The extended structure of the remote cluster B514 in M31

Detection of extra-tidal stars* **

L. Federici¹, M. Bellazzini¹, S. Galleti¹, F. Fusi Pecci¹, A. Buzzoni¹, G. Parmeggiani¹

INAF - Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127 Bologna, Italy
e-mail: luciana.federici@oabo.inaf.it

Submitted 18 Jan 2007; Accepted 6 Jun 2007

ABSTRACT

Aims. We present a study of the density profile of the remote M31 globular cluster B514, obtained from HST/ACS observations.

Methods. Coupling the analysis of the distribution of the integrated light with star counts we are able to reliably follow the profile of the cluster out to $r \sim 35''$, corresponding to $\approx 130$ pc. The profile is well fitted, out to $\sim 15$ core radii, by a King Model having $C=1.65$. With an estimated core radius $r_c = 0.38''$, this corresponds to a tidal radius of $r_t \sim 17''$ ($\sim 65$ pc). The analysis of the light profile allows also the estimate of the ellipticity and position angle of the isophotes within $r \leq 20''$.

Results. We find that both the light and the star counts profiles show a departure from the best fit King model for $r \geq 8''$ - as a surface brightness excess at large radii, and the star counts profile shows a clear break in correspondence of the estimated tidal radius. Both features are interpreted as the signature of the presence of extra tidal stars around the cluster. It is also shown that B514 has a half-light radius significantly larger than ordinary globular clusters of the same luminosity. In the $M_V$ vs. log$_p$ plane, B514 lies in a region inhabited by peculiar clusters, like $\omega$ Cen, G1, NGC2419 and others, as well as by the nuclei of dwarf elliptical galaxies.

Key words. Galaxies: individual: M 31 – Galaxies:star clusters – catalogs — Galaxies: Local Group

1. Introduction

Until a couple of years ago we lack any knowledge of M31 clusters at large (projected) distances from the center of the galaxy: the farthest known cluster was G1, at $R_p \sim 35$ kpc from the center of M31, while (a few) Galactic globulars are found out to galactocentric distance of $R_{GC} \sim 120$ kpc (10 at $R_{GC} > 30$ kpc, according to Harris (1996)). Recent searches have identified several new remote clusters in M31 (Huxor et al. (2004); Galleti et al. (2005); Bates et al. (2003); Martin et al. (2006)). These studies seem to indicate that a relatively large number of globulars are still to be discovered in the extreme outskirts of M31. A significant sample of distant globulars may provide extremely useful information on the early evolution of the halo of M31. In particular, it has been suggested that bright globular clusters may be the remnants of disrupted nucleated dwarf galaxies (Freeman & Bland-Hawthorn (2002)), and references therein; see also Brodie & Strader (2006): if this were the case the probability of finding the observational fingerprints of these kind of phenomena is much higher at large distances from the center of parent galaxies, where substructures may survive for long times (Bullock & Johnston (2004)) and the overall stellar density is very low. Moreover, the structure and evolution of clusters orbiting in very-low density environments is a very interesting topic in itself.

In Galleti et al. (2006b, hereafter G06b) we have presented deep Hubble Space Telescope - Advanced Camera for Survey photometry of the recently discovered cluster B514 (Galleti et al. (2005), hereafter G05), lying at $R_p = 55$ kpc from the center of M31. The derived Color Magnitude Diagram (CMD) revealed that B514 is a genuine old and metal poor globular cluster ($[Fe/H] \approx -1.8$, confirmed also by the spectroscopic estimate by G05). The cluster is very bright ($M_V \approx -9.1$) and appears quite extended, similarly to the brightest remote cluster of the Milky Way, i.e. NGC 2419. Here we present the analysis of the surface brightness distribution of B514 obtained from the same HST-ACS data. Coupling the surface brightness profile obtained from the integrated light - for the inner parts - to star counts in the outer region, and thanks to the extremely low level of background density in the field, we were able to identify an unequivocal break in the outer profile of the cluster, indicating the presence of extra-tidal stars (see Johnston et al. (1995); Combes, Leon & Meylan (1999); Grillmair et al. (1995, 1996); Leon, Meylan & Combes (2000)). Extra-tidal components and/or extended tidal tails have been observed in several Galactic globulars (see Grillmair et al. (1995); Leon et al. (2000); Testa et al. (2001); Odenkirchen et al. (2003); Lee et al. (2004); Belokurov et al. (2006); and references therein). Holland et al. (1997) and Barmby, Holland & Huchra (2002), hereafter BHH, found some M31 clusters whose light profile exceeds the best fit King (1962,1966) model in the outermost regions, and interpreted this discrepancy as an extra-tidal component. Grillmair et al. (1996) found the same kind of discrepancy in three M31 clusters; they were able to follow the density profile of the clusters to significantly below the background level by coupling the light profile with the profile obtained from star-counts. By applying a simi-
lar technique, we are able to follow the profile of B514 out to \( r \sim 35'' \). Moreover, we found that B514 has a half-light radius \( (r_h) \) larger (by \( \geq 15\% \)) than typical globular clusters of the same luminosity, a characteristic shared by a few very peculiar systems, like \( \omega \) Cen, M54, G1 and NGC 2419 (see Mackey & van den Bergh 2005), hereafter MB05, and Hasegan et al. (2005), for a thorough discussion.

