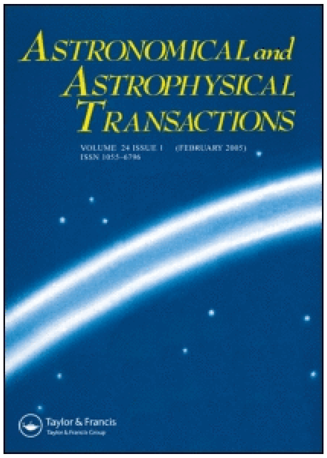

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Dynamics in dense stellar clusters: Binary black holes in galactic centres

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DYNAMICS IN DENSE STELLAR CLUSTERS: BINARY BLACK HOLES IN GALACTIC CENTRES

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The dynamics of a massive binary system in a galactic nucleus are presented. These are the first results from simulations applying a hybrid 'self consistent field' (SCF) and direct Aarseth N-body integrator (NBODY6), which synthesises the advantages of the direct force calculation with the efficiency of the field method. The code is aimed for use on parallel architectures and is therefore applicable for collisional N-body integrations with extraordinarily large particle numbers ($> 10^5$). It opens the perspective to simulate the dynamics of globular clusters with realistic collisional relaxation, as well as stellar systems surrounding a supermassive black hole in galactic nuclei.

KEY WORDS Dense clusters, binary black holes, galactic centres

1 BLACK HOLES AND GALAXIES

The picture of galaxy evolution by hierarchical merging of galaxies seems to be well established. On the other hand, there is evidence that larger galaxies harbour a supermassive black hole in their centre. It would therefore seem likely that two merging galaxies would each conceal a supermassive black hole. This brings up issues regarding the fate of these objects, such as the formation of a bound binary system and its effect on the dynamics of the merged galaxy, for example: if indeed these two black holes form a binary, on what timescale? Similarly, what would be the effect of surrounding stars on the hardening of this binary? And on what timescale will both black holes coalesce?

These problems can be tackled using N-body simulations. This work introduces some details of the problem of a sinking black hole binary. Furthermore it gives answers to the above questions from N-body simulations carried out with a new hybrid method for collisional stellar dynamics. The method is described elsewhere (Hemsendorf, 2000).

2 THE SINKING BINARY BLACK HOLE PROBLEM

Following Begelman, Blandford and Rees (1980), the central black holes of two galaxies will coalescence in the course of a galactic merger. During the early stages of the merger, the stellar component will form a nearly spherical system within the short timescale for violent relaxation. After that, the two supermassive black holes move through the stellar component with a velocity similar to the initial relative motion between the two galaxies. From this moment on, both massive bodies will feel dynamical friction. This friction leads the black holes to the newly-formed galactic centre, while the frictional force becomes more efficient with increasing density. Through this process, the black holes must inevitably 'find' each other and form a binary system (Makino, 1997).

After being bound, the binary hardens through dynamical friction. Assuming the centre of mass of the binary to be fixed at the centre of mass of the surrounding galaxy, dynamical friction must become less efficient with increasing binding energy of the binary. An encounter on a timescale longer than the orbital timescale of the binary cannot harden it efficiently. Close encounters become more and more important for the hardening rate. The most efficient process for binary hardening in this stage are the stars which gain very large velocities in three body encounters with the black holes. Because this process can evacuate the surrounding of the binary from stars, the hardening timescale can become very long. However, this is not true if the supply of stars undergoing close three body encounters with the supermassive objects remains high. N-body simulations with high particle numbers can help set constraints on this problem (Makino *et al.*, 1993; Quinlan and Hernquist, 1997).

3 COLLISIONAL STELLAR DYNAMICS WITH EUROSTAR

A numerical simulation of the hardening phase (until the massive black holes start to send out gravitational waves) must be able to follow three body encounters. For this reason, the Keplerian potential should not be softened in the dense part of the integrated system. The code must be able to integrate large angle encounters in an efficient way, while neither requiring too much computing time nor introducing energy errors. The overall N-body integration does not need to be symplectic, but should keep the energy error as low as possible. On the other hand, in a system showing a core halo structure the bulk of the stars in the halo move in the regime of the mean field of the whole cluster. Computationally, the central part of the system could best be treated using a collisional integrator, the halo part of the central galactic cluster by a mean field method.

