DYNAMICS AND EVOLUTION OF GLOBULAR CLUSTERS

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ABSTRACT. This paper reviews some recent theoretical results on the evolution of cores in globular clusters, including the effects of relaxation, binaries, and a central black hole.

This review is concerned with the dynamical processes which may occur in globular clusters, and their effects. Though 'external' influences, especially tidal gravitational fields, play an important dynamical role in determining the observable structure of clusters, we shall deal almost entirely with 'internal' processes, such as two-body relaxation. Our aim is to review our current understanding of the effects of these processes, especially where they may influence the theoretical interpretation of the observable properties of clusters. Purely theoretical problems, though challenging and important, are not our main concern. Most of our explicit references are to recent work, and for further references prior to 1978, the thorough review by Lightman & Shapiro (1978) should be consulted.

1. METHODS OF COMPARING THEORY AND OBSERVATIONS

In principle there are two quite distinct ways of comparing observations of clusters with theory. The traditional way is to compare the observed stellar distribution in an individual cluster (e.g. by star counts) with that of some equilibrium model. But now that this has been done for sufficiently many clusters (e.g. Peterson & King 1975), it becomes possible in principle to study the distributions of various quantities (such as core mass), and to compare these with what might be expected theoretically. This is what was attempted by Lightman, Press & Odenwald (1978) in their controversial study of the central relaxation times of observed clusters.

An advantage of the traditional method is that each cluster provides a detailed comparison with the selected model; but the models used have generally been chosen for their analytic convenience, and in some dynamical respects they are unrealistic (see section 3).

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Also the result of such a study may tell us little about the dynamical evolution of clusters, and this (potentially) is the strength of the second method. Though we study only one or two quantities from each cluster in this method, their distribution should contain information about the evolution of the clusters, just as the distribution of stars on a colour-magnitude diagram is closely connected with their evolution.

Since we wish to concentrate on processes affecting mainly the central parts of the clusters, we shall choose two parameters which, for a given mass spectrum, define the properties of its core. We choose measures of the core mass, M_c, and core energy, E_c, which we *define* to be

$$M_c = \frac{4\pi}{3}\rho_c r_c{}^3 = \frac{9}{2\sqrt{\pi}}\frac{(v_c{}^2)^{3/2}}{G^{3/2}\rho_c{}^{\frac{1}{2}}} = 9.3\times 10^3\left(\frac{v_c}{1\ \mathrm{kms}^{-1}}\right)^3\left(\frac{\rho_c}{1M_\odot \mathrm{pc}^{-3}}\right)^{-\frac{1}{2}} M_\odot \qquad (1)$$

$$E_c = \frac{3}{2}M_c v_c{}^2 \qquad (2)$$

where v_c is the central r.m.s. velocity in one component, ρ_c is the central mass-density, r_c is the core radius defined by King (1966), and G is the gravitational constant. Using values from Peterson & King (1975) we obtain Fig.1.

Note that the clusters are concentrated in a relatively narrow band. Presumably this distribution partly reflects conditions at the formation of the clusters, and partly their subsequent evolution. In what follows we shall plot theoretical evolutionary tracks for clusters on diagrams like Fig.1, but the rate at which evolution proceeds will often be expressed in terms of the central relaxation time, here defined as

$$t_{rc} = \frac{(3v_c{}^2)^{3/2}}{35.4\log(.4N_c)mG^2\rho_c} \qquad (3)$$

(cf. Spitzer & Hart 1971a), where m is the mass of one star, and N_c will be taken to be the number of stars in the core. Lines of constant t_{rc} are plotted also on Fig.1, with $N_c = 10^5$ in the logarithmic factor, and $m = 0.5M_\odot$.