2. The surface brightness profile of B514

Since the details of the observations and data reduction are reported in G06b, here we recall just a few essential elements, referring the interested reader to that paper. The cluster has been observed with the Wide Field Channel of the ACS. The WFC has a total field of view of 202'' \times 202'' and a pixel scale of 0.049'' pixel\(^{-1}\). The observational material is constituted by three F606W images (total \( t_{exp} = 2412 \) s) and three F814W images (total \( t_{exp} = 2419 \) s), and the associated combined (drizzled) images. The cluster is placed in the center of one of the two ACS/WFC chips (Chip 2), while Chip 1 sample the field population (see G06b and below). If not otherwise stated, magnitudes are always in the VEGAMAG scale as defined by Sirianni et al. (2005). The reddening corrections are performed as in G06b, assuming \( E(B - V) = 0.10 \); a distance modulus \( (m - M)_0 = 24.47 \) is also assumed, after McConnachie et al. (2005), corresponding to \( D_C = 783 \) kpc. At this distance 1'' correspond to 3.8 pc and one ACS/WFC pixel to 0.19 pc.

The extreme crowding conditions prevent the full resolution into stars of the densest region of M31 globular clusters, even at the exquisite spatial resolution achieved by HST cameras. However, very accurate and well resolved surface brightness profiles can be obtained studying the distribution of their integrated light (see, for example, Fusi Pecci et al. (1994); Djorgovski et al. (2003); BHH). This technique, very successful in the bright inner regions of the clusters, is limited in the outermost part of the clusters, where the low luminosity density coming from cluster stars may be overwhelmed by the brightness of the background. In this regime star counts may be much more efficient, since cluster stars may be easily identified out to large radii, under favorable conditions (see Grillmair et al. (1999)). The ACS field studied here lies more than three degrees apart from the center of M31 and it appears to have an exceedingly low density of background stars (see G06b and below). This allowed us to derive a reliable light profile, completely unaffected by incompleteness, out to \( r \sim 20'' \), and to extend the analysis out to \( r \sim 35'' \), in completely uncrowded regions, by counting stars having colors and magnitudes typical of the cluster population.

2.1. The light profile

The light profile has been obtained independently from the F606W and F814W drizzled images. A few heavily saturated foreground stars (all at \( r > 26'' \) from the cluster center) have been excised from the images and replaced with the mean value of the surrounding background, to avoid contamination of the profile.

The light profiles were derived using the XVISTA software, maintained by J. Holtzman. XVISTA iteratively resolves the profile by fitting ellipses to the observed light distribution until a stable solution is reached (see Fusi Pecci et al. (1994); Djorgovski et al. (2003), for examples of applications to M31 clusters, and Lauer (1985), for a detailed description of the usage). The code provides as output, the coordinates of the center, the surface brightness, the ellipticity \( (e = 1 - b/a) \), and the position angle (PA, in degrees, measured anti-clockwise from the North direction) of each fitted ellipse, as well as the total amount of light enclosed within each ellipse. The profiles are derived with a single pixel step. This resolution is appropriate for the innermost regions of the cluster \( (r \geq 2'' - 3'') \) where the light intensity is very high, while at larger radii provides a quite noisy profile. This problem is solved by getting an average of the whole profile over 10 px bins: this sampling ensure a satisfying level of noise out to \( r \sim 20'' \). The background level is estimated as the average surface brightness in large \((\sim 100 \times 100 \text{ px})\) "empty" areas far away from the cluster. The level of background is very low \((\mu_{F606W} \sim 29.5 \text{ mag/arcsec}^2)\) and the final background-subtracted profiles were verified to be very robust to variations of the adopted background. The uncertainty on the position of the center is of order of \( \sim 2 \) px in the X and Y directions: variations on the assumed position of this size doesn’t affect significantly the derived profiles. The derived intensity profiles can be directly converted into magnitude/arcsec\(^{-2}\) units using the VEGAMAG zero points of Sirianni et al. (2005). The derived F660W and F814W profiles are shown in Fig. 1. The "x"s in the innermost 2'' are from the original 1-pixel step profiles, while the open circles with error bars are the averages in 10 pixels bins. The profiles are quite smooth, well-behaved and very similar in shape, at least out to \( r \approx 8'' \), i.e. the radius enclosing \( \approx 90\% \) of the whole cluster light. Outside this radius both profiles show a marginal excess of light with respect to the best-fitting King (1962) model (see below), but the F814W profile appears more noisy, probably because of the larger weight associated to the contribution of individual bright RGB stars in this redder passband. The F606W light profile is reported in Tab. 3. The apparent integrated magnitudes in the VEGAMAG system \( \text{mag}_F, F606 \) and \( \text{mag}_F, F814 \) were estimated by integrating the respective light profiles.

We take the Half Width at Half Maximum (HWHM) of the profile as the core radius (King 1962, Spitzer 1987). Once fixed this parameter we searched for the King’s models providing the best-fit to both profiles. In order to take in the proper account the ACS Point Spread Function (PSF) in measuring the light profile, the King models have been convolved with analytic F606W/F814W PSFs models, modeled on observed bright stars, as done by Barmby et al. (2007). All the comparisons between observed profiles and King’s models presented in the following involve only PSF-convolved theoretical profiles. In Tab. 1 we report both the observed and the de-convolved best-fit parameters (see below). The former must be adopted when dealing with the observed profiles, while the latter must be used in the comparisons with other clusters. We note that the adoption of PSF-convolved profiles results in small changes (\( \leq 10\% \)) in the cluster parameters, as usually occurs for extended M31 clusters like B514 (see Barmby et al. 2007).

