Dynamical Evolution of Dense Stellar Systems
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Dynamical Evolution of Rotating Globular Clusters with Embedded Black Holes

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Abstract. Evolution of self-gravitating rotating dense stellar systems (e.g. globular clusters) with embedded black holes is investigated. The interplay between velocity diffusion due to relaxation and black hole star accretion is followed together with cluster differential rotation using 2D+1 Fokker Planck numerical methods. The models can reproduce the Bahcall-Wolf $f \propto E^{1/4}$ ($\propto r^{-7/4}$) cusp inside the zone of influence of the black hole. Angular momentum transport and star accretion processes support the development of central rotation in relaxation time scales, before re-expansion and cluster dissolution due to mass loss in the tidal field of a parent galaxy. Gravogyro and gravothermal instabilities conduce the system to a faster evolution leading to shorter collapse times with respect to models without black hole.

Keywords. methods: numerical, gravitation, stellar dynamics, black hole physics, globular clusters: general

1. Introduction

The improvement of our knowledge and methods in the field of rotating dense stellar systems is extremely important for modelling systems like globular clusters and galactic nuclei, where a central star-accreting black hole comes into the game. Direct integration of orbits (N-Body method) has been applied to the problem. However, N-Body simulations only provide a very limited number of case studies, due to the enormous computing time needed even on the GRAPE computers. Moreover, in young dense clusters, supermassive stars may form through runaway merging of main-sequence stars via direct physical collisions, which may then collapse to form an IMBH.

2. Diffusion and loss-cone accretion

The Fokker-Planck approximation is applied for an axisymmetric system in flux conservation form, following :

$$\frac{df}{dt} = \frac{1}{p}\left(-\frac{\partial F_X}{\partial X} - \frac{\partial F_Y}{\partial Y}\right) \tag{2.1}$$

p is the phase volume per unit X (dimensionless energy) and Y (dimensionless angular momentum). The loss-cone limit is defined by the minimum angular momentum for an orbit of energy E:

$$J_z^{min}(E) = r_d\sqrt{2(E - GM_{\rm BH}/r_d)} \tag{2.2}$$

where r_d is the disruption radius of the BH, calculated following Frank & Rees (1976):

$$r_{\rm d} \propto r_*(M_{\rm BH}/m_*)^{1/3} \tag{2.3}$$

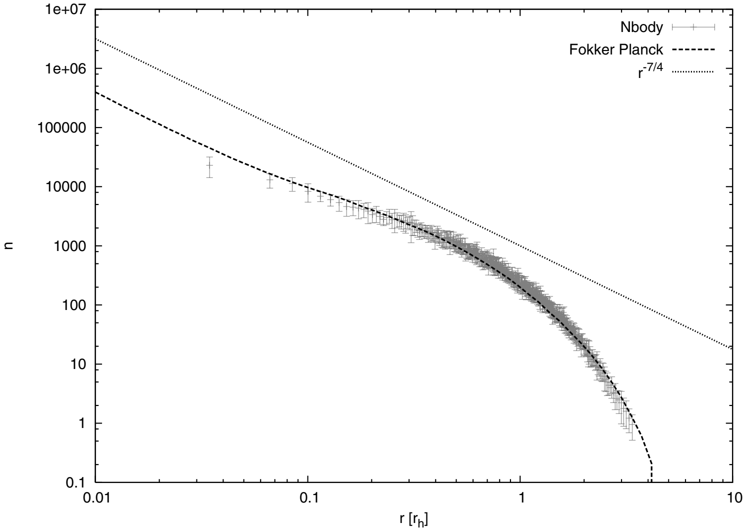

Figure 1. Comparison with an N-Body run using 10000 particles (Bahcall-Wolf cusp) at a time where $M_{\rm bh}/M_{\rm cl} = 0.1$.

r_* and m_* are the stellar radius and mass, respectively.

The contribution of $f(X, Y)$ to accretion, at each energy-angular momentum grid cell is given by:

$$\Delta f_{\rm acc} = P_a(Y)(f^{\rm old} + \Delta f) \tag{2.4}$$

where $P_a(X, Y, Y^{\rm diff})$ is the probability of accretion by the BH and $\Delta f_{\rm acc}$ is the fraction of $f(X, Y)$ which goes into the loss-cone, due to diffusion in the inner/outer direction (Fiestas 2006).

The NBody6++ code has been modified in order to treat accretion of stars, which approach the BH inside its tidal disruption radius (Eq. 2.3)

3. Numerical results

As initial configurations, truncated King models with added bulk motion are used. Their adopted distribution function is

$$f(E, J_z) \propto \exp\left(-\beta\Omega_0 J_z\right) \cdot \left[\exp\left(-\beta(E - E_{\rm tid})\right) - 1\right], \qquad E < E_{\rm tid} \tag{3.1}$$

and 0 otherwise. $\beta = 1/\sigma_{\rm c}^2$ and Ω_0 is an angular velocity. The initial conditions of each model are fixed by the triple $(W_0, \omega_0, M_{\rm BH_i})$.

