Dynamical Evolution of Dense Stellar Systems
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Dynamical Evolution of Star Clusters with Intermediate Mass Black Holes and Primordial Binaries

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Abstract. The evolution of a star cluster is strongly influenced by the presence of primordial binaries and of a central black hole, as dynamical interactions within the core prevents a deep core collapse under these conditions. We present the results from a large set of direct N-body simulations of star clusters that include an intermediate mass black hole, single and binary stars. We highlight the structural and dynamical differences for the various cases showing in particular that on a timescale of a few relaxation times the density profile of the star cluster does no longer depend on the details of the initial conditions but only on the efficiency of the energy generation due to gravitational encounters at the center of the system.

Keywords. stellar dynamics – globular clusters: general – methods: n-body simulations – binaries: general

1. Introduction

Dense stellar systems such as globular clusters are extremely fascinating astrophysical laboratories, where many physical processes – stellar dynamics, evolution and hydrodynamics – concur to shape their evolution. A realistic numerical modeling of these systems is outside the current hardware capabilities, even if the situation is likely to improve in the near future thanks to the GRAPE-DR (see Jun Makino's contribution in these proceedings). However globular clusters have appealing properties from the point of view of modeling, such as single old stellar population, quasi spherical symmetry, established dynamical equilibrium and quasi isotropy in the velocity dispersion tensor. Therefore even a simplified model has the hope to describe the key features in the evolution of these systems.

In this framework we decided to focus on the dynamical evolution driven by gravitational relaxation especially in presence of primordial binaries and intermediate mass black holes (IMBHs). Despite a growing evidence for the presence of a significant population of binaries in globular clusters and promising hints for IMBH signatures, these components are often neglected due to the dramatic increase in computational resources required in a simulation where the local dynamical timescale may be many orders of magnitude smaller than the global relaxation timescale (for example hard binaries have an orbital period of a few hours, while the half-mass relaxation time can be up to a few billion years). Thus we have started a simulation program aimed at systematically characterizing by means of direct N-body simulations the dynamical interplay of binaries and IMBHs in the center of dense stellar systems, initially using simple equal mass isolated models with up to 100% primordial binaries (see Heggie, Trenti & Hut 2006) and then progressively adding the influence of a tidal field (see Trenti, Heggie & Hut 2007), a central IMBH (see Trenti *et al.* 2007a, or primordial triples (see Trenti *et al.* 2007b).

To date we have completed about 1000 runs, exploring a wide parameter space for single stars and work is underway to extend the study to systems with a mass spectrum and stellar evolution.

One of the most important conclusions from the first part of this project and the one on which we focus these proceedings is that the collisional evolution of a star clusters does not depend on the details of the initial density profile one start with, but uniquely on the efficiency of the production of energy in the system. Therefore independently of the initial concentration, within a few to ten relaxation times star clusters with single stars only will reach a high concentration "core collapsed" configuration with a core to half mass radius $r_c/r_h \approx 0.01$. Instead in presence of a significant population of primordial binaries the core radius will be much larger $r_c/r_h \approx 0.05$ and in presence of a central IMBH the core may be even larger $r_c/r_h \gtrsim 0.1$. Given its insensitivity to the initial concentration, the core to half mass radius of well relaxed system does appear to be a powerful indicator of the dynamical properties of the system available even for globular clusters in nearby galaxies. Of course an accurate data-model comparison is required, as observations are based on light, while our core definition depends on mass (see Trenti, Heggie & Hut 2007 for a detailed discussion of different core radius definitions).

2. Cluster Evolution: The physical picture

Star clusters with up to a few hundred thousands stars have a two body relaxation time much shorter than the age of the universe, so that their internal long term evolution is driven by gravitational interactions.