The derived F660W and F814W profiles are shown in Fig. 1 compared to PSF-convolved King’s models with concentration parameter \( C = \log(r_c/r_h) = 1.4, 1.5, 1.6, 1.7 \). If we limit to the most reliable region within \( r = 8'' \) (encompassing \( \sim 19 \) core radii), the best fit is achieved with the \( C = 1.7 \) model for the F606W profile and \( C = 1.6 \) for the F814W profile.

We can gain some insight of the uncertainty associated with many observed/derived parameters by the comparison between the estimates obtained in the F606W and F814W profiles. For size parameters, (core radius \( r_c \), half-light radius \( r_h \), tidal radius \( r_t \), see King (1962)) we adopt the mean of the independent es-
convolved King models of different concentration, from C=1.4 to C=1.7, from left to right. The adopted core radius and central surface brightness are also reported.

The parameters of B514 obtained by this team are in good agreement with those presented by us here and in Galleti et al. (2006b).

A summary of the measured structural parameters is presented in Tab. 1, while Tab. 2 shows the derived parameters, i.e. those involving assumptions on distance and reddening and/or transformations to the standard Johnson-Kron-Cousins photometric system. The latter are achieved with the transformations presented in G06a. Note that if Sirianni et al.'s transformations are used instead, slightly brighter V magnitudes are obtained (by ∼0.06 mag), while the final I magnitudes are the same to within ±0.02 mag, r_c, r_h and surface brightness measures reported in Tab. 2 are derived from average de-convolved values, μ_r_h is the mean surface brightness within r_h, while μ(0) is the central value of the surface brightness.

In a very recent paper, Mackey et al. (2007) reported on the CMDs and (observed) half-light radii and integrated magnitudes of eight M31 clusters, including B514 (their GC4), from independent ACS observations. The parameters of B514 obtained by this team are in good agreement with those presented by us here and in Galleti et al. (2006b).

In the upper panel of Fig. 2 we show the color profile of B514. The profile is remarkably constant in the inner 6”, while it becomes very noisy in the outer regions. It is clear that in the low-surface-brightness outer parts the contribution of individual RGB/BHB stars may be important to establish the local color. A general tendency toward redder colors in the outer regions can be noted, a phenomenon that has been observed also in other clusters (see Djorgovski et al. 1991, Djorgovski & Piotto 1993, and Barmby et al. 2002). However, in the present case, we regard this trend as of marginal significance, given the uncertainties.

The middle and lower panels of Fig. 2 display the ellipticity and position angle profiles, respectively. In both cases, once verified that the profiles obtained from the F606W and F814W were fully consistent, we averaged the two. B514 has a mean ellipticity ⟨ε⟩ = 0.19 ± 0.07, quite high for a globular cluster, but not extraordinary (MB05). A sizable enhancement of the ellipticity is apparent between r ∼ 8” and r ∼ 15”. A twist of the isophotes seems to occur in the same radial range (lower panel, PA changing by ∼30”), suggesting a disturbed morphology in this range. The overall conclusion is that the cluster is rather elongated in the NW-SE direction, as is apparent by simply looking at the image (G06b).

In the upper panel of Fig. 3 we show the CMDs for the Chip containing the isochrones with ⟨c⟩ = 1.7, from left to right. The adopted core radius and central surface brightness are also reported.

The half-light radii have been computed also by performing aperture photometry on circular concentric annuli; this independent procedure provided the same results obtained with XVISTA, indicating that the estimate of this parameter is very robust. Also the estimates of the apparent integrated magnitudes have been checked in this way, and the results obtained with different methods are fully consistent.

A summary of the measured structural parameters is presented in Tab. 1, while Tab. 2 shows the derived parameters, i.e. those involving assumptions on distance and reddening and/or transformations to the standard Johnson-Kron-Cousins photometric system. The latter are achieved with the transformations presented in G06a. Note that if Sirianni et al.'s transformations are used instead, slightly brighter V magnitudes are obtained (by ∼0.06 mag), while the final I magnitudes are the same to within ±0.02 mag, r_c, r_h and surface brightness measures reported in Tab. 2 are derived from average de-convolved values, μ_r_h is the mean surface brightness within r_h, while μ(0) is the central value of the surface brightness.

In a very recent paper, Mackey et al. (2007) reported on the CMDs and (observed) half-light radii and integrated magnitudes of eight M31 clusters, including B514 (their GC4), from independent ACS observations. The parameters of B514 obtained by this team are in good agreement with those presented by us here and in Galleti et al. (2006b).

In the upper panel of Fig. 2 we show the color profile of B514; the continuous line is the overall mean color and the dotted lines encloses the ±1 standard deviation range. Middle panel: ellipticity profile. Lower panel: position angle profile. The latter two profiles are the average of the profiles obtained from the F606W and F814W images. The meaning of the lines is the same as in the upper panel.

Fig. 1. Surface brightness profiles (in mag/arcsec^2) of B514 in F606W (upper panel) and F814W (lower panel). The "x"s in the innermost region are from the 1-pixel step profile, while the open circles are average values over 10 px bins. The curves are PSF-convolved King models of different concentration, from C=1.4 to C=1.7, from left to right. The adopted core radius and central surface brightness are also reported.

Fig. 2. Upper panel: color profile of B514; the continuous line is the overall mean color and the dotted lines encloses the ±1 standard deviation range. Middle panel: ellipticity profile. Lower panel: position angle profile. The latter two profiles are the average of the profiles obtained from the F606W and F814W images. The meaning of the lines is the same as in the upper panel.

