MULTIWAVELENGTH PHOTOMETRY IN THE GLOBULAR CLUSTER M2*

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ABSTRACT

We present a multiwavelength photometric analysis of the globular cluster M2. The data set has been obtained by combining high-resolution (Hubble Space Telescope/WFPC2 and ACS) and wide-field (Galaxy Evolution Explorer) space observations and ground-based (MEGACAM-CFHT, EMMI-NTT) images. The photometric sample covers the entire cluster extension from the very central regions up to the tidal radius and beyond. It allows an accurate determination of the cluster center of gravity and other structural parameters derived from the star count density profile. Moreover, we study the Blue Straggler Star (BSS) population and its radial distribution. A total of 123 BSSs have been selected, and their radial distribution has been found to be bimodal (highly peaked in the center, decreasing at intermediate radii, and rising outward), as already found in a number of other clusters. The radial position of the minimum of the BSS distribution is consistent with the radius of avoidance caused by the dynamical friction of massive (1.2 M☉) objects over the cluster age. We also searched for gradients in the red giant branch (RGB) and the asymptotic giant branch (AGB) populations. At the 2σ level, we found an overabundance of AGB stars within the core radius and confirmed the result of Sohn et al. that the central region of M2 is bluer than the outer part. We show that the latter is due to a deficit of very luminous RGB stars in the central region.

Key words: binaries: general – blue stragglers – globular clusters: individual (M2) – stars: evolution

Online-only material: machine-readable table

1. INTRODUCTION

In this paper, we present multiwavelength observations of the Galactic globular cluster M2 (NGC 7089). These observations are part of a large project aimed at characterizing the ultraviolet (UV) bright populations of old stellar systems and determining the impact of “stellar dynamics on the cluster evolution by studying their “exotic” populations. As in our previous study of NGC 1904 (Lanzoni et al. 2007c), we use Hubble Space Telescope (HST) high-resolution UV and optical data for the high-density central region of the cluster and a combination of ground-based wide-field optical data (MEGACAM-CFHT and EMMI-NTT) and UV data from the Galaxy Evolution Explorer (GALEX) for the cluster outskirts. Combining these samples allows an accurate determination of the center of gravity, the stellar density profile and the structural parameters. In this paper, we focus on the Blue Straggler Star (BSS) population as tracers of the dynamical state of the host cluster and products of the interplay between stellar evolution and stellar dynamics. We also discuss possible radial gradients in the asymptotic giant branch (AGB) stars and other stellar populations. We defer a discussion of the horizontal branch (HB) population to a future paper.

In the optical color–magnitude diagram (CMD), BSSs are bluer (hotter) and brighter than the main-sequence (MS) stars, thus mimicking a stellar population significantly younger than the “normal” cluster stars. As shown by Shara et al. (1997), BSSs are more massive than normal stars, suggesting that some mass-increasing mechanism drives their formation. Possible explanations involve mass transfer between binary companions, the merger of a binary system, and the collision between single and/or binary stars (McCrea 1964; Zinn & Searle 1976). Clear differentiation among these possibilities is difficult, since primordial binaries can sink to the cluster center, where stellar collisions may significantly alter their evolution. Similarly, gravitational interactions can generate new binary systems and possibly kick them out of the cluster core. With this caveat, we define primordial binary BSSs (PB-BSSs) as those formed by mass-transfer processes (possibly up to complete coalescence) in primordial binaries which evolved in isolation in the cluster. Collisional BSSs (COL-BSSs) are those generated by mechanisms where stellar collisions played a major role. We therefore expect PB-BSSs to mainly populate the external regions of the cluster, where the collision probabilities are lower. COL-BSSs preferentially form in the central regions because of the higher stellar densities. These formation mechanisms may work simultaneously with different efficiency depending on the environment surrounding the cluster.

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7 A distinction between PB-BSSs and COL-BSSs requires high-resolution spectroscopic studies (see the case of 47 Tucane in Ferraro et al. 2006b); in fact, characteristic chemical signatures are expected on the surface of PB-BSSs so that accurate measurement of the stellar surface abundances can distinguish between the two types of stars (Sarna & de Greve 1996), while they are not predicted in the case of COL-BSSs (Lombardi et al. 1995).
Observed BSS radial distributions have been particularly important in demonstrating the complex interplay of the various phenomena. Typically, the BSS radial distributions have been found to be bimodal (peaked in the clusters center and outskirts and with a dip at intermediate radii; see references in Dalessandro et al. 2008a; see also Beccari et al. 2008 for M53). Only two clusters deviate from this pattern: ω Centauri (ω Cen; Ferraro et al. 2006a) and NGC 2419 (Dalessandro et al. 2008b). In those clusters, the BSS radial distribution is indistinguishable from that of the other cluster stars. Simple dynamical simulations (Mapelli et al. 2004, 2006; Lanzi et al. 2007a) suggest that the observed bimodality can be modeled assuming that PB-BSSs and COL-BSSs co-exist in the same cluster with relative fractions that vary from one case to another. The radial distributions observed in NGC 2419 and ω Cen could be the observational evidence that mass-segregation processes have played a minor role in altering the BSS radial distributions and that the observed BSS population is mainly composed of PB-BSSs.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Data Sets

