SURFACE BRIGHTNESS PROFILES FOR A SAMPLE OF LMC, SMC, AND FORNAX GALAXY GLOBULAR CLUSTERS

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ABSTRACT

We use Hubble Space Telescope archival images to measure central surface brightness profiles of globular clusters around satellite galaxies of the Milky Way. We report results for 21 clusters around the LMC, five around the SMC, and four around the Fornax dwarf galaxy. The profiles were obtained using a recently developed technique based on measuring integrated light, which is tested on an extensive simulated data set. Our results show that for 70% of the sample, the central photometric points of our profiles are brighter than previous measurements using star counts with deviations as large as 2 mag arcsec$^{-2}$. About 40% of the objects have central profiles deviating from a flat central core, with central logarithmic slopes continuously distributed between $-2.2$ and $-1.2$. These results are compared with those found for a sample of Galactic clusters using the same method. We confirm the known correlation in which younger clusters tend to have smaller core radii, and we find that they also have brighter central surface brightness values. This seems to indicate that globular clusters might be born relatively concentrated, and that a profile with an extended flat core might not be the ideal choice for initial profiles in theoretical models.

Key words: globular clusters: general — stellar dynamics

1. INTRODUCTION

The observational study of internal dynamics of globular clusters (GCs) has benefitted from imaging from space, as well as enhanced spectroscopic capabilities on the ground. Noyola & Gebhardt (2006, hereafter Paper I) measure surface brightness (SB) profiles from Hubble Space Telescope (HST) images for a sample of 38 Galactic globular clusters. The results from that work show that half of the objects in the sample are not consistent with having central flat cores, but instead, the distribution of central surface brightness logarithmic slopes is continuous from $-0.2$ to $-0.8$. The ages of the Galactic clusters are all confined to a narrow range older than $\sim 10$ Gyr (Salaris & Weiss 2002; De Angeli et al. 2005). It is desirable to measure central SB profiles of globular clusters with younger populations to find out if these central cusps are also observed in less evolved clusters. Globular clusters around Milky Way satellites are ideal targets for this task, since they have a larger age range, they are relatively near, and many of them have been observed with HST.

Surface brightness profiles have been obtained for GCs in the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and Fornax dwarf galaxies in various studies using ground-based data. For the LMC clusters, star counts (Kontizas et al. 1987), aperture photometry (Mateo 1987; Elson 1991), and hybrid techniques (Elson et al. 1987) have been used to obtain surface density profiles for a variety of subgroups (rich, old, young, disk, and halo clusters). For the SMC clusters, only a few studies have measured density profiles from star counts (Kontizas & Kontizas 1983; Kontizas et al. 1986). A couple of studies measure density profiles from aperture photometry for globular clusters around the Fornax dwarf galaxy (Smith et al. 1996; Rodgers & Roberts 1994). All of these studies are very useful for studying SB profiles at large radius, but at small radius they suffer from the usual seeing and crowding problems associated with ground-based observations.

A large systematic study of surface brightness profiles obtained from space-based imaging has been carried out by Mackey & Gilmore (2003a, 2003b, 2003c, from now on collectively referred to as MAC03). They gather a broad sample of LMC, SMC, and Fornax galaxy GCs imaged with WFPC2. They obtain SB profiles by measuring star counts weighted by brightness from which they derive fundamental quantities like central density and core radius by fitting Elson-Fall-Freeman (EFF) profiles (Elson et al. 1987; Elson 1991), which are power-law plus core profiles with three parameters: core radius, central surface brightness, and slope of the power law. They determine that 20% ± 7% of the clusters in their sample are consistent with a post-core-collapse morphology, a similar number to the one found for Galactic clusters (Trager et al. 1995). When they compare their profiles with previous results obtained from ground-based images, they find that important aspects of the nature of the profiles can be measured by improving the spatial resolution. McLaughlin & van der Marel (2005, hereafter MVM05) combine the data from MAC03 with star count profiles from ground-based data in order to obtain a more accurate photometric normalization. They fit the renormalized dereddened resulting profiles with variety of models such as King fits (King 1966), an alternate modified isothermal model by Wilson (1975) which has more extended envelopes than a King model, and a power law plus core model like the one used in MAC03. They conclude that the Wilson fits provide the best description of the outer part of the clusters for both old and young populations.