2. THEORIES OF CORE EVOLUTION

2.1 Basic evaporative model

This model treats the core as if it were an isolated subsystem, losing mass and energy at the fractional rates

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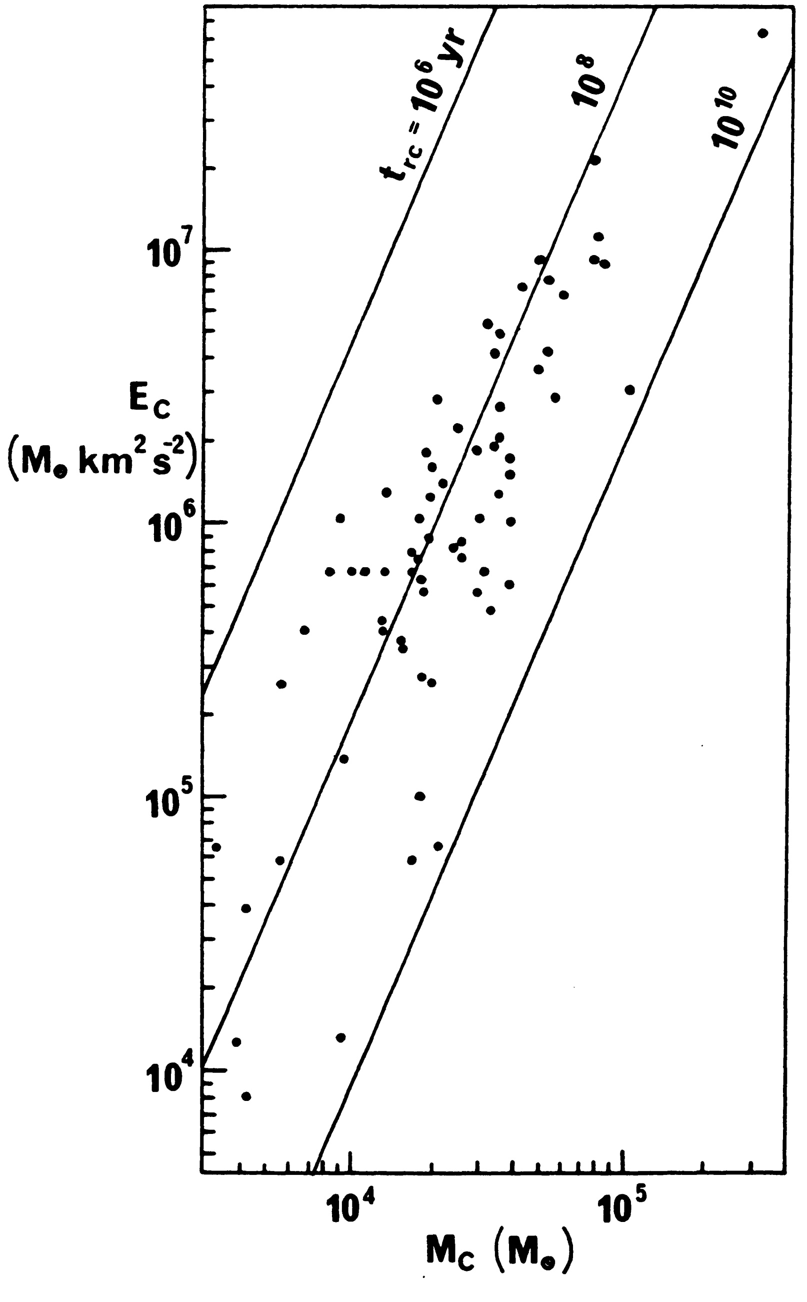

Fig.1. Core mass, M_c, and core energy, E_c, for 69 globular clusters listed by Peterson & King (1975). Data from the right-hand half of their Table IV was used only when no data was available in the left-hand half.

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$$\frac{1}{M_c}\ \frac{dM_c}{dt} = -\frac{p}{t_{rc}} \tag{4}$$

$$\frac{1}{E_c}\ \frac{dE_c}{dt} = -\frac{q}{t_{rc}} \tag{5}$$

where p,q are dimensionless constants. This model has the status of a reasonable guess which happens to accord (in some respects) with the results of computational models. However it can be shown (Heggie 1979a) that equations of the form (4) and (5) follow if the evolution of the core is homologous, and it can be argued that such evolution is to be expected (Lynden-Bell 1975). There now exists a theory of homologous evolution based firmly on the Fokker-Planck equation of collisional stellar dynamics (Heggie 1979b), and another is under development (Lynden-Bell & Eggleton, private communication). These theories lead automatically to values for p and q. However, in the context of the evaporative model there is a theoretical argument (Lightman & Shapiro 1978) which purports to show that the constant q in equation (5) is negligible. In the same context, probably the most reliable way of estimating p is by comparison with Monte Carlo results, which would yield values of order .01 . For a rather different theory of core collapse, see Da Costa & Lightman 1979, and Da Costa & Pryor 1979.