The present work is based on a combination of different high-resolution and wide-field data sets. The high-resolution set consists of a series of WFPC2 and ACS images taken at various wavelengths ranging from the UV to the optical bands. The WFPC2 images (Prop. 8709, P.I.: Ferraro) were obtained through the UV filters F160BW and F255W with total exposure times \( t_{\text{exp}} = 1800 \) s and \( t_{\text{exp}} = 2000 \) s, respectively, and through the optical filters F336W and F555W with exposure times \( t_{\text{exp}} = 1800 \) s and \( t_{\text{exp}} = 106 \) s. The center of the cluster is located in the WF2 chip (pixel scale \( \sim 0.1 \) pixel\(^{-1}\)).

The photometric reduction of these data was performed using ROMAFOT (Buonanno et al. 2005), and the photometric package SExtractor (Bertin & Arnouts 1996). The wide-field set is composed of data obtained with three different instruments:

1. EMMI-ESO-NTT—B and V images (with \( t_{\text{exp}} = 40 \) s and \( t_{\text{exp}} = 20 \) s) were taken with the ESO Multi Mode Instrument (EMMI) at the NTT during an observing run in 2007 July (P.I.: Ferraro, Prop. 079.D-0325). We used the EMMI Red CCD that is composed of two chips of \( 4612 \) x \( 9 \) x \( 33 \) pixel\(^{-1}\)). The images were corrected for geometrical distortions and effective flux (Sirianni et al. 2005). The photometric reduction was performed using the photometric package SExtractor (Bertin & Arnouts 1996).

2. MEGACAM-CFHT—A combination of short and long MEGACAM exposures taken through the g (\( t_{\text{exp}} = 24 \) s and \( t_{\text{exp}} = 240 \) s) and r (\( t_{\text{exp}} = 48 \) s and \( t_{\text{exp}} = 480 \) s) filters was retrieved from the Canadian Astronomy Data Centre (CADC4). The wide-field imager MEGACAM is mounted at Canada–France–Hawaii Telescope (CFHT) and consists of 36 CCDs of \( 2048 \times 4612 \) pixels each. For this work, we used two different pointings in which the cluster center is located between chips 27 and 36, and chips 19 and 28, respectively. This allowed a coverage of an area of \( 2 \times 1 \) deg\(^2\) and a complete sampling of the cluster well beyond its tidal radius. The data were pre-processed, astrometrized, and calibrated by using the Elixir pipeline. We performed the data reduction using SExtractor (Bertin & Arnouts 1996). Each chip in each image was reduced separately and then combined with all the others for obtaining a catalog with g and r magnitudes and positions of the detected stars.

3. GALEX—A complete coverage of the cluster in the UV bands was obtained using GALEX data (FOV of about \( 1 \) deg\(^2\)) through the FUV (1350–1750 Å) and NUV (1750–2800 Å) detectors (program GI-056, P.I.: Schiavon). Because of the high concentration of M2 and the low angular resolution of the GALEX channels (4′′ in FUV and 6′′ in NUV), we used the GALEX data only for \( r \geq 200 \)′′ from the center of gravity (see below). The reduction of GALEX data was performed independently for each filter with DAOPHOTII/ALLFRAME (Stetson 1987).

3. DEFINITION OF THE PHOTOMETRIC CATALOGS

3.1. Astrometry and Photometric Calibration

All the catalogs were put on the absolute astrometric system using a large number of stars in common with the Sloan Digital Sky Survey (SDSS) catalog. As a first step, we obtained the astrometric solution of the 72 chips of MEGACAM by using the procedure described in Ferraro et al. (2001, 2003) and a specific cross-correlation tool. All the stars in common with the GALEX, EMMI, and HST samples were then used as secondary astrometric standards in order to put all the catalogs in the same astrometric system. Several hundred astrometric standards have been found in each step, allowing a very precise astrometry for each catalog. At the end of the procedure, the estimated error in the absolute positions, both in right ascension (\( \alpha \)) and declination (\( \delta \)), is about 0′′.2.