Elson et al. (1989) and Elson (1992) find an interesting relation between core radius and age for a sample of LMC globular clusters in which the core radius seems to increase with ages between 1 Myr and 1 Gyr and then shows a wide range of values for older clusters. Using HST data, de Grijs et al. (2002) explore the matter for a sample of rich LMC globular clusters and find that young clusters tend to have small core radii, while older clusters have an
increasingly large spread of core radii. MAC03 explored this relationship and found that the relation is also valid for globular clusters around other Milky Way satellites besides the LMC.

We concentrate in the central part of each cluster since this is the region for which our technique has found differences in the SB shape when compared to profiles obtained from star counts for some clusters. Improving the measurements in this region and merging the results from our Galactic sample with those of this new sample can increase our understanding of their dynamical evolution. The LMC, SMC, and Fornax galaxy globular cluster systems offer a unique window of opportunity to test if there are fundamental differences between systems due to their age.

2. SIMULATIONS

In Paper I we performed a large number of simulations in order to establish the best method for measuring surface brightness profiles from HST images and also to estimate the uncertainties of our measurements. Results from that paper indicate that the only way to measure reliable surface brightness profiles from integrated light is by using high signal-to-noise ratio images. In order to evaluate how our findings for Galactic GCs translate to clusters further away, we again perform extensive simulations, which we describe in detail in this section.

2.1. Image Construction

The way we create a simulated image is by adding synthetic stars on a background image using the task addstar in DAOPHOT (Stetson 1987). The background image we use is a WFPC2 image of a very unpopulated field for which the few present stars have been cleanly subtracted. The input star lists are created in the same way as in Paper I. With a given SB profile and a luminosity function, stars are generated randomly around a given center (the middle of the chip) following the two probability distributions, the surface brightness for radial distribution, and the luminosity function for the magnitude distribution. The supplied luminosity function comes from Jimenez & Padoan (1998), and it is corrected using the distance modulus for the LMC. The observed luminosity function is extended in the faint end in order to include unresolved background light in the simulated images, so we expect to recover fewer stars than the number we input.

In Paper I we simulated SB profiles with the shape of various power laws. This gave us a good feel for our ability to recover a given central slope, but we could not test our ability to measure turnover radius. In order to better test our method, this time we create a series of profiles formed by two power laws joined at a break radius with a variable sharpness of break, better known as Nuker profiles (Lauer et al. 1995). A Nuker profile is defined in the following way:

\[
I(r) = I_b 2(\beta - \gamma) \alpha (\frac{r}{r_b})^{-\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right] (\gamma - \beta) \alpha,
\]

where \(r_b\) is the break radius, \(I_b\) is the surface brightness at the break radius, \(-\gamma\) is the asymptotic inner slope, \(-\beta\) is the asymptotic outer slope, and \(\alpha\) is the sharpness of the break. By using this type of profile, we are capable of reproducing the characteristics of observed central profiles for the sample. We create six different input profiles, whose parameters are summarized in Table 1. The radial extent of the simulated clusters is 400 pixels, which is equivalent to 18.4\arcsec with the PC pixel scale (0.046\arcsec pixel\(^{-1}\)).

Once we have the input profiles, we proceed to create multiple realizations of a given model including different numbers of stars. Using various DAOPHOT tasks we add synthetic stars to the background image. We use as the input point-spread function (PSF) the one calculated for the LMC cluster NGC 1835 with a PSF radius of 9 pixels. Judging by the number of recovered stars in the real data, we create images with three different amounts of input stars: 200,000 input stars, which yields \(~10,000\) detected stars; 50,000 input stars, giving \(~6000\) detected stars; and 10,000 input stars, for which we find \(~2000\) stars. The majority of the real clusters in the sample are comparable to the first two cases. The different realizations have the exact same input parameters but come from different, nonoverlapping star lists. We create 10 realizations for the 200,000 input stars case and 20 for the other two. It is worth noting that the number of detected stars decreases with increasing input central slope for the same number of input stars. For the steepest central slope \(~8000\) stars are found compared to the \(~10,000\) for the zero central slope cases. To avoid confusion, we always refer to the simulated data sets by the number of input stars rather than the number of detected stars.

2.2. Center Determination

Having an accurate estimate of the center position is a key step to measuring an accurate density profile. Our technique for finding the center of a cluster is described in detail in Paper I. We take a guessed center, divide the image into eight sectors converging at that center, count the stars in each sector, and calculate the standard deviation of those eight numbers. We change to a different guessed center and perform the same operation. In the end we have a grid of guessed centers with a standard deviation value associated with them. We fit a surface using a spline smoothing technique (Wahba 1980; Bates et al. 1986) and choose the minimum of this surface as our center.

