THE ASTROPHYSICAL JOURNAL, **277**:L49–L52, 1984 February 15

SURFACE PHOTOMETRY IN CORES OF GLOBULAR CLUSTERS

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Received 1983 September 20; accepted 1983 November 9

ABSTRACT

Photographic ultraviolet surface photometry has been carried out in nine southern globular clusters, to look for a brightness excess like that in M15. The effect is found in three of the clusters, and possibly in a fourth. Their profiles are consistent with the predictions of theory for a post–core-collapse stage. The core peak phenomenon does not seem to correlate with the presence of strong X-ray sources.

Subject headings: clusters: globular — stars: stellar dynamics — X-rays: sources

Although the density distributions in globular clusters appear to follow a very simple pattern (King 1962, 1966), one observed anomaly has always stood out. The rich, concentrated cluster M15 (NGC 7078) has an excess of brightness in its central regions (Newell and O'Neill 1978; Aurière and Cordoni 1981) relative to the smooth, shouldered core that all other clusters have seemed to show.

Ad hoc attempts have been made to model the central density peak in M15 by adding a black hole (Newell, Da Costa, and Norris 1976) or a clump of neutron stars (Illingworth and King 1977). But it is also tempting to connect such a central peak with the outstanding anomaly on the theoretical side of cluster structure. Both simulations and analytic theory (for a review, see Lightman and Shapiro 1978) have firmly predicted a runaway collapse of cluster cores on a time scale short enough that it should already have happened in many clusters. Yet there is little evidence to suggest collapsed cores. Only in M15 is the central brightness excess clear cut (although its interpretation is not). Otherwise, Aurière (1982) has suggested a small excess in NGC 6397, star counts in the central part of NGC 1851 (Bahcall, Lasker, and Wamsteker 1977) show a barely significant excess, and several observers have remarked qualitatively on an apparent brightness peak at the center of NGC 6624 (Bahcall 1976; Faÿ *et al.* 1977; Harvel and Martins 1977; Canizares *et al.* 1978).

To complicate the issues even further, three of these clusters contain strong X-ray sources. Although the observational evidence now favors such sources being interacting binaries (Grindlay *et al.* 1984), an earlier alternative suggestion was that they are central black holes (Bahcall and Ostriker 1975; Silk and Arons 1975); in the present context, these might be regarded as the product of core collapse.

Such a breadth of speculation and surmise cries out for facts. We therefore undertook a careful examination of the centers of a number of other clusters to see if the M15 effect exists elsewhere. The clusters were chosen for the characteristics that distinguish M15; they include all five clusters listed by Peterson and King (1975) as having a central concentration $\log r_t/r_c$ greater than 2.00 (NGC 104 [47 Tuc], 1851, 5824, 6093 [M80], and 7099 [M30]), plus the X-ray clusters NGC 6440, 6441, and 6624; NGC 6681 (M70) was added because of its very small core radius.

The technique chosen was photographic surface photometry. Plates were taken at the Ritchey-Chrétien focus of the Cerro Tololo Inter-American Observatory (CTIO) 4 m reflector ($6''.56$ mm^{-1}), on IIIa-J emulsion, so as to minimize the effect of plate grain. The ultimate limitation on accuracy, however, is sampling error due to the photometric dominance of a small number of red giant stars; the plates were therefore taken in the ultraviolet (UG1 or UG2 filter) in order to suppress the effect of the red giants as much as possible. (The single exception was NGC 6440, which was observed in the red [IIIa-F + GG495] because interstellar absorption makes it too faint in the UV.) From the data given by Peterson and King (1975), exposures were calculated that would give central densities of about 3 in each cluster image. Some of the exposures, taken in moonlight, show a sky background; those taken in the dark do not. The standard CTIO sensitometer spots were impressed during each exposure.

