TKira—A Hybrid N-Body Code

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Abstract. Accurately modeling the evolution of a star cluster in a strong tidal field poses unique computational challenges. We present a hybrid code that combines the strengths of two different approaches to computing gravitational forces. The internal, collisional, dynamics of the cluster is followed with a direct N-body integrator, KIRA, while the galactic tidal field is modeled with a cosmological code, GADGET, that uses a Barnes-Hut tree to evaluate gravitational forces in $O(N \log N)$ time. The quadrupole moment at the center of mass of the cluster is used to compute the external potential and provides a mechanism for mass loss. This forms a robust, bidirectional interaction. The advantages of combining two highly-developed and well-established software packages at such high level are obvious and many; not the least of the these is the ability to include other physical processes, e.g., stellar evolution.

One problem to which we applied this technique is the evolution of a dense star cluster near the Galactic Center. We are also using this code to explore the effects of the strong time variation in the tidal field of merging galaxies on the evolution of young star clusters forming during the merger.

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Traditional methods of modeling dynamical friction on star clusters have been, principally, semianalytical approximations based on assumptions of smoothness of the galactic potential. While for a certain, limited, class of problems it is valid, this approach is clearly inappropriate for many interesting scenarios of cluster evolution, e.g., time variable tidal field.

We present a scheme that evolves the external system together with the cluster using a collisionless method. We decided to use existing software packages for the two parts of the system: the KIRA integrator from STARLAB (Portegies Zwart *et al.* (2001)) for detailed modeling of the internal dynamics of the cluster and GADGET (Springel *et al.* (2001)) for the external collisionless system. The simulation proceeds in the following way:

(*a*) The cluster and the galactic system are created and initialized separately, using appropriate tools.

(*b*) The particle that will represent the cluster in the external system is initialized with its mass and the desired position and velocity. At this point the initial conditions are fully specified; the next steps are shown in Fig. 1 and form the main loop of the simulation.

(*c*) GADGET integrates the external system for Δt.

(*d*) Quadrupole moment $Q_{ij} = \frac{\partial a_i}{\partial x_j}$ at the center of mass of the cluster is computed by numerical differentiation.

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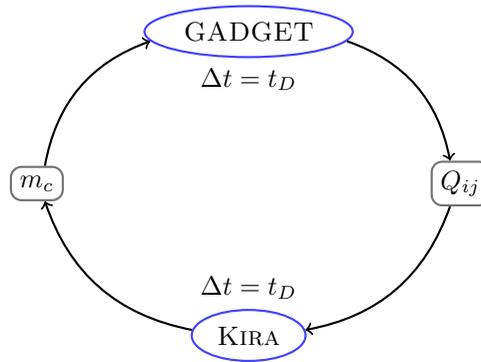
Figure 1. The high-level structure of TKIRA. After GADGET evolves the external system for Δt, the quadrupole moment $Q_{ij} = \frac{\partial a_i}{\partial x_j}$ is obtained at the cluster center of mass. KIRA uses this to approximate the external potential, evolving the cluster for another Δt; it then iteratively computes the new bound mass.

(*e*) KIRA integrates the cluster for Δt, using Q_{ij} as the estimate of the external field.

(*f*) The new bound mass of the cluster is estimated based on particle energies. A separate, distance criterion is used to permanently remove cluster particles that have strayed beyond two Jacobi radii.

While the original motivation for the development was to investigate the dynamical friction of dense nuclear clusters, it quickly became apparent that the same code can be applied to much more general problems involving strong, time-variable tidal field. To this end, we are considering the internal dynamics of a cluster whose parent galaxy is undergoing a merger. This is a considerably more difficult problem with a much larger parameter space. A somewhat related but considerably more general effort to simulate multiscale astrophysical systems is the *Multiscale Multiphysics Scientific Environment*; (see `http://muse.li`).

Even from the limited range of systems to which we have applied this code, several improvements have already become obvious. For problems where the changing mass of the cluster does not alter its orbit, the last step *(f)* can be safely omitted from the calculation. As there is no feedback of the cluster on the external potential, the quadrupole moment along the trajectory of the cluster particle can be now precomputed ahead of time, completely decoupling the two systems. Another refinement would be to include more than one cluster in the same simulation; this would open the doors to even more interesting systems. Unfortunately, this requires more substantial modification to the scheme.

References

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