2.1.1. Color profile, ellipticity and position angle

In the upper panel of Fig. 2 we show the color profile of B514. The profile is remarkably constant in the inner 6", while it becomes very noisy in the outer regions. It is clear that in the low-surface-brightness outer parts the contribution of individual RGB/BHB stars may be important to establish the local color. A general tendency toward redder colors in the outer regions can be noted, a phenomenon that has been observed also in other clusters (see Djorgovski et al. 1991, Djorgovski & Piotto 1993, and Barmby et al. 2002). However, in the present case, we regard this trend as of marginal significance, given the uncertainties.

The middle and lower panels of Fig. 2 display the ellipticity and position angle profiles, respectively. In both cases, once verified that the profiles obtained from the F606W and F814W were fully consistent, we averaged the two. B514 has a mean ellipticity ⟨ε⟩ = 0.19 ± 0.07, quite high for a globular cluster, but not extraordinary (MB05). A sizable enhancement of the ellipticity is apparent between r ∼ 8” and r ∼ 15”. A twist of the isophotes seems to occur in the same radial range (lower panel, PA changing by ∼30”), suggesting a disturbed morphology in this range. The overall conclusion is that the cluster is rather elongated in the NW-SE direction, as is apparent by simply looking at the image (G06b).

2.2. The profile from star counts

For star counts we adopt the same catalog as G06b, including only well measured stars (see G06b, for details). Table 5 (online material) reports the photometry of the individual stars. In the upper panels of Fig. 3 we show the CMDs for the chip contain-


Table 1. Observed and de-convolved parameters

| Parameter | F606W | F814W | Average | De-convolved |
|-----------|-------|-------|---------|--------------|
| \( r_c \) [arcsec] | 0.38 | 0.45 | 0.42±0.03 | 0.38 |
| \( r_b \) [arcsec] | 1.52 | 1.73 | 1.6±0.2 | 1.44 |
| \( r_c \) [arcsec] | 19.0 | 18.0 | 18.8±2.5 | 17.0 |
| C | 1.7 | 1.6 | 1.65 | 1.65 |
| \( \mu(0) \) [mag/arcsec²] | 16.41 | 15.83 | 16.33/15.74 \(^a\) | 16.33/15.74 \(^a\) |
| \( \mu_0 \) [mag/arcsec²] | 18.5 | 17.9 | 18.4/17.5 \(^b\) | 18.4/17.5 \(^b\) |
| mag, [VEGAMAG] | 15.48±0.06 | 14.71±0.06 | 14.71±0.06 | 14.71±0.06 |

\(^a\) De-convolved F606W/F814W central surface brightnesses.
\(^b\) De-convolved F606W/F814W half-light radius surface brightnesses.

---

ing the cluster (Chip 2) and for the chip presumably sampling the field population (Chip 1, see G06b). The reported contour is the filter we adopt to select likely cluster members on the CMD; it encloses Red Giant Branch (RGB) and Horizontal Branch (HB) stars having \( F814W \leq 25.5 \). The filter efficiently excludes obvious color outliers and faint stars whose membership can be uncertain. In the lower panels the X,Y map of the two samples - in their relative positions - is presented. The horizontal continuous line marks the boundary between the two chips. The stars selected by the filter are plotted as heavy dots. The larger circle has a radius of 50″ and is the largest circle that can be fully enclosed within one WFC chip. The following analysis is restricted only to filter-selected stars within this circle. The background level of the stellar density is estimated from the whole 50″ circle in Chip 1 as \( p_{\text{bgk}} = 0.0043 ± 0.0013 \) stars/arcsec\(^2\), while we derive the cluster profile from selected stars in Chip 2. It can’t be excluded that cluster stars are present also in Chip 1. However, estimating the background level in the range \( X < 50″, X > 150″ \) regions of both chips (enclosed by dotted lines in the lower right panel of Fig. 3), and in the \( Y < -50″, Y > -50″ \) regions of Chip 1 (separated by the long dashed horizontal line in the lower right panel of Fig. 3), we found that the background is the same as that measured in the 50″ circle, within \( < 2 - \sigma \), ranging from \( 0.0024±0.0010 \) stars/arcsec\(^2\) to \( 0.0056±0.0015 \) stars/arcsec\(^2\), and there is no discernible density gradient outside \( r = 50″ \) from the cluster center. To have a more reliable estimate of the background level we would need observations of a larger (or more distant) field that, unfortunately, is lacking. However, this implies that, if anything, we are slightly overestimating the background. The possible associated bias would act against the detection of feeble extra-tidal components, hence it cannot be at the origin of the excess of surface brightness at large radii that is discussed below.

The derived profile is shown in Fig. 4a. The profile is very extended: a level of 5-σ above the background is reached at \( r \approx 31″ \), while the (adopted) background level is reached at \( r \approx 35″ \). This plot shows one of the main results of the present paper: not only the observed profile clearly extends much beyond the tidal radius derived from the light profiles but, above all, a clear change of slope is detected at \( r \approx 18″ \), i.e. near \( r_c \) itself. Note that the excess between \( r \approx 18″ \) and \( r \approx 30″ \) is many \( \sigma \) above the background, hence it is very significant, even if it encloses just a tiny fraction of the total cluster light.

