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A PRELIMINARY SURVEY OF COLLAPSED CORES IN GLOBULAR CLUSTERS

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ABSTRACT

This is a preliminary report on surface photometry of the major fraction of known globular clusters, to see which of them show the signs of a collapsed core. We find more than 20 examples, or one-fifth of the total. Core classifications are given for all clusters examined. The fraction of collapsed-core clusters may be an index of how long a cluster takes to reexpand after collapse.

Subject headings: clusters: globular — stars: stellar dynamics

I. INTRODUCTION

A focal problem today in the dynamics of globular clusters is core collapse. It has been predicted by theory for decades (Hénon 1961; Lynden-Bell and Wood 1968; for a review, see Spitzer 1985), but observation has been less alert to the phenomenon. For many years the central brightness peak in M15 (King 1975; Newell and O'Neil 1978) seemed a unique anomaly. Then Aurière (1982) suggested a central peak in NGC 6397, and a limited photographic survey of ours (Djorgovski and King 1984, hereafter Paper I) found three more cases, including NGC 6624, whose sharp center had often been remarked on (cf., e.g., Canizares *et al.* 1978).

But even if it is assumed that the central peaks of brightness are indeed collapsed cores—and we shall so assume in the present *Letter*, even if only for convenience of terminology—they still seemed few. Moreover, the observing list of Paper I had been chosen in a highly selective way, aimed at finding collapsed cores: the clusters all had high central densities, and several of them were chosen because they contained X-ray sources. (One of the conclusions of Paper I, however, was that the X-ray phenomenon is probably not directly related to core collapse.) For these and various other reasons we set out to make a systematic survey of globular cluster cores. The present *Letter* is a preliminary report on the results of that survey. (An earlier paper by Djorgovski and Penner 1985) was based on some of this same material.)

II. OBSERVATIONS

All our observations were short direct exposures with CCDs. At Lick Observatory we used a TI 500 × 500 chip and a GEC 575 × 385, on the 1 m Nickel reflector. The only filter available at Lick was red. At CTIO we used a GEC 575 × 385, with *B*, *V*, and *R* filters, and an RCA 512 × 320, with *U*, *B*, *V*, *R*, and *I* filters, on the 1.5 m reflector. In the CTIO observations we tried to concentrate on the shortest practicable wavelengths; but faintness, reddening, and poor short-wavelength sensitivity often kept us from observing in *U* or even in *B*. All four cameras had scales of the order of 0".4 pixel^{-1} and our field sizes were around 3′.

For calibration of the images we used the usual collection of bias frames, dome flats, and blank-sky exposures; our procedures will be described in detail in a later more complete publication. We also observed standard stars for magnitude zero-points (when the sky was photometric) and for eventual calibration of our color systems. For the zero points, however, we shall probably rely more heavily on fitting our cluster profiles to photoelectric measures of the same clusters taken from the literature.

We observed 113 clusters in all, 32 of them with more than one chip, and 15 of them from both hemispheres. Twenty-eight clusters were observed in only a single color, the others mostly in two or three colors, and a few in all five colors.

The many hundreds of cluster images will take much future effort to reduce, and the combination, zero-pointing, color calibration, and discussion of the results will take even longer. What we have done first, however, is to derive at least one good radial profile for each cluster. Our method was as in Paper I: after finding a center of symmetry and removing obvious foreground stars, we divided the cluster into concentric annuli and used the total light in each annulus to derive a mean surface brightness. Again we divided each annulus into eight sectors, so as to derive an empirical sigma for each point on our profile.

The Lick profiles are of course in the red band, but for the CTIO material we used *U* and *B* images whenever possible. From these profiles we are able to distinguish a number of collapsed-core clusters, a further list of possible ones, and a list of clusters whose cores clearly belong to the "normal" category—by which we mean a core that fits a King model of moderate to high concentration.

