OBSERVED SURFACE DENSITIES IN GLOBULAR CLUSTERS

Ivan R. King
Astronomy Department
University of California, Berkeley

ABSTRACT. This review of observations is oriented toward the problem of core collapse in globular clusters. After a brief discussion of methods of determining surface densities, recent results are cited which show that the central brightness peak seen in M15 also appears in several other clusters. The central peaks of brightness are interpreted as the result of core collapse, which theories have repeatedly predicted. If binaries stabilize the collapsed core, the cluster should follow a Hénon model. In two of the three cases tested this model is a reasonable fit. Remaining theoretical questions are listed, as are observational needs.

1. INTRODUCTION

I am glad to be able to open this Symposium by presenting globular clusters from an observational point of view. There are several reasons for saying this. First, the symposium is indeed devoted largely to globular clusters rather than open clusters, because the problems of the globulars are more straightforward and well defined. Second, in a conference where theoretical talks outnumber observational ones by three to one, it is a good thing to be able to start by emphasizing the essential role that observations play.

Not that I wish to set observations against theory; they are two parts of the same story, and neither is the center. When Robert Benchley, the humorist, was an undergraduate at Harvard, he was faced with an exam question requiring a discussion of a U.S.-Canadian fisheries dispute, as seen from either point of view. Benchley chose the point of view of the fish. In this vein, but more seriously, I ask you to consider the point of view of the globular clusters. Our central effort should be to understand what their reality is. The name for this task is interpretation, and both theory and observation merely offer tools for it. Computational experts, too, should recognize that the heavens have more than a hundred analog computers that always get the right answer, by definition. Observation tries to read those answers,

J. Goodman and P. Hut (eds.), Dynamics of Star Clusters, 1–17.

while theory tells us what to look for. The interaction of the two shows us what the observations mean, and what the theory should interpret.

Of the questions concerning globular clusters, the one that I think will receive the most attention at this meeting is core collapse. Instead of introducing it directly, however, I would rather give a little background, in order to place the core-collapse question in its setting.

The basic dynamical equilibrium of globular clusters is fairly well understood. (For a summary, see King 1981.) Relaxation, through stellar encounters, drives the velocity distribution as close to Gaussian as it can get, given the existence of a finite escape velocity. In a steady, self-gravitating system this velocity distribution implies a corresponding density distribution, which can be found from a straightforward algorithm. Except for scale factors, the only free parameter is the tightness of binding of the cluster, relative to the galactic tidal field. The cluster models calculated in this way form a one-parameter family (Fig. 1), and they fit actual clusters (as, for example, in Fig. 2). This picture is a satisfying one, because given their different binding energies, clusters are as simple as they can possibly be.

Unfortunately the picture that I have just sketched is badly oversimplified. Difficulties arise, it is true, from anisotropic velocity distributions and from the stratification of stars of different mass; but by far the worst problem is the dynamical evolution of star clusters, which turns out to be unstable. This phenomenon is discussed lucidly by Spitzer in this volume; here I will merely note two ways of looking at the problem. One is that relaxation ejects stars and causes the cluster to contract (since its binding energy is shared among fewer stars); the contraction speeds up the relaxation, and the whole thing runs away. A second point of view is that beyond a certain central concentration the core of the cluster can no longer stay in equilibrium with the envelope. It makes a thermodynamic turnabout, energy flows the wrong way, and the center of the cluster collapses. I will not try to reconcile these two points of view, or even to discuss whether they are in some way equivalent. Either way, we should expect the core of a cluster eventually to collapse. This really should happen, in actual clusters. The central concentrations of many clusters are on the verge of instability, and the relaxation times in these and other clusters are short enough to drive them over the brink before long -- so much so that we wonder why they have not collapsed long since.

Much of this volume is devoted to description and discussion of the theories and calculations that predict core collapse. Here I will merely reproduce a single example (Fig. 3), which is typical of the Monte Carlo calculations of a decade ago. Since the seminal work of Hénon (1961) and Lynden-Bell and Wood (1968), theoreticians have had little doubt about core collapse.

Fig. 1. Projected densities for a family of models based on a steady-state relaxing velocity distribution (King 1966a).

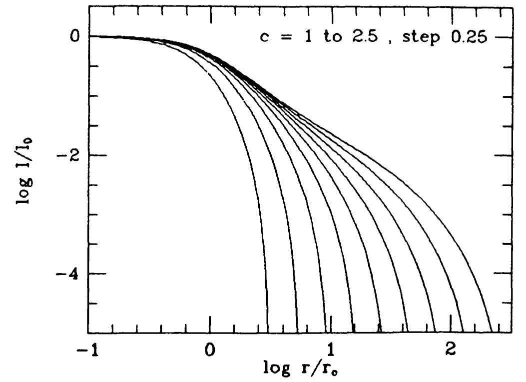


Fig. 2. Surface densities in 47 Tucanae, fitted to a model from the family shown in Fig. 1 (Illingworth and Illingworth 197).

