Publications of the Korean Astronomical Society
30: 345 ∼ 347, 2015 September

pISSN: 1225-1534
eISSN: 2287-6936
http://dx.doi.org/10.5303/PKAS.2015.30.2.345

EVOLUTIONARY MODELS OF ROTATING DENSE STELLAR SYSTEMS WITH EMBEDDED BLACK HOLES

Jose A. Fiestas
National Astronomical Observatories of China, Chinese Academy of Sciences, Datun Lu 20A, Chaoyang District, Beijing 100012, China
E-mail: fiestas@nao.cas.cn
(Received November 30, 2014; Reviced May 31, 2015; Aaccepted June 30, 2015)

ABSTRACT

We present evolutionary models of rotating self-gravitating systems (e.g. globular clusters, galaxy cores). These models are characterized by the presence of an initial axi-symmetry due to rotation. Central black hole seeds are included in our models, and black hole growth due to the consumption of stellar matter is simulated until the central potential dominates the kinematics of the core. Our goal is to study the long-term evolution (Gyr) of relaxed dense stellar systems which deviate from spherical symmetry, and their morphology and final kinematics. With this purpose in mind, we developed a 2D Fokker-Planck analytical code, and confirmed its results using detailed N-Body simulations, applying a high performance code developed for GPU machines. We conclude that the initial rotation significantly modifies the shape and lifetime of these systems, and cannot be neglected in the study of the evolution of globular clusters, and the galaxy itself. Our models give a constraint for the final intermediate black hole masses expected to be present in globular clusters.

Key words: methods: numerical – gravitation – stellar dynamics – black hole – galactic nuclei – globular clusters: general

The centers of most galaxies contain a massive BH. The time scales involved are of the order of the relaxation time, or

$$t_{\rm r} \approx 0.065\ \sigma^3/(G^2 m_\star \rho \ln\Lambda) \qquad (1)$$

where ρ is the mass density, σ is the 3D velocity dispersion and $\ln\Lambda$ is the Coulomb logarithm (Spitzer, 1987). We adopt $\Lambda = 0.11N$. (Heggie et al., 1994).

We study the evolution of dense stellar systems harboring growing black holes, using direct N-Body methods. The central black hole has a mass of $M_\bullet/M_{\rm tot} = 0.01 - 0.05$. Particle numbers are N = 128000 and N= 256000. Simulations were run in parallel on the 85 node Laohu cluster (Beijing, China), the GPU cluster Kepler at ARI-ZAH (Heidelberg, Germany); and the 40 nodes Dirac cluster at NERSC (Berkeley, USA). We use the parallel GPU code φGPU (Berczik et al., 2011). These simulations have an energy conservation $\Delta E/E_0 < 10^{-4}$, even after 10^4 N-Body time units, and use a softening parameter of 10^{-5}. Our Fokker-Planck models are described in Fiestas & Spurzem (2010), where we improved our method by implementing a multi-mass stellar distribution in the code. Initial models are rotating asymmetric King Models, with parameters $W_0 = 6$ and $\omega_0 = (0.0, 0.3, 0.6, 0.9)$. We consider two-component models defined by particle mass ratios $\mu = m_h/m_l$, and total mass fraction $f_h = M_h/M$, where m_h is the individual heavy particle mass, m_i the individual light particle mass, and f_h the total mass fraction of the heavy component.

Fig. 1 shows the final density distribution in the XZ-plane. Ellipticity is observed as well, after the system relaxes. This is a first sign that BH-dense stellar systems maintain a significant amount of rotation, as it was observed in single-mass models (Fiestas et al., 2012).

The motion of stars surrounding the black hole, of mass $M_\bullet$, inside the influence radius $r_{\rm n}$ are directly influenced by its gravitational field (for an isothermal sphere $M(< r_{\rm n}) = 2M_\bullet$). The BH central potential heats the core, through capture of the kinetic energy of stars in bound, high energetic orbits in the cusp. Energy flux is achieved by small-angle, two-body encounters, by which stars lose energy and move closer to the center, while the stars with which they interact gain energy and move outward from the cusp into the ambient core. Angular momentum transport outwards is initially enhanced by gravo-gyro instabilities (Hachisu, 1982), and maintained by stars, captured by the deep potential, where tangential motion is dominant. The result is that orbits with high $J_{\rm z}$ remain in the center after the system relaxes.

Orbits in the region of influence of the BH become Keplerian bounded. Their velocity dispersion approximates a power-law of -1/2 within $r_{\rm n}$. The velocity dispersion grows significantly inside $r_{\rm n}$ and faster when the cluster is close to collapse, due to the presence of the deep central potential. Correspondingly, the Bahcall-

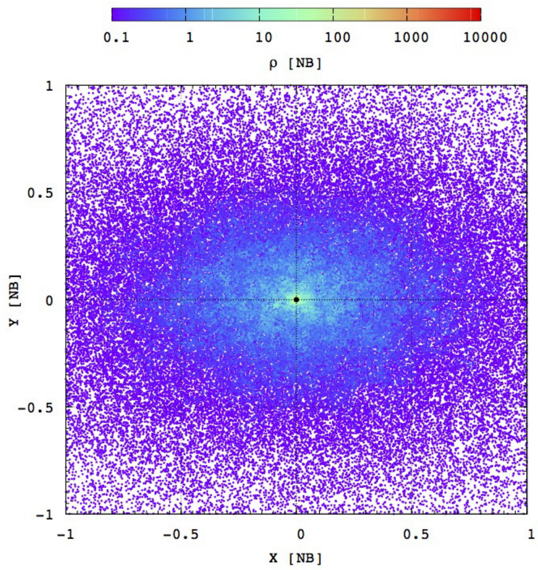

Figure 1. Final density on the XZ-plane for two component models, and $M_{\rm bh} = 0.05$

Wolf cusp ($\gamma = -1.75$) is reached by the massive component of our 2-mass models. The lighter component reaches a stable configuration with a power law of -1.25. This behavior was previously predicted by Bahcall & Wolf (1977).