Adopting $q = 0$, we find that a typical evolutionary track in the mass-energy diagram is that shown in Fig.2(a). Since the time-scale for evolution of the core is roughly $100t_{rc}$, a cluster accelerates as it moves to the left (where t_{tc} is shorter), leading to what is called "core collapse". Therefore we would expect the distribution of real clusters to thin out to the left in Fig.1, as indeed it does. Fall & Malkan (1978) have considered in detail what initial distribution would lead to the observed distribution. Conversely, Lightman et al (1978) showed that the distribution of t_{rc} was consistent with evolution according to (4) and (5) from an initial power-law distribution (which is still reflected in the existing distribution of clusters with long t_{rc}). However, on this theory many clusters must have collapsed already, and these authors supposed that such clusters must have effectively dispersed promptly after the core collapsed. The dispersal mechanism was not specified, and the correctness of their supposition remains in serious doubt, but it does seem very likely that some clusters have collapsed already. This is implied by the existence now of clusters with $t_{rc} \simeq 10^7$yr (which will collapse in about 10^9yr), unless we are living at a very special epoch. We shall return to the question of post-collapse evolution later (section 2.5).

Since $M_c \to 0$ on core collapse in a cluster of *point* masses, this process does not lead to the existence of anything resembling a black hole. However, real stars will undergo dissipative encounters when collapse is well advanced, and this could conceivably lead to the formation of a collapsed object of mass $\lesssim 10^3 M_\odot$ (Milgrom & Shapiro 1978, Bisnovatyi-Kogan 1978). Actually we shall see that this may not happen under certain conditions (section 2.5).

2.2 Monte Carlo Models

Though Cohn's new method of integrating the Fokker-Planck equation (Cohn 1979) offers important advantages, most of our reliable, detailed information on the dynamical evolution of globular clusters comes from Monte Carlo models. They lead to evolutionary tracks like that in Fig.2(b) for single-component systems. Again there is acceleration to the left, but E_c definitely decreases. In the presence of two mass-components the core of the heavy stars collapses, but the light stars scarcely evolve, at least for certain mass ratios (Fig.2(c)). The importance of these results is that core collapse may not involve the bright stars which we can now observe, because there is likely to be a population of more massive collapsed objects, i.e. the remnants of stars whose evolution is now complete. Using a multi-component lowered-Maxwellian model, Illingworth & King (1977) showed that the surface brightness distribution of M15 could be explained by a small population of $2M_\odot$ neutron stars with a sufficiently small core radius. Perhaps this can be interpreted as a collapsed core, but it would be desirable to perform fresh Monte Carlo simulations of two-component systems with a mass fraction more representative of the values found by Illingworth & King, in order to verify that the bright stars are not entrained in the collapse process.

One of the important mechanisms at work in multi-component models is the tendency towards equipartition. Indeed under some circumstances it is not possible to achieve equipartition (Vishniac 1978, who generalises an earlier result of Spitzer's), and so this tendency can be a permanent driving mechanism. By treating this process in a suitably simplified way, Lightman & Fall (1978) have extended the evaporative theory to two-component systems, and there is fair agreement with Monte Carlo calculations.

Somewhere between the evaporative and Monte Carlo models (on a scale of reliability) lies the hydrodynamic method of Larson, which has been extended to two-component systems by Saito & Yoshizawa (1976) and by Angeletti & Giannone (1977b,c). The latter authors have considered also the effects of mass-loss during stellar evolution (Angeletti & Giannone 1977a, 1979), which is likely to have been particularly important in the past, and they have shown that the tendency to core collapse is inhibited thereby. However the hydrodynamic method is not well suited to dealing with a continuous distribution of masses, and so the effects of the mass loss tend to be rather too dramatic, as all the stars of one discrete mass-component lose mass at the same time.

