Chapter IV

Review Papers

Evolution of Globular Clusters

Poster papers were also set up downstairs

Paul Hodge checking in

THE EVOLUTION OF THE SYSTEM OF GLOBULAR CLUSTERS

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1. INTRODUCTION

Globular clusters have a sufficiently distinct character that we can treat the system of globular clusters, as a distinct object which has a size, mass and angular momentum, but also, an internal density distribution, velocity distribution, and, in general, a detailed interior structure. Shapley, of course, pioneered in the effort to model, that is to describe, the existing state of the system from our vantage point. At the present time we probably have an inventory of clusters which is largely complete, and for the majority of the identified systems we have good knowledge (cf for example Webbink, 1985) of positions in the galaxy, one component of galactic velocity and a sufficiently detailed picture of the interior dynamical state to characterize each cluster by a luminosity and two radii: a core radius r_c where the surface density has fallen to half the central value, and a tidal radius r_t determined by a fit to the King (1966) truncated isothermal profiles, which is thought to represent the radius beyond which the tidal force due to the galaxy effectively exceeds the force due to the clusters own gravity.

Treated as a dynamical system, can we go beyond description to the conditions which establish physical equilibrium? The answer is yes, but satisfying equilibrium conditions does not convey very much information. In an axisymmetric galactic potential (surely true to first order), any distribution in phase space which is a function of the integrals (J_z, E) will, due to Jeans' theorem, satisfy the Vlasov equation. It is quite likely that for most galactic orbits there exist three integrals which, consistent with our imperfect knowledge of the kinematic quantities, can be approximated by (J^2, J_z, E), total angular momentum, angular momentum about the galactic rotation axis and energy. Several authors have constructed such equilibrium solutions, with best fit indications (cf Frenk and White, 1980) that the degree of rotation (dependence on J_z) is small overall, although not perhaps small for the subset of "disk" systems (Zinn, 1985), the degree of velocity anisotropy (dependence on J^2) also small, and velocity distribution approximately gaussian with no significant

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variation over the galaxy. Thus to a remarkable degree the system can be described, at the present time, as a simple isotropic isothermal distribution $f(p,q) = \mathrm{Const}\ \exp(-E/kT)$ with a temperature $3kT \equiv \langle v^2 \rangle$ smaller than that of the underlying mass distribution by a factor 4/7. This would allow the total mass density of the galaxy to fall as $\rho(r) \propto r^{-2}$ between r = 3 kpc and r = 30 kpc and the globular cluster distribution fall off approximately as $r^{-3.5}$ in that region (cf Zinn, 1985), with both laws steeper exterior to this region and flatter interior to it. Mathematically put, if both the total density ρ_t and the density of clusters ρ_{cl} have, over some part of space, constant velocity dispersions ($\langle v^2 \rangle_t$, $\langle v^2 \rangle_{cl}$) and exist in equilibrium in the same potential ϕ_t, then

$$\frac{1}{\rho_{cl}} \vec{\nabla} P_{cl} = \frac{1}{\rho_t} \vec{\nabla} P_t = \vec{\nabla} \phi_t \quad , \tag{1}$$

or

$$\langle v^2 \rangle_{cl}\ \vec{\nabla} \ln\rho_{cl} = \langle v^2 \rangle_t\ \vec{\nabla} \ln\rho_t \quad . \tag{2}$$

Since $P = \frac{1}{3} \rho \langle v^2 \rangle$ for each component, we find that

$$\rho_{cl}(\vec{r}) = \mathrm{Const}\ \rho_t(\vec{r})^{\left(\langle v_t^2 \rangle / \langle v_{cl}^2 \rangle\right)} = r^{-2\left(\langle v_t^2 \rangle / \langle v_{cl}^2 \rangle\right)} \quad , \tag{3}$$

where the last equation assumes a flat rotation curve.

The result, although simple, is quite surprising, since the stars comprising the globular clusters are in most respects similar to those in the spheroidal population of the galaxy. Thus, despite the fact that the chemical composition (including gradients) and the age of the two populations are broadly similar, the spheroid is, in contrast to the cluster system, locally quite anisotropic (axis ratios)~(2:1:1) and has a much smaller core radius (0.1 kpc vs 1 kpc).

