference is that EHB/BHK stars in NGC 2419 are much more spread out in color \((B - I) \sim 1\) than the same population in \(\omega\) Cen. The rms scatter between the magnitude measurements in the two single images, is \(\sigma_B \sim 0.1\) and \(\sigma_I \sim 0.24\) mag in the \(B\) and \(I\) bands, respectively. Thus the photometric error in \((B - I)\) is \(\sigma_{B-I} \sim 0.26\) mag at the level of

\(^7\) However, note that the annular region between 20'' and 60'' from the cluster center is well sampled (at \(\sim 70\%\)) by the ACS sample.
BHk stars. The observed color spread is about 4σ and may thus be real. To demonstrate more clearly the striking similarity of these HBs, in Figure 5 we show the normalized B magnitude distribution of HB stars. The percentage of stars in three portions of the branch is also designated in the figure. Beyond general appearance, the HBs are quantitatively similar: (1) both the HBs extend for almost 4.5 mag; (2) both the distributions show a well-defined peak, an extended tail, and a EHB/BHk clump; (3) the bulk of the HB population (58%) is localized in the brightest 1 mag portion of the branch; (4) the BT is 10%–12% of the population; and (5) both the EHB/BHk clumps extend for roughly 1.5 mag and they comprise ~30% of the total HB population.

As discussed in Dalessandro et al. (2008), the nature of BHk stars is still unclear; they may be related to the so-called late hot flashers (Moehler et al. 2004; Catelan 2007), or due to high helium abundances (as suggested by Busso et al. [2007], in the case of NGC 6388; see also Caloi & D’Antona 2007; D’Antona et al. 2005), or related to the evolution of binary systems (Heber et al. 2002). However, the detection of a population of BHk stars in a low-metallicity cluster such as NGC 2419 clearly demonstrates that the process producing these extremely hot HB stars can efficiently work in any metallicity environment: NGC 6388 ([Fe/H] ~ −0.4), NGC 2808 ([Fe/H] ~ −1.1), ω Cen ([Fe/H] ~ −1.6), M54 ([Fe/H] ~ −1.8), and NGC 2419 ([Fe/H] ~ −2). It is interesting to note that NGC 2419 is very massive, as are the other BHk clusters. We have also checked the EHB/BHk radial distributions with respect to the brightest portion of the HB and the RGB. The significance of the difference has been quantified with a Kolmogorov-Smirnov (KS) test; the radial distribution of the BHk population is consistent with that of normal cluster stars, in agreement with similar findings in NGC 6388 (Rich et al. 1997, Dalessandro et al. 2008) and ω Cen (Ferraro et al. 2004). However, the evidence presented in § 4.2 demonstrates that NGC 2419 is not relaxed even in the central regions; hence no segregation is expected for these stars even in the case that they were binaries. Moreover, as discussed in Dalessandro et al. (2008), it is important to remember that the lack of segregation of the EHB/BHk population is not a firm proof of the nonbinarity of EHB/BHk stars, since they could be low-mass binaries, with a total mass similar (or even lower) than “normal” cluster stars (for example, a 0.5 M⊙ He-burning star with a 0.2 M⊙ He white dwarf companion).

3.1. Density Profile and Distance Modulus Estimate

The (V, V − I) CMDs of the HST and Subaru samples defined in § 2.2 are shown in Figure 6. Thanks to the high-resolution ACS images of the cluster core and the wide FOV of the Subaru observations, we have properly sampled the stellar population over the entire cluster extension. We then used this data set to determine the projected density profile of NGC 2419 using direct star counts, from Cgrav out to about 1000″.