All the WFPC2 magnitudes (\( m_{\text{B160}}, m_{\text{B255}}, m_{\text{m336}}, \) and \( m_{\text{m55}} \)) were calibrated in the STMAG system using the equations and zero-points listed in Holtzman et al. (1995) and the same procedure described in Ferraro et al. (1997, 2001). Then the stars in common between the other catalogs and the WFPC2 sample were used to transform all the magnitudes to the same photometric system. In particular, the F606W of the ACS catalog, the EMMI instrumental V magnitudes, and MEGACAM g magnitudes were transformed to the VSTmag by using appropriate color equations. The EMMI B instrumental magnitudes were put in the STMAG system. The ACS F814W magnitudes were calibrated in the STMAG system using the prescriptions of Sirianni et al. (2005), and the r MEGACAM mag was transformed to the SDSS system. The GALEX instrumental FUV and NUV magnitudes were calibrated to STMAG system using the stars in common with the WFPC2.

3.2. Center of Gravity

The center of gravity has been obtained following the procedure adopted in our previous work (see, for example, Lanzi et al. 2007c). A first estimate of the cluster center was performed by eye on the WF2 chip of the WFPC2 image, then the exact measure of \( C_{\text{grav}} \) was obtained by means of an iterative procedure that averages the absolute positions.
of stars lying within \( \sim 10'' \) from the first guess center. In order to avoid biases and spurious effects, we considered two samples with two different limiting magnitudes \( V < 19.7 \) and \( V < 19.2 \). The values of \( C_{\text{grav}} \) obtained with the two samples agree within 1''.

We adopt the mean value as the best estimate of \( C_{\text{grav}} \): \( \alpha = 21^h33^m27^s \) (R.A. = 323.3623340) and \( \delta = -0^\circ49'22.8'' \) (decl. = -0.8230465). This new determination is substantially different from the center reported by Harris (1996) on the basis of the surface brightness profile and using photographic plates: our \( C_{\text{grav}} \) is located at \( \sim 35'' \) west (\( \Delta \alpha \sim 35'' \), \( \Delta \delta \sim 0'' \)) from the Harris center.

3.3. Sample Definition

Once all the data sets have been photometrically homogenized and put in the same reference frame, and the cluster center has been determined, we have built a single catalog by combining the following subsamples: (1) the WFPC2 sample, composed of all the stars detected in the WFPC2 FOV, (2) the ACS sample, comprising all the stars in the ACS FOV complementary to the WFPC2 one, (3) the EMMI sample, complementary to the previous two and including only stars with distance \( r < 200'' \) from \( C_{\text{grav}} \), and (4) the MEGACAM/GALEX sample made of stars with \( r > 200'' \) included in the MEGACAM FOV (of course only a fraction of these stars also has GALEX magnitudes). The criteria used for these definitions have been chosen to sample the highly crowded central regions of the cluster with the highest spatial resolution and UV band data (thus to maximally limit the effects of photometric errors and stellar blends), while covering the entire cluster extension by means of wide-field images. The maps of the adopted samples are shown in Figures 1 and 2. In Figure 3, the \((V, U - V)\) CMD of the WFPC2 sample is shown.

3.4. Density Profile

We have determined the projected density profile of M2 by measuring the star counts over the entire cluster extension. Only stars with \( 15.2 < V < 19.2 \) in the combined sample, covering the cluster extension from \( C_{\text{grav}} \) to \( r = 1800'' \) were considered (see Figures 4 and 5). The area was divided in 36 annuli all centered on \( C_{\text{grav}} \). Each annulus was divided into an adequate number of subsectors in which the stellar density has been calculated as the ratio between the number of stars and the subsector area. For each annulus, the resulting density is given by the average of the corresponding subsector densities and the error is quoted as the square root of the variance of the subsector densities. In this procedure, we have also taken into account the incomplete area coverage of the most external annuli and the largest CCD gap in the MEGACAM FOV.

The observed density profile is plotted in Figure 6. The sample nicely covers the entire cluster extension. The four outermost annuli (with \( r > 600'' \)) show a flattening of star counts giving a direct estimate of the stellar background in the cluster direction: for \( 15.2 < V < 19.2 \), the background star density is \( \sim 0.7 \) stars arcmin\(^{-2}\). The observed profile is well reproduced by an isotropic single-mass King model with concentration \( c \simeq 1.51 \) and core radius \( r_c \simeq 17'' \). The corresponding tidal radius is \( r_t \simeq 550'' \). Since there is an uncertainty of about 15%
in the determination of \( r_c \), in our analysis below we will consider all stars lying within \( r < 650'' \). The newly determined cluster parameters are substantially different from those reported by Harris (1996) based on the luminosity center and the surface brightness distribution (\( c = 1.8 \) and \( r_c = 20'' \)) and from the even higher concentration model found by Pryor & Meylan (1993; \( c = 1.9 \) and \( r_c = 20'' \)). As shown in Figure 6 (dashed line), a King model with the parameters quoted by Harris (1996) does not reproduce the observed profile. In contrast, a reasonable agreement (within the errors) is found with the values estimated by McLaughlin & van der Marel (2005; \( c = 1.59 \) and \( r_c = 19'' \)). Assuming a distance modulus \( ( m - M)_V = 15.49 \) and a reddening \( E(B - V) = 0.06 \) (Harris 1996), we find a real distance \( d \simeq 12.5 \text{kpc} \), and a core radius \( r_c \simeq 1.02 \text{pc} \).