The CCD images are unfortunately not always suitable, for very poor clusters or for clusters with large cores. Since the latter are easily studied by other means, we augmented our own CCD profiles by collecting from the literature a number

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TABLE 1

Classification of Cluster Cores

Name	Type[a]	Source[b]	Name	Type[a]	Source[b]	Name	Type[a]	Source[b]	Name	Type[a]	Source[b]
104	n	pg	Pal 4	n	scK	6366	n	scK	6637	n	Kr
288	n	scK	6093	n	B	6380	c?	V	6638	n	r_G
362	c?	V	6101	n?	V	Trz 1	c	V	6642	c?	B
1261	n	V	6121	n	scK	Ton 2	n	B	6652	n?c?	V
AM1	n?	B	6139	n	V	6388	n	V	6656	n	B
1851	n	pg	6144	n	Kr	6397	c	B	Pal 8	n	B
1904	c?	V	Trz 3	n	SS	6401	n	B	6681	c	pg
2298	n	V	6171	n	B	6402	n	r_G	6712	n	Kr
2419	n	r_G	6205	n	pe	Pal 6	n	V	6715	n	V
2808	n	U	6218	n	pe	6426	n?	B	6717	c?	B
Pal 3	n	scK	6229	n	r_G	6440	n	pg	6723	n	B
3201	n	scK	6235	n	B	6441	n	pg	6749	n?	r_G
Pal 4	n	scK	6254	n	pe	Trz 5	n	r_G	6752	c	B
4147	n?c?	r_G	6256	c	B	Trz 6	c	B	6760	n	r_G
4372	n	B	Pal 15	n?	scH	6453	c	B	Trz 7	?	B
4590	n	Kr	6266	c?	V	6496	n?	V	6779	n?	r_G
4833	n	SS	6273	n	B	Trz 9	c	V	Pal 10	?	B
5024	n	pe	6284	c	U	6517	n	r_G	1927-30	n	scP
5053	n	scK	6287	n	B	6522	c	B	6809	n	scK
5139	n	scK	6293	c	U	6528	n	B	Trz 8	n?	SS
5272	n	pe	6304	n?	B	6535	?	r_G	Pal 11	?	B
5286	n	V	6316	n	B	6539	n	Kr	6838	n	Kr
5466	n	scK	6325	c	B	6541	n	V	6864	n	V
5634	n	r_G	6333	n?	scK	6544	c?	B	6934	n	r_G
5694	n	V	6341	n	r_G	6553	n	B	6981	n	r_G
I4499	n?	scP	6342	c	B	6558	c	U	7006	n	r_G
5824	n	pg	6352	n?	B	I1276	?	r_G	7078	c	B
Pal 5	n?	SS	6355	c	B	Trz 11	n?	R	7089	n	pe
5897	n	scK	6356	n	r_G	6569	n	B	7099	c	pg
5904	n	pe	Trz 2	c	B	6584	?	B	Pal 12	n	V
5927	n	B	HP	c	B	6624	c	pg	Pal 13	n	scO
5946	c	B	6362	n	scK	6626	n?c?	r_G	7492	n	scK
5986	n	B									

[a] Type.—c = collapsed; n = normal; c? = probable/possible; c; n? = probable n; n?c? = weak indications of c; ? = unclassifiable.

[b] Source.—U, B, V, R or r_G = CCD image in that band (r_G is Lick red); pg = uv photographic profile (Paper I); scK = star counts (King *et al.* 1968); scH = star counts (Harris and van den Bergh 1984; scP = star counts (Peterson 1976); scO = star counts (Ortolani *et al.* 1985); pe = photoelectric; SS = Sky Survey.

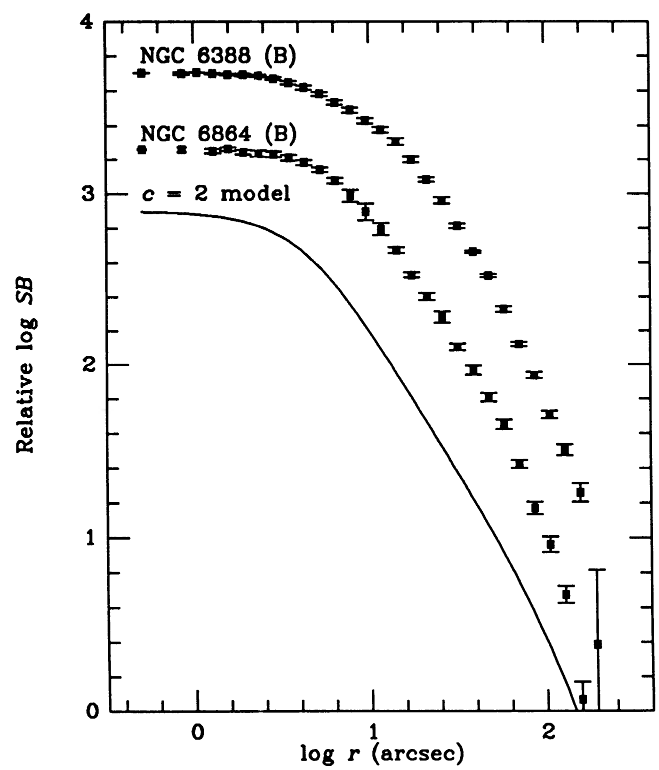

Fig. 1.—Photometric profiles of two high-concentration clusters that are well fitted by King models, along with model curve for $c = 2.0$

