Future prospects: Merging data with models

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**Abstract.** Globular clusters are stellar dynamical systems which evolve on stellar evolutionary and both internal and external dynamical timescales. Quantitative comparison of cluster properties with realistic evolutionary dynamical models is becoming feasible, and will underpin the subject in the next few years. A few examples of the types of analysis becoming possible are presented.

1. Introduction

Considerable progress has been reviewed at this meeting in quantifying the luminosity function of globular cluster systems at birth, and its evolution due to a mix of stellar evolution and environmental effects. Even greater progress has been made in quantifying the stellar mass function in clusters, and its spatial evolution (mass segregation). Cluster ages and morphologies are now available in large numbers and many environs. The next stage is to develop and apply full time-dependent dynamical models, including the (dark) stellar remnants and external tides, use these to predict stellar colour-magnitude data, and compare these models to the mix of imaging (HST, NGST, AO/8metre, ..) and kinematic (GAIA, SIM, massive IFU studies...) which will become available over the next few years. In this talk I shall illustrate the next developments beyond King models, noting our biggest current challenges: determining the internal kinematics of clusters, and careful studies of very young clusters, to quantify the range of initial conditions.

2. Dynamical models: young wine

The GRAPE N-body machines are in operation, and already producing fruit (Makino 2002). Available codes include very extensive treatment of stellar evolution, and are limited largely by a lack of observational constraints on the boundary conditions at young ages, and (temporarily) by star numbers. Real simulations of clusters as rich as those in the LMC are however already possible (figure 1). These simulations illustrate both the wealth of information potentially available in an observational colour-magnitude diagram (CMD), and how complex is the ‘main sequence turn-off’ in a young cluster. Future CMD analyses clearly must do more than fit a single isochrone from evolutionary models of single stars in such circumstances. Similar new opportunities for understanding exist in older clusters, especially from careful consideration of blue stragglers.
3. Real Dynamical models: cluster internal evolution

The evolution of a (globular) star cluster is a function of stellar evolution, as noted above, and also internal and external dynamical effects. The most sensitive internal parameters have long been suspected to be initial density, fraction of hard binaries, and the stellar IMF. Recent results have highlighted the irrelevance of some of these, and the need for more understanding of the others.

Figure 2 presents a recent example of a relevant study, determining the core radius-age distribution for clusters in the Galactic satellites (LMC, SMC, Fornax, Sgr). It is apparent from figure 2 that there is a substantially greater dispersion in core radius size in older clusters than exists in young clusters. Does this indicate a range of initial conditions, with (by chance?) few large young clusters forming today, or evolution, with core radius increasing with age? Cluster size is determined by the pressure-gravity balance, so core radius evolution can be due either to a pressure change (increased stellar velocity dispersion) at approximately constant total potential, or to decreasing binding energy, from mass loss, at approximately constant velocity dispersion, or some combination of both.

A recent series of HST studies and N-body has addressed these issues. The easiest possible cause to check is the stellar IMF. A very top-heavy IMF will lead to more stellar evolution-induced mass loss than will a shallow IMF, and consequently very different contributions to the natural evolutionary change in gravitational potential depth. The left panel of Figure 3 illustrates the effect different IMF slopes would have on core radius evolution. It also identifies three pairs of clusters, of similar age and very different core radius, whose IMFs were determined from deep HST imaging.
Figure 2. The top left figure shows the cluster core radius vs age relationship, derived from HST imaging data for 53 LMC clusters by Mackey and Gilmore (2002). The 3 images show a typical young cluster (lower left: NGC2156) and two old clusters (NGC1916, NGC1841 - top), similar in every way except for their clearly different core radii. THIS FIGURE AVAILABLE IN gif FORMAT

The IMFs were indistinguishable – an apparently universal observation in studies of globular cluster IMFs –, excluding this as a contribution to core radius differences between the clusters (de Grijs et al 2002). The right panel of figure 3 addresses the initial condition question: might the core radii be an extreme function of stellar mass, so that comparison of young and old at similar apparent magnitudes, but effectively at very different stellar masses, is misleading. That is, might there be an extreme range of initial mass segregations. This figure shows core radii of the six clusters studied for their IMFs determined at the same low mass (0.8M⊙). While all core radii are larger (there is substantial early/initial mass segregation in clusters), the increased range of core radii with increased age is still apparent.

3.1. Stellar IMFs in clusters

It is worth noting here a recent study of an extremely diffuse stellar ‘cluster’, the UMi dSph galaxy (Wyse et al 2002). This galaxy has similar metallicity, age and stellar mass to a large old globular cluster, but has a vastly lower stellar density, and a vastly higher dark matter content. Thus, comparison of its stellar IMF with that of similar metallicity and age clusters provides a direct test of possible environmental effects on the IMF. Comparison of the UMi luminosity function with that of its two ‘twin’ clusters, M15 and M92, is shown in Figure 4. The mass functions are clearly very similar. This result supports an increasing
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Figure 3. The LMC core radius-age relation, with the direction of evolution resulting from different stellar IMF slopes indicated (left panel). The three pairs of clusters studied to limit IMF changes are indicated. Right: the effect of mass on core radius for the 3 pairs of studied clusters. Core radii for 6 clusters determined for turn-off stars and stars of 0.8Msun are connected by dots. As expected from mass segregation, clusters are larger when low-mass stars are used as tracers, but the form of the age-core radius relation is retained. (from deGrijs et al. 2002)

number of studies which show that the IMF at low masses behaves as a universal constant. While neither expected nor understood, this does remove a potentially troublesome free variable from dynamical studies.