Given the extreme crowding conditions in the inner part of the cluster and the strong density gradient, it is expected that the completeness of the sample is subject to radial variations. Fig 4b clearly illustrates the actual case by comparing the light profile (that is completely unaffected by incompleteness) and the background-subtracted star counts profile (reported in Tab. 4). A linear radial scale is adopted to provide a clearer comparison. This plot shows that incompleteness significantly affects star counts for \( r \leq 6″ \), becoming more and more important toward the center of the cluster, until, as said, it reaches 100% at \( r \leq 2″ \). However an excellent match of the profiles can be achieved in the range \( 10″ \leq r \leq 20″ \) (i.e. to the end of the light profile). This clearly proofs that for \( r \geq 10″ \) there is no more variation of the incompleteness with radius and, consequently, star counts provide a fair and fully reliable description of the real profile in the considered range. The vertical shift applied to the star counts profile to match the light profile automatically provides also the normalization constant to transform surface stellar densities into surface brightness. Therefore, the two profiles can be joined into one, covering the full \( 0 \leq r \leq 35″ \) range, as shown in Fig. 5.

Is it possible that the excess component beyond \( r_c \) and/or the observed change of slope can be due to sources unrelated to the cluster? This possibility is very hard to conceive, since (1) the adopted quality selections (G06a) and the CMD filter limit the analysis to relatively bright, well behaved stars that shouldn’t suffer from any serious contamination, and (2) it is very hard to imagine a “field” population whose surface density decreases with distance from the cluster center. We must conclude that the detected surface density excess at large radius and the change of slope in the profile are genuine properties of the cluster. A change of slope in the outer regions of the surface density profile is generally interpreted as the signature of the presence of tidally stripped stars (see Combes et al. (1999), Johnston et al. (1999); Leon et al. (2000), and references therein). For brevity, in the following we will refer to the stars beyond the break in the profile as to extra-tidal stars.
3. Discussion

A general prediction of incompleteness theoretical studies of tidal tails is that the slope of the surface brightness profile is different for bound stars and extra-tidal stars (see, for example, Combes et al. (1999), C99; Yim & Lee (2002); Johnston et al. (1999); Montuori et al. (2007)). Johnston et al. (1999) predicts that the surface density of stars in the tails should decrease as $r^{-1}$, in agreement with most observations of extra-tidal stars around Galactic globulars (Grillmair et al. (1998); Leon et al. (2000); Testa et al. (2000); Odenkirchen et al. (2003)). On the other hand C99 conclude that that such shallow slope is to be expected in the tidal tails at large distances from the parent cluster - i.e. fully unbound independent tidal debris - while in the vicinity of the cluster - i.e. immediately beyond the tidal radius - the density should decrease as $r^{-\alpha}$ with $\alpha \geq 3$ or larger, and the involved stars cannot be considered as completely unbound. C99 explain the discrepancy with the observed slopes as due to imperfect subtraction of a very noisy background, typical in most Galactic cases. It is interesting to note that in the present case, where we deal with stars in the proximity of the cluster and the background is virtually non-existing, the density of extra-tidal component decreases significantly faster than $r^{-1}$, and it is compatible with $\rho_S \propto r^{-3}$ (the thick segment superposed to the outer profile in Fig. 5).

In any case, the only possible alternative to explain the observed excess of stars and the change of slope in the profile at $r_t \approx 18''$ it is to postulate that the cluster is embedded in a very low surface brightness stellar system, that is, for instance an unknown dwarf galaxy. We consider this hypothesis as unlikely, since (a) the density of the detected extra-tidal component decreases with distance from the center of the cluster, that would be possible only if the cluster resides at the center of the hypothesized system,(b) the surface brightness of the extra-tidal component is $\gtrsim 26$ mag/arcsec$^2$, significantly lower than the typical central surface density of local dwarf spheroidals (Mateo (1998); but see Zucker et al. (2004), for a counter-
Fig. 5. Total surface brightness profile obtained by joining the light (dark grey circles) and the star-counts (light grey squares) profiles. The light curve is the (PSF-convolved) King model best fitting the light profile. The dark segment in the outer part is a surface density $\propto r^{-3}$ power law.

3.1. Bright clusters and the nuclei of dwarf ellipticals

Extragalactic surveys performed with high spatial resolution cameras are revealing the existence of new kinds of stellar systems. The Extended Clusters (ECs) found by Huxor (2005) are a typical example, but other kinds of extended clusters have been identified in more distant galaxies (see Peng et al. (2006), for a thorough review and discussion). Hilker et al. (1999) and Drinkwater et al. (2000) recently discovered a new kind of dwarf galaxies inhabiting galaxy clusters that are slightly more luminous than the brightest globular clusters and significantly more compact than any dwarf galaxy, the Ultra Compact Dwarf galaxies (UCD). It has been suggested that such systems are the dense remnant of tidally harassed nucleated galaxies (Drinkwater et al. (2003)). In this context a new perspective on the possible relations and differences among these various system is gradually emerging, and the comparison among the structural properties may provide interesting insights in this sense.