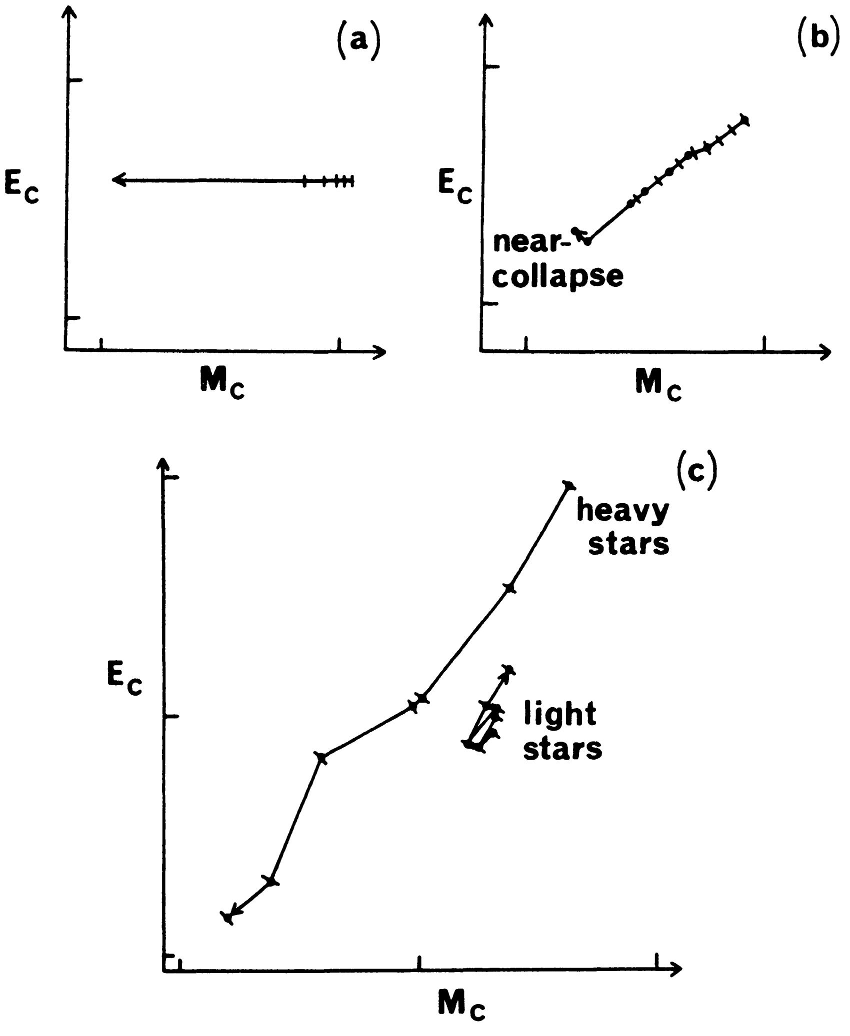

Fig.2. Theoretical evolutionary tracks for the cores of globular clusters, plotted in terms of core mass and core energy. Coordinates are logarithmic in arbitrary units, and ticks correspond to factors of ten. Equal intervals of time are indicated by ticks on some of the evolutionary tracks.
(a) Basic evaporative model at constant E_c.
(b) Monte Carlo model D1 by Spitzer & Thuan (1972). All stars have the same mass.