We test the accuracy of our center determination technique by applying it to these simulated images. Figure 1 shows the average measured center and the standard deviation of the measurements for different groups of simulations. The maximum deviation observed is \(~7\) pixels, which is equivalent to \(~0.3\arcsec\). These results are better than those in Paper I. We believe the reason for this is that there are more stars enclosed in the same projected radius due to the distance difference, and therefore, the center estimation is improved.

2.3. Surface Brightness Profiles

We compare the results of measuring the density profile from integrated light versus doing it using star counts. We refer the reader to the detailed discussion in \(\frac{\beta}{2.3}\) of Paper I about the strengths and weaknesses of each method. Results from that paper indicate that using a robust estimator to calculate the number of counts per pixel in a given area is the best way to recover the central part of the profile. For that reason we use the same robust estimator, the biweight (Beers et al. 1990), for our measurements in this work.

| Model | Inner Slope \(\gamma\) | Outer Slope \(\beta\) | Break Radius (pixels) | Hardness of Brake \(\alpha\) |
|-------|-----------------|-----------------|---------------------|---------------------|
| 1     | 0.0             | 1.8             | 85                  | 2                   |
| 2     | 0.0             | 2.5             | 340                 | 3                   |
| 3     | 0.2             | 2.5             | 90                  | 1                   |
| 4     | 0.4             | 1.6             | 90                  | 2                   |
| 5     | 0.7             | 1.8             | 90                  | 2                   |
| 6     | 0.9             | 2.0             | 90                  | 1                   |
We observe that the uncertainty in the slope measurements between input and measured magnitudes is typically ~0.1 mag, which is enough to push some stars from a fainter magnitude bin to a brighter one. For intermediate-magnitude stars, the same effect happens for the regions near the core; the efficiency for finding these stars falls to 50%–70% depending on the shape of the profile. The efficiency for finding the fainter stars is lower in any radial bin; it is a few percent in the center and up to 50% for the regions at large radii. As expected, these numbers become more extreme for the cases with steeper central slopes, since crowding is worse then. For the case with 50,000 input stars, the trends are similar, but the numbers are less extreme. Stars in the brightest magnitude bin are found with an efficiency close to 100% for the cases with flatter central slopes. The efficiencies for the cases with steeper central slopes are very similar to those with 200,000 input stars. Finally, for the cases with 10,000 input stars, the efficiencies for finding the input stars are all close to 100%, except for the faintest stars in the central region of the cluster, which are around 70%–80% depending on how steep the central slope is. The conclusion from this analysis is that when correction factors are calculated for star count measurements, the factors are dependent on the shape of the density profile and the number of existing stars. If one assumes the wrong shape or the wrong number of stars in the cluster, the correction factors will be incorrect.

Stars are counted in and divided by the area of each annulus. The above discussion about the efficiency for finding stars implies that the stars below a certain brightness are never found with 100% efficiency; therefore, we exclude them from the star lists. We compare the obtained star count profiles with those obtained by measuring integrated light from the four different images (full, subtracted, 10% subtracted, and 2% masked). Results from these measurements are shown in Figure 2 for the 200,000 input star case and Figure 3 for the 50,000 input star case. In both figures we show models 1, 4, and 5, which have central slopes of 0, −0.4, and −0.7, respectively. We find that, depending on the shape of the input model, the profiles measured in the subtracted, partially subtracted, or masked images follow the input profile best. For the least concentrated cases, the measurements from the subtracted and 10% subtracted image seem to follow the profile best, but for the more concentrated cases, the subtracted and 10% subtracted cases tend to look flatter in the center than the input profile. For these cases, the profile from the masked image seems to be a better choice. The star count profiles are always much noisier than the light profiles in the central regions, and they show a consistent bias in the central regions for the cases with steep central slopes.

We test how well we recover the input central slope for the different shapes of input profiles and for the different measurement methods. Since we measure the central slope by taking a first derivative of the profile, we need a smooth version of it. For this, we apply the one-dimensional version of the spline smoother mentioned in § 2.2. This allows us to recover information from the profile without fitting any parametric model to the data. We exclude the star count profiles from these measurements because the central parts of the profiles are too noisy for the spline smoother to get a reasonable fit. The first derivative of the smooth profile has a section toward the center where it is constant; we take this constant value as the measured central slope. After measuring the central slope for the different realizations, we calculate the average and the standard deviation for each case. We show the input versus measured central slopes in Figure 4.