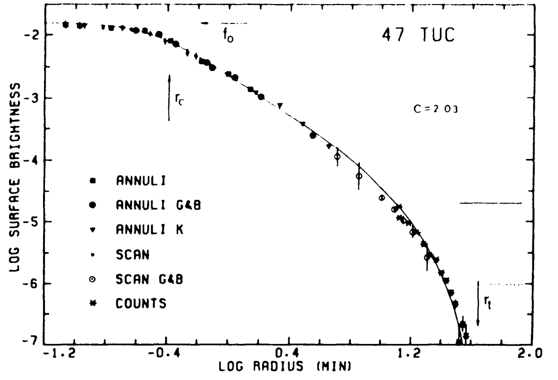
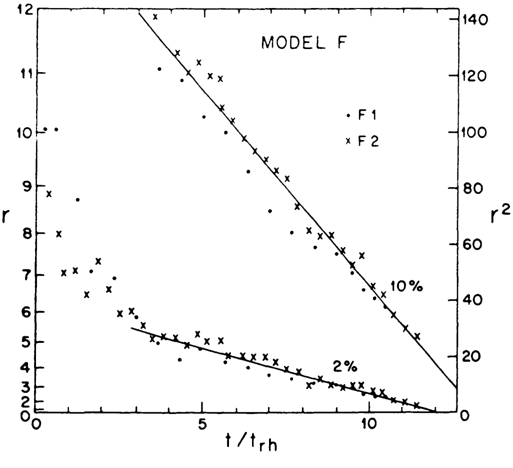


Fig. 3. Final contraction of cluster core in a Monte Carlo calculation (Spitzer 1976). The two curves show the radii containing 2% and 10% of the mass, respectively.



Observationally, however, the situation has been less clear. It appeared that nearly all clusters lived on the tranquil sequence of models that I have described, without any inkling of the doom that

https://doi.org/10.1017/S0074180900147175 Published online by Cambridge University Press

lurked in the theoretical crystal ball. Only M15 refused to behave simply; its brightness rises continuously in the center, instead of flattening into a typical cluster core. This anomaly has been commented on frequently; suffice it to reproduce some data of 18 years ago (Fig. 4):

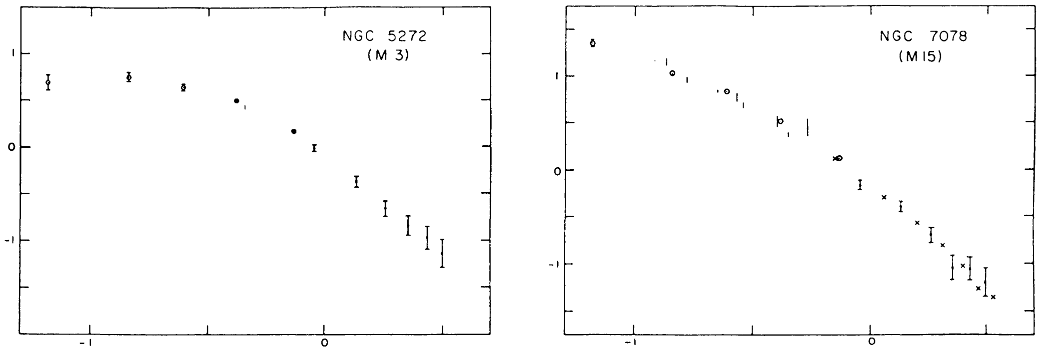


Fig. 4. Photoelectric surface brightnesses in M3 and M15 (King 1966b).

Is this core collapse? It has the right appearance indeed, but why did this type of profile seem to be confined to this one cluster? The answer has turned out to be that there are indeed other such clusters but that the observations had been inadequate to detect them -- or else marginally sufficient observations had been inadequately interpreted. It was not the crystal ball that was cloudy, but the telescope -- or at least those who were looking through it.

2. OBSERVATIONAL DATA

2.1 Methods of Observation

To explain the observational situation I shall have to fill in a little background about the observation of density distributions in globular clusters. Again I refer to a more detailed discussion elsewhere (King 1980) and will merely mention the factors that are directly relevant here.

Even in globular clusters the limitation in density studies is generally the small-number statistics of the stars, when they are taken region by region. The smoothest density studies involve counts of the numerous faint stars. In the central regions, however, the faint stars are too crowded, and only the less numerous bright stars can be counted. Close to the center of a dense cluster, even the bright stars are too crowded to be counted reliably. The images of many of them can be pried apart by heroic efforts (see, for example, Aurière and Cordoni 1981),

https://doi.org/10.1017/S0074180900147175 Published online by Cambridge University Press

but this will yield only colors and magnitudes of individual stars. Densities cannot be determined reliably in this way, because the ability to separate stars depends on the density itself.

In the central regions of a dense cluster, densities can be measured only by surface photometry -- measuring the amount of integrated starlight per unit area. The traditional method of doing this has been by photoelectric photometry. The procedure is indirect. It would be of little use to trail a measuring aperture across a cluster, because the light in a small aperture tends to be dominated by so few individual stars that it is statistically quite unstable. Far better is to measure through a set of apertures of graduated size, all centered on the cluster center, and to difference successive apertures to get the total amount of light in each annulus. It does not matter that this procedure violates the stricture against differencing data; the observational errors are of little consequence compared with the statistical uncertainty in the amount of light in the small areas involved.

