SURFACE PHOTOMETRY OF GLOBULAR CLUSTERS

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ABSTRACT. Much of what we know about the structure, dynamics, and evolution of globular clusters derives from their observed density profiles, and their interpretations. In this review, I will briefly describe the problems and techniques specific to the surface photometry of globular clusters, show some new results, and offer suggestions for future ground-based work.

Globular clusters are our main testing ground for the dynamics of stellar systems. All manner of interesting processes takes place in these systems, on the time scales generally shorter than the Hubble time: two-body relaxation, core collapse and its reversal, tidal shocks, possibly even gravothermal oscillations, equipartition, etc. The main channel for testing our theories are the projected *density* profiles of clusters, which in the absence of a strong mass segregation (a well-justified assumption) we can almost always identify with their *surface brightness* profiles. Therein lies the importance of surface photometry. Substantial progress has been achieved in the last few years in obtaining more complete, and better quality data. An important stimulus was provided by the vigorous theoretical activity related to the problems of core collapse, and the post-collapse dynamical evolution: the volume edited by Goodman & Hut (1985) contains several excellent reviews. In this paper, I will first describe the modern techniques used in surface photometry of globular clusters, summarize some of the new results, and finally suggest some possible directions for the future work. For the earlier work in this field, and more complete accounts of the relation between the density profiles and the underlying stellar dynamics, the reader should consult the reviews by King (1975, 1980, 1981, 1985) and Spitzer (1984), and the references therein.

Good to excellent surface brightness and/or star counts profiles now exist for almost all known Galactic globulars, that is, some 130 clusters. Published surveys include King *et al.* (1968), Illingworth & Illingworth (1976), Peterson (1976), Djorgovski & King (1984, 1986), Kron, Hewitt & Wasserman (1984), Djorgovski & Penner (1985), Hertz & Grindlay (1985), Lugger, Cohn & Grindlay (1985), Lugger *et al.* (this conference), etc. The ellipticities and ellipticity gradients were measured by White & Shawl (1987). Much of the new data has not been systematically analysed yet, but in a year or so we should have a new compilation

J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 333–346.

of dynamical and structural parameters for globular clusters, which would replace the classical, but now obsolete study of Peterson & King (1975), or the somewhat heterogeneous compilation by Webbink (1985).

Most of the difficulties and problems associated with surface photometry of globulars are caused by their "bumpy" nature: clusters are composed of finite numbers of stars, and a large fraction of the total light is contributed by a relatively small number of giants. There is not much that one can do about this, except to use the bluest bandpass possible: in the U band, for example, the HB and the RGB stars have approximatelly the same luminosity, so that a relatively large number of stars contributes most of the light, and thus the $1/\sqrt{n}$ fluctuations are smaller. This rule was often emphasized by Ivan King (e.g., in his 1985 review). The second important source of difficulties is the presence of foreground stars, in particular at low Galactic latitudes or in the Bulge, where most of the clusters are. This difficulty can be coped with if one uses an imaging detector, as will be briefly described below, but it is much more detrimental for a concentric-aperture photometry work.

There are several techniques which can be used in measuring the surface brightness profiles of clusters: First, there is "real" surface photometry, done with an imaging detector, such as a CCD, or a photographic plate. This is the best way, but it is usually good only for the inner regions of clusters (which are dynamically the most interesting, anyway). Second, there are star counts, which are currently the only way of measuring profiles in the tidal cutoff region. With the HST, we should be able to do star counts in the cores, and that should prove to be very interesting, as it may give us the first solid evidence for mass segregation or population gradients in clusters. Third, one may use concentric-aperture photoelectric photometry. That technique suffers from centering and foreground difficulties much more than the imaging work, and is completely insensitive to the core structure. It should not be trusted for radii less than ~ 10 arcsec, and it really works only in the intermediate regions, and only if the foreground is not too heavy. Finally, there are techniques not worth serious attention, such as one-dimensional scans (which are noisy, and need to be inverted...), etc. I will concentrate here on the imaging surface photometry work; King (1986) gives further discussion and comparisons of various methods and techniques.

Generally, the foreground stars need to be removed before any of the photometry is performed. This can be done interactively (by hand and a cursor), simply by editing out or flagging all pixels suspected of being polluted with the foreground stars, or uncorrected detector defects (bad CCD columns, etc.). Flagged pixels or areas are then ignored by the profile-computing routines. A much better approach to this task is allowed by the modern digital stellar photometry software, such as the famed *DAOPHOT*. One can form a color-magnitude diagram of all resolved stars in the frame, or simply find all stars sufficiently brighter than the obvious cluster giants, and then remove them by point-spread function (PSF) fitting and subtraction. The process is illustrated here in Fig. 1. It may be necessary to flag the central pixels from underneath the removed stars, just to guard against the imperfect PSF subtraction. This technique has the advantage of being more objective and more automatic than the simple star flagging by hand, and it is more reliable, especially if there is color information available.