The best-fit model reproduces the observed profile out to 400'' very well, while at larger distances the observed star counts show an excess with respect to the model. While this discrepancy is not statistically significant, it deserves further investigation since it could be the signature of tidal distortion in the outer regions (see Leon et al. 2000 for more details). Another interesting feature of density profile is that the innermost point seems to deviate from the canonical flat-core King model. This is also worthy of future investigation since similar features might be related to the presence of an intermediate mass-black hole (e.g., Miocchi 2007; Lanzoni et al. 2007b).

## 4. THE BSS AND REFERENCE POPULATION SELECTION

### 4.1. The BSS Selection

In this section, we describe the procedure that we have followed to select the BSS population and to construct the BSS radial distribution in M2. At the UV wavelengths, hot populations such as BSSs and extreme-HB stars are the brightest objects, while cool populations (such as red giant branch (RGB) stars) appear quite faint (see Figures 7 and 10). Because of this, we always prefer to use the UV-CMD as the reference plane for the BSS selection. Moreover, since the \( HST \) spatial resolution dramatically reduces problems connected with crowding and blends, we have primarily selected the BSS population by considering the WFPC2 sample in the \( ( m_{255}, m_{255} - U ) \) plane. In order to avoid contamination from the subgiant branch (SGB)
stars, we selected only stars with $m_{255} < 19.55$, that is about 1 mag brighter than the turn-off (TO) point ($m_{255} \simeq 20.5$). The number of BSSs thus selected in the WFPC2 sample is 82.

As in previous studies, we used the UV-selected BSSs in common with the ACS sample to define a selection box in the $(V, V-I)$ plane. We have adopted a limiting magnitude $V \sim 19.2$, and the red edge is at $(V-I) = 0.55$ (see Figure 8). The total number of BSSs found in the ACS sample is 20. In the EMMI catalog, the BSSs have been selected in the $(V, B-V)$ CMD, using the same cut in the $V$ filter as for ACS sample. Considering the quality of the diagram, the color limit was set to $(B-V) < 0.32$ to avoid spurious detections and blends from TO and SGB stars: nine BSSs have been selected in this way (see Figure 9). In the most external region sampled by our observations ($r \geq 200''$), the combination of the MEGACAM and the GALEX samples allows the construction of an UV CMD. Since both the GALEX NUV and the HST $m_{255}$ magnitudes have been calibrated on the STMAG photometric system (see Section 3.1), we have used the same threshold (NUV < 19.55) adopted for the WFPC2 sample to define the selection box in the

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**Figure 7.** UV CMD of the WFPC2 sample. The selected BSS population is marked as filled dots, and RR Lyrae stars as asterisks.

**Figure 8.** $(V, V-I)$ CMD of the ACS sample. The different stellar populations discussed in the paper are marked with different symbols (same as in Figure 7 plus squares and triangles for the RGB and HB stars, respectively).

**Figure 9.** Optical CMD of the EMMI sample. The symbols have the same meaning as in Figure 8.

**Figure 10.** UV (left panel) and optical (right panel) CMDs of the MEGACAM/GALEX sample. The NUV magnitudes have been obtained by matching the optical data with GALEX observations. The symbols have the same meaning as in Figure 8.
The BSS Population of M2

| Name | R.A. (degree) | Decl. (degree) | m_255 | U  | B  | V  | I  | r  |
|------|--------------|---------------|-------|----|----|----|----|----|
| BSS 1 | 323.3714411  | -0.8178864    | 18.296| 18.526| 0.000| 17.276| 15.678| ...|
| BSS 2 | 323.3698276  | -0.8177717    | 17.413| 17.460| 0.000| 17.828| 16.353| ...|
| BSS 3 | 323.363459    | -0.8316575    | 18.095| 17.625| 0.000| 17.147| 16.653| ...|
| BSS 4 | 323.3622994  | -0.8218842    | 18.652| 18.077| 0.000| 17.638| 16.720| ...|

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

(NUV, NUV–V) plane. The result is shown in Figure 10, where 12 BSSs have been selected for r \( \geq 200'' \). The right panel of Figure 10 shows the location of the selected BSSs in the (V, V−r) plane. In summary, a total of 123 BSSs have been selected in M2 (see Table 1).