Photoelectric observations of this sort have two drawbacks, however. First, the observer usually centers on the cluster by a somewhat coarse eye-estimate. Second, and more fundamental, photoelectric observations are unable to work accurately with apertures smaller than 5 or 10 seconds in diameter, because the seeing is time-variable and too much light flickers in and out of the edges of such a small area. The next observation has a different sequence of jiggles, and the photometric accuracy of a sequence of observations is poor.

For the present problem high angular resolution is important. At the distances of even nearby globular clusters, the phenomena that we are discussing subtend only a few seconds of arc. Thus we need good telescope scale, reasonably good seeing, and the ability to make effective use of them. The way to achieve accurate high-resolution surface photometry is to make measurements on a recorded image, in which all parts have been observed simultaneously over the same interval of time. Seeing then blurs the image, but it does not introduce photometric distortions.

In principle, any imaging device will do, as long as it is capable of reliable photometry. CCD's are in many respects ideal, because of their speed, linearity, and dynamic range. Traditional photography can also be used reliably, however; and it actually offers some advantages, particularly in ultraviolet observations, where most CCD's are rather insensitive.

Why should one prefer the ultraviolet? The answer is the statistical fluctuations in the integrated surface brightness, which is dominated very much by a small number of bright stars. At longer wavelengths the major contributors are the few red giants, and the brightness distributions are quite ragged. As we go to shorter wavelengths, however, the importance of the red giants is reduced; more individual stars contribute effectively to the light, and the accuracy improves. The nature of the improvement is clear if we examine HR diagrams of the same globular cluster in V and in U (Fig. 5). Moving to the ultraviolet has flattened out the red-giant branch, so that a much larger number of individual stars makes effective contributions to the light. Also, clusters that have a strong horizontal branch (like M3, for which these diagrams were made) have an even larger number of effective contributors.

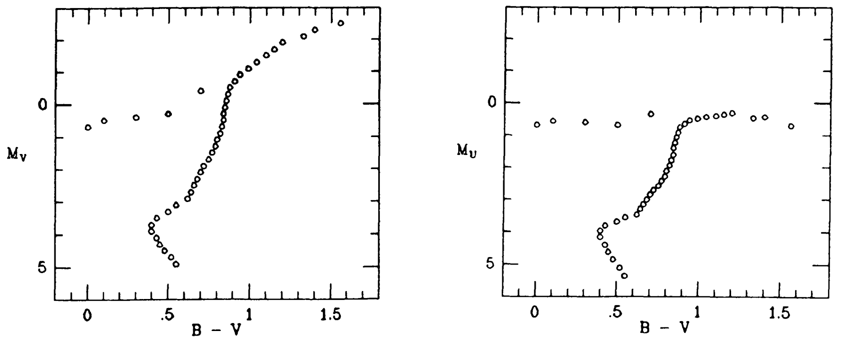


Fig. 5. Schematic HR diagrams for M3 in V and in U.

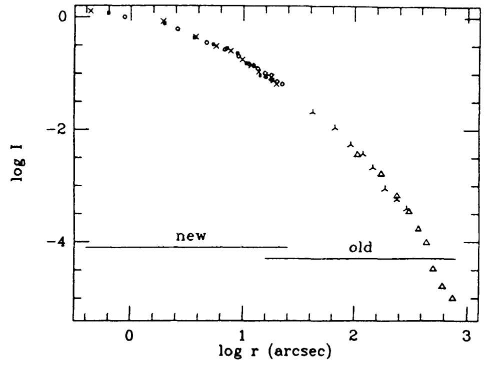
2.2 Recent Results

The foregoing reasoning was the starting point of a recently published study (Djorgovski and King 1984) of the central regions of nine high-concentration southern globulars. U-sensitive photographs were taken at large scale, so that photographic grain had no effect and small areas could be measured well. Sensitometer spots provided reliable calibration. PDS tracings at high resolution were converted to intensity, point by point, and the light was added up in each annulus, just as a photoelectric photometer would do, if it could work with such a high resolution.

The improvement in resolving power is dramatic. Figure 6 shows, for one cluster that turned out to be particularly interesting, the previously available density data, from star counts, and the region to which our new observations give access.

The results were also exciting (see Figure 7). Of the nine clusters, three clearly show the M15 effect: NGC 6624, 6681, and 7099. To emphasize the difference between these and normal clusters, Figure 8 shows a fitting of models from Fig. 1 to a normal cluster and to a condensed-core cluster. In NGC 5824 the fit is reasonably good, but in NGC 6624 it is hopeless; the brightness never flattens into a normal core but continues to rise toward the center until it is lost in the

Fig. 6. Surface densities in NGC 7099, showing the radial range covered by previous and by new observations.