The plates were traced on the Berkeley PDS microdensitometer, using a 1024^2 raster of 20×20 μm pixels. After removal of interfering bright foreground stars (typically one or two per cluster), all densities were converted to intensity, using the corrected spot intensities given by Schweizer, Gonzalez, and Saa (1980). Each characteristic curve was examined individually, and no densities were used that were judged to be too far down on the toe of the curve or too close to the sky level, whichever was the limitation.

The center of each cluster image was found by mirrored autocorrelation of a moderate-sized central region. We have examined the chosen centers on contour diagrams of the clusters and believe that most are accurate to a small fraction of an arc second and that they are better than an arc second even in the most ragged cases. We emphasize that we did not center on the brightest single point in a way that might falsely sharpen a peak; any error in our centering procedure would tend to flatten a peak instead. After centering, each image was divided into concentric annuli, and the light intensity was summed in each annulus and converted to a mean surface brightness. We thus have the equivalent of photoelectric surface

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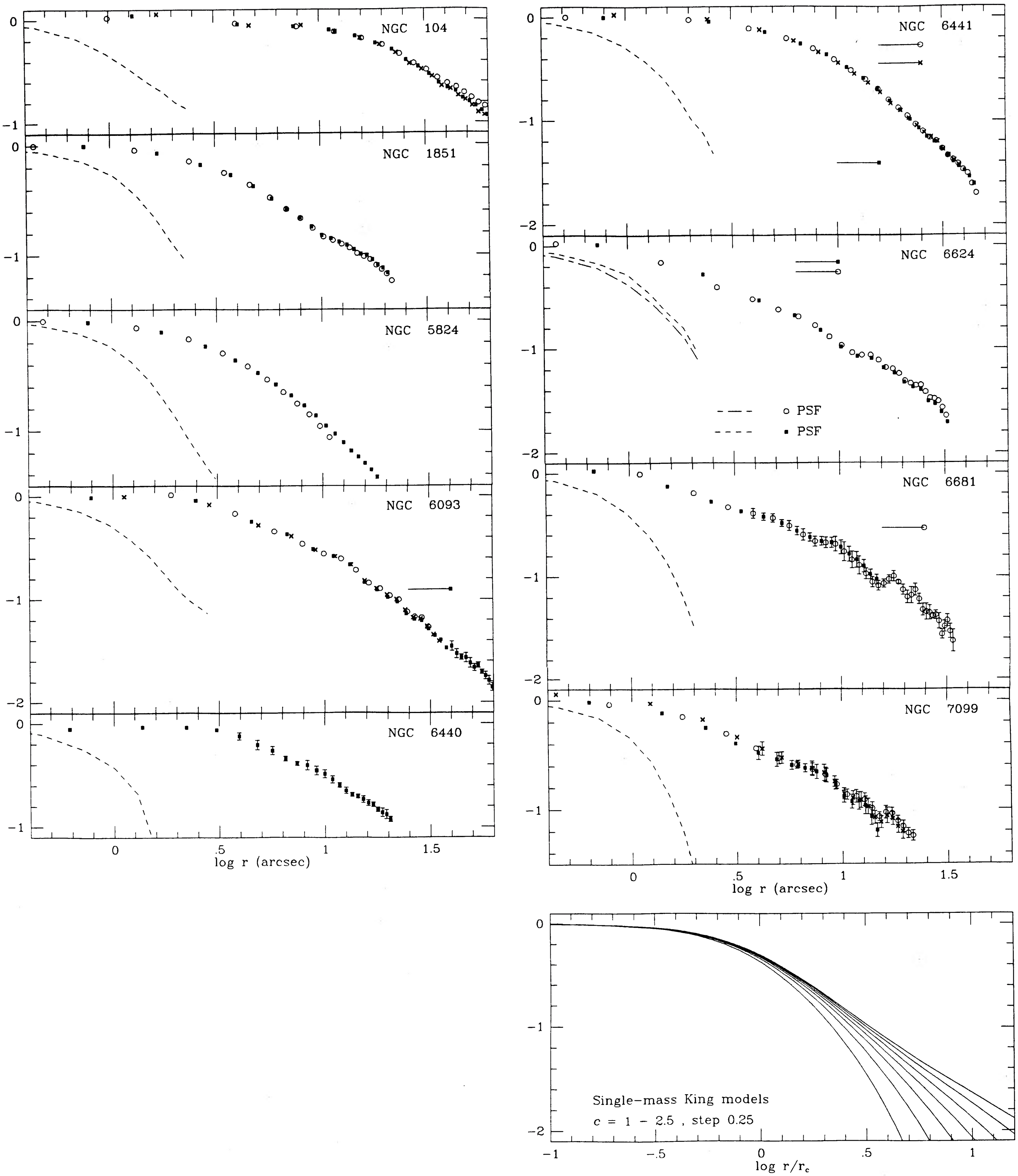