4.2. The Reference Populations

As discussed in other papers (see Ferraro 2006 and references in Dalessandro et al. 2008a), we also need to select a reference population which is representative of the “normal” cluster population. As in other works of this series, we have used the HB and RGB stars as reference populations. The selection of the RGB stars has been performed in the optical planes. For all of the samples, a magnitude cut at V < 18 has been adopted. However, for our analysis, only stars with V > 16 were used in order to avoid saturated stars in the ACS and MEGACAM/GALEX sample (Figures 8 and 10). The color limits of the selection boxes have been chosen to follow the RGB ridge mean line in each CMD while avoiding regions with high probability of field star contamination (the selected RGB stars are marked with empty squares in Figures 8, 9, and 10).

In the WFPC2 and MEGACAM/GALEX samples, the HB stars have been selected on the basis of their positions in the (m_255, m_255−V) and (NUV, NUV−V) CMDs, respectively (see the left panel of Figure 10 for the wide-field sample). The positions in the optical MEGACAM/GALEX plane of the selected HB stars (Figure 10, right panel) have been used to define the selection box for the ACS and EMMI samples (see Figures 8 and 9). By cross-correlating our catalog with the catalogs of RR Lyrae stars found by Lee & Carney (1999) and Lázaro et al. (2006), we have identified all of the 42 known variables (they are marked as asterisks in Figures 7, 8, 9, and 10) and we have included them in our HB sample. The total number of HB stars within r < 650'' is 875 (525 in WFPC2, 184 in ACS, 270 in EMMI, and 168 in MEGACAM/GALEX samples). The magnitude range of the RGB reference population is the same as that adopted for the “faint” RGB discussed below.

For a more quantitative analysis, we computed the population ratios N_{BSS}/N_{HB} and N_{BSS}/N_{RGB} (where N_{pop} is the number of stars belonging to a given population) in six concentric annuli centered on C_{grav}. To do this, we had to evaluate the impact of field star contamination on each population. The field stars predominantly lie in a vertical sequence at 0.2 < (V − r) < 0.5 and dramatically affect the RGB population (see Figure 5, right panel). An estimate of the field star contamination can be directly obtained from our sample by considering an annulus at 1900'' < r < 2400'' (≈70% of which is sampled by the MEGACAM data) far beyond the tidal radius of the cluster (r_t ≈ 550''). We counted the number of field stars in this annulus lying within the BSS, HB, and RGB selection boxes shown in Figures 8, 9, and 10, and we derived the following values for their density: \( \rho_{BSS} \approx 0.01 \) stars arcmin \(^{-2}\), \( \rho_{RGB} \approx 0.06 \) stars arcmin \(^{-2}\), while no field stars have been found within the HB selection box. These values have been used to statistically decontaminate the star counts in each annulus.

The star counts for each annulus are listed in Table 2. These values have been used to compute the ratios N_{BSS}/N_{HB} and Kolmogorov–Smirnov (K–S) test gives a probability of \( \approx 10^{-6} \) (4σ significance level) that the radial distribution of the BSS is extracted from the same parent distribution of the reference population.

5. RESULTS

5.1. The BSS Radial Distribution

Having defined the reference populations, we can now examine the BSS radial distribution. The BSS cumulative radial distribution is shown in Figure 11 with the distributions of the HB and RGB stars shown for comparison. The BSS population is more segregated in the central regions and less concentrated in the outer parts than either the HB and the RGB stars. The cumulative radial distribution is shown in Figure 11 with the distributions of the HB and RGB stars as reference populations. The selection of the “normal” cluster population. As in other works of this series, we have used the HB and RGB stars as reference populations. The selection of the RGB stars has been performed in the optical planes. For all of the samples, a magnitude cut at V < 18 has been adopted. However, for our analysis, only stars with V > 16 were used in order to avoid saturated stars in the ACS and MEGACAM/GALEX sample (Figures 8 and 10). The color limits of the selection boxes have been chosen to follow the RGB ridge mean line in each CMD while avoiding regions with high probability of field star contamination (the selected RGB stars are marked with empty squares in Figures 8, 9, and 10).

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in Figure 12 (central and upper panels, respectively). They are clearly bimodal, with a high BSS frequency in the central and outer regions, and with a broad minimum at about 120′′.

Table 2
Number Counts of BSS, HB, and RGB Stars, and Fraction of Sampled Luminosity

| r/",r/" | N_BSS | N_HB | N_RGB | L_samp / L_tot |
|---------|-------|------|-------|----------------|
| 0       | 20    | 54   | 171   | 454            |
| 20      | 50    | 27   | 636   | 0.30           |
| 50      | 100   | 20   | 513   | 0.25           |
| 100     | 200   | 10   | 348(2)| 0.18           |
| 200     | 300   | 7    | 94(3) | 0.05           |
| 300     | 650   | 4(1) | 59(12)| 0.02           |

Note. The values listed out of the parenthesis correspond to the number of stars assumed to belong to the cluster (and thus used in the analysis), while those in the parenthesis are estimated to be contaminating field stars (see Section 5.1).