To understand the present state of the globular cluster system we must go further than a consideration of equilibrium and treat evolution, which hopefully will specify more uniquely the physical state of the system. Here it is useful to bring in a metaphor from the study of the internal structure of stars. It was possible to construct equilibrium models in the fashion of Emden and Chandrasekhar before there was any accurate knowledge of atomic or nuclear physics, but specification of even main sequence models required understanding the atomic sources of opacity. To determine the unique characteristics of a given star with a specific age required modeling stellar evolution with enough understanding of the microphysics to calculate energy generation rates. Similarly, a knowledge of the microphysics of the globular cluster system, which is an understanding of the physical processes affecting individual clusters, is required to treat the evolution (but not the equilibrium) of the globular cluster system. Our inventory of relevant physical processes has been growing and it is quite possibly still incomplete in essential ways, but the obvious lacunae, which existed until just a few years ago have now been filled. As an example, it was known (Antonov, 1962, Lynden-Bell and Eggleton, 1980; Cohn, 1980) that after of order 15 half-mass relaxation times, a typical cluster would undergo a process called "core collapse" during which the central values of density and velocity would -according to existing theories -approach infinity in a finite time. It was obvious that real clusters could pass through this phase (which only affected the centers) successfully, but how they did so was unknown. Now (cf IAU Symposium #113) we know of several processes which are potentially able to produce a "bounce" and reexpansion. Thus, we are now in a position to start assembling the pieces, putting together the microphysics with the equations for statistical equilibrium and evolution, to describe evolutionary paths which the system may have taken.

The first questions to be answered are obvious: can we account for the differences between spheroid and globular cluster system kinematics as due to evolution of the latter? A further more radical question suggests itself: can the spheroid itself be the result of the destruction of an initially much more populous system of clusters? In Section 2 a catalog of physical processes will be presented and in Section 3 I will briefly summarize my understanding of our present preliminary knowledge of the system evolution.

2. PHYSICAL PROCESSES AFFECTING CLUSTER EVOLUTION

2.1 Evolution of Internal Structure

2.1.1 Evaporation, Core Collapse and Expansion. As is well known, the rms escape velocity from a self-gravitating system is only a factor of two larger than the rms velocity itself. Thus, if the velocity distribution were everywhere locally a Maxwellian, 0.74% of the stars would have energies sufficient to excape. Hence, we are led to define a quantity ξ_e , the fractional evaporation per unit half-mass relaxation time (Spitzer 1987),

$$t_{rh} \equiv 0.135 \frac{N^{1/2} \; r_h^{3/2}}{m^{1/2} \; G^{1/2} \ln\Lambda} = 1.8 \times 10^5 \frac{r_h(pc)^{3/2} \; N^{1/2}}{(m/m_o)^{1/2}} \text{ yrs} , \qquad (4)$$

where N is the number of stars in the cluster and m is the mean stellar mass. Detailed numerical treatments of the evolution of isolated clusters summarized by Spitzer (1987) indicate that for isolated, single component, precollapse systems, an appropriate estimate for ξ_e is

$$\xi_e = - \frac{1}{N} \frac{dN}{dt} t_{rh} = 4 \times 10^{-3} \quad , \qquad (5)$$

about half the value of the naive estimate given earlier. If this process were to act alone, the cluster would evaporate totally in a time which may be estimated as $t_{ev} \approx t_{rh}(0)/4\xi_e \approx 60\ t_{rh}$ with the loss in the a time interval $0<t<15\ t_{rh}$ of one quarter of the total mass.

However, after the central density exceeds the half-mass density by more than a factor of 177, the core contracts rapidly. The process may be understood as due to the negative heat capacity of self-gravitating systems. The temperature gradiant in the cluster carries heat outward, causing the core to contract, which in turn forces its temperature higher in an unstable fashion. The process stops and reverses when some source of heat in the cluster appears which can balance the conductive flux. Current theory indicates that either binaries formed by two body (Fabian, Pringle and Rees, 1975; Lee and Ostriker, 1986) or three body (Hut, 1985) processes will be the vehicle; or stellar collisions will either directly or indirectly (through production of high mass stars which explode) cause mass loss from the center which acts as an effective heat source.

In any case for $t>15t_{rho}$ the clusters should follow the evolution prescribed by Henon (1961, 1965, see also Goodman, 1984) within which energy generation in the core approximately balances conductively carried flux at the half-mass point and the cluster steadily expands. For an isolated cluster in this phase $r_h \propto t^{2/3}$ and $v_h \propto t^{-1/3}$.