We observe that the uncertainty in the slope measurements increases as the number of input stars decreases. For the 10,000 input star case, the profiles from the subtracted and 10% subtracted images yield smaller uncertainties. These two cases tend to
underestimate the central slopes for the concentrated and rich (200,000 and 50,000 input stars) cases, while the slopes recovered from the masked images seem to follow the input better. For all the rich cases, the measurements for the model with the steepest central slope overestimate the slope; we think this could be due to the fact that so many stars are being input at the center that not enough stars are being input for the outer parts, which would explain the fact that we find fewer stars for this case.

We test our ability to measure the input break radius by measuring the minimum of the second derivative, which is the radius at which the curvature is maximum. Our results show that we can measure the break radii for the simulated clusters to within 10% accuracy. The majority (all except two) of the observed clusters have a reported core radius larger than the one for our simulations, so we are confident that we can measure such break radii.

2.4. Uncertainties

We refer the reader to the detailed discussion in § 2.4 of Paper I about the sources for uncertainty when measuring surface density profiles from integrated light versus measuring it from star counts. In order to properly estimate our uncertainties, we compare the photometric scatter between different realizations having identical input parameters with the biweight scatter estimate. In Paper I we find that the biweight scatter has to be scaled in order to match the photometric scatter measured from the different realizations. For these new simulations we find that the scaling factors
change due to the differences in our input shapes and to simulating clusters at larger distances (the number of stars in a given annulus and differences in PSF). As done in Paper I, we compare these scaling factors with those obtained for real data from an alternative method discussed in § 3.5.

We also estimate the error in our central slope measurements by comparing the scatter of measured slopes with the known input slope for every simulated cluster. The results are shown in Figure 4. We confirm what we learned from analyzing Figures 2 and 3. The slope uncertainties are smaller for the subtracted and partially subtracted cases, but they are biased low for the cases with steep cusps and large number of input stars. Also, the slope measurements are more uncertain for the clusters with 10,000 input stars. The figure suggests to take the measurements from the masked image for the cases with steep central profiles and the measurements from the subtracted or 10% subtracted for the others. In the case of 10,000 input stars, the subtracted case always seems to be better and is not biased.

3. DATA AND ANALYSIS

3.1. Sample

As mentioned in Paper I, there are minimum requirements for an image to be suitable for measurements with our technique. The image needs to have a minimum number of counts, which can be obtained by having a large number of stars present due to richness or high concentration, or by having long exposure times. We establish that detecting stars 6 mag fainter than the horizontal branch with a signal-to-noise ratio of 20 is a minimum requirement for low-concentration clusters. This criterion can be relaxed for
highly concentrated clusters and for those with a large number of stars \( M_V < -7.5 \). Taking into account these requirements, we gather 30 clusters from the HST archive. The sample contains 21 clusters in the LMC, five in the SMC, and four in the Fornax dwarf galaxy. When images are available in two filters (F555W and F814W), we align and combine the images in order to improve the signal-to-noise ratio. We believe we are justified in doing this because the color gradients for the radial range that we are measuring are smaller than the photometric uncertainties. If no alternative image is available, we use the single F555W data set. In general, we analyze only the chip in which the center of the cluster lies; the only exception is the cluster Kron 3, for which we use all four chips. The size of one WFPC2 chip is large enough to contain a few core radii for every cluster in the sample. The scale of the CCD is \( 0.100 \) pixel\(^{-1} \) for the WF chips and \( 0.046 \) pixel\(^{-1} \) for the PC chip.

We use the WFPC2 associations from the Canadian Astronomy Data Center Web site.\(^1\) These images are spatial associations of WFPC2 images of a given target. The raw data frames are processed through a standard reduction pipeline, grouped in associations, and combined. The available data are a multigroup image with frames for the three WF and the PC chips. It is straightforward to align and combine two of these images from different filters if they belong to the same program, which is the case for every object with two images available in our sample.

3.2. Image Processing

We process the data in the same way as for the simulated images. We choose the frame where the cluster center is located; this is usually the PC frame, but for a few cases, it is one of the WF frames. We trim the image in order to eliminate the noisy edges and then proceed to perform basic photometry with various DAOPHOT tasks. First, we use the find task to make a preliminary list of detected stars, then we perform aperture photometry with the task phot in order to choose candidates for PSF construction. We find that PSF stars have to be chosen by hand because a single bad PSF star can have an important effect on the final PSF construction. Once we have a list of PSF stars, we perform

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\(^1\) See http://cadcwww.dao.nrc.ca.
an iterative procedure in which we subtract the neighbor stars from the PSF stars and then recalculate the PSF. In this way, the PSF construction is less affected by crowding. Using the final constructed PSF we subtract all the stars from the image, leaving behind an image containing only background light. We also create an image with the brightest 10% stars subtracted and another one using the world coordinate system (WCS) information contained in the header of each image. The WCS information for two different images can make the coordinates for same location vary by a few arcseconds. The center is always measured on the primary data set (the F555W image) when two images were combined.