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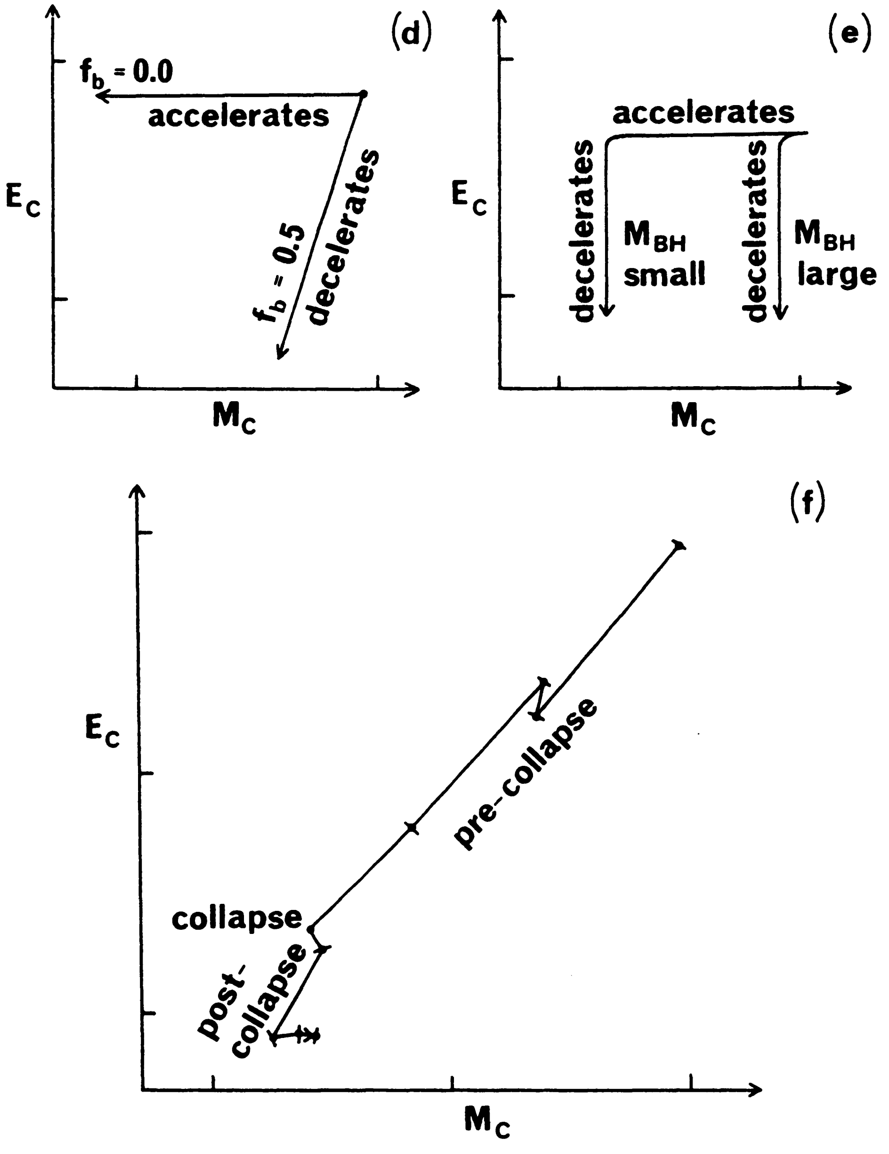

(c) Two-component Monte Carlo model B3 of Spitzer & Hart (1971b). This was based on an early version of the Monte Carlo code, which was later improved. Mass ratio was 5 : 1 , the total mass of the heavy component being 10% of the whole.
(d) Evaporative models with fraction f_b of binaries. (e) Evaporative models with black hole of mass M_{bh} (schematic). (f) Monte Carlo model 72, with a central energy source. (Based on unpublished results by kind permission of Dr. Hénon.)

2.3 Primordial binaries

In the cores of the densest globular clusters, any binary with semi-major axis $a > 1AU$ will have suffered at least one close encounter with a single star during the lifetime of the cluster so far (Hills 1977). Now encounters between a binary and a field of single stars tend to release kinetic energy provided that the binary is "hard", i.e. $\frac{Gm^2}{2a} \gtrsim \frac{3}{2} mv_c^2$ (Heggie 1975, Hills 1975a). Though the fraction of binaries in globular clusters, f_b, is difficult to determine, the effect of this release of energy could be substantial, as has been shown in the framework of the evaporative model by Hills (1975b). Equation (5), with $q = 0$, is then modified to give

$$\frac{1}{E_c} \frac{dE_c}{dt} = - \frac{q' f_b}{t_{rc} \ln N_c} \tag{6}$$

where q' is a new constant. Two representative evolutionary tracks are shown in Fig.2(d), from which it can be seen that the binaries tend to inhibit core collapse. Indeed, too large a value of f_b would prevent core collapse altogether, and Hills used this result, together with known sizes of cluster cores, to place an upper limit on f_b. However Hills' evaporative model assumes that f_b remains fixed as the core evolves, and it has been shown by Monte Carlo simulations (Spitzer 1978) that f_b actually increases in the core, presumably because of dynamical friction. Then binary-binary interactions lead to the destruction of many of the binaries in the core. These simulations also show that heating of the core by binaries is less efficient than previously thought, because much of the energy released is absorbed outside the core. The net result of these effects is that core collapse is delayed but not prevented. Thus primordial binaries, as a source of energy, can support the core against collapse only temporarily, much as a star ultimately collapses when its nuclear fuel is exhausted.