FIG. 1.—Radial surface-brightness profiles of nine globular clusters. The vertical scale is log of surface brightness, relative to center. Different symbols refer to different plates, dashed curves to point-spread functions. Sky levels are shown when they are significant. The bottom right panel shows a set of King (1966) models on the same scale.

photometry, but with a resolving power and a pattern that are normally unreachable by photoelectric photometers. As a measure of accuracy, we followed Newell and O'Neill (1978) in dividing each annulus into eight sectors, and we used the residuals of the sector means from the annulus mean to derive a mean error for the latter.

Since several of the clusters have quite sharp centers, a point-spread function (PSF) was determined for each plate, by tracing a well-exposed star image.

The results will merit extensive discussion, including comparison with other data and fitting of dynamical models, but the bare data are of such interest that we consider them worthy of rapid communication. Profiles of the nine clusters are shown in Figure 1. In each graph, the individual plates are shown as different symbols; the error bars are described above but are shown only when they are significantly larger than the points. The dashed lines are the PSFs; for NGC 6624, the two PSFs differ enough that both are shown. When the sky level that was subtracted out was appreciable, it is shown as a horizontal line.

The points presented are sometimes oversampled; the annulus spacing is equal to 1, 2, or 4 times the half-width at half-maximum of the PSF. (The spacing was 4 HWHM for NGC 104, 2 for NGC 6093, 6441, and 6624, and 1 for the rest. The choice was made in such a way as to display the maximum possible information without hopelessly overcrowding the points.) And of course the points representing different plates are redundant in the same sense.

The figure also includes single-mass King (1966) models plotted on the same scale. Five of the nine cluster profiles can be fitted by high-concentration curves of this family, but NGC 6093 is a marginally poor fit, and NGC 6624, 6681, and 7099 do not fit at all. (In addition, NGC 1851 has a bump that we will return to below.)

To illustrate this distinction, we show a fit in Figure 2 and an honest but hopeless attempt in Figure 3. For NGC 5824 (Fig. 2) the best fit is with a concentration index $c \equiv \log r_t/r_c = 1.75$, whereas Peterson and King (1975) give $c = 2.51$. Their value comes, however, from separate fittings of r_c from data at the center and r_t from data in the envelope, without any attempt at an overall fit. Our present curve is in excellent agreement with the core data that we have found in their working files. We suspect, moreover, that the small discrepancy between the $c = 1.75$ and 2.5 curves in this inner region may fall in the range that is embraced by the difference

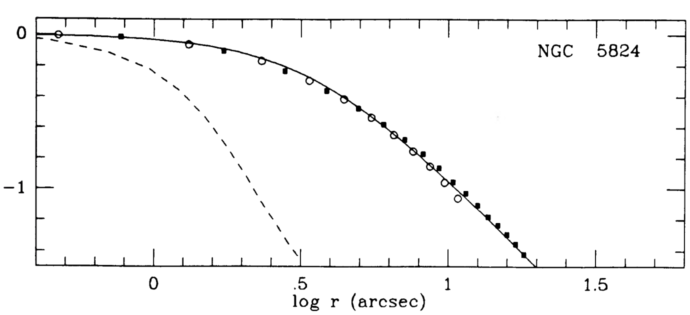

FIG. 2.—Fitting of a King (1966) model ($c = 1.75$) to NGC 5824.