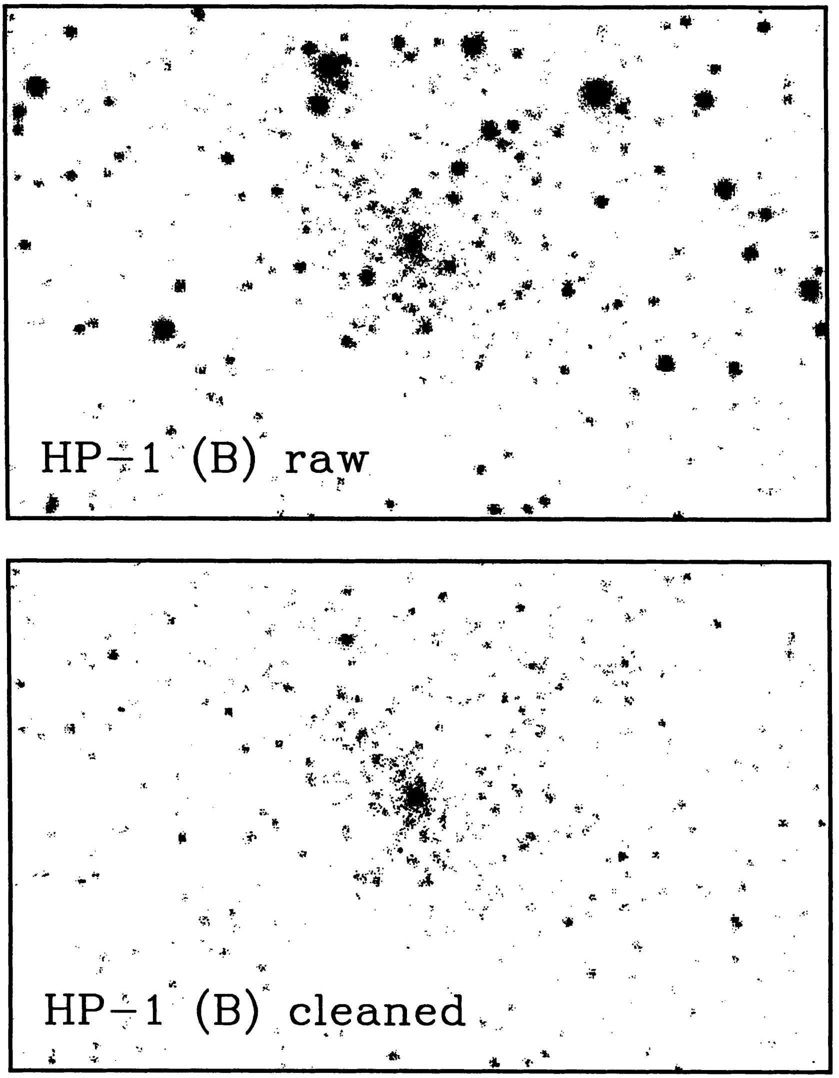

Fig. 1. An example of *DAOPHOT* foreground cleaning. The technique is particularly effective for the heavily obscured clusters at low Galactic latitudes, like the HP-1 shown here, and for the bluer bandpasses. A color-magnitude array of all well-resolved stars was formed; there is no need for the zero-point or color calibrations. The cluster giant branch was evident, and all brighter stars which were clearly outside the cluster sequence were then removed by the PSF fitting and subtraction. Even if the color information is not available, one can remove all stars brighter than the obvious cluster giants.

The next problem that one encounters is the cluster centering. Missing the true cluster center would always artificially flatten the profile, and may hide a possible post-collapse core. One centering method, developed by Ivan King, is the mirror-autocorrelation technique, illustrated in Fig. 2. This method is very robust, and it uses the full two-dimensional information present in the image. An alternative technique, the maximum symmetry method, was developed by Hertz & Grindlay (1985), and it employs separate centering in X and Y projections.