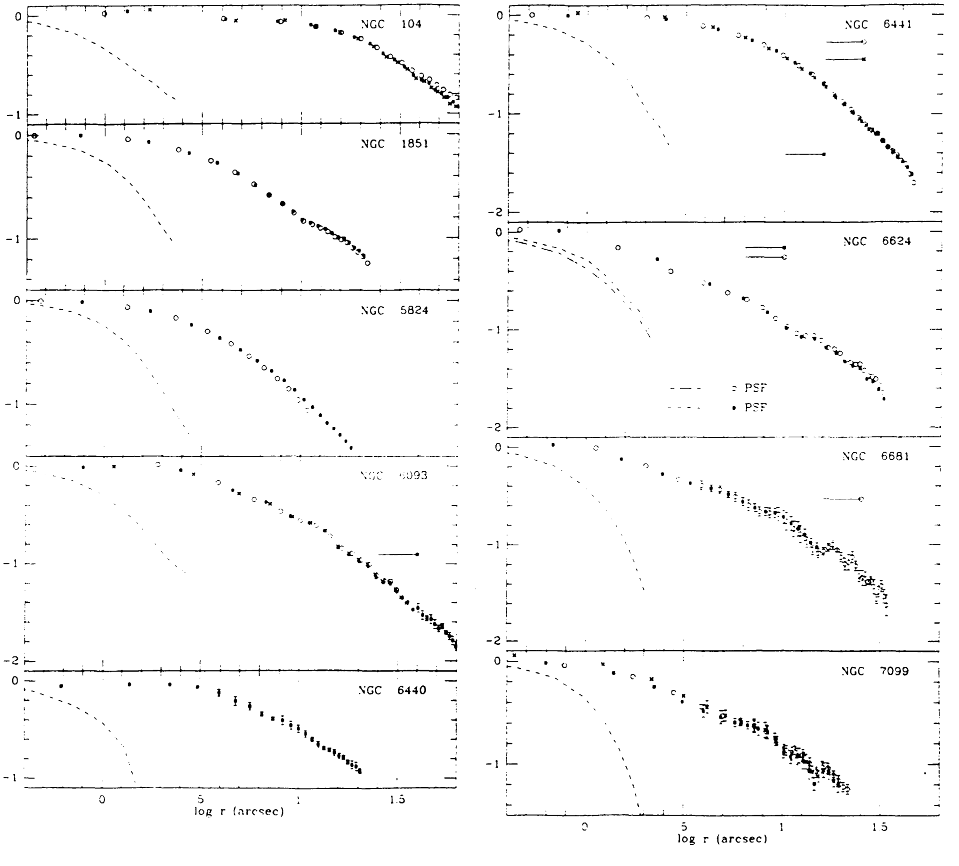


Fig. 7. Surface densities in 9 high-central-density southern globular clusters (Djorgovski and King 1984).

https://doi.org/10.1017/S0074180900147175 Published online by Cambridge University Press

seeing disc. Instead, it seems to fit much better to a −1 power of radius, which agrees with a singular isothermal sphere in projection. (I will return to this question in greater detail later.)

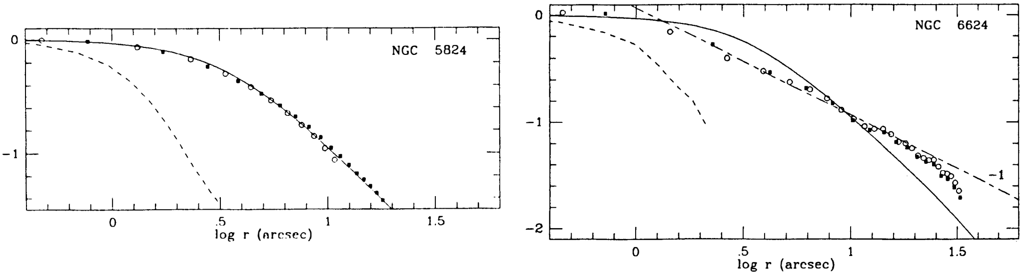


Fig. 3. Normal-cluster models fitted to the normal cluster NGC 5824 and to the abnormal cluster NGC 6624.

Another provocative phenomenon in Fig. 7 is the indication of bumps in the brightness curves. These may or may not be real. In NGC 6681 the bump is almost certainly not real; by going back to the original images I have been able to pick out the individual bright stars that are responsible for the prominent bump at ordinate 1.2. In NGC 1851 the bump at 1.2 (or dip at 1.0) might conceivably be real -- but personally I doubt it.

To give a better feel for the roughness or smoothness of the images, I have reproduced in Figure 9 the central contours of a very smooth cluster and a moderately ragged one.

