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Orbits of stars in the central parsec

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Abstract. We describe a novel *N*-body code designed for simulations of the central regions of galaxies where the accelerations are dominated by forces from one or more, supermassive black holes. Applications to two sample problems are presented: 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.

Key words. Galaxy: center – stellar dynamics – methods: *N*-body simulations

1. Introduction

Standard *N*-body integrators have difficulty reproducing the motion of tight binaries, or following close hyperbolic encounters between stars. This difficulty is particularly limiting for studies of the centers of galaxies like the Milky Way, where the gravitational potential is dominated by a (single or binary) supermassive black hole. While some attempts have been made to efficiently simulate such systems (e.g. Sigurdsson et al. 1995; Baumgardt et al. 2004; Matsubayashi et al. 2007), it remains difficult to achieve the required accuracy and performance. One approach (e.g. Löckmann & Baumgardt 2008) is to fix the position and velocity of the most massive particle and approximate the stellar orbits as perturbed Keplerian ellipses. Here we present a new hybrid code that achieves high accuracy and speed without such restrictions.

Our code is based on the "algorithmic regularization" (AR) method (Mikkola & Merritt 2006) which effectively removes singularities using a time transformation accompanied by the leapfrog algorithm. The AR scheme produces exact trajectories for the unperturbed two-body problem and provides regular results for more general cases. Unlike some regularization schemes (Aarseth 2003), AR is well suited to integration of systems with large mass ratios and allows the use of velocity-dependent terms, e.g. the post-Newtonian expansion. Recently, Mikkola & Merritt (2008) have presented an implementation of the AR scheme, called AR-CHAIN, which includes post-Newtonian terms to order PN2.5.

In this paper we describe the performance of a new, hybrid *N*-body code that incorporates AR-CHAIN. The new code, called φGRAPEch, is based on (the serial version of) φGRAPE, a general-purpose, direct-summation *N*-body code which uses GRAPE

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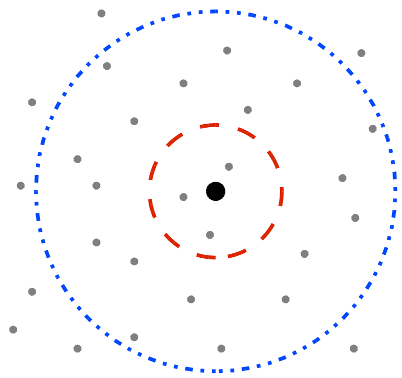

Fig. 1. Schematic view of the hybrid N-body code. Dots represent the central BH (black) and surrounding stars (grey). Stars within $r_{\rm rcrit}$ (red circle) are treated in the ARCHAIN taking into account perturbations from stars inside $r_{\rm perturb}$ (blue circle).

special-purpose hardware to compute accelerations (Harfst et al. 2007).

2. The hybrid N-body code

2.1. Implementation

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 $r_{\rm crit}$ (red circle), are precisely integrated in the AR-CHAIN part of the code. This also takes into account perturbations from stars within $r_{\rm perturb}$ (blue circle). Particles outside of $r_{\rm perturb}$ only act upon the center-of-mass motion of the chain. Outside the chain, orbits are integrated using the standard Hermite scheme in φGRAPE. 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. A detailed description of the implementation of the hybrid code can be found in Harfst et al. (2008).

2.2. Performance tests

Figure 2 shows the energy conservation and elapsed time for integrations of a model that mimics the distribution of stars around the Milky Way black hole. The two critical parameters are η, the accuracy parameter in the Hermite integrator, and $r_{\rm crit}$, the maximum distance from the black hole at which a particle enters the chain. Also shown is the performance of φGRAPE without the regularized chain. The figures show the expected scaling of the Hermite scheme with the accuracy parameter: time steps increase linearly with η making the integration faster and less accurate. Energy conservation generally improves for larger values of $r_{\rm crit}$, as more and more particles are removed from the N-body integration and are treated more accurately in the chain. The integration time increases rapidly with $r_{\rm crit}$ reflecting the $\sim n_{\rm ch}^3$ dependence of the chain. Nevertheless it is clear that for all values of η, there exist values of $r_{\rm crit}$ such that the hybrid code is both more accurate and faster, than φGRAPE alone.

3. Results

We applied our new code to simulate the dynamics 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 $r = 0.1$ 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 75 000. 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: S0-1, S0-2, S0-16, S0-19, and S0-20 (using data from Ghez et al. 2005).

While evolving our 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 S0-2 should evolve approximately linearly with time due to the (essentially fixed) torques resulting from finite-N departures of