3.4. Surface Brightness Profiles

Once we have measured a center, we calculate the surface brightness profile from the four different images of each cluster. We calculate surface brightness by estimating the biweight (as explained in §2.3) of the number of counts per unit area in a series of concentric annuli. The choice of the size of annuli in which we measure the profile is given by a trade-off between spatial resolution and noise. For images with very high signal-to-noise ratio, we can use smaller steps, while for more sparse cases, smoother profiles are obtained by increasing the size of the bins at the cost of decreasing the spatial resolution. We use three different sets of annuli: the first one goes from 1 to 25 pixels with steps of 4 – 6; the second goes from 20 to 100 pixels with steps of 12–15; and the third one from 100 to 380 pixels with steps of 40 – 60.

In §2.3 we observe that for the simulated images the star count profile tends to underestimate the profile at the center, and it is noisier than the integrated light profile. For this reason, we decide
not to calculate the star count profiles for these data sets. Also, we observe that the profiles coming from the unsubtracted image are always noisier than those obtained from the other images, so we never use the “full” profile as our final result. For every set of simulations, the subtracted and 10% subtracted images always yield smoother profiles; unfortunately, they appear to be biased toward the center for the profiles with steep central slopes, so we can only use them when all four profiles are consistent with a central flat profile. If there are systematic differences between the original and masked profiles and the two subtracted ones in the sense that the first two are steeper than the latter two, then we use the profile from the masked image, since this is the one that traces the central cusp best in our simulations.

In Paper I we find the photometric zero point by integrating our measured light profiles and comparing them to previously obtained profiles from ground-based data. We cannot do the same thing here because our profiles have a smaller radial extent. For the cases in which our central profile differs significantly from previous measurements, the radial extent in which the two profiles agree is not large enough for us to make a meaningful comparison of enclosed light. We also observe that the differences in shape between our measurements and those obtained by MAC03 are always inside the turnover radius. We therefore use the data points outside the core radius to normalize our profiles to the EFF fits by MVM05. We choose to normalize to these profiles because points outside the core radius will be resolution-dependent. For this reason, we fit a high-order polynomial and take the minimum of the fit instead of the minimum of the second derivative as our break radius. In Paper I we find that the core and break radius coincide for clusters having a flat core, but they do not coincide for cases presenting a cusp.

The difference in shape from our measurements and the parametric fits will affect the measurement of the half-light radius. Since we are using EFF fits for the outer part, and these fits are formally infinite, we have to truncate them in order to measure the total enclosed light. We use the tidal radius measured by MVM05 as a truncation radius and measure the half-light radius for our smooth profiles. Having an estimate of the total luminosity and using the \( M/L \) values calculated by MVM05, we can estimate the total mass of each cluster and thus estimate the median relaxation time as described in Binney & Tremaine (1987, p. 747):

\[
t_{\text{rh}} = \frac{2.06 \times 10^6}{\ln(0.4M_\odot/(m))} (m)^{-1} M^1_\odot r_h^{3/2}.
\]

We assume a mean mass of 0.5 \( M_\odot \), as in MVM05. Results from these calculations are presented in Table 3.

### 3.5. Data Uncertainties

We describe how we estimate uncertainties for the simulations in § 2.4. The method is based on different realizations for which the photometric zero point is estimated directly. We use an alternative method to calculate the uncertainties for real data, and we calibrate this method against that used for the simulations, as we did in Paper I. We assume a smooth underlying stellar radial profile, so the uncertainties of the photometric points should reflect deviations from a smooth curve in a statistically meaningful way (i.e., have a Gaussian distribution around the mean value). We calculate the rms difference between the smooth profile and the data points for the central region. The biweight yields an estimate for the central location (SB value) and scale (scatter); this scale value is divided by the square root of the number of sampled pixels and used as the initial uncertainty for individual photometric points. We then calculate the ratio of the biweight to the rms, which should represent our lack of inclusion of shot noise from the stars. This ratio depends on the extent of the radial bins (i.e., the number of pixels used); therefore, we use different scalings for the different realizations in order to make sure that the scalings coincide. The average scaling for the inner points is about 3, and about 10 for the outer points. These numbers are consistent with what we found in the simulations. Thus, we are effectively including shot noise from stars. The largest uncertainties occur for sparse clusters, as expected.