Table 3. Background-subtracted F606W Surface Brightness profile from the integrated light.

| $r$ (arcsec) | $\mu_{F606W}$ mag/arcsec$^2$ | $\epsilon_\mu$ mag/arcsec$^2$ |
|-------------|-----------------------------|-------------------------------|
| 0.24        | 16.7                        | 0.1                           |
| 0.73        | 17.9                        | 0.1                           |
| 1.23        | 18.8                        | 0.2                           |
| 1.71        | 19.7                        | 0.1                           |
| 2.20        | 20.2                        | 0.2                           |
| 2.69        | 20.5                        | 0.2                           |
| 3.18        | 21.2                        | 0.2                           |
| 3.67        | 21.6                        | 0.2                           |
| 4.16        | 22.1                        | 0.2                           |
| 4.65        | 22.2                        | 0.2                           |
| 5.14        | 22.5                        | 0.4                           |
| 5.63        | 22.8                        | 0.2                           |
| 6.12        | 23.1                        | 0.3                           |
| 6.61        | 23.5                        | 0.3                           |
| 7.11        | 23.1                        | 0.6                           |
| 7.59        | 23.5                        | 0.4                           |
| 8.09        | 24.0                        | 0.2                           |
| 8.57        | 24.3                        | 0.4                           |
| 9.06        | 23.9                        | 0.3                           |
| 9.55        | 23.9                        | 0.4                           |
| 10.05       | 24.1                        | 0.4                           |
| 10.53       | 24.8                        | 0.5                           |
| 11.02       | 24.6                        | 0.3                           |
| 11.51       | 24.8                        | 0.3                           |
| 12.01       | 24.5                        | 0.8                           |
| 12.49       | 25.0                        | 0.5                           |
| 12.98       | 25.4                        | 0.4                           |
| 13.47       | 25.8                        | 0.4                           |
| 13.96       | 26.0                        | 0.3                           |
| 14.45       | 25.7                        | 0.4                           |
| 14.94       | 26.2                        | 0.6                           |
| 15.43       | 26.1                        | 0.6                           |
| 15.92       | 26.2                        | 0.6                           |
| 16.41       | 26.2                        | 0.6                           |
| 16.90       | 26.7                        | 0.6                           |
| 17.40       | 26.7                        | 0.7                           |
| 17.89       | 26.7                        | 0.6                           |
| 18.38       | 26.6                        | 1.4                           |
| 18.86       | 27.0                        | 0.5                           |
| 19.35       | 27.0                        | 0.6                           |

In this line, MB05 compared globular clusters from different galaxies in the $M_V$ vs. $log r_h$ diagnostic plane (see also Hasegan et al. (2005)). They found that the bulk of globulars lies below the line $log r_h=0.25 M_V+2.95$. All the objects that are found above this threshold, namely $\omega$ Cen, NGC 2419, M54 and G1, are very bright and anomalous clusters: all of them were previously indicated as possible remnants of disrupted nucleated dwarf galaxies (Freeman & Bland-Hawthorn (2002). The $M_V$ vs. $log r_h$ plane has a distinct advantage with respect to other similar diagnostic planes (as, for instance, $M_V$ vs $\mu_Y(0)$, Kormendy (1985)), since $r_h$ is a quite easy-to-measure and reddening independent quantity.

In Fig. 6 we show the position of B514 and other interesting systems in the $M_V$ vs. $log r_h$ plane. Filled circles are Galactic globular clusters, from MB05; grey crosses are M31 globulars, our own estimates from HST images; open circles are Galactic globular clusters, from MB05; grey crosses are M31 globulars, our own estimates from HST images. Open circles are

---

Footnote: These estimates have been obtained with a profile analysis strictly homogeneous to that performed here for B514; the results have been compared with the independent estimates by BHH: the agreement between the observed parameters from the two sources is very good.
Table 4. Background-subtracted F606W Surface Brightness profile from star counts.

| r (arcsec) | $\mu_{F606W}$ (mag/arcsec$^2$) | $\epsilon_r$ (mag/arcsec$^2$) |
|------------|-------------------------------|-------------------------------|
| 10.41      | 24.7                          | 0.1                           |
| 11.64      | 25.0                          | 0.1                           |
| 12.86      | 25.3                          | 0.1                           |
| 14.09      | 25.8                          | 0.1                           |
| 15.31      | 26.2                          | 0.1                           |
| 16.54      | 26.6                          | 0.2                           |
| 17.76      | 27.0                          | 0.2                           |
| 18.99      | 27.1                          | 0.2                           |
| 20.21      | 27.2                          | 0.2                           |
| 21.44      | 27.4                          | 0.2                           |
| 22.66      | 27.5                          | 0.2                           |
| 23.89      | 27.8                          | 0.2                           |
| 25.11      | 28.0                          | 0.2                           |
| 26.34      | 28.1                          | 0.2                           |
| 27.56      | 28.4                          | 0.2                           |
| 28.79      | 28.6                          | 0.2                           |
| 30.01      | 29.1                          | 0.3                           |
| 31.24      | 29.5                          | 0.3                           |
| 32.46      | 29.6                          | 0.3                           |
| 33.69      | 29.9                          | 0.3                           |
| 34.91      | 29.8                          | 0.3                           |

$^a$ The star counts profile has been converted into surface brightness units (mag/arcsec$^2$) with the relation $\mu_{F606W} = -2.5\log(\rho_r) + 23.20$, according to the normalization shown in Fig. 4.

The M31 clusters of Mackey et al. (2007), seven of them having $R_p > 30$ kpc (in the following we will refer to these clusters as M-GC1, M-GC2, ..., M-GC10); asterisks are ECs from Mackey et al. (2006); open stars are UCDs in the Fornax cluster from De Propris et al. (2005). The continuous line is the Mackey & van den Bergh threshold mentioned above. Apart of B514, the real novelty of Fig. 6 with respect to previous versions (MB05; Huxor et al. (2005); Belokurov et al. (2007)) is that for the first time it is possible to report also the position of the nuclei of dwarf nucleated ellipticals (red triangles). Côté et al. (2006) measured half-light radii and $g_{AB}$, $z_{AB}$ integrated magnitudes of the nuclei of several dwarf ellipticals in Virgo from deep ACS/WFC images. We converted $g_{AB}$ magnitudes into V magnitudes with the transformation:

$$V = g_{AB} - 0.31(g_{AB} - z_{AB}) \quad (r.m.s. = 0.1 \ \text{mag})$$

that we have obtained from 166 bright stars of the cluster NGC2419 that are in common between the $g_{AB}$, $z_{AB}$ photometry we obtained from archive ACS/WFC data and the secondary standards provided by Stetson (2005) for this cluster. Then, we converted the integrated V magnitudes into absolute magnitudes by adopting the reddening and distance modulus provided by Côté et al. (2006).