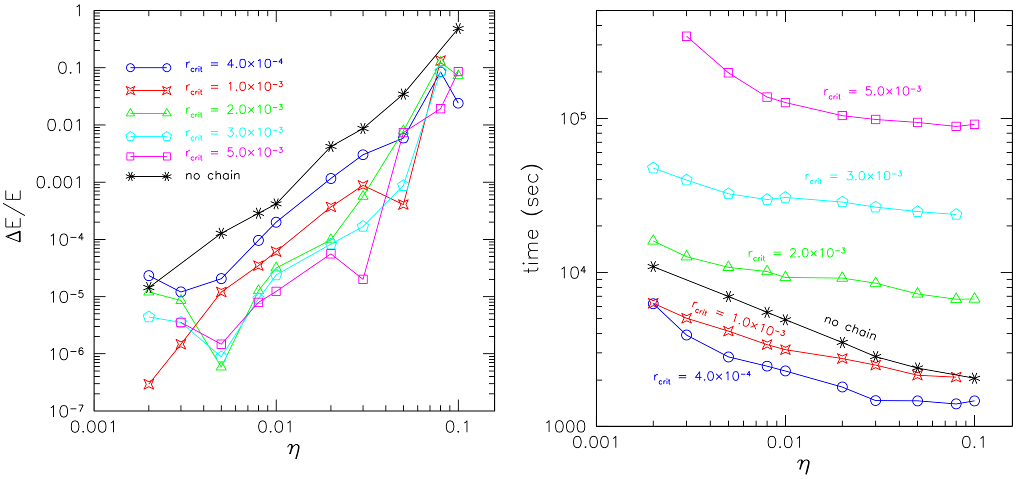

Fig. 2. Results from performance tests: shown on the left is the energy conservation in integrations until t = 1 ($\sim 10^4$ yr) for a model with 10^4 particles. Black line (asterisks) are for φGRAPE without the regularized chain. Elapsed time for the same integrations can be seen on the right.

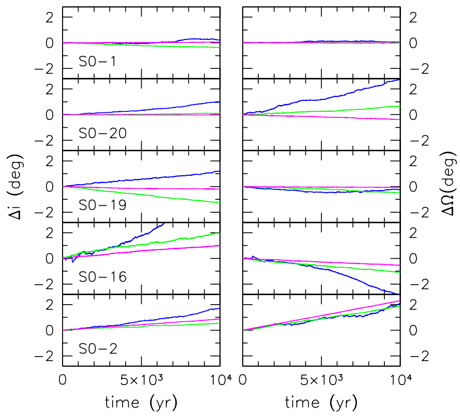

Fig. 3. Evolution of the orbital plane of the S-stars over time in integrations with different particle numbers: $N = 10^3$ (magenta), $N = 10^4$ (green), $N = 7.510^4$ (blue).

the overall potential from spherical symmetry. This evolution is illustrated for all the S-stars in Fig. 3 for three different particle numbers. Plotted are the two Keplerian elements (i, Ω) = (inclination, right ascension of ascending node) that measure the orientation of the orbital planes. These angles would remain precisely constant in any spherical potential and their evolution is due entirely to finite-N departures of the potential from spherical symmetry. Simple arguments can be used to predict that orbital elements should evolve in this regime as a function of the typical perturber mass, the number N of stars within a sphere of radius a, the semi-major axis of the test star, and the (Keplerian) orbital period $P(a)$ (Rauch & Tremaine 1996). These predictions are quite consistent with our results, e.g. the dependence of the evolution on N is well reproduced.

As a second application, we used φGRAPEch to follow the relativistic inspiral of an intermediate-mass black hole (IMBH) into the Galactic SMBH. Fig. 4 shows the time evolution of the distance between the IMBH and the SMBH in this integration. The timescale for the inspiral is identical to the theoretically predicted one. The presence of stars has no significant effect on the rate of inspiral. Stars that interact strongly with the SMBH-IMBH binary can be ejected from the Galactic center and such ejections are a possible source of the so-called hyper-velocity

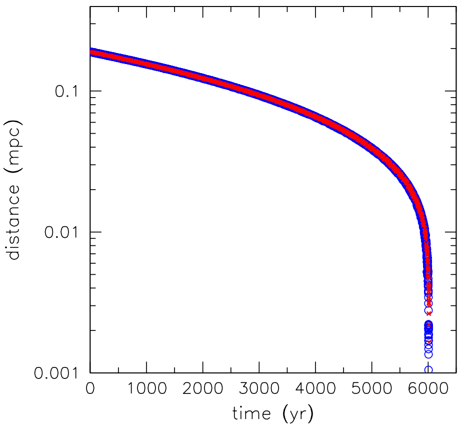

Fig. 4. Evolution of the distance between the IMBH and the SMBH over the inspiral time. The blue and red points refer to simulations containing stars and an IMBH in isolation, respectively.

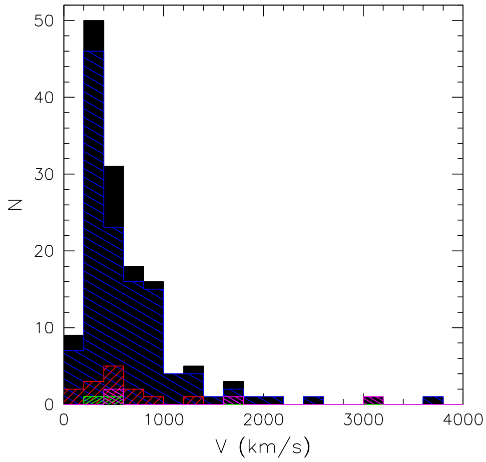

Fig. 5. Velocity distribution for stars and stellar remnants escaping from the SMBH at the end of the IMBH inspiral. The distribution of escapers is presented in black (main-sequence (blue), white-dwarfs (red), neutron stars (green), black holes (magenta)).

stars (Brown et al. 2006). Fig. 5 shows the distribution of ejection velocities for stars unbound to the SMBH at the end of the IMBH inspiral. The peak of the distribution is at ~ 300 km/s. Interestingly, about 30% of the ejected stars have velocities 700 km/s, i.e. large enough to escape the bulge and reach the Galactic halo as hyper-velocity stars. About 150 stars are ejected during the inspiral, which results in an average ejection rate of ~ 20000 Myr^{-1}. This rate is somewhat higher than observed in other simulations (e.g. Baumgardt et al. 2006), presumably because most of the ejections we see are from stars on orbits that intersect the binary at time zero, and many of these stars would have been ejected at earlier times.

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