When the system is made of single stars only, the classical mechanism of gravothermal instability is dominant (Spitzer 1987). Two-body encounters drive a heat flow from the central region of the star cluster, which behaves like a self gravitating system with negative specific heat, to the halo. This triggers a thermal "collapse" on the timescale of the heat flow process. The "collapse" phase lasts for several relaxation times until an efficient form of energy generation in the center can stop the process by providing an energy production rate equal to the energy loss rate by two body relaxation from the region of the core. This happens when one or more binaries are formed due to three body encounters in the dense central region, point at which a series of gravothermal oscillations with multiple core bounces can set in with an overall self-similar expansion of the cluster.

The presence of a more efficient central energy source, which may be in the form of primordial binaries, a central intermediate mass black hole, stellar mass black holes, mass loss from massive stars – possibly enhanced by physical collisions – changes significantly the standard gravothermal collapse picture. In all the cases where the energy release is higher than that due to dynamically formed pairs the equilibrium core size is larger due to a self-regulation mechanism. In fact, if the central energy production is too high the core is heated up and expands until a steady configuration is reached. This happens for example starting from a $W_0 = 11$ King model with 10% primordial binaries (see Trenti, Heggie & Hut 2007 and fig. 1). The presence of a tidal field does not influence much the self similar evolution of the density profile up to the half mass radius except in the latest stage of the life of the system, when more than 90% of the initial mass has been lost.

3. Results from direct N-body simulations

The initial conditions of our runs are tidally limited models with up to 19961 stars of equal mass. The initial density profile is that of a King model with different concentrations (W_0 parameter from 3,5,7 and 11). The runs with primordial binaries have a number

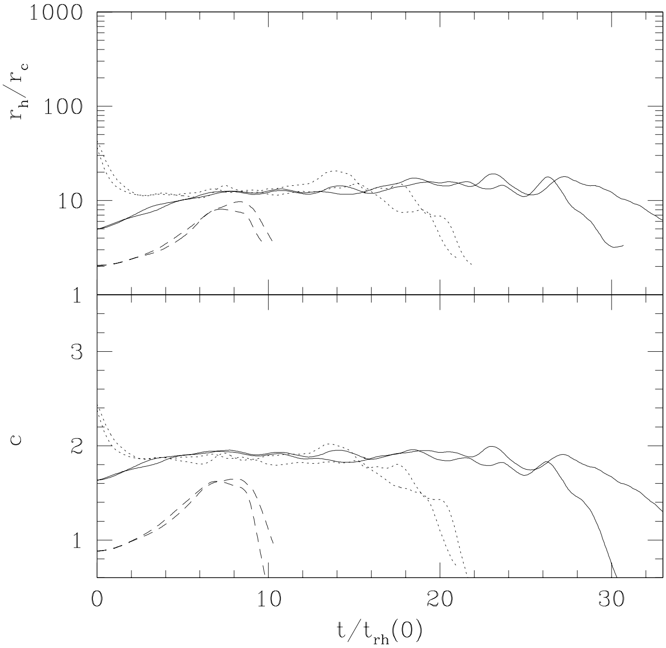

Figure 1. Evolution of the ratio of the half mass to core radius (upper panel) and of the concentration parameter $c = \log r_t/r_c$ for different King models with $f = 10\%, 20\%$. The solid line refers to simulations starting from $W_0 = 7$, the dotted line to $W_0 = 11$ and the dashed line to $W_0 = 3$; the number of particles used is 16384. The evolution quickly erases differences due to initial conditions, and during binary burning c and r_h/r_c evolve very similarly.

fraction of 10% and 20% (that is 20% and 40% in mass). In the runs with an IMBH, a central point particle has a mass of the order of a few percent of the total mass of the system (see Trenti *et al.* 2007a). The evolution of the system has been followed by direct integration until tidal dissolution of the system, using Aarseth's NBODY6 (Aarseth 2003), which has been slightly modified to guarantee and adequate treatment of the dynamical interactions around an IMBH (see Trenti *et al.* 2007a for full details).