There are a number of very interesting indications emerging from Fig. 6.

1. In addition to the clusters already noted by MB05, i.e. M54, ω Cen, NGC 2419 and G1, there are a few other bright M31 globulars lying above the “ordinary globular cluster” threshold: B514, M-GC3, M-GC5, G76, G280, G219, and G302. All of these systems are classified as globular clusters but have half-light radii significantly larger than those of typical genuine globular clusters of the same metallicity.

2. The distribution of nuclei nicely overlaps the position of these anomalous clusters. In particular, the nuclei of dwarf ellipticals appear to join the brightest globulars to the anomalous “above-threshold” clusters and to the UCD galaxies, which have been also interpreted as the nuclear remnants of shredded galaxies (Drinkwater et al. 2003). This is the first time that a clear connection between the structure of nuclei, UCDs and anomalous clusters is directly established by comparing sizable samples. It would be of great interest to extend the comparison to velocity dispersions, but unfortunately these quantities are not available for the sample of nuclei considered here (but see Hasegan et al. (2005)) and for most of M31 globulars, including B514.

3. ECs, on the other hand, seem to have a different nature, somehow intermediate between globular and open star clusters (Peng et al. 2006).

4. The remote clusters B514 ($R_p \approx 55$ kpc) and M-GC5 ($R_p \approx 78$ kpc) lie above the $\log r_h - M_V$ threshold, while M-GC1 ($R_p \approx 46$ kpc) and M-GC10 ($R_p \approx 100$ kpc) are located well below the threshold, fully immersed within the distribution of ordinary globular clusters. This demonstrates that a large half-light radius is not a distinctive characteristic of remote clusters.

5. It is interesting to note that the faint Galactic satellites recently discovered by various SDSS teams (see Belokurov et
It is interesting to have a closer look to the anomalous “above-threshold” clusters. $\omega$ Cen and G1 clearly host stars of different chemical composition (and, presumably, age), hence - unlike classical globulars - they were able to sustain chemical evolution (see, Sollima et al. 2005; Bekki & Freeman 2003; Meylan et al. 2001, and references therein). Both clusters are quite elliptical in shape, similar to B514. M54 resides within the nucleus of the Sagittarius dwarf spheroidal (Monaco et al. 2003) and there are indications of a small metallicity spread among its stars (Sarajedini & Layden 1995). G76 is a relatively metal poor cluster ([Fe/H] $\approx$ −1.3, Rich et al. 2005), hereafter R05 that is projected onto a very dense star forming region in the disc of M31 (Bellazzini et al. 2003). The extreme crowding conditions in this region prevents a clear interpretation of the wide RGB shown in its CMD as obtained by R05, but this feature clearly leaves room for a possible metallicity spread. G280 is a quite metal rich ([Fe/H] $\approx$ −0.5, R05) and bright cluster; like G76 it is projected onto a high density background. G302 is a metal poor cluster ([Fe/H] $\approx$ −1.7, R05) with a blue horizontal branch. Its CMD (R05) is quite clean and it suggest that G302 is a normal single-population cluster. G219 is a metal poor cluster ([Fe/H] $\approx$ −1.9, R05) located at $\approx$ 20 kpc from the center of M31. Bellazzini et al. (2003) noted that G219 is projected onto the giant stream discovered by Ibata et al. (2001). It is remarkable, in the present context, that both G302 and G219 are among the rare M31 clusters with a detection of extra-tidal stars, as B514 (Holland et al. 1997; Grillmair et al. 1996). NGC2419 is a remote metal-poor Galactic globular whose CMD is very similar to that of B514 (Harris et al. 1997). As B514 it show no obvious sign of a metallicity spread, but this may be very difficult to find out from the CMD of very metal-poor clusters (see MB05). It has to be noted that NGC2419 has a half-light radius as large as those of the largest $e$ nuclei and UCD galaxies.

In summary, B514 fully lies into the region of the $M_V$ vs. log $r_h$ plane that appear forbidden to ordinary clusters, in company of a few other clusters, many of which present some kind of peculiarity. The fact that the same region hosts also the nuclei of dwarf ellipticals provide support to the hypothesis that these bright extended clusters can be the remnant of disrupted galaxies (Freeman & Bland-Hawthorne 2002; MB05, and references therein; see Brodie & Huchra for a thorough discussion on the role of globular clusters within a cosmological context). On the other hand, it is possible that ordinary clusters are allowed to attain extended structures if their orbit never drives them in the inner part of the parent galaxy, as it may be the case of NGC2419 and B514 (see van den Bergh, Morby & Pazder 1991). However, the coexistence of ordinary and “above-threshold” clusters in the outermost regions of M31 (see point 4, above) does not support this hypothesis.

In any case the present study confirms that globular clusters in the outskirts of M31 may reveal many interesting features, thanks also to the favorable observing conditions (as for instance, the very low background). Remote clusters are rare in the Milky Way, and they are typically quite faint, with the only exception of NGC2419 (see Mackey et al. 2007 and Galletti et al. 2007). Hence, M31 may provide the opportunity of a systematic study of a kind of stellar system that is very rare in the Galaxy.