2.4 Primordial black hole

Much effort has been expended on investigating the consequences of the hypothesis that some globular clusters may contain a central black hole of mass $\lesssim 10^3 M_\odot$. The physics of the cusp of stars which would form around it is now reasonably well understood, and its structure has been calculated in several ways (Frank & Rees 1976, Bahcall & Wolf 1976, 1977, Shapiro & Lightman 1976, Lightman & Shapiro 1977, Shapiro & Marchant 1978, Marchant & Shapiro 1979, Young 1977, Cohn & Kulsrud 1978; for an alternative view see Ipser 1978a,b). One of the consequences is that the black hole absorbs mass from the core and emits energy into it, but little work has been done on the resulting evolution of the core.

Shapiro (1977) has shown that, under certain assumptions (Frank 1978), the evaporative model (with $q = 0$ in equation (5)) is modified to become

$$\frac{1}{M_c}\frac{dM_c}{dt} = -\frac{p}{t_{rc}} - \frac{m}{M_c}F \qquad (7)$$

$$\frac{1}{E_c}\frac{dE_c}{dt} = -m\frac{E_{crit}}{E_c}F\ln\frac{r_{crit}}{r_t} \quad . \qquad (8)$$

Here F is the rate at which stars are consumed, which can be calculated; r_t is the radius at which stars are consumed; r_{crit} is the radius from which the largest number of consumed stars originate; and E_{crit} is the binding energy per unit mass at that radius. According to Shapiro's results the mass of the black hole, M_{bh}, does not change much, and the core shrinks much as it would do in the absence of the black hole as long as

$$M_c \gg \frac{20M_{bh}}{[\ln(\tfrac{1}{2}N_c)]^{1/3}} \quad .$$

Thereafter the core expands, at almost constant mass, on a time-scale of order

$$.08\,\frac{\ln(\tfrac{1}{2}N_c)}{\ln(r_{crit}/r_t)}\left(\frac{M_c}{M_{bh}}\right)^3 t_{rc} \quad .$$

Two possible evolutionary tracks are shown schematically in Fig.2(e).

When we consider the doubtful theoretical status of the evaporative model, it is evidently desirable that these conclusions should be tested using a reliable method such as Monte Carlo simulation. Furthermore they only inform us about the evolution of the core, and cannot be used directly to discuss the evolution of the rest of the cluster.

2.5 Post-collapse

The presence of a sufficiently massive black hole can arrest core collapse, if Shapiro's conclusions are correct, and it may be that core collapse could be reversed also if mass-loss or tidal shocking were sufficiently vigorous (Spitzer & Chavalier 1973). Otherwise we must consider whether any new process would come into play as the core collapses, and how the subsequent evolution of the core might be affected. At least two possible processes have been discussed.

(a) Formation of binaries. This may be by three-body or dissipative two-body processes, and the resulting modifications to the evaporative model have been considered by Alexander & Budding (1979)

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and by Dokuchaev & Ozernoi (1978). Although binaries may be ejected from the core, the formation of new binaries can presumably proceed at such a rate as to prevent further collapse of the core, in a self-regulating manner (Hénon 1975).

(b) Formation of a black hole. This may occur as a result of dissipative core collapse (Milgrom & Shapiro 1978). However, if the stellar component which collapses consists of heavy collapsed remnants (see section 2.2), then dissipation may be unimportant, and collapse may end with the formation of one or more binaries, as above.

Whether or not core collapse ends with the formation of binaries or a black hole, we can think of the result as a source of energy near the centre of the cluster. Hénon (1975), who was thinking mainly about binaries, argued that the precise nature of the source is immaterial, and so he computed some Monte Carlo models using an artificial source at the centre (Fig.2(f)). The collapse of the core is virtually unaffected by the energy source, but as the collapse reaches completion the source emits a large amount of energy in a very short time. Thereafter the evolution of the core proceeds very slowly; for example the core radius increases only modestly from its value at the end of the collapse phase. In some respects the core is now like a star which has reached the main sequence, energy generation near the middle just counteracting the tendency to collapse.