Stars with V < 19.5 are saturated in the ACS sample and therefore have been excluded from the analysis; however, since they are small in number, this produces a negligible effect on the global result. In order to avoid incompleteness biases we have also excluded stars fainter than V = 23.5. Using the same procedure described in Ferraro et al. (1999b), the whole sample has been divided into 24 concentric annuli, each centered on Cgrav and suitably split in a number of subsectors. The number counts have been calculated in each subsector and the corresponding densities were obtained dividing them by the sampled area (taking into account the incomplete spatial coverage of the region between 20″ and 60″). The stellar density of each annulus was then defined as the average of the subsector densities and its standard deviation computed from the variance among the subsectors. The resulting projected surface density profile is plotted in Figure 7. As apparent, the outermost two points show a flattening of the stellar number density, and their average (corresponding to ~4 stars arcmin−2) has therefore been used as an estimate of the background contribution. The derived radial density profile is well fit by an isotropic single-mass King model (Fig. 7, solid line), with concentration c = 1.36 and core radius r_c = 20″, yielding a “formal” value of the cluster tidal radius of r_t ~ 460″.
and a half-mass radius of $r_h \sim 58''$. These parameters are essentially equal to those obtained by B07 and in good agreement with other previous determinations (see, e.g., Table 2 in B07).

We also used the available high-quality data set for deriving an independent estimate of the distance to NGC 2419. To do this, we compared the CMD shown in Figure 3 to that of M92 (NGC 6341), one of the “prototype” Galactic GCs, with similar metallicity ([Fe/H] $\sim$ -2; Ferraro et al. 1999a). We used a combination of WFPC2 and ACS data of M92 (F.R. Ferraro et al. 2008, in preparation), obtained through filters F555W ($\sim$V) and F814W ($\sim$I). We shifted the CMD of M92 onto that of NGC 2419 until a good match between the main evolutionary sequences (RGB, HB, subgiant branch, and TO region) of the two clusters was reached (see Fig. 8). This required a color shift $\delta(V-I) = 0.14$ and $\delta V = 5.25$, similar to that obtained by Harris et al. (1997) from an analogous comparison based on independent data sets. Figure 8 shows that a really nice matching of all the evolutionary sequences of the two clusters can be achieved. This evidence also suggests that the two clusters have a similar age (in agreement with Harris et al. 1997, who estimated an age difference of $\sim$1 Gyr for the two objects).

By assuming the distance modulus $(m - M)_0 = 14.78$ and the reddening $E(B - V) = 0.02$ for M92 (Ferraro et al. 1999a), and by using the standard absorption coefficient ($A_V = 3.1$ and $A_I = 1.7$), we obtained $E(B - V) = 0.12 \pm 0.03$ and $(m - M)_V = 20.09$, corresponding to a true distance modulus $(m - M)_V = 19.72$, for NGC 2419. The reddening obtained from this procedure is in good agreement with the value derived by Harris et al. (1997), who quoted $E(B - V) = 0.11$, and it is also in agreement with the value $E(B - V) = 0.08$ adopted by R07 within the errors. Taking a conservative estimate of $\sigma \sim 0.1$ mag, we finally adopt $(m - M)_0 = 19.7 \pm 0.1$. This yields a real distance $d \simeq 87 \pm 4$ kpc. Within the uncertainties, this estimate is in agreement with both that found by Harris et al. (1997; $d = 81 \pm 2$ kpc) and that obtained by R07 using the mean luminosity of the RR Lyrae stars ($d = 83.2 \pm 1.9$ kpc). Assuming this distance, the physical dimensions of the core radius and of the half-mass radius of the cluster can be obtained; given $r_c = 20''$ and $r_h = 58''$ (see above), we obtain $r_c = 8.4$ pc and $r_h = 24.5$ pc, respectively. By adopting the total integrated magnitude $V_I = 10.47$ quoted by B07, the absolute cluster magnitude is $M_V = -9.6$. This value, combined with the size of the half-mass radius, confirms the anomalous position of NGC 2419 in the $r_h$ versus $M_V$ plane (van den Bergh & Mackey 2004).