Figure 13. Radial distribution of the doubled normalized ratio of BSSs (large dots) and HB stars (gray rectangular regions). The vertical size of the gray rectangles correspond to the error bars.

Figure 12. Radial distribution of the population ratios N_HB/N_RGB, N_BSS/N_HB, and N_BSS/N_RGB as a function of the radial distance from the cluster center, expressed in units of the core radius. The arrows mark the position of the radius of avoidance (see Section 5).

of sampled light, as shown in Renzini & Fusi Pecci (1988). Conversely, the radial distribution of the BSS double normalized ratio (R_BSS) confirms the bimodal behavior: it is peaked in the central regions, decreases to a minimum value at about 9r_c, and then rises again in the cluster outskirts.

The location of this minimum at r ∼ 9r_c can be related to the dynamical evolution of the cluster and in particular to the radius of avoidance (r_avoid). This parameter is defined as the radius within which all the stars as massive as 1.2 M⊙ (the assumed mass for BSSs) have already sunk to the center because of mass segregation (Mapelli et al. 2004, 2006). Using the dynamical friction timescale formula (e.g., Mapelli et al. 2006) under the assumption of a cluster age t = 12 Gyr, a central velocity dispersion of σ_0 = 8.2 km s^{-1} (Pryor & Meylan 1993), we obtained r_avoid ∼ 7r_c. This position is fully compatible with the position of the observed minimum.

5.2. The AGB Problem

Beccari et al. (2006) found a significant overabundance of AGB stars in the very central regions of 47 Tuc. This excess could be due to contamination of genuine AGBs by massive (1.1–1.5 M⊙) objects in late evolutionary stages (e.g., in the HB phase, as suggested by Sills et al. 2009). Presumably these objects arise from binary systems (mainly BSSs) segregated in the cluster core because of dynamical effects. To search for a similar result in M2, we used the WFPC2 and the EMMI sample where the brightest evolutionary sequences are well defined up to the RGB tip at V ∼ 13. We selected AGB stars in the (V, U−V) plane for the WFPC2 sample and in the (V, B−V) for the EMMI sample as shown in Figure 14. It was not possible to use either the ACS or the MEGACAM/GALEX samples because of saturation problems.

To study the radial distribution we divided the covered region into 5 concentric annuli centered on C_{grav} and counted the number of AGBs and HBs lying in each annulus. It was not possible to do a statistical decontamination of the AGB population because the MEGACAM/GALEX sample saturates at V ∼ 15.5. However, we would expect that in the central...
regions it does not appreciably affect the observed radial distribution. Figure 15 upper panel shows the behavior of the population ratios $N_{\text{AGB}}/N_{\text{HB}}$ as a function of the distance from the cluster center. As apparent from the figure, while the mean value of the 4 outermost annuli is $\sim 0.12 \pm 0.03$, fully consistent with the value expected from the evolutionary timescales (Renzini & Fusi Pecci 1988), the ratio turns out to be higher ($\sim 0.19 \pm 0.03$) in the outermost annulus (corresponding to $r_c$). This central overconcentration of the AGB population corresponds to an excess of about 30% (or 9–10 more stars) in the first annulus. This value is compatible with the lifetimes and populations ratios computed by Sills et al. (2009) for evolved collisional products, supporting the idea of a possible contamination by evolved BSSs. To further investigate this feature we also computed the double normalized ratio. The incomplete spatial coverage has been taken into account. The radial distribution of $R_{\text{AGB}}$ (see Figure 15, bottom panel) fully confirms this behavior, showing a central peak ($R_{\text{AGB}} \sim 1.4$) within $r_c$, while in the outer part the ratio remains constant at $R_{\text{AGB}} \sim 1$ fully in agreement with $R_{\text{HB}}$.

Purely on the basis of small number statistics introduced by binning, the AGB central peak is marginally significant ($< 2\sigma$). However, the significance of the peak can also be evaluated with a K–S test on the cumulative distribution, which is shown in Figure 16. The probability that the AGBs are drawn from a different distribution from the HBs is 93% ($\sim 1.8\sigma$). The BSS distribution is also shown in Figure 16. While AGBs are more concentrated than HBs, they are less concentrated than BSSs, with a 98% probability that they are extracted from a different parent family. In this respect, they are different from the AGBs in 47 Tuc where AGBs and BSSs have similar radial distributions.