It would be very interesting to compute other models with different types of energy source to check Hénon's ingenious argument, though use of the evaporative model would suggest that the structure of at least the core is affected by the nature of the source. Post-collapse evolution is one of the most intriguing problems of stellar dynamics.

2.6 Stability theories

There is a strong belief among many theorists that core collapse is a manifestation of the "gravothermal catastrophe", which was predicted by Lynden-Bell & Wood (1968). They had investigated thermodynamic stability limits for models based on the isothermal, lowered Maxwellian, and truncated Maxwellian distributions. This subject has been studied again recently in other ways in the context of both stellar and gaseous systems (Horwitz & Katz 1977, 1978, Katz, Horwitz & Dekel 1978, Katz 1978, Hachisu & Sugimoto 1978, Hachisu, Nakada, Nomoto & Sugimoto 1978, Nakada 1978, Lightman 1977).

Stability limits can be expressed in terms of the quantity K defined by

$$K = \frac{1}{2}\frac{v_e^2}{v_c^2} \qquad (9)$$

where v_e is the escape velocity at the centre of the cluster. Katz (1979) has shown that the maximum of the K-distribution among observed clusters lies close to the stability limit for lowered-Maxwellian models. Why such an effect should occur is difficult to understand. Though there is evidence from computer models that the nature of core collapse may change somewhat as the stability limit is passed (Katz 1979, Cohn 1979), these models show no tendency to congregate around the limit as the observed clusters appear to do.

3. MODEL-FITTING

The customary way of comparing theory and observation is model-fitting. A convenient model is chosen, and its free parameters are adjusted to optimise the fit with observations. The most popular models are lowered Maxwellian models (King 1966) which ensure

(a) that the central parts are nearly relaxed; and
(b) that there is a finite radius, modelling tidal effects.

In some cases a spectrum of masses is introduced, and these are assumed to be in equipartition.

Such models quite faithfully embody dynamical theory as it was before the results of computer simulations became available, but it can be seen now that they are defective in at least two respects. In the first place the velocity distribution can be markedly anisotropic in the computer simulations, and this should now be included in model-fitting by using anisotropic models, as Michie (1963) recommended on theoretical grounds in the context of open clusters. The models discussed by Davoust (1977) provide satisfactory fits to a number of computer simulations. Secondly, the assumption of equipartition can be unrealistic. Though there is a strong tendency towards equipartition and mass segregation between the heaviest stars and those of intermediate mass, say a factor three smaller, there is much less apparent tendency to equipartition between the stars of intermediate mass and those below (cf. Spitzer & Hart 1971b).

Whether anisotropies and departures from equipartition are important depends partly on the stage which a cluster has reached in its dynamical evolution, and this is the topic with which this review will close. Clusters with central relaxation times exceeding about 10^9yr cannot have evolved very far from initial conditions. On the other hand those with $t_{rc} \simeq 10^7$yr must be evolving relatively rapidly. If these clusters are still undergoing core collapse, then existing Monte Carlo models are the most reliable guide to the kinds of theoretical models which we should attempt to fit to the observations. However, as Lightman et al (1978) pointed out, the existence of clusters with such short relaxation times makes it likely that the cores of many clusters must have collapsed already. How would we recognise such clusters?

It is possible that some event occurs at the close of core collapse - such as the formation of a sizeable black hole - which might conceivably lead to the rapid dispersal of the cluster. However there are grounds (see section 2.5) for supposing that the collapsing core creates one or more binary stars which could then support the core against further collapse. Unfortunately our dynamical understanding of these phenomena is rudimentary, even at an empirical level, and so it is not yet possible to propose detailed models for clusters in the post-collapse phase of their evolution. Nevertheless it is tempting to speculate what such a cluster would look like. The bright stars, which may not have been involved in the collapse process, would exhibit a moderate core radius not greatly different from its initial value (cf. Fig.2(c)), and the collapsed core would manifest itself mainly by the effects of its gravitational field on the distribution of bright stars. In other words, the cluster might look very like M15.