4. THE POPULATION OF BSSs

4.1. Population Selection

To select the BSS population we have chosen to use the $(B - I)$ CMD, in which the BSS sequence is better defined. To avoid spurious effects due to subgiant branch star blends and Galaxy field star contamination, only stars brighter than $B \simeq 23.6$ (corresponding to $\sim 1$ mag above the TO) and with $B - I < 0.75$ have been selected (see Fig. 9). The resulting number of candidate BSSs in the HST sample is 183. The position of the bulk of these stars in the ACS $(V, V - I)$ CMD has then been used to define the BSS selection box for the Subaru sample. This is shown in Figure 10, with the faint and red edges corresponding to $V \simeq 23.3$ and $V - I < 0.48$, respectively. The resulting number of candidate BSSs found in the entire Subaru sample is 67, out of which 49 are found within the “safe” distance of $\sim 500''$ from the cluster center. This distance is slightly larger than the “formal” tidal radius obtained in § 3.1 and takes into account possible uncertainties in the determination of the latter. The positions and magnitudes of all the 232 candidate BSSs thus selected are...
listed in Table 1, which is available in full size in electronic form.\(^8\)

Reference populations representative of the “normal” cluster stars are needed to properly study the BSS radial distribution. We considered both the HB and the RGB. Since the HST and the Subaru samples have the \(V\) and \(I\) filters in common, we performed

\(^8\) Several SX Phoenicis variables have been found by R07. However, a direct comparison between these stars and our BSS sample is not possible, since the R07 catalog is not yet published.

4.2. BSS Radial Distribution

A first qualitative comparison between the cumulative radial distribution of BSSs and that of the reference populations (see Fig. 11) has been performed using the KS test. This gives 70\% and 50\% probabilities that the BSS population is extracted from the same population as the HB and RGB stars, respectively. Hence there is preliminary evidence that the radial distribution of BSSs is indistinguishable from that of the “normal” cluster population, in contrast to what found in most of the typical GCs (see references in Dalessandro et al. 2008).

For a more detailed analysis, we have used the same technique described in previous works (see, e.g., F06). The sampled area within \(r = 500''\) has been divided in five concentric annuli centered on \(C_{\text{grav}}\). In each of these we have counted the number of BSS, HB, and RGB stars. However, the examination of the external regions \((r > 500'')\) of the Subaru sample CMD suggests that the selected (BSS, HB, and RGB) populations can be affected by contamination from stars in the Galactic field. In order to account for this effect we adopted the statistical correction used in previous papers (see, e.g., Dalessandro et al. 2008). To do this we selected a rectangular region of \(\sim 70\) arcmin\(^2\) located at \(r > 650'',\) i.e., well beyond the formal tidal radius of the cluster. The CMD of this region clearly shows that the Galaxy field population is dominant relative to the cluster one. Then we counted the number of stars in this region lying in the BSS, HB, and RGB selection boxes shown in Figure 6 and derived the following values of the field star densities: \(D_{\text{field}}^{BSS} = 0.03\) stars arcmin\(^{-2}\), \(D_{\text{field}}^{HB} = 0.06\) stars arcmin\(^{-2}\), and \(D_{\text{field}}^{RGB} = 0.14\) stars arcmin\(^{-2}\).
These quantities allow us to estimate the impact of the field contamination on the selected samples; 6 BSSs (~2%), 12 HBs (~1.5%), and 31 RGBs (~1%), essentially all in the most external annulus, could be field stars (see Table 2). Although the effect of the field contamination is small, in the following we use the statistically decontaminated samples in order to determine the population ratios and the radial distribution.