3.2. Dynamical models: what is the answer?

If mass loss variations are not the origin of the range of cluster sizes, might it be a range of heating processes? Current studies suggest not. N-body simulations of the effects of the two most important processes, primordial hard binaries and external tidal effects, have recently been completed. Primordial hard binaries, a dominant heat source in cluster dynamical evolution, are certainly important. However, hard binaries act more as an isothermal reservoir, preventing core collapse, than as a heat engine, systematically increasing the internal dispersion. External tides are also surely important in cluster evolution, and lead to evaporation, as the several recent discoveries of tidal tails illustrate. However, external tides act on the outer parts of clusters more than the cores: they are inefficient at heating core radii (figure 5) in realistic potentials like those of the galactic satellites.

Unsatisfactorily, we are left with initial conditions: large clusters formed large, possibly due to differences in star formation efficiency, and stayed that way, until evaporated by external tides. All is not gloom: this does lead to new possibilities for the analysis of cluster system evolution. If the large clusters are weakly bound, they become a tracer of the dynamical history of their environs.
Figure 4. The stellar luminosity function of the UMi dSph galaxy, compared to those for two globular clusters (M15, M92) of similar age and metallicity. The stellar low mass IMF is manifestly similar, even though these systems cover the full stellar density range in the Universe. From Wyse et al (2002)

Figure 5. Core radius evolution for N-body simulations of clusters similar to those in the LMC, on orbits about a point-mass representing the LMC. (Wilkinson et al in prep)
If they are not, possibly exotic processes are involved. We consider each option in turn.

4. **Exotic dynamics**

Do globular clusters host black holes? Observationally, this question remains open. However, massive black holes are apparently ubiquitous in the dense nuclear stellar clusters of galaxies, and low-mass black holes are well-known in X-ray astronomy. Black holes can and do exist, so it is of interest to investigate how they might evolve in a cluster. The prediction is not obvious: in principle, the two holes merge after orbital decay dominated in its late stages by gravitational radiation. But the centre of a dense star cluster is an active environment, with continual dynamical interactions. Do these continual star-binary interactions encourage or delay black hole coalescence? Specifically, do two low-mass black holes merge (and perhaps seed an eventual super-massive nuclear black hole), or do they act as an extreme hard binary, and disrupt the cluster? Or both?

The key parameter for binary coalescence is the binary orbital eccentricity: GR radiative orbital decay is rapid only if the orbital eccentricity approaches unity. But the orbit is continually scattering/scattered by cluster stars. Which process dominates? Some recent GRAPE calculations by Sverre Aarseth of merging clusters, each of which contains a black hole, are shown in Figure 6: while this is not always the case, in these examples a merger occurs before effective cluster disruption. A side-effect is also apparent: the stars scattered out of the cluster by the black hole binary have a considerable dispersion: no cold tidal-tail would be seen in such a case. Perhaps cold tidal tails are the strongest evidence that globular clusters do not host more than one black hole.

5. **Dynamics and the environment**

Large weakly-bound clusters are readily damaged by tides. So if they exist a gentle history may be inferred. Do they exist, and where? Figure 7 illustrates the type of analysis which is becoming possible, combining dynamical models with morphological studies.

Figure 7 illustrates the significant correlation between core radius size and stellar horizontal-branch (HB) morphology seen in Galactic globular clusters. This does not require a direct connection: one might prefer to explain HB morphology (at least in part) as an age effect. It does allow one to deduce that the ‘young halo’ clusters defined by HB morphology have not lived long in a harsh tidal field. Interestingly, the right panel shows that a very similar distribution of core radii is seen in satellite cluster systems. The tidal field in these systems is gentle: no disk or bulge shocking. So one may speculate that the satellites display a core size distribution which is modified from the ‘primordial’ distribution only by internal processes. Comparison of the present satellite distribution with that of Galactic field clusters, with appropriate allowance for recent destruction, then determines the satellite late accretion rate/fraction into the galaxy.

Such analyses, now becoming possible, link the evolution of cluster systems directly with the evolution of a system of individual clusters, making quantitative the whole life cycle of these stellar dynamical systems.
Figure 6. N-body simulation (by Sverre Aarseth) of the evolution of a merger of two clusters each containing an intermediate mass black hole. Clusters of 120K and 240K stars are shown. This rigorous GR calculation shows that the two black holes can merge into a single central hole (eccentricity=1: top panel) before the cluster is effectively unbound. The bottom panel shows that many stars are ejected well above the escape velocity: this evolutionary path would not leave a detectable ‘tidal debris stream’ after cluster disruption.
Figure 7. LHS: Top left: $\text{[Fe/H]}$ vs HB-type, defining the three subsystems following Zinn – bulge/thick disk (top left), ‘old halo’, (right, and on the solid line), and ‘young halo’ (below the line). Other panels: core radius distributions for the three subsystems. The young halo distribution clearly differs from the other two, consistent with a different dynamical history. RHS: core radii distribution for old clusters from the 4 Galactic satellites, LMC (14), SMC (1), Fornax (5) and Sgr (5). The distribution clearly is similar to that of Galactic ‘young halo’ clusters. (from Mackey & Gilmore, this meeting)

6. Acknowledgement

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