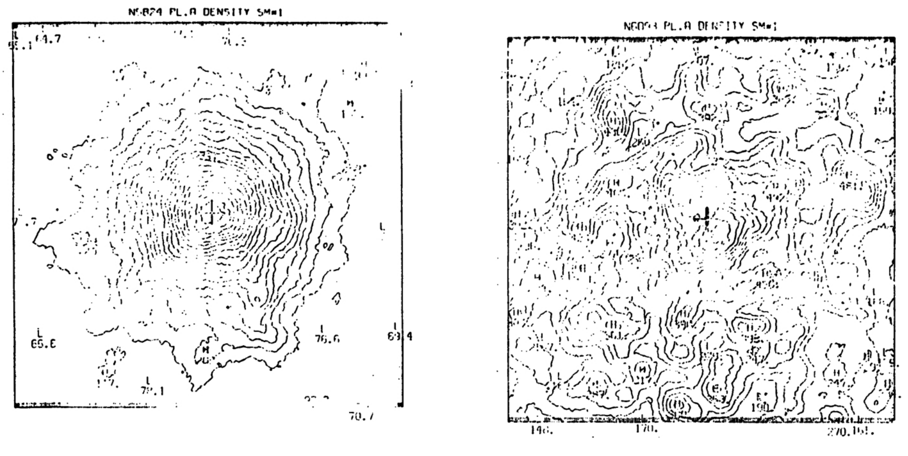


Fig. 9. Contours of the central regions of UV images of NGC 5824 and 6093.

3. COMPARISON WITH THEORY

3.1 Immediate Conclusions

Including M15, we now have four clear cases of what I will hereafter refer to as collapsed cores. The first question to ask is, what other characteristics do they have to distinguish them from normal clusters? Unfortunately there is no simple answer. One characteristic that they all share is high central density. That may indeed be physically significant, but the fact is that the clusters in this study were chosen largely for that characteristic in the first place. They also have a short relaxation time, but they were chosen for that characteristic too. And in neither case is the correlation with collapsed cores good, even within this selected sample, as is easily seen from the values of central densities and relaxation times given by Peterson and King (1975). I will return later to the implications of this, but for the time being let us simply note that the correlation is poor.

A very interesting question is whether the presence of a collapsed core correlates with the emission of X-rays, as might have been suspected from the existence of an X-ray source in M15. The answer is clearly negative. NGC 6624 is indeed an X-ray source, but NGC 6681 and 7099 are not, and the well-known X-ray sources NGC 6440 and 6441 have normal cores. X-rays from globular clusters are spectacular fireworks, but they are no more responsible for collapsed cores than ordinary fireworks are responsible for the holiday that they celebrate. The connection might in fact go in the opposite direction; a collapsed core may well provide dynamical surroundings that are particularly conducive to the formation of the close binaries that are believed to be responsible for X-rays in globular clusters.

3.2 Tentative Theoretical Picture

It may be, however, that a coherent picture is now beginning to emerge from the observations and the theory. Evolution, due to stellar encounters, causes the cores of some clusters to undergo a runaway collapse. In its final stages the collapse leads to a spatial density law of −2.2 power (−1.2 power in projection), but this phase is so brief in time that it is unlikely to be observed. The collapse is finally halted by the formation of one or more binaries, a phenomenon that becomes more and more inevitable as the density increases and the number of stars in the central peak decreases. The binaries stabilize the core, supplying energy at the same rate at which relaxation removes it. Relaxation keeps the stabilized core isothermal, with a velocity dispersion that is the same as that in the surrounding part of the envelope. Small changes occur as binaries are ejected and new binaries form, but for the most part the cluster remains for a long time in this state, with a core profile that is for all practical observational purposes a singular isothermal sphere.

https://doi.org/10.1017/S0074180900147175 Published online by Cambridge University Press

A very similar model was predicted in detail in Hénon's thesis (Hénon 1961). He imposed the condition that a cluster remain self-similar while relaxation takes place at its appropriate rate at all points. Since, except for self-similarity, his assumptions were nearly the same as mine (King 1966a), it is not surprising that his model is very close to the limit of my model sequence at high central concentration. This is effectively a singular isothermal model with a tidal cutoff. There are small physical differences, which lead to density differences that are less than the thickness of the line in a graph; but in what follows I shall use the high-concentration limit of the so-called King models, and shall refer to it as a Hénon model.

3.3 Comparison with Observation

Thus, according to the tentative theoretical interpretation that I have sketched, a post-collapse cluster should look like a Hénon model. What do the observations say about this? The answer is very incomplete, but I have been able to assemble some data for three of the collapsed-core clusters. In Figure 10 is shown a fit of NGC 6624 to a Hénon model. The data are taken from Djorgovski and King (1984), from photoelectric photometry by van den Bergh (1977) and by Canizares et al. (1978), and from star counts by Bahcall and Hausman (1977). The fit is reasonably good, except for a central depression of the observations that can clearly be attributed to the seeing-limited resolution. In Figure 11 is shown a similar fit for NGC 7099, where the outer data are taken from star counts by King et al. (1968). Again the fit is reasonable.

For M15 I have combined the central photoelectric photometry shown in Fig. 4 (King 1966b) with star counts in the envelope (King et al. 1968). The result is shown, fitted to a Hénon model, in Figure 12. (Better data are available in the center [Newell and O'Neil 1978], but I have not yet had a chance to plot them on the necessary scale.) The fit is not very good, especially in the envelope; I would find this discouraging were it not for the better fit in the other two cases. The difficulty in M15 may be due to the fact that the outermost densities come from star counts of low-luminosity stars ($M_V \sim +8$), which should have a distribution different from that of the giant stars on which the central part of the curve depends. Indeed, the deviation is in this sense -- a flatter distribution for the stars of the outer envelope.

