High resolution in $z$-direction: The simulation of disc-bulge-halo galaxies using the particle-mesh code SUPERBOX

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SUPERBOX is known as a very efficient particle-mesh code with highly-resolving sub-grids. Nevertheless, the height of a typical galactic disc is small compared to the size of the whole system. Consequently, the numerical resolution in $z$-direction, i.e. vertically with respect to the plane of the disc, remains poor. Here, we present a new version of SUPERBOX that allows for a considerably higher resolution along $z$. The improved code is applied to investigate disc heating by the infall of a galaxy satellite. We describe the improvement and communicate our results. As an important application we discuss the disruption of a dwarf galaxy within a disc-bulge-halo galaxy that consists of some $10^6$ particles.

1 Introduction

When modelling the dynamics of galaxies, several numerical techniques can be applied. Most useful are direct $N$-body codes, tree codes, and particle-mesh codes.

Two problems, however, become evident. The relaxation time of the stellar disc of a spiral galaxy is larger than the Hubble time. Therefore, the long-term evolution of a disc is essentially collisionless. In simulations of unperturbed galaxies, – i.e., in the absence of, for instance, stellar bars, spiral arms, molecular clouds – the thickness of their discs is an appropriate measure of how collisionless the code is: if the unperturbed disc thickens with time, then two-body encounters prevail and the relaxation time of the system is unrealistically short. We call this effect “numerical (or artificial) heating”. (We assume that the number of particles is sufficiently large.) As an instructive example, we refer to Velázquez & White (1999). They compared their simulations of sinking satellites (which cause a heating of the disc) to a corresponding undisturbed model. However, even in isolation the disc in their models heats up numerically and thickens. The second concern is the spatial resolution. In particular, a code is required to reliably resolve a disc in $z$-direction, i.e. vertically with respect to the plane of the disc.

SUPERBOX is an improved particle-mesh code and has been applied to a wide variety of dynamical problems. Here, we mention the simulation of the high-velocity encounter of NGC 4782/4783 (Madejsky & Bien 1993), the dynamical evolution of a low-mass satellite galaxy (Klessen & Kroupa 1998), the decay of satellite dwarf galaxies in flattened dark matter haloes (Peñarrubia et al. 2002), dynamical friction in flattened systems (Peñarrubia et al. 2004), and an investigation of large scale inhomogeneity and local dynamical friction (Just & Peñarrubia, 2005). Spinnato et al. (2003) studied the inspiral of a black hole to the Galactic centre, and Khoperskov et al. (2007) simulated unstable modes in a collisionless disc. Most recently, Fellhauer et al. (2008) published on the dynamics of the Bootes dwarf spheroidal galaxy, and Peñarrubia et al. (2008) investigated the tidal evolution of dwarf spheroidals of the Local Group.

In this paper, we are aiming to demonstrate that SUPERBOX is both, collisionless and capable of high resolution. The main application is the interaction of a disc-bulge-halo galaxy with an infalling satellite galaxy.

2 The philosophy of SUPERBOX

SUPERBOX is a particle-mesh code which treats $N$ gravitating particles (“superstars”) self-consistently in a nested system of 3D Cartesian grids and sub-grids, so-called boxes, with $n = 2^m$ cells in each dimension. In this context, “self-consistent” means that, in our models, all components are represented by gravitating particles. Typically, a computation with $n = 2^7$ and $N = 10^7$ takes a few days on a standard PC or workstation. The basic idea behind SUPERBOX is to increase the resolution only at places where it...
is necessary (Bien et al. 1990). For instance, a disc-bulge-halo galaxy and an infalling satellite galaxy are placed into a coarse grid (“global grid”, i.e. the “local universe”), while each galaxy belongs to a finer co-moving grid, called “outer grid”. Each central region (“core”) is resolved in a yet finer sub-grid (“inner grid”).

More precisely, each galaxy utilizes five grids. In Fig. 1 these five principal grids are shown. Particles are counted in the shaded areas only. \( R_{\text{core}} \) is the radius of the “core”, \( R_{\text{out}} \) is the maximum radius of the outer grid and \( R_{\text{sys}} \) is the radius of the global grid. The grids are defined as follows:

- **Grid 1** is the high-resolution grid and resolves the centre of the galaxy.
- **Grid 2** has an intermediate resolution and contains only particles inside \( R_{\text{core}} \).
- **Grid 3** is equal to grid 2, but it contains only particles between \( R_{\text{core}} \) and \( R_{\text{out}} \).
- **Grid 4** is the (fixed) global grid and contains only particles inside \( R_{\text{out}} \).
- **Grid 5** is equal to grid 4, but contains only particles outside \( R_{\text{out}} \).

The corresponding five potentials can be linearly superposed to form the total potential. Due to the additivity of the potential (and hence the accelerations) all galaxies under consideration are treated consecutively in the same five grid-arrays.

- For a superstar with \( r < R_{\text{core}} \), the potentials of grids 1, 3 and 5 are used; \( r \) is the distance from the centre.
- For \( R_{\text{core}} < r < R_{\text{out}} \), the potentials of grids 2, 3, and 5 are used.
- For \( r > R_{\text{out}} \), grids 4 and 5 are used.

In principle, the number of galaxies in SUPERBOX can be arbitrary and is not restricted to two interacting systems (Fellhauer et al. 2000), or an isolated galaxy.