One then proceedes with the profile derivation. The image is divided into annular, concentric pseudo-apertures, each of which is divided in a number of sectors (most authors use 8 sectors, as that is an easy number to implement, and it is an almost optimal one). This process is illustrated in Fig. 3. The use of sectors to determine the internal error-bars is essential: most of the errors are due to the discreteness of light distribution in the cluster, and all other sources of

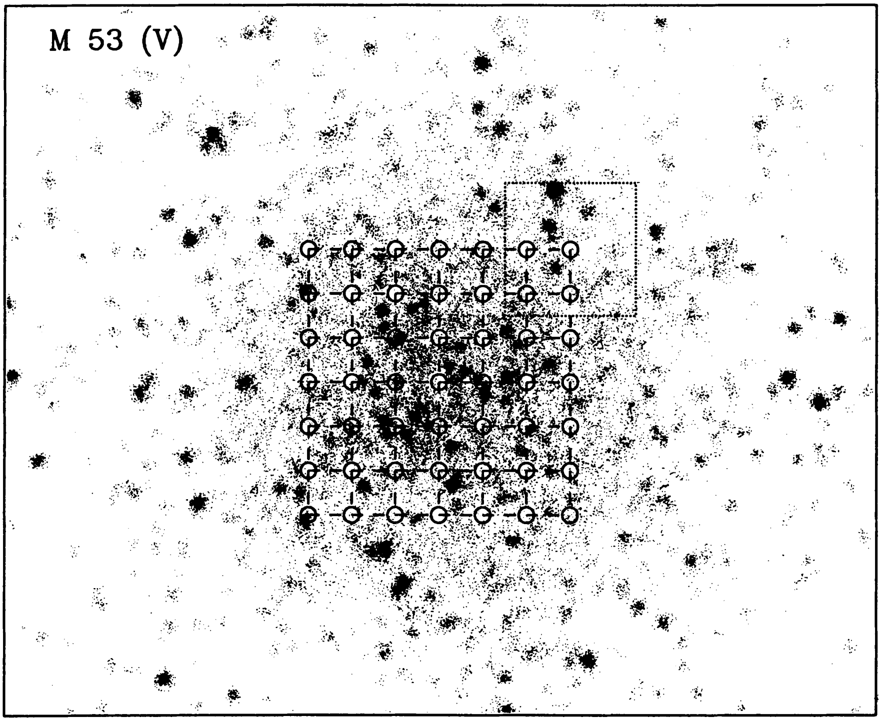

Fig. 2. Mirror-autocorrelation centering is performed as follows: A grid of test centers (circles) is set to cover the cluster core. At each test center, a square window sub-array (dotted lines) is extracted, and amplitude of the autocorrelation of this data sample with its mirror image is computed. Thus, there is one number (autocorrelation amplitude) at each test center, and it is maximized for the most symmetric sample. Finally, a paraboloid is fitted to this grid of amplitudes. The vertex of the paraboloid is the optimal cluster center.

errors tend to be negligible in comparison. The error-bars also signal a presence of azimuthal asymmetries, or "bumps": if there is a lump of stars, or an unremoved foreground star somewhere in the aperture, the corresponding data point will be artificially high, but the error-bar will be appropriatelly increased as well. In particularly difficult cases, it may be advantageous to use the *median* of the mean surface brightness in sectors in each annulus, rather than the mean; this is a more robust way, but it is not flux-conserving, since we are dealing here with highly asymmetric, non-gaussian noise. A more complete discussion of various sources of errors is given by Illingworth & Illingworth (1976) and Newell & O'Neil (1978).

Finally, there is the problem of sky determination, which can be accute in the case of small-field CCD's. A practical way of doing it is from the mode or the median of a sky histogram, which is compiled from the pixels as far from the cluster center as possible. This sky estimate will necessarly be polluted by the unresolved cluster light, but the situation is much better here than it is in the case