5.3. Color Gradients

Sohn et al. (1996), hereafter S96, found that M2 has a radial color gradient, in the sense that the central regions are bluer than the outer parts, with a variation of about $(B - V) \sim 0.1$. To investigate this interesting feature we computed the $(U - V)$ integrated color within 90″ from $C_{\text{grav}}$, which approximately corresponds to the region used by S96. We divided the WFPC2 sample in five concentric annuli (the first corresponding to $r_c$), and computed the color of each annulus from the resolved stars by considering three different magnitude cuts: $V < 16$, $16 \leq V < 20$, and $V < 20$. As shown in Figure 17 (upper panel), we found that when only the brightest stars are included $(V < 16$, black and open dots in Figure 17) a color difference $\Delta(U - V) \sim 0.18$ between the center (bluer) and the outer annuli is apparent. Even
if this is a less than 2σ result, it is consistent with the finding of S96. When also fainter stars are included (i.e., for V < 20), the color gradient decreases, and if the brightest stars are excluded (16 < V < 20) it completely disappears and (U−V) remains constant all over the considered radial range. To further investigate this behavior, we made the same computation for the ACS sample using the (V−I) color. In this sample, saturation occurs at about V = 15, so the test is limited to the population with 16 < V < 20. No color gradient is visible in the bottom panel of Figure 17. Our results therefore indicate that the observed color gradient is due to the brightest stars and not to an overconcentration of BSSs or blue faint objects. This seems in disagreement with the conclusion of S96, who found the color gradient only when using resolved stars with V < 16. However, as already discussed by these authors, the poor seeing conditions and the spatial resolution of the instrument (0.56 pixel−1) used in their analysis did not allow them to sample all the populations with acceptable photometric accuracy. To more deeply understand the origin of the detected color gradient, we further investigated the properties of the brightest populations in the very central regions of M2. Since the AGB is 0.2–0.3 mag bluer than the RGB in (U−V), we first investigated whether the AGB central excess (Section 5.2) could account for the observed color gradient. We therefore artificially canceled the AGB central peak, by randomly excluding 10 stars from the innermost bin, and re-computed the central color: this still yields a center bluer than the exterior. Very bright RGB stars therefore remain the only candidates. In order to test this hypothesis we compared the radial distribution of the brightest portion of the RGB (V < 16) in the WFPC2 sample (see Figure 14, left panel) to the faint (V ≥ 16) one. The radial distributions of these populations clearly show that the brightest giants are less concentrated than the faintest ones, with a 99% probability (about 2.5σ) that they are extracted from a different parent family (see Figure 16 and the upper panel of Figure 18). We have therefore re-computed the central color after having artificially increased the number of bright RGBs in the innermost bin, thus to flatten the radial distribution of the bright-to-faint RGB ratio (to this purpose, we have randomly extracted 25 bright RGBs from the observed luminosity function). This completely removes the color gradient (bottom panel of Figure 18). Hence we conclude the color gradient found by S96 and confirmed here is due to a deficit of bright RGB stars in the center rather than a surplus of fainter blue stars.

6. SUMMARY

The BSS population of M2 can be characterized as what is emerging as “normal”: a bimodal radial distribution with a minimum in the zone of avoidance, and with a value of the central BSS specific frequency (N_{BSS}/N_{HB}) which is also typical. Bimodal distributions are a very common feature of the Galactic GC BSS populations (Dalessandro et al. 2008a). Only two clusters, NGC 2419 and ω Cen, deviate significantly from this pattern. Both of these systems are very large. There is even some doubt that ω Cen is a true GC (Bekki & Freeman 2003). Of the bimodal clusters only two, NGC 6388 (Dalessandro et al. 2008a) and NGC 5024 (Beccari et al. 2008), have minima in their BSS radial distributions which differ significantly from r_{avoid}. Presumably this arises because of a lower efficiency of the dynamical friction in these two clusters, for reasons yet to be explained.

As Beccari et al. (2006) found for 47 Tuc, we find an excess of AGB stars in the center of M2. Because of the smallish sample size, the excess is only marginally significant, and unlike in 47 Tuc, the AGB population is not as concentrated as the BSS one. In agreement with S96, we find that the integrated color of the central region of M2 is bluer that the exterior. We show that this color gradient is due to a deficit of bright RGB stars, and not to an excess of faint blue objects, such as BSS or HB stars. A similar deficit of bright RGB stars has also been found in the very massive GC NGC 2808 (Sandquist & Martel 2007). They
do not explore the radial dependence of their result, and neither of the two mechanisms they discuss for producing a deficit (neutrino losses and extra mass loss) would have an obvious radial dependence. We view our AGB surplus and bright RGB deficit as suggestive—given the short lifetime in these phases it is impossible to do better than 2σ in M2 or any single cluster. If similar results are found in other clusters, there would be interesting consequences for stellar evolution theory and stellar population studies. Given this, it would be highly desirable that future photometric studies of GCs were designed in such a way that unsaturated photometry of the brightest stars was possible.