In the new method *EuroStar*, both the collisional code NBODY6++ (Aarseth, 1993) and the collisionless method SCF (Hernquist and Ostriker, 1992) are merged to optimise large-N collisional N-body simulations. As shown here, it is well suited for simulations of the stellar dynamics around black holes in galactic nuclei. The resulting code runs on a wide variety of parallel computers and is therefore able to handle extraordinarily large particle numbers.

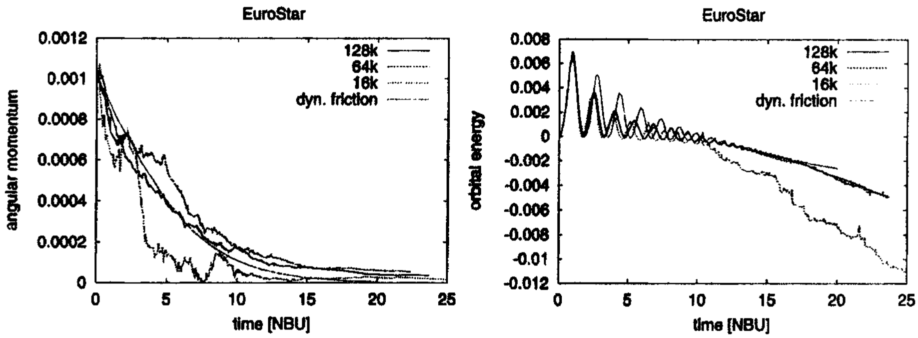

Figure 1 Evolution of the angular momentum and the binding energy of a binary black hole system integrated by the hybrid code. *Left panel:* The angular momentum of the binary black hole as a function of time (in N-body units). *Right panel:* The orbital energy as a function of simulation time. Once this energy becomes negative, both black holes are bound to each other.

4 FIRST RESULTS

The first results from *EuroStar* were obtained by simulating the motion of two massive particles in a sea of 16384, 65536, and 131072 light particles. The particles are distributed according to Plummer's model and $R = 3\pi/16$. The massive particles are initially placed symmetrically around the centre of mass of the stellar component. Their initial radius is at $r \approx 0.64 r_{\rm h}$, their initial velocity is 13.6% of the circular velocity at this radius, and their mass is 1% of total system mass each. The framework of the two body problem allows the study of the orbital parameters of the black hole motion. Once the binary is bound, the stars are left to serve as perturbers.

Assuming the black holes are moving in a sea of infinitely light particles, they mainly feel the forces from the mean potential of the stellar component, their partner black hole, and the dynamical friction (Chandrasekhar, 1943). Using these ingredients, a simple toy-model can compute the expectations for the decaying orbit. The results from the three N-body simulations are compared with the toy model in Figure 1. The plot on the left hand side of Figure 1 shows the evolution of the two-body-orbital angular momentum of the black hole binary. As shown, the orbital angular momentum reacts very sensitively to black hole – stellar particle encounters. For the 16384 particle run the evolution of the angular momentum shows strong fluctuations, while the curves for the runs with higher particle numbers show a smoother shape. Once the binary becomes bound after approximately 10 N-body time units, the prediction from the toy model decouples from the simulations. This is caused by the softened potentials used in the toy model to simplify the code. The softening leads to smaller orbital velocities at late stages in the toy code. Through these smaller velocities, dynamical friction becomes more efficient than in the N-body runs without any softening.

The plot on the right hand side shows the evolution of the two body binding energy as a function of time in N-body units. Once the energy becomes negative, the massive particles become bound to each other and the two body approach is a valid approximation for the orbital parameters. As for the figure showing the angular momentum, individual encounters of the stellar particles with the massive particles lead to step-like structures in the hardening phase after $t = 10$ for the 16k particle run. This effect is less important in the runs having 64k and 128k particles. The N-body simulations follow the predictions from the toy model. The decoupling after $t = 18$ is, again, caused by the softening applied to the black hole forces in the toy model. When scaled to physical units, the black holes would have an initial distance of 50 pc and an initial mass of $10^9 M_{\odot}$. They would converge to a distance of 41 AU within 5 million years.

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