In the same way as in Paper I, we calculate the uncertainties in slope measurements from a bootstrap technique. The bootstrap approach follows that in Gebhardt et al. (1996). From the initial smooth profile, a new profile is created by generating random values from a Gaussian distribution with the mean given by the initial profile and the standard deviation from the photometric uncertainties. A hundred profiles are generated in this way, and the 16%–84% quartiles are measured for the errors. These estimated errors are compared with the scatter measured for the simulated cases in Figure 4, and the two independent error measurements
agree quite well, which gives us the confidence that the uncertainties calculated with the bootstrap method are reliable. In Paper I we perform one more check on our slope uncertainties by measuring the effect of increasing the uncertainties on photometric points by a factor of 2. From the bootstrap method, we find that the slope uncertainties increase by a modest factor, less than 2, for most clusters. Thus, the slope uncertainties are not too sensitive to individual photometric errors.

4. RESULTS AND DISCUSSION

4.1. Surface Brightness

The measured surface brightness profiles for the entire sample are shown in Figures 5–7. For each cluster we show our normalized photometric points with error bars, and a smooth profile made from the combination of our photometric points inside ~10º and MVM05 EFF fits outside that radius. For comparison we show the MVM05 EFF fits in that region. We would like to stress that our measured photometric points at radii larger than ~10º do not participate in the construction of the smooth fit; instead, the EFF fits are used in that region. For about half the sample (17 objects), the agreement between our measurements and the EFF fits of MVM05 is excellent, even for those cases in which the central photometric point by MAC03 is barely inside the turnover radius (such as Fornax 2) or does not lie on top of the EFF fit (such as NGC 1651, NGC 1898, or NGC 2100). There is only one case (NGC 1754) for which our photometric points are fainter than the EFF fit. For the remaining 12 objects, our photometric points are brighter than the EFF fit by more than 0.5 mag arcsec−2, with three objects (NGC 2019, R136, and Fornax 3) having differences larger than 2 mag arcsec−2.

MAC03 identify a few clusters that they think agree with the expected post-core-collapse (PCC) morphology by showing a power-law cusp in their central profile. NGC 2005 and NGC 2019 are identified as clear cases of PCC morphology with central power-law slopes of ~0.75. NGC 1835 and NGC 1898 are marked as good candidates for PCC morphology, but they have lower power-law slopes of ~0.45 and ~0.30. Three more clusters, NGC 1754, NGC 1786, and NGC 1916, have incomplete profiles and are classified as intriguing due to their small cores, but are not placed as firm PCC candidates. Fornax 5 is also considered a good candidate for a PCC cluster based on its small core and central profile shape. Our results for these seven clusters confirm the presence of a steep cusp for NGC 2005, NGC 2019, and NGC 1916 and a shallow cusp for NGC 1786. The rest of the cases all show flat central cores. Our reported values of the central slopes are different from the power-law slopes of MAC03; this makes sense since they are fitting a power law to photometric points on a larger radial range than that in which we are measuring central slopes.

Independently of PCC morphology, we identify a few more clusters as having clear central cusps (with central slopes steeper than ~0.20), such as NGC 1866, NGC 2031, Fornax 3, and Fornax 4, and some showing shallow cusps (with central slopes flatter than ~0.20), such as NGC 1868, NGC 2214, and Fornax 2. When the luminosity density central slopes are taken into account, a similar classification arises: NGC 1866, NGC 1916, NGC 2005, NGC 2019, and Fornax 3 have steep cusps with LD logarithmic slopes...
steeper than \(-1.00\), while NGC 1754, NGC 1868, NGC 2031, and Fornax 4 show shallow cusps with slopes between \(-0.2\) and \(-1.0\). The cluster R136 is discussed in a separate section (§4.2).

We should note that some of these clusters have half-light relaxation times longer than their measured age; they cannot be expected to have undergone core collapse, and therefore, another mechanism has to be invoked to explain the central nonzero slopes. Bastian & Goodwin (2006) and Goodwin & Bastian (2006) suggest that young star clusters can be out of virial equilibrium due to rapid gas losses, and therefore, the shape of their surface brightness profiles can change on relatively short timescales.