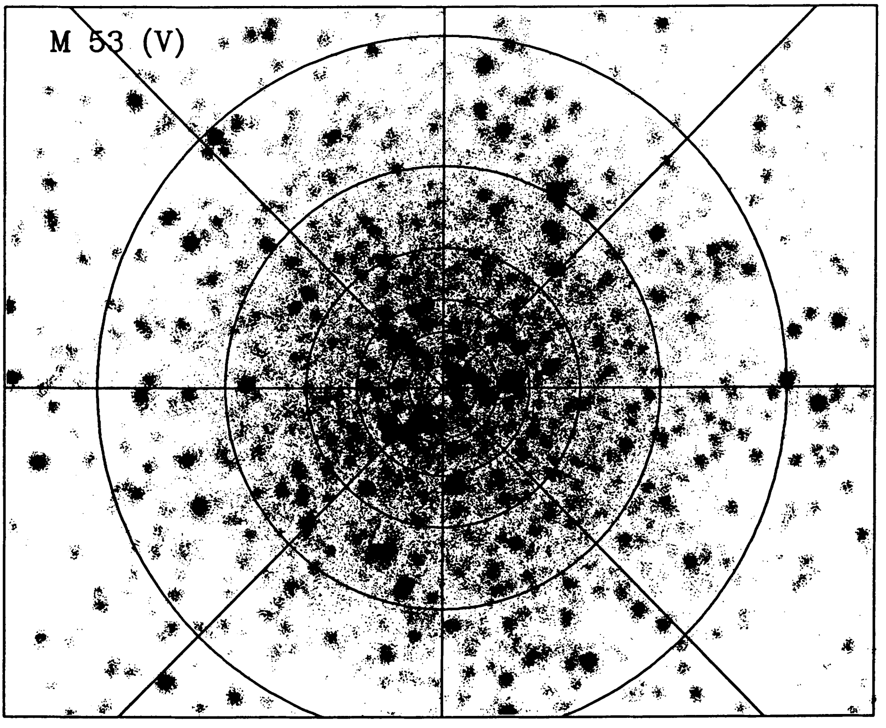

Fig. 3. Aperture grid for the photometry. Concentric circular annular apertures are centered on the optimal cluster center. The aperture spacing is typically chosen to be equidistant logarithmic. Each annulus is subdivided into eight sectors. Mean surface brightness of all non-flagged pixels in each sector is computed. Mean and the sigma of the values for the eight sectors are adopted as the mean surface brightness for the annulus and its internal error.

of surface photometry of galaxies: most of the light in clusters comes from the resolved giants, and their pixels do not affect the mode or median of the sky histogram very much. The small residual pollution would make the sky too bright; however, there is also an opposing effect: the unremoved background/foreground of faint stars and galaxies would add to the signal in the central regions, which is treated as being from the cluster alone. Thus, the uncertainity of sky determination in the CCD work may be important only for the outermost point or two of a cluster profile.

The final step in surface photometry is the determination of the photometric zero-pont for a profile, if that is needed (it is certainly unimportant for the morphological studies). One major advantage of imaging detectors is that the data can be taken in non-photometric conditions, and calibrated later. This is a point in which the photoelectric aperture work can make its most useful contribution.

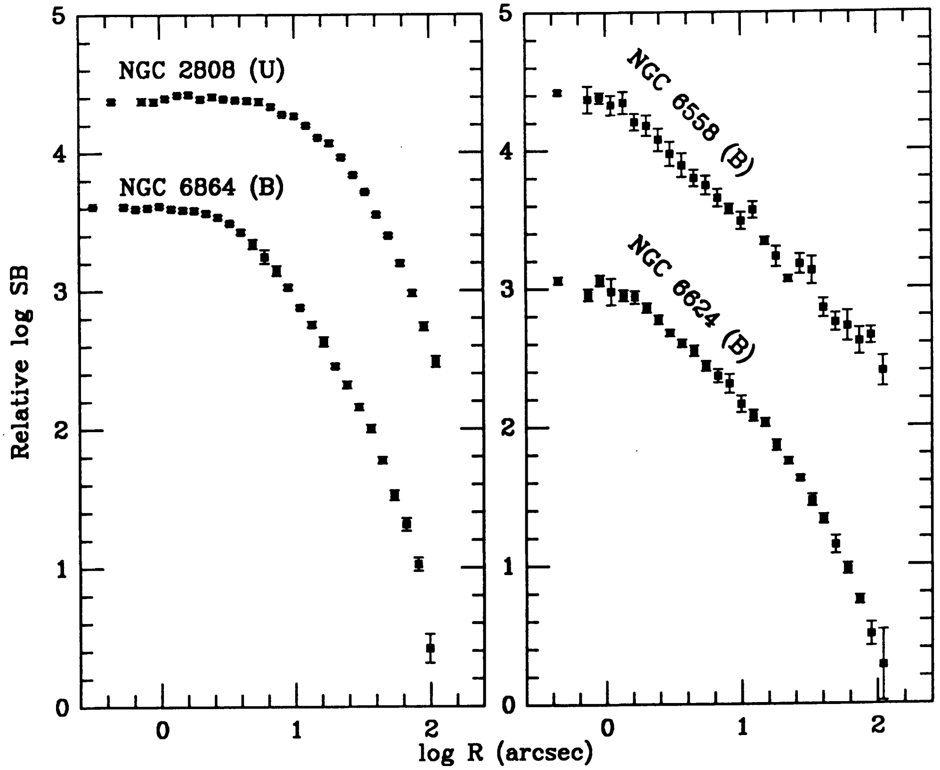

Fig. 4. Profiles of clusters with different core morphology, plotted on a 1:1 log-log scale. On the left, two clusters described well by the King (1966) models; they are distinguished by flat cores and steep envelopes. On the right, two clusters with the post-core-collapse morphology; their central parts are relatively shallow, slope $\simeq$ -1 power-law cusps, going into the seeing disk.

https://doi.org/10.1017/S0074180900042583 Published online by Cambridge University Press