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REFERENCES

Beccari, G., Ferraro, F. R., Possenti, A., Valenti, E., Origlia, L., & Rood, R. T. 2006, AJ, 131, 2551
Beccari, G., et al. 2008, ApJ, 679, 712
Bekki, K., & Freeman, K. C. 2003, MNRAS, 346, L11
Bellazzini, M., Fusi Pecci, F., Messineo, M., Monaco, L., & Rood, R. T. 2002, AJ, 123, 1509
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Buonanno, R., Buscema, G., Corsi, C. E., Ferraro, I., & Iannicola, G. 1983, A&A, 126, 278
Buonanno, R., & Iannicola, G. 1989, PASP, 101, 294
Dalessandro, E., Lanzoni, B., Ferraro, F. R., Rood, R. T., Milone, A., Piotto, G., & Valenti, E. 2008a, ApJ, 677, 1069
Dalessandro, E., Lanzoni, B., Ferraro, F. R., Vespe, F., Bellazzini, M., & Rood, R. T. 2008b, ApJ, 681, 311
Ferraro, F. R. 2006, arXiv:astro-ph/0601217
Ferraro, F. R., D’Amico, N., Possenti, A., Mignani, R. P., & Paltrinieri, B. 2001, ApJ, 561, 337
Ferraro, F. R., Fusi Pecci, F., Cacciari, C., Corsi, C., Buonanno, R., Fahlnan, G. G., & Richer, H. B. 1993, AJ, 106, 2324
Ferraro, F. R., Paltrinieri, B., Rood, R. T., & Dorman, B. 1999, ApJ, 522, 983
Ferraro, F. R., Sills, A., Rood, R. T., Paltrinieri, B., & Buonanno, R. 2003, ApJ, 588, 464
Ferraro, F. R., Sollima, A., Rood, R. T., Origlia, L., Pancino, E., & Bellazzini, M. 2006a, ApJ, 638, 433
Ferraro, F. R., et al. 1997, A&A, 324, 915
Ferraro, F. R., et al. 2006b, ApJ, 647, L53
Fusi Pecci, F., Ferraro, F. R., Bellazzini, M., Djorgovski, S., Piotto, G., & Buonanno, R. 1993, AJ, 105, 1145
Harris, W. E. 1996, AJ, 112, 1487
Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065
Lanzoni, B., Dalessandro, E., Ferraro, F. R., Mancini, C., Beccari, G., Rood, R. T., Mapelli, M., & Sigurdsson, S. 2007a, ApJ, 663, 267
Lanzoni, B., Dalessandro, E., Ferraro, F. R., Miocchi, P., Valent, E., & Rood, R. T. 2007b, ApJ, 668, L139
Lanzoni, B., et al. 2007c, ApJ, 663, 1040
Lázaro, C., Ferro, A. A., Arévalo, M. J., Bramich, D. M., Giridhar, S., & Poretti, E. 2006, MNRAS, 372, 69
Lee, J.-W., & Carney, B. W. 1999, AJ, 117, 2868
Leon, S., Meylan, G., & Combes, F. 2000, A&A, 359, 907
Lombardi, J. C., Jr., Rasio, F. A., & Shapiro, S. L. 1995, ApJ, 445, L117
Mapelli, M., Sigurdsson, S., Colpi, M., Ferraro, F. R., Possenti, A., Rood, R. T., Sills, A., & Beccari, G. 2004, ApJ, 605, L29
Mapelli, M., Sigurdsson, S., Ferraro, F. R., Colpi, M., Possenti, A., & Lanzoni, B. 2006, MNRAS, 373, 361
McCrea, W. H. 1964, MNRAS, 128, 147
McLaughlin, D. E., & van der Marel, R. P. 2005, ApJS, 161, 304
Miocchi, P. 2007, MNRAS, 381, 103
Pryor, C., & Meylan, G. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco, CA: ASP), 357
Renzini, A., & Fusi Pecci, F. 1988, ARA&A, 26, 199
Sandquist, E. L., & Martel, A. R. 2007, ApJ, 654, L65
Sarna, M. J., & de Greve, J. P. 1996, QJRAS, 37, 11
Shara, M. M., Saffer, R. A., & Livio, M. 1997, ApJ, 489, L59
Sills, A., Karakas, A., & Lattanzio, J. 2009, ApJ, 692, 1411
Sirianni, M., et al. 2005, PASP, 117, 1049
Sohn, Y.-J., Byun, Y. I., & Chun, M.-S. 1996, Ap&SS, 243, 379
Stetson, P. B. 1987, PASP, 99, 191
Zinn, R., & Scarfe, L. 1976, ApJ, 209, 734