4.2. **R136**

R136 is known to be an extremely young object at the center of the 30 Doradus Nebula in the LMC. It is considered to be a young version of a globular cluster due to its large content of O-type stars. Main-sequence stars with masses as high as \(120 \, M_\odot\) have been detected in it (Massey & Hunter 1998). The estimated age for the most massive stars is \(<1–2\) Myr, and the mass function agrees very well with a Salpeter initial mass function (IMF). This makes R136 a unique and very peculiar object because it allows us to study star clusters in the way they looked just after formation. The surface brightness profile that we measure has a logarithmic central slope that is steeper than anything measured before for a globular cluster and steeper than anything predicted by dynamical models like core collapse. This makes us suspect that we are not resolving a core or a turnover radius for this object and that our central slope measurement corresponds to the slope just outside the turnover radius for the other objects. We decide to include R136 in every systematic measure we made for other clusters, but we caution the reader that its location in different distributions, particularly those dealing with central SB slope, should be taken with a grain of salt for this reason. The central surface brightness value for this object implies a central density of \(8 \times 10^6 \, M_\odot\) pc\(^{-3}\).

4.3. **Combining Two Samples**

In order to explore possible correlations between physical quantities, we combine the results for this sample with those for the Galactic sample from Paper I. From now on, we refer to the objects in the LMC, SMC, and Fornax dwarf galaxy as the “satellite sample” or “satellite clusters.” We compare the central slope measurements for both samples by plotting the slope histograms side by side (Fig. 8). We note that in both SB and LD central slopes, the satellite sample extends to steeper slopes than the Galactic sample. In total, 63% of the satellite sample is consistent with having flat cores, and the remaining objects display a continuous distribution of central slopes between 0 and \(-1.4\) for surface brightness, and between 0 and \(-2.2\) for luminosity density. From Paper I we know...
that 50% of the Galactic sample is consistent with having flat cores, a smaller fraction than for the satellite sample. For the Galactic sample we do not find any object with central slopes steeper than \(-0.8\) for SB or \(-1.8\) for LD, and we find two objects (R136 and Fornax 3) steeper than that in the satellite sample. Even when these differences are taken into account, the main conclusion that the slope distributions are inconsistent with a bimodal distribution of flat and PCC cores is the same for both samples.

We plot a variety of physical quantities against each other in order to explore possible correlations in both samples. The metallicity and age values are taken directly from MVM05. We observe in Figure 9 that the younger clusters, which belong to the satellite sample, have a narrower metallicity and total mass ranges (\(-1 < \text{[Fe/H]} < 0\) and \(3 \times 10^3 \, M_\odot < M_{\text{tot}} < 10^5 \, M_\odot\), respectively) than the old ones. This can be due to the fact that for our sample the young clusters sample a small linear age regime, so they have fewer chances of populating the extreme mass regime. Both metallicity and total mass do not show any clear correlations with other physical quantities. The outer slope shows weak correlations for the satellite sample in the sense that clusters with steeper outer slopes seem to be older and have fainter central surface brightness and larger break radius. The Galactic clusters appear to have shallower outer slopes than the satellite ones, but this could be due to the

![Graphs showing various data points and trend lines for different clusters.](image-url)
effect of the difference between the Chebychev and the EFF fits used for each sample (see §3.4). The Galactic clusters might show steeper outer slopes if they were analyzed in the same way as the satellite ones, or vice versa. We note that there seems to be a narrow range of outer slopes between $-2$ and $-3$ for the clusters with steep central slopes for both samples. There is a trend of clusters with steeper central slopes having brighter central surface brightness values. Every cluster with $\mu(0) < 14.0$ mag arcsec$^{-2}$ has a central logarithmic slope steeper than $-0.4$. Central surface brightness seems to be fainter for older clusters, but this is only observed for the satellite sample. Regarding the break radius, we should clarify that the lack of clusters with break radii larger than $\sim 4$ pc in the Galactic sample is a selection effect due to the fact that we required the core radius to fit on the WFPC2 field of view. Since the satellite clusters are 4–14 times further away than the average Galactic cluster, we can include clusters with larger break radius for the satellite sample. We note that all the clusters with a central surface brightness brighter than $\sim 16$ mag arcsec$^{-2}$ have break radii smaller than $\sim 2$ pc. Our measured break radius follows the same trend observed for core radius versus age by other authors (Elson et al. 1989; Elson 1992; de Grijs et al. 2002). Clusters younger than 1 Gyr have break radii smaller than 4 pc, while older clusters span a wide range of break radii. We notice that every cluster with central SB slope steeper than $-0.5$ has a half-light relaxation time shorter than 1 Gyr. Finally, the SB slope versus LD slope relation for the satellite clusters lies right on top of the one observed for Galactic clusters, which in turn is similar to the one observed for galaxies (Gebhardt et al. 1996).