For NGC 6681 I have unfortunately been unable to find any density data other than those in Fig. 7.

This is all that the observations can say at the present time about my theoretical surmises. It appears that the interpretation that I have suggested is by no means excluded, but it certainly has not yet received a ringing endorsement.

Fig. 10. Fit of a Hénon model to combined surface densities in NGC 6624.

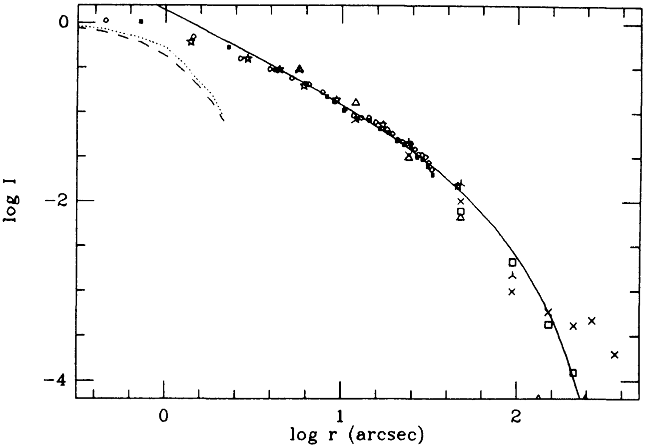


Fig. 11. Fit of a Hénon model to combined surface densities in NGC 7099.

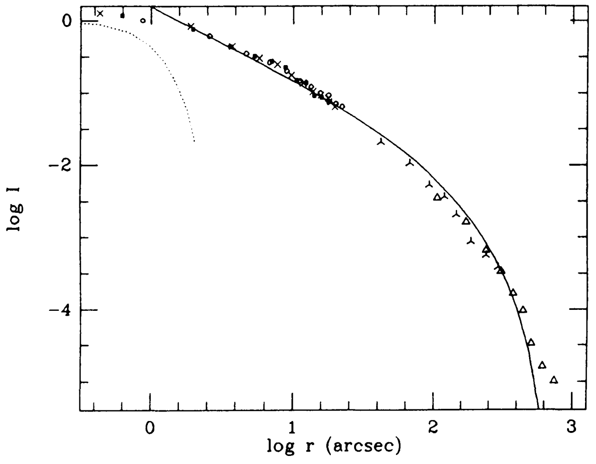
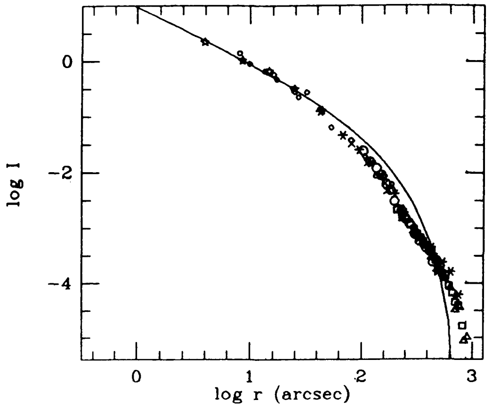


Fig. 12. Fit of a Hénon model to combined surface densities in M15.



3.4 Frequency of Collapsed Cores

Besides the radial profile in an individual cluster, there is another way in which the theory can be confronted with observation. How many collapsed-core clusters are there? And are they the right ones -- that is, are they the ones that theory predicts will go the fastest? Here we run into a real contradiction: there are not enough collapsed-core clusters. In a survey that is reported briefly at this symposium, Djorgovski and Penner have looked at the centers of more than 30 additional clusters, including all those north of declination -20 degrees that are worth looking at, and they have turned up only two more probable cases and two others that are "possible."

Relaxation times of only two of the collapsed-core clusters are given by Peterson and King (1975). The values at the centers are 121 Myr for M15 and 15 Myr for NGC 7099. Their Table IV includes 16 other clusters with central relaxation times less than 100 Myr, and many of these have already been observed, with negative results. To be sure, the relaxation times given by Peterson and King have considerable uncertainties, especially for collapsed-core clusters, which do not fit the models that they used; but the numbers must mean something. Even worse, all relaxation times in this range imply a collapse time that is less than a Hubble time. Even though such a prediction refers to the future rather than to the present state of the clusters, it seems highly improbable that so many clusters should now be close to disaster while so few have yet reached it.

This anomaly has frequently been noted, and attempts have been made to interpret it. Lightman, Press, and Odenwald (1978) have suggested that core collapse is a disaster indeed, so much so that the cluster is destroyed by it; they assert that our remaining globular clusters are only the fortunate few that have been able to avoid core collapse until now. But this seems a most improbable picture, even aside from my previous suggestion that we do see some real post-collapse clusters. What seems fatal to their picture is that Lightman et al. fail to indicate how the collapse of a small core could cause the dissipation of the much more massive envelope of a cluster.

