Abstract

We describe a novel N-body code designed for simulations of the central regions of galaxies containing massive black holes. The code incorporates Mikkola’s “algorithmic” chain regularization scheme including post-Newtonian terms up to PN2.5 order. Stars move along the chain by adding a new perturber using a fifth-order integrator with forces computed on a GRAPE board. Performance tests confirm that the hybrid code achieves better energy conservation, in less elapsed time, than the standard scheme and that it reproduces the orbits of stars tightly bound to the black hole with high precision. The hybrid code is applied to two sample problems: the effect of finite-N gravitational fluctuations on the orbits of the S-stars; and inspiral of an intermediate-mass black hole into the galactic center.

The hybrid N-body code

The basic idea of the hybrid N-body code is depicted in Fig. 1. Orbits of particles close to the central BH, i.e. within \( r_{\text{crit}} \) (red circle), are precisely integrated in the AR-CHAIN part of the code. This also takes into account perturbations from stars within \( r_{\text{perturb}} \) (blue circle). Outside the chain, particles outside of \( r_{\text{perturb}} \) only act upon the center-of-mass motion of the chain. Outside the chain, orbits are integrated using the standard Hermite scheme eGRAPE. The GRAPE hardware is used in this part of the calculation to achieve maximal speed. Again depending on distance, particles may either react to the chain’s center of mass or the resolved chain. At the end of every step, checks are performed to find particles that enter or leave the chain, and, in case it is needed, treated accordingly. The number of particles integrated in the chain is typically of order of a few up to a few tens.

Performance tests

We tested the performance of the hybrid N-body code using various realizations of a model designed to mimic the density profile of the star cluster around the Milky Way supermassive black hole. Figure 2 shows the energy conservation and elapsed time for integrations until \( t \approx 10^{7} \text{yr} \) for a model with 10^5 particles. Black line (asterisks) are for eGRAPE without the regularized chain. Elapsed time for the same integrations can be seen on the right.

Results

Fig. 1: Schematic view of the hybrid N-body code. Dots represent the central BH (black) and surrounding stars (grey). Stars within \( r_{\text{crit}} \) (red circle) are treated in the AR-CHAIN taking into account perturbations from stars inside \( r_{\text{perturb}} \) (blue circle).

Model of the Galactic Center

Our N-body model of the Galactic Center is based on the collisionally relaxed, multi-mass model of Hopman & Alexander (2006) with a steep truncation at \( r = 0.1 \text{pc} \). The model includes the SMBH and four stellar components: main sequence stars, white dwarves, neutron stars, and stellar mass BHs. The total number of stars found in this model is \( \approx 75000 \). In addition, we included as test stars five particles with orbital elements corresponding to the five, shortest-period S-stars observed near the galactic center: S01-1, SD-2, SD-15, S0-19, and S0-20.

While evolving out model of the Galactic center we closely follow the orbital evolution of the five S-stars included in the model. On short timescales, the angular momentum of stars like SO-2 should evolve approximately linearly with time due to the (essentially fixed) torques resulting from finite-N departures of the overall potential from spherical symmetry. This evolution is illustrated for all the S-stars in Fig. 4a for three different particle numbers. Plotted are the two Keplerian components: main sequence stars, white dwarves, neutron stars, and stellar mass BHs. The total number of stars found in this model is \( \approx 75000 \). In addition, we included as test stars five particles with orbital elements corresponding to the five, shortest-period S-stars observed near the galactic center: S01-1, SD-2, SD-15, S0-19, and S0-20.

As a second application, we used eGRAPE\text{ch} to follow the relativistic inspiral of an intermediate-mass black hole (IMBH) into the Galactic SMBH. Our model includes the SMBH and four stellar components: main sequence stars, white dwarves, neutron stars, and stellar mass BHs. The total number of stars found in this model is \( \approx 75000 \). In addition, we included as test stars five particles with orbital elements corresponding to the five, shortest-period S-stars observed near the galactic center: S01-1, SD-2, SD-15, S0-19, and S0-20.

References

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