5. SUMMARY AND DISCUSSION

We obtain central surface brightness profiles for 21 clusters in the Large Magellanic Cloud, five in the Small Magellanic Cloud, and four in the Fornax dwarf galaxy. We construct and analyze a large number of simulated images in order find the most suitable way to obtain surface brightness, as well as to estimate our uncertainties. The profiles are constructed by measuring integrated light with a robust statistical estimator. We combine $HST$ WFPC2 images in two filters (F555W and F814W) when available and present profiles normalized to $V$-band magnitudes.

When our results are compared with previous results that use different analysis techniques, we find very good agreement for $\sim 60\%$ of the sample. For the remaining 40\%, our central photometric points are brighter than previous measurements. Most central surface brightness values change from previously reported ones with values up to 2 mag brighter. For some objects in the sample, the new measured surface brightness profile is no longer compatible with a flat core parametric fit. The main reason for this difference is the increased spatial resolution of $HST$, but also because we use a nonparametric estimate as opposed to the traditional King model fits. For some of the observed profiles the departures from a flat core model are small but significant. We confirm the existence of a steep central cusp for three clusters previously classified as post–core collapse. We also find a subpopulation of objects with shallow cusps with logarithmic central slopes between $-0.2$ and $-0.5$. When we plot a variety of physical quantities searching for correlations, we find indications that the younger clusters tend to have smaller break radii, shallower
Fig. 9.—Surface brightness central and outer logarithmic slopes, logarithmic break radius (in parsecs), central surface brightness, metallicity, logarithmic age, and total mass plotted against each other for the LMC + SMC + Fornax sample (open circles) and the Galactic sample (filled circles). R136 is shown as a star symbol. We also show in the top right corner two panels with SB slope vs. half-light relaxation time and vs. LD slope (the solid line represents the LD slope = SB slope + 1). The distances to the clusters are assumed to be 45 kpc for the LMC, 60 kpc for the SMC, and 140 kpc for the Fornax dwarf galaxy.
outer slopes, and brighter central surface brightnesses. In particular, the youngest cluster in the sample, R136, shows the steepest central profile and the brightest central surface brightness. We also observe a clear correlation in which the clusters with the steepest central slopes are the ones with the brightest central surface brightness.

There have been two mechanisms explored for producing cusps in star clusters: core collapse and the presence of an intermediate-mass black hole in the center of the cluster. A detailed discussion and references on this subject can be found in § 1.2 of Paper I. The range of three-dimensional density slopes is wider for core collapse than for black hole models, but they both center around the same value, approximately $-1.65$. However, only the four clusters with the steepest profiles in our sample fall in this range. In the case of core collapse, the slope depends on the mass of the stars used to measure the profile and of those that dominate the mass of the core, so this could extend the range toward shallower slopes. Another factor of uncertainty is the time dependence of the core-collapse model when the core goes through gravothermal oscillations. According to Fokker-Planck simulations, a star cluster will spend a considerable amount of time in between successive collapses, where the light profile resembles a King model with a flat core. Unfortunately, these models do not give enough details about the slope of the density profile during intermediate stages of post-collapse bounce, or about the time spent in intermediate stages.

As discussed in Paper I, an alternative way to explain the shallow cusps is by invoking the result by Baumgardt et al. (2005). They perform simulations of stellar clusters with intermediate-mass black holes in their centers and find that, after a Hubble time, the projected density distribution of the clusters shows shallow cusps with slopes around $-0.25$. For this sample, we find four objects that fall within this regime, but only kinematical data can confirm the possible existence of a central black hole for these objects.

The observed correlations with age observed for the satellite sample (§ 4.3) point out the possibility of clusters having very concentrated profiles during the early stages of their evolution. In particular, the break radius-age relation observed here and by many authors tells us that the sizes of cores depend on the dynamical evolution of the clusters. The input density profiles for various dynamical simulations have almost always been characterized by King or Plummer models. This could be biased toward large flat cores, when more concentrated profiles could be more appropriate. This is true for core-collapse models, as well as models containing a central black hole. Tables with the complete photometric points and smooth profiles for every object in this sample can be found in the CDS VizieR service.

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