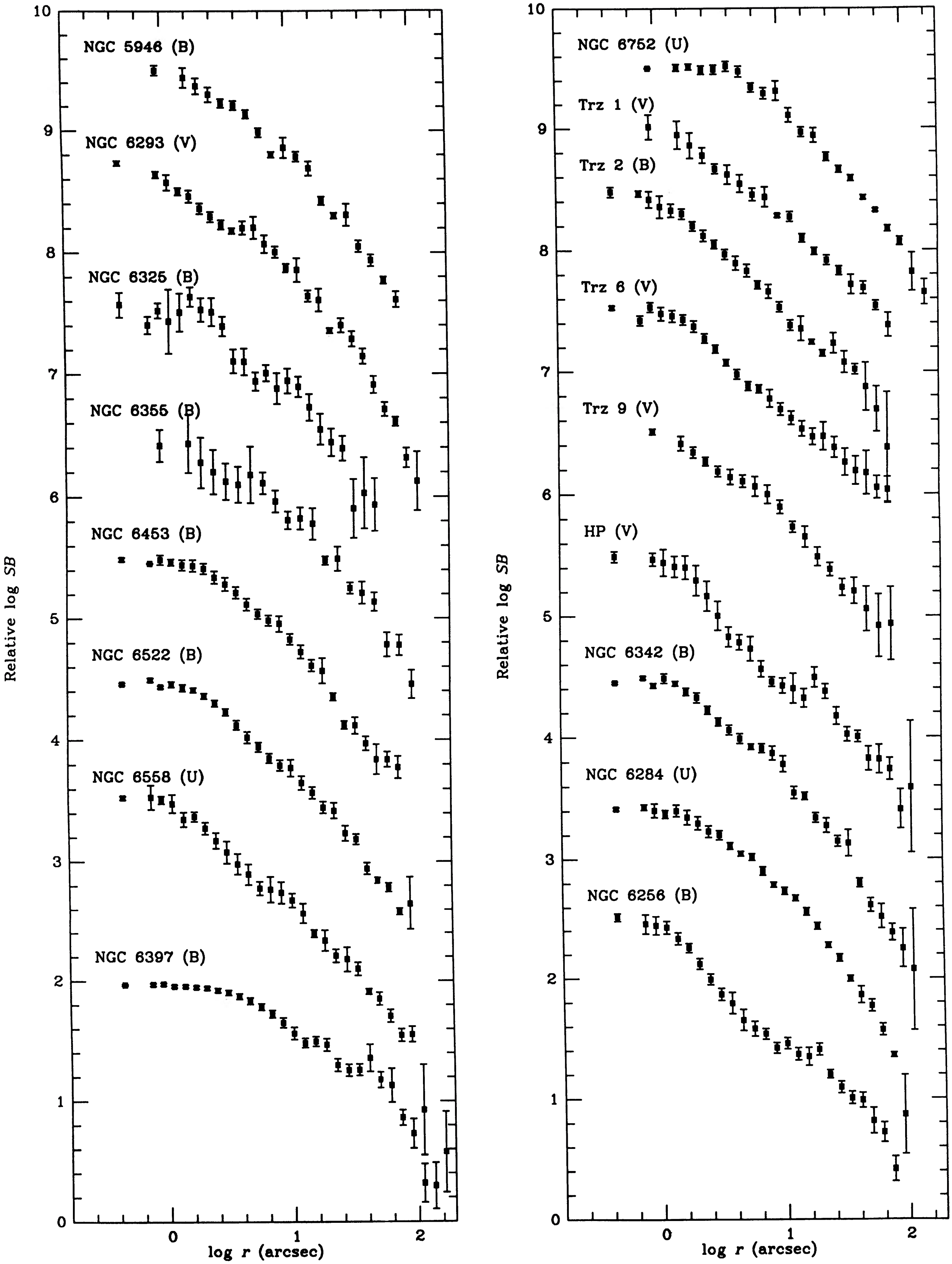

FIG. 2.—Photometric profiles of 17 clusters that appear to have collapsed cores (marked "c" in Table 1)

of star-count profiles (King *et al.* 1968; Peterson 1976; Harris and van den Bergh 1984; Ortolani *et al.* 1985), as well as photoelectric profiles by King (1966) and electronographic profiles by Kron, Hewitt, and Wasserman (1984). In a few cases we judged normality by eye estimates on one of the Sky Surveys.