But for a tidally limited cluster the energy input drives mass over the tidal boundary causing the total mass to linearly approach zero. Calculations by Lee and Ostriker (1987) show that, in the post core collapse stage, the rate is approximately

$$\dot{N} = -20 \ln(0.4N_i)/t_{tid} \quad , \qquad (6)$$

where t_{tid} is given in terms of the mean density within the tidal radius ρ_t

as

$$t_{tid} \equiv 2\pi \left(\frac{4\pi}{3} G\rho_t\right)^{-1/2} \quad . \qquad (7)$$

This typically will cause the cluster to disintegrate totally in a time t_{ev} which can be conveniently expressed in units of its orbital galactic period

$$t_{ev} = 1.3 \left(\frac{N_c}{10^5}\right)\left(\frac{R}{kpc}\right)\left[\frac{V_c}{220 km/s}\right]^{-1} \times 10^{10}\ yrs \quad , \qquad (8)$$

where N_c is the number of stars in the system (~3/4 of the initial number) at the time of core collapse.

2.1.2 Tidal Shocks. When a cluster passes through the galactic plane, there is a short period during which matter in the disc acts to compress the cluster (Ostriker, Spitzer and Chevalier, 1975). A similar tidal force acts on clusters passing near the inner parts of the galactic spheroid. The impulsive energy input causes the cluster to expand making it still more subject to tidal shocks. If this process were the only one acting (and allowing for its acceleration) the time to destruction would be

$$t_{sh,d} = \frac{GM_c P_c V_c^2}{20 g_m^2 r_h^3} \qquad (9)$$

(cf Spitzer 1987), where g_m is the maximum z acceleration in the galactic disc and P_c is the orbital period.

If one were to simply model the bulge shocking by the same method, one would merely replace g_m by the appropriate tidal accelleration which, for a cluster perastion of R_{per} in a galaxy with a flat rotation curve, gives

$$g_m \rightarrow a_m = \frac{V_{cir}^2}{R_{per}} \quad . \qquad (10)$$

Spitzer (1987) discusses the combined (and at first paradoxical) effects of evaporation and shocks for isolated clusters. Depending on cluster characteristics and position in the galaxy, evaporation, tidal overflow or either of the two shock processes may be the dominant destructive force. All lead ultimately to small, low surface density clusters which might be difficult to detect and recognize.

2.1.3 Interaction with other massive components of the Galaxy. There are various possibilities for interactions of clusters with other components of the galaxy that are more speculative, where the effects might be important but the physical process assumes a component whose existance is in doubt.

2.1.3.1 Massive Black Holes. Wielen (1987) has analyzed the effects on globular clusters of a hypothetical halo of massive ($\sim 10^{6.3} M_{\odot}$) black holes that has been postulated by Lacey and Ostriker (1985) and by Ipser and Semenzato (1985). He finds that substantial depletion would have occurred due to tidal interactions between the clusters and the comparable mass black holes but that, within the uncertainties of our knowledge of the original cluster distribution, it is not possible to dismiss this conjecture that such a halo does exist.

2.1.3.2 *Molecular Clouds*. Grindlay (1985) has examined the effects of disruptive collisions with molecular clouds. If there were a substantial population of clouds with internal mass density larger than those of the clusters, this effect could also be important. Chernoff et al (1986) showed that for some clusters evolution would be significantly accelerated.

2.1.3.3 *Cluster Cluster Interactions*. Currently, the cluster number density is so small that this process is quite unimportant, but if one were to speculate that most of the galactic spheroid component had been initially in globular clusters, the total number would have been ~100 times greater than at present and cluster-cluster interactions, especially in the inner parts of the galaxy could have been devastating. One can estimate the destruction rates simply by scaling to the calculations of Wielen (1987), since the cluster and black hole masses and velocities are similar.

2.1.3.4 *Triaxiality*. Lastly, it may be interesting to mention a relatively newly discussed mechanism treated in other contexts by Norman et al (1985) and Binney and Ostriker (1987). In an axisymmetric galaxy, the perigalacticon distance of a cluster orbit is fixed even as the orbit processes, but if the galactic potential is triaxial, another possibility exists. If the orbit is loop-like, it is qualitatively similar to those in an axisymmetric galaxy. But some fraction of orbits will be box-like. These, ultimately fill the space available to them, and in particular, will come arbitrarily close to the central point in a manner qualitatively like orbits in a three dimensional harmonic oscillator. Thus, destructive tidal interactions either of the Roche overflow type or of the shock type will always occur given enough time. In work currently underway at Princeton, it appears that even a very modest degree of triaxiality in the galaxy (i.e. enough to produce the "expanding" 3 kpc arm as an artifact of noncircular motions) could result in very effective destruction of low density clusters in the inner few kiloparsecs of the galaxy.