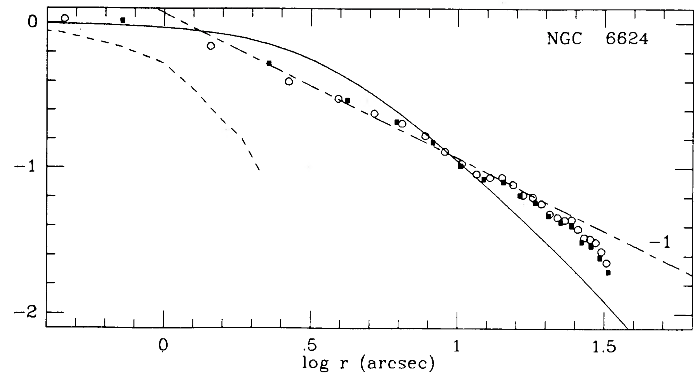

FIG. 3.—Comparison of surface densities in NGC 6624 with same model used in Fig. 2. The "−1" line is explained in the text.

between single-mass models and the more realistic multi-mass models that should eventually be used.

For NGC 6624, however, there is no fit at all (Fig. 3). The points climb continuously toward the center, until they are flattened by the seeing disk—just as in the case of M15—except that the present results are more detailed and striking.

Also shown in the figure, as a matter of considerable interest, is a line of slope -1, which is very close to the projected density profile corresponding to the singular isothermal law that is predicted by several post-collapse theories (see, for example, Inagaki and Lynden-Bell 1983; Heggie 1984; and Goodman 1984). It is tempting to suggest that M15 and three or four of our sample are post-collapse clusters.

We note, at the same time, that our data cannot exclude the slightly shallower logarithmic slope that would surround a black hole (Bahcall and Wolf 1976, 1977), nor the slightly steeper slope of a core during the process of collapse. The latter case seems *a priori* unlikely, however, because the actual collapse of a core is quite rapid, while the post-collapse stage, in which central binaries support an isothermal envelope around them, is of long and perhaps unlimited duration.

We note also the clear observational indication that a central brightness peak of the kind discussed here is not connected with the presence of a prominent X-ray source. NGC 6440 and 6441 have X-rays, with a normally shaped central core; NGC 6681 and 7099 have anomalous brightness peaks, but no X-rays.

As for central black holes, there are two arguments to the contrary (beyond Occam's razor). First, current theories of the consequences of core collapse (as referred to above) suggest the orderly maintenance of a singular isothermal core, rather than a coalescence into a black hole. Second, a black hole would be likely to emit X-rays, as it interacted with its surroundings, and the lack of correspondence between anomalous cores and X-ray sources has just been pointed out.

Finally, we note the apparent extra shoulder in NGC 1851, from 10″ to 20″ radius (or, conversely, perhaps a dip around 10″). Even though the points plotted are two-fold redundant (from the two plates) and also two-fold oversampled, the trend of the rises and falls is very smooth and might possibly be significant. Again, the cause might be related to the mixture of stellar masses. The hump is reminiscent of the fitting of M3 by Da Costa and Freeman (1976) with a multi-mass model.

The profile of NGC 6681 also has prominent bumps in its outer parts. Here, however, we have verified that the irregularities are due to individual bright stars (presumably foreground) that were not removed in our conservative cleaning of the images.

The authors regret that their AAS abstract concerning this project (King and Djorgovski 1983) was composed at a premature stage and fails to state the present striking conclusions. It should be disregarded.

We are grateful to François Schweizer for taking several plates, for allowing some of these clusters to be used for engineering tests of the camera, and especially for initiating and carrying out the recalibration of the sensitometer. We also thank Piet Hut for discussions of core-collapse theory, and Robert D. Mathieu for a critical reading of the manuscript. S. D. was supported during part of this time by a University of California fellowship. The entire project has been supported by NSF grant AST 80-20606.

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