$M_{\rm BH}$ grows through accretion of low-$J_{\rm z}$ stars while central density increases and the BH-potential ($\sim GM_{\rm BH}/r$) dominates the stellar distribution within its influence radius $r_{\rm a}$.

The final steady-state, long-dashed line (FP) and crosses (N-Body) in Fig. 1, evolves towards a power-law of $\lambda = -1.75$, according to $n \propto r^{\lambda}$ (Bahcall & Wolf 1976; Lightman & Shapiro 1977; Marchant & Shapiro 1980). It forms inside $r_{\rm a}$ and is maintained in the post-collapse phase, while the evolution is driven through energy input from the central object. Very close to the center the density profile flattens due to the effective loss-cone accretion. Fig. 2 shows the evolution of density in the meridional plane (ρ, z). In the regions where BH star accretion dominates, the cusp forms a strong colour gradient towards the center. At the same time, the system loses mass through the outer

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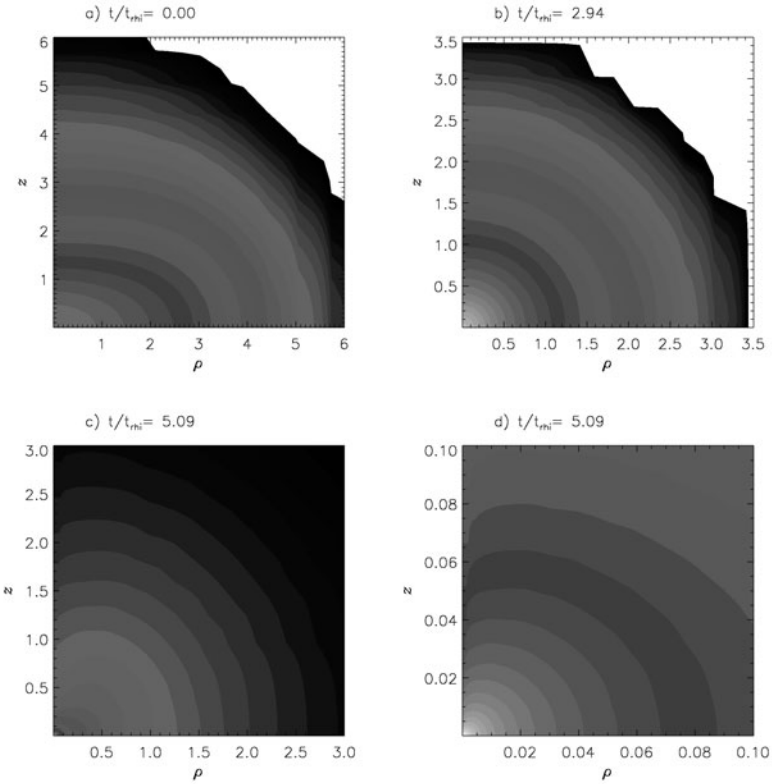

Figure 2. Evolution of density distribution in the meridional plane. Cylindrical coordinates (ρ, z) are used. Lighter zones represent higher isodensity contours. Note that scales are different in each plot and Fig. 2d shows a zoom of the central parts of Fig. 2c (insider $r_{\rm a}$). The time is given in units of initial half-mass relaxation time ($t_{\rm rhi}$).

tidal boundary. Particularly, at later times, the density of stars is higher in ρ-direction (equatorial plane, very close to the BH) than in z-direction (Fig. 2c,d).

$M_{\rm BH}$ stalls at $\sim 0.01\, M_{\rm cl}$ at post-collapse time, and remains nearly constant afterwards, while BH mass accretion rate ($dM_{\rm BH}/dt$) reaches a maximum at collapse time, due to the higher density of orbits in the core, and falls afterwards. Cluster mass ($M_{\rm cl}$) loss in the tidal field of the parent galaxy is very strong during the re-expansion of the core.

BH models experience in a similar way, the onset of gravogyro instabilities (Hachisu 1979; Hachisu 1982), as angular momentum diffuses outwards, leading to an increase of central rotation. BH accretion of stars on orbits of low $J_{\rm z}$ sets off, an ordered motion of high-$J_{\rm z}$ bounded orbits around the central BH supports central rotation. At the same time, stars in the core are heated via the consumption of stars in bound, high energetic orbits in the cusp.

As seen in Fig. 3, angular velocity grows over time stronger in the inner Lagrangian-radii for the BH model, as a consequence of the faster dynamical evolution (gravogyro + gravothermal instabilities). Post collapse evolution is present only in the system harbouring a black hole. Thus, as the BH grows and rotation increases in its zone of influence ($r \sim r_{\rm a}$) angular momentum continues being transported out of the core. In the outer parts, rotation is continuously depleted.