All classifications were done by both authors independently, and differences were reconciled by discussion.

III. RESULTS

In Table 1 are the results of our preliminary survey. Successive columns give the NGC number or other designation, our classification, and the type of observation on which it is based. The source of star-count observations is coded by the initial of the first author of one of the papers referred to in the preceding paragraph. Of the 129 entries in the table, 21 are classified "c", seven "c?", three "n?c?", 78 "n", 14 "n?", and six "?".

To illustrate our results we show first, in Figure 1, two high-concentration clusters that fit King models rather well. By contrast, in Figure 2 we show most of the clusters that are marked "c" in Table 1. (Profiles of NGC 6624, 6681, 7078, and 7099 have appeared elsewhere [Newell and O'Neil 1978; Djorgovski and King 1984].)

IV. DISCUSSION

At IAU Symposium 113 (Goodman and Hut 1985) there were extensive discussions of the theory of core collapse. Among the puzzling questions that emerged were why so few clusters showed collapsed cores, and why those that did were not necessarily the clusters with the densest centers or the shortest relaxation times.

We can now look at better statistics. Table 1 has 123 clusters, other than those marked with a mere "?". Of these, we find that 21 show collapsed cores; if we give half-weight to the seven that are marked "c?", this is $24\frac{1}{2}$ out of 123, or about one in five. Is one to judge then that only one cluster out of five is dynamically advanced enough to have undergone core collapse? We believe not, because the dynamical time scales of individual clusters do not agree with such a conclusion. We will not be in a position to assign absolute time scales to all the clusters until we have zero points on our photometry, but data for many of them are already available in the compilation of Peterson and King (1975).

Thus we can see that NGC 5824, which shows a completely normal profile, has a central relaxation time of only 2.5×10^7 yr. In general, core collapse in any cluster should take place about $3t_{rh}$ from now (Spitzer 1975); since $t_{rh} \approx 10t_{rlx,c}$, this is less than a billion years from now. If NGC 5824 were a unique example, it might be reasonable that we see it at a stage so precariously close to core collapse; but there are many other similar clusters, and it is quite implausible that we live in an era when they have all come simultaneously to the verge of catastrophe.

In addition, there is no obvious correlation between showing a collapsed core and having a short relaxation time. What seems much more plausible to us is that clusters such as NGC 5824 have undergone core collapse some time in the past but have now reexpanded to a normal state, as a result of energy input by the binaries that form in an ultradense core (see Ostriker 1985 and many other sources). Since the binaries eventually eject themselves from the cluster through recoil in close encounters with single stars, the cluster is then free to collapse again. (We note that during the collapse process a cluster looks normal except during a final stage that, although much studied theoretically, is too brief to be observed.) It therefore seems quite possible that the 1:5 proportion of collapsed cores that we see is simply an index of the fraction of time that a cluster takes to regain a normal profile, in this cycle of collapse and reexpansion. We cannot, however, reject Larson's (1984) suggestion that unseen massive objects may be the source of stabilization.

Since many of the curves in Figure 2 have a straight portion that suggests a power law—as do many theoretical scenarios—we fitted power laws to 17 "c" cluster profiles for which we have CTIO *UBV* CCD data. To avoid the seeing disk we began our radial fitting range at 2″–3″, and we stopped at 20″–30″ to avoid the eventual steepening into a King-model envelope. The individual power-law slopes are uncertain by 0.03 to 0.20. Their median is -0.90, with quartiles a few hundredths on either side. This slope may be significantly shallower than the singular isothermal -1, and it seems rather steeper than the -0.75 that is predicted by most black hole models.

Another striking result is that the collapsed-core clusters are much more concentrated to the Galactic center. Distances are not available for all of the clusters in our study, but for 20 "c" and "c?" clusters the mean and median galactocentric distances are 4.2 and 2.7 kpc, respectively; for 91 "n" and "n?" clusters the corresponding distances are 14.8 and 7.6 kpc. This difference might result from the greater tidal shocks near the Galactic center, as predicted by Chernoff, Kochanek, and Shapiro (1986).

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