The core morphology of globular clusters shows the existence of two distinct types: the well-known family of King (1966) models, characterized by flat cores and steep envelopes, and the power-law cusps with slopes $\sim$ -1, approximating singular isothermal spheres, which gradually roll off into a King-model envelope, or a tidal cutoff. We now believe that the two families represent different stages of dynamical evolution of globular clusters: the clusters with cusps are those which underwent the core collapse, and its reversal. Their existence was first predicted in the pioneering work by Hénon (1961). Examples of clusters with different morphology are shown in Fig. 4. The characteristic which distinguishes the post-core-collapse (PCC) clusters is the existence of a shallow (slope $\simeq$ -1) power-law section of the profile in their central parts, going into the seeing disk. This can be checked by subtracting a -1 power-law from the data. However, it is a mistake to think of PCC centers as something occuring at very small angular scales, and hiding in the seeing limit: these power-laws typically cover tens of arcseconds. It is also inappropriate to think of PCC clusters as King models with an "extra" spike or a cusp in the middle; the structure of these whole clusters is fundamenally different, although they may be regarded as infinite-concentration limiting cases of the King sequence. There is always a fundamental dynamical difference: the centers of PCC clusters are thought to contain close binaries, which serve as sources of energy, stabilizing the cluster, and generating a positive radial flow of energy which gradually expands the cluster envelope. There is nothing like that in the King models, whose phase space distribution is a steady-state, lowered Maxwellian, without any energy flow. In both cases, however, there is a loss of stars due to evaporation in the tidal cutoff regions.

Given enough time, every cluster should go through core collapse, unless it evaporates away first. The collapse time can be as short as a few half-mass relaxation times, and it is shortened substantially if there is a mixture of stars of different masses (Inagaki & Saslaw 1985). The collapse and the recovery are thought to be very rapid, and once a cluster reaches the PCC state, it stays that way until it evaporates away, that is, many billions of years (Goodman 1984). Core oscillations may occur, due to the ejection and replacement of central binaries (McMillan & Lightman 1984), or due to an as-yet poorly understood gravothermal instability mechanism (Bettwieser & Sugimoto 1984). Thus, the PCC clusters are not an anomaly, but rather a natural dynamical state for evolved clusters. Indeed, in the Berkeley globular cluster surface photometry survey (Djorgovski & King 1986, Djorgovski *et al.* 1986), it was found that $\sim 1/5^{th}$ of all known Galactic globulars shows the characteristic PCC morphology. The problem is actually the other way round: there are some highly concentrated King-model-like clusters, which had enough time to collapse, but apparently did not. One possible explanation is that they *do* have collapsed cores composed of dark stellar remnants, whose dynamical evolution was too rapid for ordinary visible stars to follow (Larson 1984). Another possibility, that the clusters recover from the collapse in a *much* shorter time than what we think, seems unlikely for the reasons which will be explained below.

The results from the Berkeley survey were used to investigate relations between the cluster morphology and other properties. It was immediately noticed that the PCC clusters are more concentrated towards the Galactic center than the King-model clusters. Furthermore, the high-concentration King-model cluster are more concentrated towards the Galactic center than the low-concentration ones. By the same token, the PCC and high-concentration clusters are also more concentrated towards the Galactic plane. This effect was predicted by Chernoff, Kochanek & Shapiro (1986) before they knew about our results. They investigated the influence of tidal shocks from disk passages on cluster evolution, and found that the shocks selectively accelerate dynamical evolution: at a given initial cluster mass and central concentration, there is a critical galactocentric radius within which all clusters collapse, and outside of which all clusters dissolve. At any given moment the distribution will depend on the initial conditions, but the trend will be to have more PCC or highly concentrated survivors at lower galactocentric radii, just as is observed. Moreover, there may be a very weak trend that at a fixed galactocentric radius, more concentrated clusters tend to have higher Z-distances from the plane, which would mean more inclined orbits. In any case, the core collapse and its aftermath are not driven by the internal Antonov-Hénon and Spitzer instabilities alone. Another observed trend is that the more concentrated King-model clusters tend to have higher luminosities (or masses), but that trend is reversed for the PCC clusters: they are less massive than the high-concentration King-model clusters. This may reflect the fact that smaller-N systems have shorter dynamical time scales, and so collapse first, and/or that the PCC clusters evaporate faster because of their internal energy sources and ensuing envelope expansion. These trends are illustrated in Fig. 5. We found no significant correlation between the dynamical and the chemical properties of clusters.

The fact that there are good correlations between the cluster morphology and global variables, such as their distribution in the Galaxy, or mass, indicate that the core collapse and its reversal are a "once in a lifetime" affair, and that the clusters do not recover back to a King-model state within Hubble time. Unless, that is, if the relative durations of King-model and PCC phases in such tentative collapse-and-recovery cycles depend on the tidal shocks and mass in a suitable way, but that seems to be too contrived.