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DISCUSSION

HEGGIE: I had wanted to end my presentation by giving a scenario for the dynamical evolution of a cluster like M15, but I haven't had time. However you'll find it in the written version in the proceedings.

KING: I saved a lot of money to come to this Conference and I want to hear about M15! (Laughter).

HEGGIE: How I imagine M15 might evolve is something like this. The heavy stars which were present initially in the cluster would evolve by ordinary stellar evolution and provide us with a component of collapsed remnants. After the stellar evolution had proceeded further, these collapsed remnants would be the heaviest components in the cluster. Then those heavy components would start this process of core collapse. Then one's best guide as to what the post-collapse structure of this heavy component would be, would be the Monte Carlo calculations by Michel Hénon which I showed; this structure corresponds to a fairly stable (slowly evolving) density distribution with an extremely small core disc. At that stage I would have shown that diagram from the paper of Illingworth and King about M15, in which they show that if you invoke a component which is more massive (round about $2M_\odot$, I think) than the bulk of the stars that we can see, but a component with very small core radius, then its gravitational influence on the bright stars is just such as to give the brightness enhancement towards the centre of the cluster that is actually observed. So what I was going to end with was the statement that the next time somebody says "oh yes, core collapse - but where are the collapsed clusters?", you just point your telescope to M15 and tell them to look up.

VAN DEN BERGH: King's voyage has been worth it. (Laughter).

KEENAN: Perhaps I missed it, but what was the machine that Hénon used to pump energy in from the centre - was it binaries?

HEGGIE: It was a perfectly artificial thing, but with some of the properties of binaries. In fact, the way it worked was the following. His calculations were based on mass shells, as you know, and what he did was that every time he looked at the innermost mass shell and computed its self binding energy, which is normally *negative*; but as soon as the self binding energy of the innermost shell became positive, he just made it zero. And it doesn't happen until the central density becomes very high.

SEVERNE: You mentioned an apparent discrepancy between the stability calculation of Katz and the Monte Carlo results - the fact that the Monte Carlo results show nothing particular happening at large values of this factor, K. Could this be a case where the time scales associated with the thermodynamical instability are very long on the dynamical scales? Thermodynamic stability does not tell you anything about the rate at which the system goes unstable, does it?

HEGGIE: That's right, I suppose; you are saying that the time scale for instability may be very long, therefore the process . . .

SEVERNE: It could be, yes, it could be.

HEGGIE: But it still seems strange that the clusters should come to concentrate just at the point where the instability sets in. Isn't that true?

SEVERNE: There's no explanation for that, of course, but if the instability is slow, there's no contradiction either between the two results. Thermodynamic instability could be irrelevant.

HEGGIE: Yes, nobody I think knows if there is a precise relationship between what we call core collapse and these instabilities. It's just a guess which is deeply ingrained in our thinking.

CANNON: Yes, I wonder if you could comment on the Monte Carlo simulations in the two types you showed. One with a single mass population and then one with the two mass population. I was struck with the great difference between the two end results and doesn't it seem that neither can be anywhere near a realistic model of a star cluster that presumably has a fairly wide, continuous range of masses? I mean, not just two extremely different masses?

HEGGIE: Well, yes, exactly, but I really only wanted to make a qualitative point: if you do consider two component systems, one can get surprisingly different evolution from that of one component systems. But I agree with you. What one would really like to do would be Monte Carlo calculations with more realistic mass spectra, if observers can provide them. (Laughter).

COHEN: Well, we could make them a lot more realistic than that!

KING: One more quick comment. I react slowly to Douglas' comment that I should point my telescope at things like M15. In fact, I have pointed somebody's telescope as often as I could get hold of it at all clusters that remotely resemble M15 to see if that density excess occurs. There are little technical problems like not knowing the spot values in the sensitometer that standardize the plates. You see, even in observational work, one encounters the difficulties fairly early on that make it difficult to see results. So far, I don't see any cluster that looks similar to M15, but I can't be really sure yet.

HEGGIE: Garth Illingworth's comment about this problem was that we'll have to wait until the Space Telescope comes - perhaps we'll be able to tell then. Of course, maybe we won't get time for this project on the Space Telescope!