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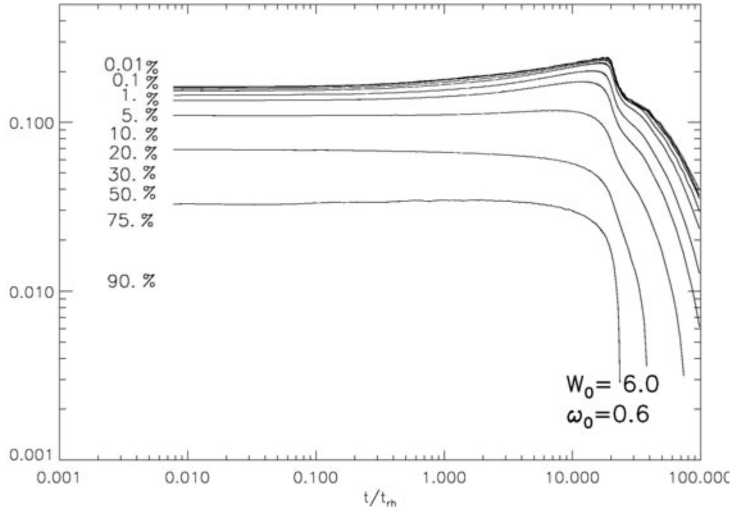
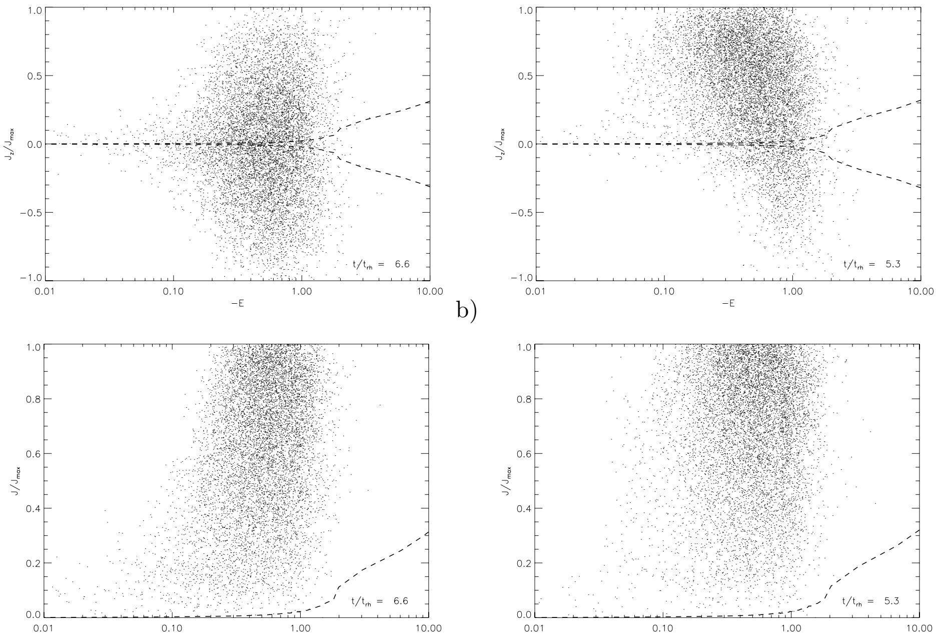


Figure 3. Evolution of angular velocity.

Fig. 4 shows the stellar distribution in the E-Jz plane, for a model with $M_{\rm bh}/M_{\rm cl} = 0.1$. In the non-rotating model ($W_0 = 3.0$) the symmetry of the stellar distribution makes a populated loss-cone from the beginning (Fig. 4a). As a consequence, the accretion rates are expected to be higher in the axisymmetric approximation ($J < J_{\rm z,min}$). In the E-J plane (Fig. 4c), the stellar distribution shows a less populated loss-cone, which would lead to a slower growth rate by using the criterion $J < J_{\rm tot,min}$ (which is implicitly used in the N-Body realisation). On the other side, the rotating model ($\omega_0 = 2.4$) shows an initial asymmetry in the distribution of stars (Fig. 4b), which is still present when $M_{\rm bh}/M_{\rm cl} = 0.1$. Nevertheless, the $J_{\rm z,min}$ approximation seems to overestimate the accretion rate, in comparison to the $J_{\rm tot,min}$ criterion (Fig. 4d). This effect is being currently investigated in order to accurate the Fokker-Planck approximation, in comparison to the direct N-Body method.

4. Conclusions and outlook

Although some constraints in the evolution of rotating clusters are still missing, like a mass spectrum or stellar evolution, as well as a more realistic criterium for galactic tidal mass loss (as observations suggest, e.g. Mackey & van den Berg 2005), the consistence of the general evolution of cluster structure in spherically symmetric systems embedding BHs and estimation of BH masses with observations makes clear that the models presented here can well reproduce the evolution of GC with embedded BHs, and that rotation constitutes an important constraint, which needs to be taken into account for the understanding of the formation and evolution of GCs, specially when it is high enough, at early times of evolution (e.g. in the young clusters of the LMC). Regarding the stellar spectrum, segregation of high mass stars is expected to drop the dispersion in the center (as reported by Kim, Lee & Spurzem 2004), leading possibly to a higher or at least more stable $V_{\rm rot}/\sigma$ in this region. Multi-mass models with BH are being currently developed and comparison to N-Body models are aimed to complement this calculations, using the highest particle number permitted at the time ($N \sim 10^6$) (Berczik *et al.* 2006).



a) b) c) d)

Figure 4. Number density of stars in the E-J plane.

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