2.2 Evolution of Orbital Parameters

2.2.1 *Dynamical Friction*. This is by now a relatively well studied phenomenon. Massive objects will spiral towards the center of the galaxy on a time scale $t_{df} \equiv (-dR/Rdt)^{-1} \propto f(v_{rms})/\rho_{gal}M_{cl}$. In a first assay of the problem Tremaine, Ostriker and Spitzer (1975) indicated that this would deplete the inner part of the galaxy ($R<1$kpc) of massive and dense clusters, but would not greatly effect other parts of the system. Further work, (cf for example Chernoff et al 1986) has left that conclusion intact, but emphasized still more strongly the dependence of the result on orbital parameters. If the galaxy is triaxial, the first effect mentioned, bulge shocking could cooperate with dynamical friction. Since almost all of the drag occurs for orbits which spend time in the denser parts of the Galaxy, those on box-like orbits may eventually wander into regions where the drag will be large even if they are initially not subject to this process.

Drag due to the interaction which the galactic disc does not seem to have been investigated. One may anticipate that for the small fraction of prograde orbits which have moderate eccentricity and small z velocity, the effect could be large.

2.2.2 Scattering by Massive Subcomponents. All of the massive components such as massive black holes, other clusters, or molecular clouds could in principle scatter globular cluster orbits. Since the scattering time is of order N periods where (1/N) is the fraction of the mass in the total system in the other component, all of these potential sources of scattering might be important. It is conceivable that the velocity distribution has been isotropized to some degree by these processes. If there is a loss cone due to destruction of clusters on highly radial orbits, then such scattering processes may be important in refilling the loss cone (or repopulating the box orbits) and thus preventing the shutdown of destructive processes.

2.2.3 Galactic Neighbors. Finally we must consider the interactions with nearby systems. Cluster swapping (Muzzio, 1986) may occur and account for some of the objects with strange orbits or metallicity. But also close passages of the Magellenic clouds (and other equivalent galaxies like M32 for M31) could have a major stirring effect. With a mass $\varepsilon = 10^{-2}$ of the galaxy its orbit carves out a volume on each close passage at distance R_p which is of order $\pi\varepsilon^{2/3}$ of the total volume within R_p within which the tidal force is large and orbits would be scattered. Since ε is of order 10^{-2} this could be a large effect if the period is not too small compared to the Hubble time.

3. OVERVIEW OF SYSTEM EVOLUTION

At a given place in the galaxy one can consider a plane in which the tidal radius and mass of local clusters are plotted. Upper and lower bounds on the mass are given by the processes of dynamical friction and tidal overflow, whereas upper and lower bounds on the radius are determined by shock and evaporation processes. Thus, there is an allowed area in this plane for clusters which have survived for a given length of time. This area shrinks as time proceeds and shrinks as one considers distances closer and closer to the galactic center. Closer than 1 kpc it is difficult for any cluster to survive for very long.

In work underway (Aguilar, Hut and Ostriker 1987) a detailed examination of the various destructive processes is presented for best estimates of the properties of the real cluster system. The reader is referred to that work for further information. An oversimplified summary of the results might state that destruction is effective

1. for all clusters with apogalacticon <2 kpc,

2. for clusters with apogalacticon <10 kpc and very elongated orbits, or unusually low density or unusually high mass,

3. for clusters apogalacticon <50 kpc with extremely low density (like the Palomar clusters).

It is premature to say at present whether the observed cluster system represents a large fraction or a small remnant of the initial cluster system.

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REFERENCES

Antonov, V. A. 1962 Vest. Leningrad Univ. **7**, 135, (cf English translation in 1985 in IAU Symposium No. 113, Dynamics of Star Clusters, J. Goodman and P. Hut, eds., Reidel, Dordrecht, p. 525).

Aguilar, L., Hut, P. and Ostriker, J. P. 1987, in preparation.

Binney, J. and Ostriker, J. P. 1987, in preparation.

Chernoff, D. F., Kochanek, C. S. and Shapiro, S. S. 1986 Astrophys. J. **309**, 183.

Cohn, H. 1980 Astrophys. J. **242**, 765.

Fabian, A. C., Pringle, J. E. and Rees, M. J. 1975 Monthly Notices Roy. Astron. Soc. **172**, 15p.

Frenk, C. and White, S. D. M. 1980 Monthly Notices Roy. Astron. Soc. **193**, 295.

Goodman, J. 1984 Astrophys. J. **280**, 298.

Grindlay, J. E. 1985 in IAU Symposium No. 113, Dynamics of Star Cllusters, J. Goodman and P. Hut, eds., Reidel, Dordrecht, p. 43.

Henon, M. 1961 Annal. d'Astrophys. **24**, 179.

Henon, M. 1965 Annal. d'Astrophys. **28**, 62.