So far, the resolution of the grids in \( z \)-direction was not optimal for discs. We overcome this problem by flattening grid 2 and grid 3 (the intermediate grids) along the corresponding \( z \) axis when the potential of the first galaxy, i.e. the disc-bulge-halo galaxy, is calculated. Typically, the flattening is \( q = 1/4 \), and thus the resolution is improved by a factor 4. The value of \( q \) should not be smaller than

\[
q_{\text{crit}} = \max \left( \frac{R_{\text{core}}}{R_{\text{out}}}, \frac{4}{n - 4} \frac{R_{\text{sys}}}{R_{\text{out}}} \right)
\]

in order to cover the inner grid and at least two cells of the global grid in \( z \)-direction.

Our present results are discussed in the following.

### 3 SUPERBOX vs TREE-GRAPE Code

We simulated a disc-bulge-halo galaxy using SUPERBOX. The parameters are

- **Disc**
  - 190 000 particles, \( 2.80 \times 10^{10} \, \text{M}_\odot \), \( R_{\text{max}} = 35 \, \text{kpc} \)
- **Bulge**
  - 63 323 particles, \( 9.33 \times 10^9 \, \text{M}_\odot \), \( R_{\text{max}} = 3.5 \, \text{kpc} \)
- **Halo**
  - 2 609 000 particles, \( 3.92 \times 10^{11} \, \text{M}_\odot \), \( R_{\text{max}} = 84 \, \text{kpc} \)

We used \( R_{\text{sys}} = 105 \, \text{kpc} \), \( R_{\text{out}} = 35 \, \text{kpc} \), \( R_{\text{core}} = 3.5 \, \text{kpc} \), \( n = 128 \), and \( q = 1/4 \). Particles outside the global...
grid are removed from the simulation. Thus, the total number of particles decreases very slightly with time. The disc-bulge-halo was built with the aid of the code MAGALIE, following Boily et al. (2001). Here, it is sufficient to note that the disc profile drops exponentially with radius and is isothermal in $z$-direction.

A comparison was made with the very popular self-coded TREE-GRAPE scheme (Fukushige et al. 2005). Such a scheme allows us to have a very fast self-gravity calculation routine with up to a few million particles per GRAPE node. Three simulations with different numbers of halo particles (257,723, 859,078, and 2,577,235) were considered. For the maximum particle number (2,577,235) the CPU time is about three days on the single GRAPE6a board. Likewise, the CPU time of SUPERBOX on a standard PC is of the same order. This demonstrates the efficiency of the SUPERBOX code.

Figure 2 shows the scale height of the disc, $z_0$, versus time; $z_0$ is determined by fitting the vertical density profile

$$\rho(z) \propto \text{sech}^2\left(\frac{z}{2z_0}\right)$$

The black colour refers to SUPERBOX results. Both dots are calculated using all disc particles for fitting $z_0$. This demonstrates that the code is intrinsically collisionless with negligible numerical heating. The line includes only 15% of the particles. The systematic effect of the TREE-GRAPE Code decreases when the number of particles increases according to the expected numerical disc heating by massive halo particles.

Figure 3 shows both, the rotation curve $v_{rot}$ and velocity dispersion $\sigma_z$ of the $z$ component after 2.4 Gyr. As before, the simulations by the TREE-GRAPE code and by SUPERBOX are compared.

### 4 Example: Highly eccentric intruder

In the following, we describe a simulation of the interaction between a disc-bulge-halo galaxy and a satellite galaxy using SUPERBOX. The satellite is represented by a Plummer sphere of 33,927 particles, corresponding to $5 \times 10^8 M_\odot$. It is orbiting on a highly eccentric orbit and finally collides with the disc-bulge-halo galaxy. Originally, the satellite starts 12 kpc above the plane of the disc having a velocity much smaller than the circular speed. The integration is over 12,000 time steps, or 2.4 Gyr. That is, the step size is 0.2 Myr.

The snapshots in Fig. 4 show how an inclined and thickened disc evolve. Here, only disc particles (blue) and satellite particles (red) are presented. For the sake of clarity, bulge and dark halo are not shown. The snapshot corre-
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Fig. 5 The orbit of the satellite is projected onto the $x$-$y$ plane.

sponding to 40 Myr gives a rough impression of the starting conditions. The second snapshot (280 Myr) shows how the satellite hits the disc. An inclined and thickened disc remains after 2400 Myr (snapshot 3). In Fig. 5 the trajectory of the satellite is projected onto the $x$-$y$ plane.

5 Conclusions

Our preliminary results can be summarized as follows.

– **SUPERBOX is a very fast particle-mesh code**
  This is evident from our comparison with the TREEGRAPE Code, see sect. 3.

– **No numerical disc heating**
  Fig. 2 clearly demonstrates that SUPERBOX is a collisionless code and thus provides a reliable description of the dynamics of galaxies. This allows us to study the long-term evolution of disc heating caused by bars, spiral arms, satellite galaxies, and other mechanisms.

– **Improved vertical resolution**
  SUPERBOX has a much better resolution in $z$-direction than before. It is possible to improve the present flattening up to a factor of 10.

The new version of SUPERBOX is quite successful and our work on disc heating and related effects is in progress. In particular, use will be made of grids consisting of $2^8 \times 2^8 \times 2^8$ cells instead of $2^7 \times 2^7 \times 2^7$. We are planning to make the code publicly available.

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