Finally, the power-law slopes in the cusps are generally close to -1, but tend to be shallower, and can be as low as -0.7 or so (the measured value depends somewhat on the radial range used: the slopes are shallower at the lower radii because of the seeing, and steeper at the larger radii, where the King-model envelope or the tidal cutoff begins). Djorgovski & King (1986) find the median value for the slopes to be around -0.9, but with a large scatter which is real. This may reflect real differences in mass spectrum between the cusps, which in turn may reflect IMF differences between the clusters.

Thus, we are now getting a good handle on the dynamical structure of Galactic globular clusters. We could use more kinematical information, but as for the surface photometry, it is unlikely that we can do much better from the ground. Some seeing-compensation schemes are worth a try, but the final word in high resolution observations of cores will come from the Hubble Space Telescope. The HST should enable us to do star counts deep into the cores, where detectable mass segregation may exist; we may even detect the true core radii or unusual central objects in the PCC clusters. Even more interesting would be to look in the cores of those puzzling high-concentration King-model clusters which should have collapsed by now. So much about the cores, but there are other interesting projects which can be done from the ground.

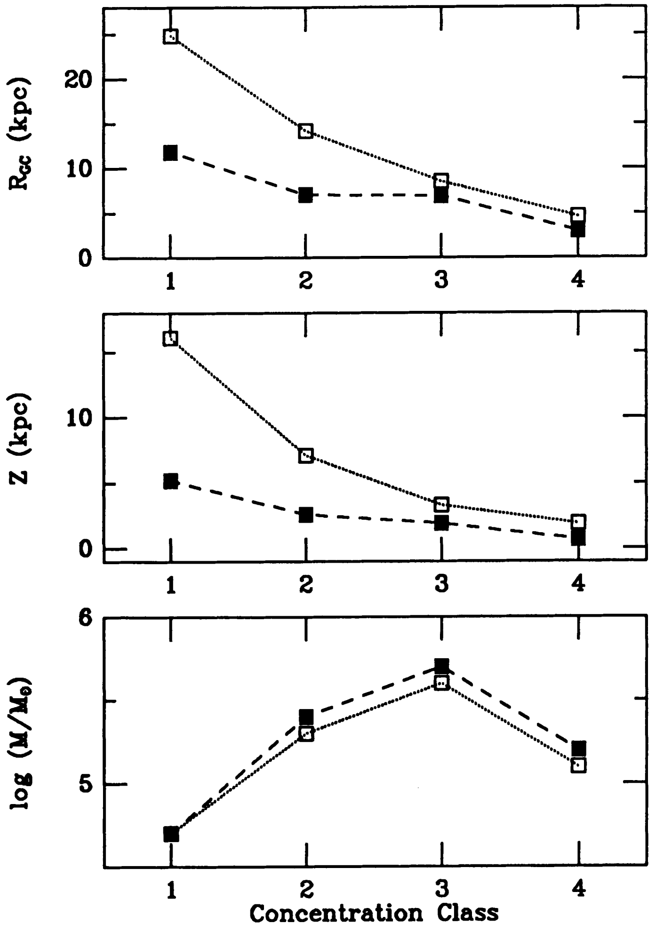

Fig. 5. Dependence of the galactocentric radius (top), distance from the Galactic plane (middle), and the cluster mass (bottom), as functions of cluster concentration. The sample of Djorgovski & King (1986) was divided in four approximately equal groups ($\sim$ 30 clusters in each group), in increasing order of concentration: class 1 are the King-model clusters with $c \leq 1.2$, class 2 are with $1.2 < c < 1.7$, class 3 with $c \geq 1.7$, and class 4 are the PCC and possible PCC clusters. Solid squares and dashed lines indicate the median values for the groups, and open squares and dotted lines the mean values. More concentrated clusters tend to be closer to the Galactic center and plane, and tend to have higher masses, except that for the PCC clusters the mass is lower again. The cluster masses were computed from their extinction-corrected visual luminosities by assuming a universal $M/L = 3$.

https://doi.org/10.1017/S0074180900042583 Published online by Cambridge University Press

First, we can move on to other galaxies: Magellanic Clouds, M 31, and the dwarf spheroidals near our Galaxy. The Magellanic clusters should be easy, they are only a few times farther than the typical Galactic globulars, and should be well resolved. They present a nice complement to the Galactic system: they have a wide spectrum of ages, they are generally less massive, and thus have shorter dynamical time scales and faster evolution, and they do not suffer the strong tidal shocks like the Galactic globulars. A good census of PCC clusters and the cluster morphology in the Magellanic Clouds may gain us some new, valuable insights in the dynamical evolution of clusters in general, and in particular solve the problem of collapse-and-recovery *vs.* the collapse-only-once. Some surveys have already started (Mateo & Hodge, or Papenhausen & Schommer, this conference; Meylan & Djorgovski, in preparation).