Hut, P. 1985 in IAU Symposium No. 113, Dynamics of Star Clusters, J. Goodman and P. Hut, eds., Reidel, Dordrecht, p. 231.

Isper, J. R. and Semenzato, R. 1985 Astron. Astrophys. **149**, 408.

King, I. 1966 Astron. J. **71**, 64.

Lacey, C. and Ostriker, J. P. 1985 Astrophys. J. **299**, 633.

Lee, H. M. and Ostriker, J. P. 1986 Astrophys. J. **310**, 176.

Lee, H. M. and Ostriker, J. R. 1987 Astrophys. J., in press.

Lynden-Bell, D. and Eggleton, P. 1980 Monthly Notices Roy. Astron. Soc. **191**, 483.

Muzzio, J. C. 1986 Astrophys. J. **306**, 44.

Norman, C. A., May, A. and van Albada, T. S. 1985 Astrophys. J. **296**, 20.

Ostriker, J. P., Spitzer, L. and Chevalier, R. A. 1975 Astrophys. J. Letters **176**, L51.

Spitzer, L. 1987 Dynamical Evolution of Globular Clusters, Princeton University Press, Princeton.

Tremaine, S., Ostriker, J. P. and Spitzer 1975 Astrophys. J. **196**, 407.

Webbink, R. F. 1985 in IAU Symposium No. 113, Dynamics of Star Clusters, J. Goodman and P. Hut, eds., Reidel, Dordrecht, p. 541.

Wielen, R. 1987 in IAU Symposium No. 126, Globular Cluster Systems in Galaxies, J. E. Grindlay and A. G. D. Philip, eds., Reidel, Dordrecht, p. 393.

Zinn, R. 1985 Astrophys. J. **293**, 424.

DISCUSSION

KING: Do your calculations give a figure for how many clusters have already undergone core collapse?

OSTRIKER: As of the present, we are unable to make such a calculation for lack of information concerning the initial distribution of cluster parameters. It is quite possible that the vast majority were destroyed.

NEMEC: Concerning the question of blue straggler formation through mergers, the 50 blue stragglers found in NGC 5466 (which has a relaxation time ~ a few billion years) would seem to be primordial, if one believes the collision probabilities given by Hills and Day, which imply only ~ a few collisions over 15 Gyr.

OSTRIKER: The required calculation would use a modification of the tidal capture cross-section which is considerably larger than the physical collision cross-section. But, if the observed blue stragglers are slowly rotating, then most were not made by mergers.

HARRIS: Your model shows that almost no cluster destruction occurs outside of 10 kpc, which oddly enough I find more interesting than the region inside where the action occurs. The observational statement that the clusters follow a wider space distribution than the halo light (as in M 87) relies more on the wide field region far outside 10 kpc than it does on the inner few kpc. Would you then agree that we are still left with the need to have a primordial distribution of clusters that is different from the halo stars all the way from the start?

OSTRIKER: I am not sure that I understand your remark. In M 87 the star and cluster distributions are parallel (on a log-log plot); in the outer regions with arbitrary offset. Thus a decrease in the cluster density in the inner parts will be translated to an apparent increase in the "size" of the cluster system.

CAYREL: If the globular cluster system in our Galaxy formed before the collapse of protogalactic gas into a disk, what kind of effect on the specifications and homogeneity of the system, had the strong gravitational potential variation associated with collapse?

OSTRIKER: In an examination of the related problem of the compression in the Z direction of the dark halo, Binney and I found only a small flattening at large radii. However, an increase in density of ~ 30% in the galactic plane is quite possible.

GRINDLAY: As you know, I have published a series of papers in the past few years suggesting that globular clusters with orbits that have low inclinations to the disk can be disrupted by GMCs at R < 4 kpc, thereby "solving" the galactic bulge X-ray source problem, In this case, your statement about cluster "survivors" being those on circular orbits needs modification since those near the plane will not survive (cf. Chernoff and Shapiro). This means, in turn, the number of disk globular clusters (cf. Zinn) must have originally been greater than now observed.

OSTRIKER: I agree that those clusters on circular orbits in the plane of the galaxy will be preferentially destroyed.

RICHER: A comment: Many observers recently have become interested in dynamical processes in globular clusters. However, many of the theoretical calculations have not been easy to interpret into things that observers can actually measure. For example, in a given globular cluster an observer can measure the luminosity function as a function of radius (the stars at a given mass). It has not been easy to convert evolutionary dynamical models of globular clusters into this kind of data. This is just a plea from one observer to a theoretician to try and keep in mind what observers can actually measure directly.

OSTRIKER: It is only in the last few years that the theoretical calculations have approached the sophistication required for comparison with nature to be sensible.