By using the King model, the distance modulus and the reddening estimated in § 3.1, the luminosity sampled in each annulus \( (L_{\text{samp}}) \) has also been estimated. Then for each annulus we computed the double normalized ratio defined in Ferraro et al. (1993),

\[
R_{\text{pop}} = \frac{N_{\text{pop}}}{N_{\text{tot}}^{\text{pop}}} \frac{L_{\text{samp}}}{L_{\text{tot}}^{\text{samp}}},
\]

with \( \text{pop} = \text{BSS}, \text{HB}, \text{and RGB} \). We find that \( R_{\text{HB}} \) and \( R_{\text{RGB}} \) are essentially constant and close to unity (see \( R_{\text{HB}} \) in Fig. 12). This is what expected for any post-MS population according to the stellar evolution theory (Renzini & Fusi Pecci 1988). Surprisingly we also find that the double-normalized ratio of BSSs is constant, and that it is fully consistent with the reference populations (Fig. 12). Using the number counts listed in Table 2, we also computed the specific frequencies \( N_{\text{BSS}}/N_{\text{HB}}, N_{\text{BSS}}/N_{\text{RGB}}, \) and \( N_{\text{HB}}/N_{\text{RGB}} \). We find that all these ratios are almost constant all over the entire extension of the cluster (see Fig. 13), confirming again that no signatures of mass segregation are visible for the BSS population of NGC 2419.\(^9\)

\(^9\) Note that this result is independent of which portion of the RGB is selected. In fact, similar results are obtained also by considering the RGB in the same magnitude range of the BSSs.
5. DISCUSSION

In most previously surveyed Galactic GCs (M3, 47 Tuc, NGC 6752, M5, M55, NGC 6388, M53) the BSS radial distribution has been found to be bimodal (highly peaked in the core, decreasing to a minimum at intermediate radii, and rising again in the external regions). The mechanisms leading to bimodal radial distributions have been studied for some clusters using dynamical simulations (see Mapelli et al. 2004, 2006; Lanzoni et al. 2007a, 2007b); the observed central peak is mainly made up of collisionally formed BSSs and/or PB-BSSs sunk into the core because of dynamical friction; the external rising branch is composed of PB-BSSs evolving in isolation in the cluster outskirts. In contrast, the BSS radial distribution of NGC 2419 is essentially the same as that of the other “normal” stars in the cluster. Previously, ω Cen was the only GC known to have a flat BSS radial distribution. F06 (see also Meylan & Heggie 1997) argued that two-body relaxation had not led to the complete relaxation of ω Cen even in the central core. Our result here suggests that the same situation holds for NGC 2419.

We can compare this observational evidence with theoretical timescales expected on the basis of the cluster structural parameters. Following equation (10) of Djorgovski (1993), we computed the cluster central relaxation time ($t_r$) by adopting $m = 0.3 M_\odot$ for the average stellar mass, $M/L = 3$ for the mass-to-light ratio, and $M_{\odot} = 4.79$ for the $V$-band solar magnitude. The integrated magnitude obtained in § 3.1 then leads to a total cluster mass of $1.7 \times 10^6 M_\odot$, and a total number of stars of $5.7 \times 10^6$. By assuming $\rho_0 \simeq 25 M_\odot$ pc$^{-3}$ (Pryor & Meylan 1993), and given the value of the core radius ($r_c = 8.4$ pc) derived in § 3.1, we obtain $t_r \sim 6$ Gyr, which is about half the cluster age ($\sim 12 - 13$ Gyr; Harris et al. 1997). Thus some evidence of mass segregation should be visible at least in the core, at odds with the observed flat distribution of BSSs. We can also compute the characteristic relaxation timescale for stars as massive as BSSs ($\rho_{\text{BSS}} \sim 1.2 M_\odot$; see F06) at the cluster half-mass radius ($r_h$) using equation (10) of Davies et al. (2004). Since $r_h \sim 24.5$ pc (see § 3.1) we obtain $t_r \sim 18$ Gyr, thus suggesting that no significant segregation is expected for stars as massive as the BSSs in the outer parts of the clusters, in agreement with our observational results. This result is similar to that found for ω Cen by F06, where the relaxation time in the core was found to be approximately half the cluster age. In the case of ω Cen a number of possible explanations were examined; for instance, the possibility that ω Cen is the relic of a partially disrupted galaxy, which was much more massive in the past. A similar argument can be advocated for NGC 2419, which has also been suspected to be the relic of a small dwarf galaxy interacting with the Milky Way (van den Bergh & Mackey 2004; Federici et al. 2007 and references therein). However, it should be noted that the above estimates of the relaxation times are rough, and since the predicted value of $t_r$ is only a factor of 2 smaller than the cluster age, more detailed computations are needed before further interpret these results.