The M 31 clusters present a more difficult challenge, because they are much less resolved. Here the problem becomes more similar to the surface photometry of galaxies, and we can use the corresponding software and methods: measure the ellipticity and position angles of isophotes easier than what we can do for the Galactic clusters, etc. The M 31 globulars are bright, and we can obtain sufficiently high S/N data as to attempt some seeing deconvolutions. As a family, they seem to be somewhat different in their stellar population properties from the Galactic globulars; comparing their dynamical properties would be very interesting. By the way, in the terms of the sampling and angular resolution, observing M 31 globulars from the ground is practically equivalent to observing globulars in the Virgo cluster with the HST. An example of surface photometry of a bright M 31 cluster Mayall II is shown in Fig. 6.

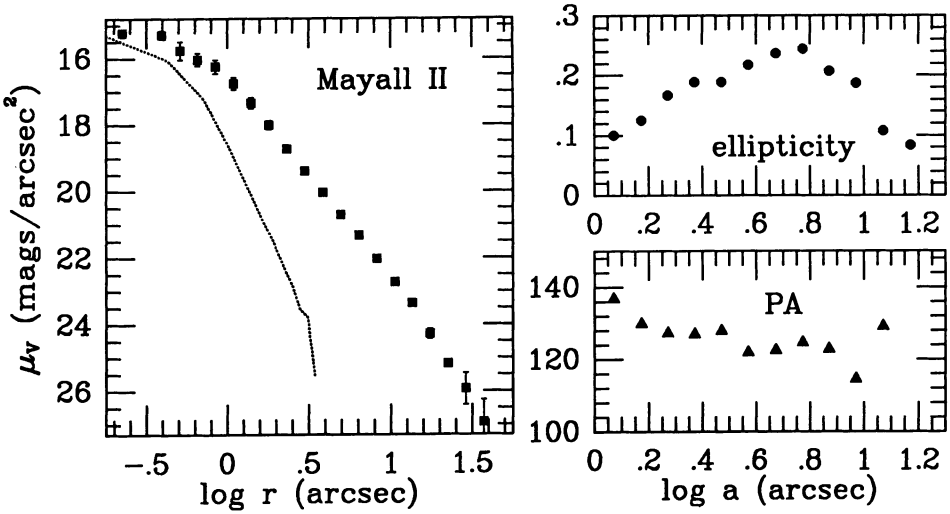

Fig. 6. Left: Circularly averaged surface brightness profile of the M 31 cluster Mayall II, plotted as a function of radius, in 2:1 log-log scale. The dotted line indicates the PSF. Right: Ellipticity and major axis position angle profiles, plotted as functions of the semi-major axis. The cluster giants are marginally resolved in a good seeing. The data were obtained with the KPNO 4-m telescope, and the exposures lasted less than 1 minute. Seeing deconvolution work on this and other M 31 clusters is now in progress (Bendinelli *et al.*, in preparation).

One disreputable project on which we should try our luck again, but with modern data and technology, are the color (or stellar mass) gradients. They could be caused by equipartition, but most clusters may still not be old enough for the effect to be appreciable. The PCC clusters may be more hopeful targets. The early reports of color gradients by Chun & Freeman (1979) are now widely regarded as being spurious, and caused by a preferred centering of photoelectric apertures on chance lumps of red giants near the cluster centers; the effects reported by Scaria & Bappu (1981) probably have a similar cause. However, several authors at this conference reported radial dependence in the fraction of blue stragglers... The subject is still wide open. The color gradients can be measured in the same way as described above for the surface brightness profiles, but by reducing two different bandpass frames at once: assure that the same cluster center is used for both frames, and compute the mean colors in the corresponding annuli and sectors. Since the same stars cause profile fluctuations in both frames, this procedure would assure that there is a good match, and provide the correct error-bars. Alternatively, one can smear both frames to have the identical PSF's, carefully register them, and produce a color frame, from which the color profile can be extracted.

There is another approach, which we may call "star stripping". Good CCD imaging data and PSF subtraction software afford us this new opportunity. First, it would be interesting to separate the giants from the unresolved background, and see if both groups have the same density distributions, and whether the star counts and the surface brightness profile (=luminosity-weighted star counts) have the same shape. It is essential to have a good handle on the completeness of star subtraction, both as a function of magnitude, and the distance from the cluster center. This is easily doable with *DAOPHOT* and similar programs, by inserting artificial stars in the data, and recovering them in repeated analysis. Comparing the "giants" and the "dwarfs" profiles may show some indications of a mass segregation. Or, one can isolate the stars by their color, or both color and magnitude (e.g., blue HB stars). The simplest thing would be just to remove the brightest giants, which cause most of the profile fluctuations, and get the color profile of the remainder in one of the ways described above.