Another interpretation is given by Cohn and Hut (1984). They suggest that many clusters have already been through collapse and that they are simply mixed into the general distribution of present-day relaxation times. But this picture also seems implausible to me, because all the post-collapse clusters should show the characteristic profile that I have just claimed is so rare. A way out would be that post-collapse cores return, in a reasonably short time, to their previous undisturbed profile; but from what I understand of the theory, this is unlikely.

But the worst anomaly, in my view, is not in the globular clusters but in the open clusters, nearly all of which have relaxation times short enough to bring on core collapse in much less than a lifetime. As

Wielen will explain later in this symposium, some of them are saved from collapse by expansive effects that come from outside, but many others are not. Observations, as far as they go, have not shown any indication of collapsed cores in open clusters, however. Perhaps they are all saved by the formation of binaries, which is much easier when the number of stars is so much smaller; but until this is demonstrated I will regard the absence of collapsed cores in open clusters as an outstanding anomaly -- or else as an indication that post-collapse cores really do expand back to normal again.

Before leaving the comparison with theory, I should acknowledge not having considered any black-hole theories. These have their basis in the idea that core collapse might lead to a coalescence of material into a black hole, which thereafter dominates the central dynamics of the cluster. Black-hole theories, which will be reviewed later in this symposium by Shapiro, have had rather little attention in recent years. This is due largely, I believe, to the demonstration (Grindlay et al. 1984) that the X-ray sources in globular clusters are much more likely to be close binary stars. But some of the current disfavor of black-hole theories must certainly be due to their inherent improbability. If this remark shows prejudice, I submit to you that it is less prejudiced than the wish to see black holes everywhere. Such a view seems to me like the reasoning of Aquinas, who began by assuming the existence of God and then assiduously sought logical proofs of it. If black holes are to be supported by scholastic argument, then I would cite against them that other stalwart medieval, William of Ockham, whose razor excises all that is not necessary. At the same time, I must acknowledge that the quest for black holes did make the positive contribution, in the hands of Lightman, Shapiro, Bahcall, and others, of promoting interest in core collapse theory at a time when many of us observers were saying that it wasn't true.

4. OUTSTANDING PROBLEMS, AND FUTURE NEEDS

4.1 Theoretical Questions

Where does all of this leave us? As an observer, I would ask the theoreticians a number of pressing questions. What is the profile of a post-collapse cluster core (not during the all-too-rapid stages of the collapse itself, but a long time afterward)? Does it retain some characteristic shape by which it can be recognized? Is the profile that of a singular isothermal sphere? Or will a collapsed core re-expand so that it shows no signs of a past collapse? Should we expect intermediate cases between collapsed cores and normal ones? For the sake of future higher-resolution observations with Space Telescope, how small should the core radius of a collapsed cluster be, after binaries stabilize it (if indeed they do)? How should the profile of a collapsed core tie onto that of its presumably undisturbed envelope? Should a collapsed core show a radial variation of velocity dispersion? Will core collapse produce a mass-segregation that might have observable consequences? What does theory predict for open clusters, and what should we look for?

With these questions I wish also to plead for one condition on the answers: give them to us in the observational domain. We know that the real universe has three dimensions, but please give us results projected into two dimensions, on the plane of the sky. You can do this easily while making the theoretical calculations, while it is hard for us to do it, especially if we have to do it by starting with astrometry on published graphs.

4.2 Observations Needed

It is of course easy to make demands on others, but what should the observers be doing meanwhile? Here also, there are some clear needs. The detailed surface photometry of cluster cores has only begun. The Djorgovski-Penner survey is only a preliminary one; it needs particularly to be followed up with a study of the smoother ultraviolet images of the interesting clusters. In addition, the southern clusters still need to be looked at. Fortunately, this work is already under way. Grindlay, Cohn, and Lugger have Cerro Tololo observing time in which they will work hard to get UV CCD images of a number of southern clusters. Djorgovski and I also have observing time, unfortunately with a CCD that does not work effectively in the UV. But with our shorter exposures we can survey a more complete list of clusters.

When a cluster is found to have an unusual core, we often lack adequate data for its envelope. Surface photometry needs to be extended farther out; and, more important, star counts to faint magnitudes are still lacking for a number of interesting clusters. Many of these are in low galactic latitude, with sometimes-appalling densities of field stars superimposed. To remove the field stars selectively, one should probably place each individual star in a color-magnitude array, so as to select cluster stars by the criterion of their having the right color for the main sequence.

When available, Space Telescope observations will be invaluable, because only then will we be able to see farther into the centers of the clusters (with about 20 times ground-based resolution). Not only will we see better central density profiles; for the first time we will have really good data on the relative distribution of stars of different mass. But ST time is very scarce; we must know beforehand which clusters are most profitable to look at.

In addition to the surface densities, we need to look much more carefully at the velocity dispersions. There are reports at this symposium by Da Costa and Freeman and by Mayor and Meylan, but they merely whet our appetites. Surface densities sample two of the six dimensions of phase space; but the addition of radial velocities will give us a third component, and the confrontation of theory with observation will be that much more effective.