Core contraction and expansion, which prevents core collapse, leads to a longer evolution, although in multi-mass models the evolutionary time in units of relaxation time is generally shortened, due to mass-segregation, and in our simulations is enhanced by energy and angular momentum diffusion between stars of different masses.

Fig. 2 shows the velocity dispersion and rotation for a model of $M_{\rm BH} = 0.05$ and rotation parameter $\omega_0 = 0.9$. We observe a signature of the central rotation of the massive stars after stellar relaxation. In addition, we see that the maximum of rotation of the massive stars moves inwards in time, opposite to the results obtained by models without BH (Kim et al., 2004). This is a sign that angular momentum is not moving only in one direction (outwards), but also to the center (inwards). Similarly, the stable flux of energy defines the density and velocity dispersion solution for relaxed systems, and angular momentum appears to maintain an inward/outward flux that makes central rotation possible. Nevertheless, we do not find a stable solution of rotation, as the angular momentum is steadily moving outwards and low J_z orbits dominate the center.

The rate of rotational velocity over velocity dispersion represents the importance of ordered motion in comparison to random motion. It is commonly measured in elliptical galaxies, in which rotation is significant, and can determine the shape of the system. Nevertheless, ellipticals are not relaxed systems, like galaxy cores and globular star clusters. Therefore, the expected relation

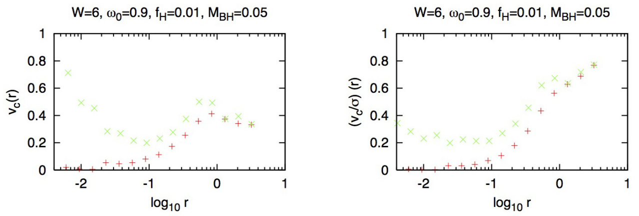

Figure 2. $V_{\rm rot}$, and $V_{\rm rot}/\sigma$ as a function of radius for two component models and initial $M_{\rm bh} = 0.05$

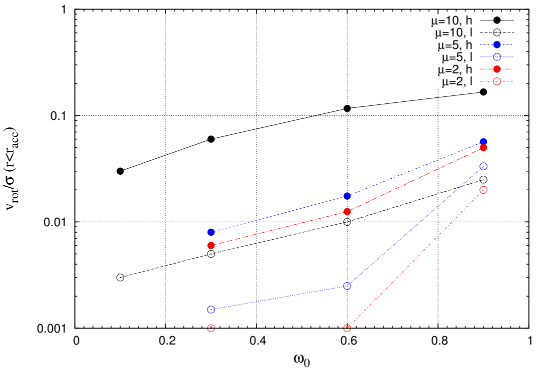

Figure 3. $V_{\rm rot}/\sigma$ inside influence radius vs. ellipticity for different mass ratios.

of these quantities does not necessarily follow that of ideal isotropic rotators, but might show deviations due to anisotropy effects. $V_{\rm rot}/\sigma$ in Fig. 2 shows that, although the velocity dispersion is strongly increasing in the center, there is still a relatively significant amount of rotation (about 20%), which can be understood as the ratio of rotational kinetic energy to total kinetic energy, which plays an important role in determining the shape of the system, particularly inside $r_{\rm n}$.

As shown, the amount of rotation present in the system during its dynamical evolution is strongly influenced by the interplay between angular momentum diffusion (gravo-gyro instability) and the redistribution of high energy orbits close to the BH (loss-cone refilling).

ACKNOWLEDGMENTS

We acknowledge support by Chinese Academy of Sciences through the Silk Road Project at NAOC, through the Chinese Academy of Sciences Visiting Professorship for Senior International Scientists, Grant Number 2009S1-5, and through the "Qianren" special foreign experts program of China for R. Spurzem.

REFERENCES

Berczik P., et al., 2011, High performance massively parallel direct N-body simulations on large GPU clusters, hpc..conf....8B

Fiestas, & Spurzem, 2010, Dynamical Evolution of Rotating Dense Stellar Systems with Embedded Black Holes, MNRAS, 405, 194

Fiestas, et al., 2012, Evolution of Growing Black Holes in Axisymmetric Galaxy Cores, MNRAS, 419, 57

Hachisu I., 1982, Gravothermal and Gravogyro Catastrophes

of Rotating and Self-Gravitating Gaseous Disks, PASJ, 34,313
Heggie D., et al., 1994, Gravothermal Expansion in an N-Body System, MNRAS, 271,706
Kim E., et al., 2004, Dynamical Evolution of Rotating Stellar Systems - III. The Effect of the Mass Spectrum, MNRAS, 351, 220
Spitzer L. Jr., 1987, Dynamical Evolution of Globular Clusters, Princeton University Press, 191