Using the same selection criteria that lead us to the discovery of B514 (G05) we have selected a conspicuous number of candidate clusters at large distances from the center of M31: at present we have obtained spectroscopic confirmation (as in G06) for four of them, all being nearly as luminous as B514 (Galletti et al. 2007). The follow-up of these remote clusters, as well as of those discovered by other teams, may hopefully open a new window in the study of the M31 system and of bright clusters as a whole.

Acknowledgements. We are grateful to Dougal Mackey and Avon Huxor for useful discussions. We acknowledge the financial support to this research by Agenzia Spaziale Italiana (ASI) and of the Italian Ministro dell’Università e della Ricerca under the grant INAF/PRIN05 1.06.08.03. Part of the data analysis has been carried out with software developed by P. Montegriffo at INAF - Bologna Observatory.

References

Barnby, P., Holland, S., Huchra, J.P., 2002, 123, 1937 (BHH) Barnby, P., McLaughlin, D., Harris, W.E., Harris, G.L.H., Forbes, D.A., 2007, AJ, 133, 2764 Bates, S.A., et al., 2004, BAAS, 29, 64.10 Bekki, K., Freeman, K.C., 2003, MNRAS, 346, L11 Bellazzini, M., Cacciari, C., Federici, L., Fusi Pecci, F., Rich, M.R., 2003, A&A, 405, 867 Belokurov, V., Evans, N.W., Irwin, M.J., Hewett, P.C., Wilkinson, M.I., 2006a, ApJ, 637, L29 Belokurov, V., et al., 2007, ApJ, 654,897 Brodie, J.P., Strader, J., 2006, ARA&A, 44, 193 Bullock, J.S., Johnston, K.V., 2001, in Satellites and Tidal Streams, F. Prada, D. Martinez-Delgado and T. Mahoney Eds., San Francisco: ASP, ASP Conf. Ser., 327, 80 Combes, F., Leon, S., Meylan, G., 1999, A&A, 352, 149 Coté, P., et al., 2006, ApJS, 165, 57 De Propris, R., Phillips, J.C., Drinkwater, M.J., Gregg, M.D., Jones, J.B., Efstathiou, E., Bekki, K., ApJ, 623, L105 Djorgovski, S.G., Piotto, G., Phinney, E.S., Chernoff, D.F., 1991, ApJ, 372, L41 Djorgovski, S.G., Piotto, G., 1993, in Structure and Dynamics of Globular Clusters, S.G. Djorgovski and G.Meylan Eds., San Francisco:ASP, ASP Conf. Ser., 50, 203 Djorgovski, S.G., et al., in New Horizons in Globular Cluster Astronomy, G. Piotto, G. Meylan and S.G. Djorgovski Eds., San Francisco:ASP, ASP Conf. Ser., 296, 479 Drinkwater, M.J., Jones, J.P., Gregg, M.D., Phillips, S., 2000, PASA, 17, 227 Drinkwater, M.J., Gregg, M.D., Harker, M., Bekki, K., Couch, W.J., Ferguson, H.C., Jones, J.B., Phillipps, S., 2003, Nature, 423, 519 Freeman, K.C., Bland-Hawthorn, J., 2000, ARA&A, 40, 487 Ferguson, H.C., Jones, J.B., Philiipps, S., 2003, Nature, 423, 519 Fusi Pecci, F., et al., 1994, A&A, 284, 349 Galletti, S., Bellazzini, M., Federici, L., Fusi Pecci, F., 2005, A&A, 436, 535 (G05) Galletti, S., Federici, L., Bellazzini, M., Buzzoni A., Fusi Pecci, F., 2006a, A&A, 456, 985 (G06a) Galletti, S., Federici, L., Bellazzini, M., Buzzoni A., Fusi Pecci, F., 2006b, ApJ, 650, L107 (G06b) Galletti, S., Bellazzini, M., Federici, L., Buzzoni A., Fusi Pecci, F., 2007, A&A, submitted Grillmair, C., Freeman, K.C., Irwin, M.J., Quinn, P.J., 1995, AJ, 109, 2553 Grillmair, C., Ahar, E.A., Faber, S.M., Baum, W.A., Lauer, T.R., Lynds, C.R., O’Neil, E.J.Jr., 1996, AJ, 111, 2293 Johnston, K.V., Sigurdsson, S., Hernquist, L., 1999, MNRAS, 302, 771 Harris, W.E., 1996, AJ, 112, 1487 Harris, W.E., et al., 1997, AJ, 114, 1030 Hasegan, M., Jordán, A., Côté P., et al., 2005, ApJ, 627, 203 Harker, M., Infante, L., Vieira, G., Kissler-Patig, M., Richtler, T., 1999, A&AS, 134, 75 Holland, S., Fahman, G.C., Richer, H.B., 1997, AJ, 114, 448 Huxor, A.P., et al., 2004, in Satellites and Tidal Streams, F. Prada, D. Martinez-Delgado and T. Mahoney Eds., San Francisco: ASP, ASP Conf. Ser., 327, 118 Huxor, A.P., Tanvir N.R., Irwin, M.J., Bata, R.A., Collett, J.L., Ferguson, A.M.N., Bridges, T., Lewis, G.F., 2005, MNRAS, 360, 1007 King, I.R., 1962, AJ, 67, 471 King, I.R., 1966, AJ, 71, 64