5. CONCLUSIONS

It appears now that globular clusters are more complicated than the previous simplified picture had suggested. The phenomenon of a central brightness peak, previously known only in M15, occurs in a number of other clusters, in very similar form. Existing observations, which are still far from adequate, are consistent with a picture of post-collapse cores that are singular-isothermal, perhaps with binaries stabilizing against further collapse. The profiles of such clusters can probably be fitted by a Hénon model, which for them is the analog of the King models for normal clusters. A serious problem, however, is why more clusters do not show these collapsed cores. Both for theory and for observation, core collapse is a challenge for the future.

REFERENCES

Aurière, M., and Cordoni, J.-P. 1981, Astron. and Ap. Suppl. 46, 347.
Bahcall, N. A., and Hausman, M. A. 1977, Astrophys. J. 213, 93.
Canizares, C. R., Grindlay, J. E., Hiltner, W. A., Liller, W., and McClintock, J. E. 1978, Astrophys. J. 224, 39.
Cohn, H., and Hut, P. 1984, Astrophys. J. Letters 277, L45.
Djorgovski, S., and King, I. R. 1984, Astrophys. J. Letters 277, L49.
Grindlay, J. E., Hertz, P., Steiner, J. E., Murray, S. S., and Lightman, A. P. 1984, Astrophys. J. Letters, 282, L13.
Hénon, M. 1961, Ann. d'Astrophys. 24, 369.
Illingworth, G., and Illingworth, W. 1976, Astrophys. J. Suppl. 30, 227.
King, I. R. 1966a, Astron. J. 71, 64.
King, I. R. 1966b, Astron. J. 71, 276.
King, I. R. 1980, in Globular Clusters, ed. Hanes, D. and Madore, B. (Cambridge Univ. Press), p. 249.
King, I. R. 1981, Quart. J. Roy. Astron. Soc. 22, 227.
King, I. R., Hedemann, E., Hodge, S. M., and White, R. E. 1968, Astron. J. 73, 456.
Lightman, A. P., Press, W. H., and Odenwald, S. 1978, Astrophys. J. 219, 629.
Lynden-Bell, D., and Wood, R. 1968, Mon. Not. Roy. Astron. Soc. 138, 495.
Newell, E. B., and O'Neil, E. J. 1978, Astrophys. J. Suppl. 37, 27.
Peterson, C. J., and King, I. R. 1975, Astron. J. 80, 427.
Spitzer, L. 1975, in Dynamics of Stellar Systems, ed. Hayli, A. (Dordrecht: Reidel), p. 3.
van den Bergh, S. 1977, Astron. J. 82, 796.

DISCUSSION

COHN: I address two questions raised by King: (1) what should a cluster look like after core collapse? (2) How long after core collapse should it look "funny?" I noted that calculations of cluster evolution including binaries that I've carried out with Hut and Goodman indicate that a central cusp with slope close to a singular isothermal forms during core collapse and persists long after core collapse. These calculations predict the evolution of the detailed density and velocity dispersion profiles.

OSTRIKER: The inner parts of M15 appear to be more centrally concentrated than the singular isothermal ($I \propto r^{-1}$) model. What is your best estimate for the logarithmic slope of the surface brightness in the inner parts?

KING: I don't know why you call it more concentrated, but I'll try to answer. The logarithmic slope is approximately -1, but I don't think that these observations could distinguish that from -0.75 or -1.25, for example. Nor is the slope constant; seeing flattens the center, and the slope gets steeper in the envelope.

LACHIEZE-REY: Three clusters out of nine in your sample show a possibility of core collapse. Do you expect this proportion to be universal (for all globular clusters) or was your sample selected to exhibit specially this effect?

KING: My clusters were carefully chosen to be those that were most likely to have this phenomenon. It is likely that rather few other clusters will show it.

BAHCALL, N.A.: Why does the M15 surface brightness profile not show the flattening due to seeing as seen in NGC 6624 and 7099? Has it been taken out?

KING: I didn't show the center of M15 in as much detail. If I had, it would have looked similar to the other two.

TREMAINE: A few years ago, singular density profiles were usually interpreted as evidence for massive black holes in the cluster centers. Is there any direct observational evidence that favors core collapse over balck holes as the explanation?

KING: No, I don't know of direct observational evidence; but the two hypotheses would presumably predict different profiles, which might be distinguishable. Against central black holes I would cite (1) Ockham's razor, (2) the fact that a black hole should have infalling material that emits X-rays - which some core-peak clusters don't, and (3) Grindlay's observation that X-ray sources are not at the centers of their clusters. But I am not asserting that the density peak is due to core collapse - I'm asking the theoreticians to tell us.

SUGIMOTO: How many stars do you think are contained within the smallest collapsed core that is recognizable by present-day ground based observations?

KING: Assuming some very rough typical numbers, the answer for a 1-arcsec seeing limitation would be about 100 stars.

INAGAKI: Some clusters have bumps in their luminosity profiles. Is there some evidence for mass segregation in such clusters?

KING: It is too hard to see mass segregation in the central regions of clusters; especially in these high-density clusters, the crowding is hopeless. This is one area in which Space Telescope will make a large breakthrough, however.

https://doi.org/10.1017/S0074180900147175 Published online by Cambridge University Press