From the observational side, the BSS radial distribution shown in Figures 12 and 13 suggests that in NGC 2419 (as in ω Cen) stellar collisions have played a minor role (if any) in modifying the radial distribution of massive objects and probably also in generating exotic binary systems. If dynamical evolution plays a central role in NGC 2419, the observed flat BSS distribution can be explained only by invoking an ad hoc formation/destruction rate balancing the BSS population in the core and in the outer region of the cluster. It is more likely that this flat distribution arises because the BSSs we are observing result from the evolution of primordial binaries whose radial distribution has not been altered by the dynamical evolution of the cluster. Thus, as in the case of ω Cen, the BSS population observed in NGC 2419 could be a pure population of PB-BSSs, and it can be used to evaluate the incidence of such a population in stellar systems.

As in previous papers (see, e.g., Ferraro et al. 1995, F06), here we compute the PB-BSS frequency as the number of BSSs normalized to the sampled luminosity in units of $10^4 L_\odot$: \[ S_{\text{PB-BSS}} = N_{\text{BSS}}/L_\odot \] (see Fig. 13, bottom). This quantity is useful for estimating the expected number of BSSs generated by PBs for each fraction of the sampled light in any stellar system, resolved or not. For NGC 2419, we find $S_{\text{PB-BSS}} = 3.1 \pm 0.6$ (see Fig. 13). Before comparing this quantity to that found in ω Cen by F06, we must account for the fact that the adopted BSS selection criteria are different in the two clusters. In NGC 2419 we considered BSSs brighter than $B < 23.6$; this threshold corresponds to $B < 18$ at the distance of ω Cen, using the value $\delta B = 5.6$ needed to shift the HB of ω Cen onto that of NGC 2419 (see Fig. 5). By adopting this threshold, 104 BSSs are found in the ACS FOV of ω Cen, and by considering the sampled luminosity, we obtain $S_{\text{PB-BSS}} = 1.6$ for this cluster. This comparison suggests that the number of BSSs per unit sampled light in NGC 2419 is twice as large as that in ω Cen. Under the hypothesis that the vast majority of these BSSs are generated by the evolution of PBs, the different $S_{\text{PB-BSS}}$ values could result from a different binary frequency in the two clusters, since PB-BSSs are expected to strongly depend on the fraction of binaries in the cluster. Indeed the first direct correlation between these two quantities (the binary fraction and the BSS frequency) has been recently detected in a sample of 13 low-density clusters by Sollima et al. (2008). Such a connection strongly supports a scenario in which the evolution of PBs is the main formation channel for BSSs in low-density environments.

The case of NGC 2419 further supports the idea that important signatures of the dynamical evolution of the parent cluster are imprinted in the radial distribution of the BSS population; indeed, the most recent results collected by our group (see Ferraro et al. 2003, 2006; Lanzoni et al. 2007a, 2007b, 2007c; Dalessandro et al. 2008) are building the ideal database from which such signatures can be read and interpreted, and are already confirming this hypothesis.

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10 This quantity is also important in evaluating the incidence of creation/destruction rate of BSSs in the central region of high-density clusters, where collisions can have played a major role in producing collisional BSSs.

11 Of course, such a value is slightly smaller than that ($S_{\text{PB-BSS}} = 2$) obtained in F06 by considering the entire sample of BSSs with $B < 18.4$.

12 A similar result is obtained if selecting the BSS population of NGC 2419 down to the same threshold used by F06 for the BSSs in ω Cen, i.e., $B < 18.4$ (which corresponds to $B = 24$ at the distance of NGC 2419).
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