Finally, one neglected aspect of globular-cluster structure are the tidal radii, which are measurable only through star counts. There is much space and need for improvement here: most of the existing measurements date from the old work by King and collaborators, when the counts were done by eye (thus the lack of enthusiasm for follow-up work). There is no reason why the star counts should not be done automatically, and better. We already have the necessary plates, the scanners, and the software. Some pioneering attempts were already done by Herzog & Illingworth (1977), and Irwin & Trimble (1984). A good way to do it would be to remove most of the foreground stars by color-magnitude selection. This approach should be much more powerful and efficient than the counts by eye. We should be able to measure or constrain the tidal radii for a much larger number of clusters than heretofore available. In the cleanest cases (rich clusters at high latitudes), we may even be able to examine the *azimuthal* structure of tidal cutoff regions, and probe directly the shapes of their Roche surfaces.

I would like to thank to my good collaborators, on whose work most of this review was based, and in particular Ivan King, Abe Oren, Howard Penner, and

Carl Vuosalo. The data for our work were obtained at Cerro Tololo and Lick observatories, whose staff provided invaluable help in numerous observing runs. Discussions with David Chernoff, Haldan Cohn, Jeremy Goodman, Josh Grindlay, Piet Hut, Shogo Inagaki, Phylis Lugger, Georges Meylan, and many others were most valuable and stimulating. Partial support from Harvard University is also gratefully acknowledged.

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DISCUSSION

BAUM: We derived core radii for 13 globular clusters in M 31, which would be of interest to compare with your M 31 data. Our results were obtained with a TI 800x800 CCD on the 1.8 meter Perkins telescope and were reported at the June 1983 AAS meeting. Observed profiles were matched with King functions convolved with the PSF.

KING: Even when an ultraviolet image is not available, one can be synthesized through pixel-by-pixel combination of B and R images. It is essential to make the point-spread functions identical, but then the synthesis works quite well and makes a smoother image with the individual red giants nicely suppressed.

COHEN: Perhaps we could use a very small telescope with poor spatial resolution but large spatial coverage to measure a new set of tidal radii for clusters in relatively uncrowded fields. Also there are new tidal radii for NGC 6229 and NGC 7006 in my recent AJ paper.

DJORGOVSKI: I do not think that CCD imaging with a wide head telescope would work because of the heavy foreground pollution. Namely, you will end up with at least one foreground star in each pixel. Steve Kent recently did such imaging of M 31, which is an even easier case and he ran into this problem.

BAILYN: We have tried to do "star stripping", of the kind you suggest, on NGC 6712 using DAOPHOT, and we run into bigger problems than one might expect, due primarily to the radial dependence of the background light. Current software is not yet able to deal with this.

DJORGOVSKI: That is an important remark, but the problem should be curable.

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ALTNER: I want to point out that IUE has shown color gradients where the central regions of several clusters (M 15, M 92) have shown an excess of blue objects. This is probably a selection effect.

COHN: Lugger, Grindlay, Bailyn, Hertz and I have found that a number of post-core collapse clusters have central surface brightness profiles with slopes significantly flatter than -1. We determine these slopes by fitting seeing-convolved power laws to the central parts of the profiles. M 15. for example, has a central slope of -0.64, which happens to agree exactly with a post-collapse evolution model, reported by Y. M. Lee at this conference, that includes nonluminous white dwarfs. We take our slopes as evidence for nonluminous remnants, in cluster cores, that are somewhat more massive than the stars that dominate the luminosity profile.

MENDEZ: We have also found that the nuclei of some clusters (NGC 6266, 7099, and others) are bluer than the whole cluster, as Bruce Altner pointed out.

RICHER: Didn't Peterson in a paper earlier this year say something about color gradients in clusters?

PETERSON, C.: Yes. The conclusion that was stressed from the study of concentric aperture photometric colors was that apparent color gradients are produced by the random spatial distribution of these bright giant stars or even field stars. The concentric aperture photometry has not produced evidence for real radial variations in color due to radial variations in the stellar population.

KRON: Electronic camera photometry is as good as counts in the outer regions of globular clusters.

FUSI PECCI: In a paper published in 1981 (Buonanno et al., Astron. Astrophys.) we have applied to M 5 the technique here suggested by Djorgovski's information on possible color gradients. In particular, using photographic plates, we have obtained both the CMO and the integrated magnitudes and colors over spots and annuli to simulate the observations made by Chun and Freeman (1979) which led them to claim the existence of a strong color gradient within that cluster. Then by "taking off" star-by-star (in a sequence, starting with the brightest) we have shown that the effect they found was due to sampling rather than to intrinsic properties of the cluster.

KING: I am sorry to contradict Gerry Kron but surface photometry in the outer parts of clusters is statistically very much inferior to star counts.