The main result on the evolution of some representative models is shown in Fig. 1 for runs with primordial binaries and in Fig. 2 for runs with an IMBH. In Fig. 1 both the core to half mass ratio r_c/r_h and the tidal to core radius ratio $c = log(r_t/r_c)$ evolve within a few relaxation times toward a common value, which is then kept quasi constant until tidal effects becomes dominant in the final stage of the evolution. Interestingly simulations with 10% and 20% of primordial binaries have a very similar evolution of their density profile. This is because the efficiency of production through binary-single and binary-binary encounters saturates when mass segregation brings the binary population in the core above $\approx 50\%$, which happens starting with more than 10% of binaries (see also Vesperini & Chernoff 1994).

The evolution of r_c/r_h is similar to that observed for simulations with primordial binaries even when a IMBH is present at the center of the system (see Fig. 2). Again a universal profile is quickly reached and then the evolution proceeds in a self similar way. The BH however is a more efficient energy source, mainly due to an enhanced interaction rate between stars within its sphere of influence, so that a $W_0 = 7$ model initially expands its core rather than contracting it.

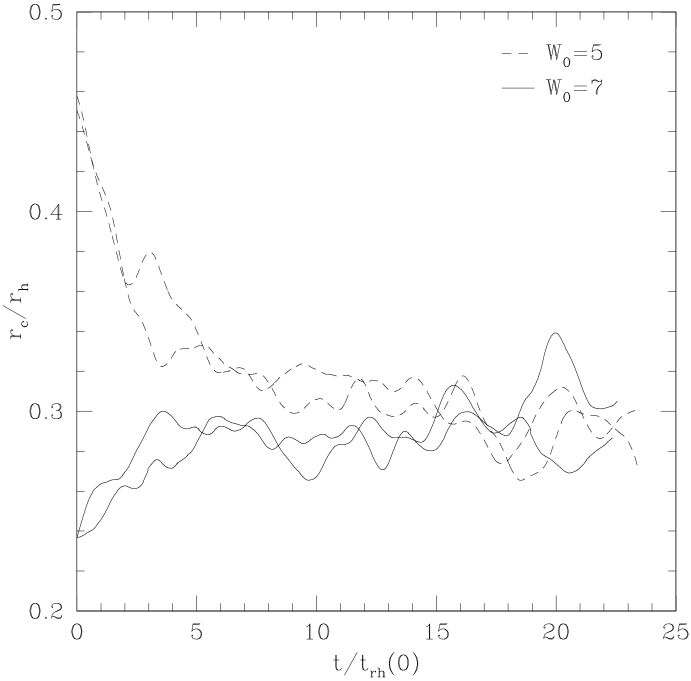

Figure 2. Core to half mass radius ratio for a series of simulations with $N = 8192$, $m_{BH} = 0.014$ and 10% primordial binaries. Different initial conditions (King profiles with $W_0 = 5, 7$) converge toward a common value for r_c/r_h.

4. Conclusion

In this proceeding contribution we highlight one important result from a project aimed at studying the dynamical evolution of star clusters with primordial binaries and intermediate mass black holes by means of direct N-body simulations (see Heggie, Trenti & Hut 2006, Trenti, Heggie & Hut 2007, Trenti *et al.* 2007a, Trenti *et al.* 2007b). We show that the density profile of a star clusters evolves toward a self-similar universal configuration on the two body relaxation time scale, with a concentration (measured for example in terms of the core to half mass radius ratio) which is sensitive only to the efficiency of the energy production in the system. Clusters with single stars only evolve toward a "core collapsed" state, as they need to reach very high central density to dynamically produce a few binaries that can eventually halt the gravothermal collapse and lead to a core bounce. Clusters with a significant population of primordial binaries and/or with a central IMBH never reach "core collapse" but rather settles in a configuration with $r_c/r_h \gtrsim 0.05$. With a detailed data-model comparison, the use of r_c/r_h could provide unique insight onto the dynamical status of observed old globular clusters not only in the Milky Way but also in nearby galaxies.

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