Galaxy-Galaxy-Scattering: Head-on Encounters Between Isotropic Equal Mass Plummer Models

Peter Teuben
Dept. of Astronomy
University of Illinois
Urbana, IL 61801

Piet Hut
Institute for Advanced Study
Princeton, NJ 08540

Introduction

The research reported on here is part of a large study of the physics of interacting galaxies.

Over the last few decades it has become increasingly clear that encounters between galaxies may have affected the evolution of galaxies in a drastic way, both during and after their formation. While little is known about the formationof galaxies, once they have been formed, the environment continues to exert an important influence on them. This study concentrates on encounters: galaxy-galaxy scattering.

Galaxies can be morphologically subdivided into elliptical galaxies and spiral galaxies. The first category is a featureless triaxial hot (high kinetic energy in random motion) stellar system with little rotation. The second category, spiral galaxies, can be thought of as a multi-component system. The first component consists of a thin disk of stars and gas (from which new stars are continuously being formed) which is rapidly rotating. The second component is a nuclear bulge which is dynamically close to a mini-elliptical galaxy. Recent data suggest that the visible matter in these two components is only a fraction of the total mass of a spiral galaxy. Up to 90% of the mass may be in an invisible and more spherical component, which extends to a much greater radius than the visible part of the galaxy. This dark halo must play an important role in the overall dynamics of a disk galaxy, contributing to the stability of the disk component and influencing the rotation of the outer regions.

In modeling the interaction between stellar systems, gravitation will dominate the mass distribution. In later stages of the project it will be necessary to include the effects of gas dynamics, as even the appearance of a galaxy is often biased against the presence of gas. As this is the first paper in a series, we shall start with the most simple representation of a galaxy-galaxy interaction: a head-on encounter between two equal spherical galaxies. This will only give us one physical parameter: the impact velocity.

We represent a galaxy by a spherical distibution of point masses, where the density distribution, $\rho(r)$, is given by

$$\rho(r) = \left(\frac{M}{3/4\,\pi R^3}\right)\left(1 + \frac{r^2}{R^2}\right)^{-5/2}$$

where M is the total mass and R is the scale length of the system. This model was first used by H.C. Plummer in 1911 to describe the light distribution of globular clusters. It can also be used as a first approximation for elliptical galaxies. A random number generator is used to sprinkle the stars in configuration space according to the above density law. The velocities were isotropically assigned such that the distribution of stars in energy space follows the following simple law:

$$f(E) \sim (-E)^{7/2}$$

where E is the total (kinetic and potential) energy of a star. It has been known that such isotropic Plummer models are stable configurations and hence can be used to study certain stellar systems. The stellar systems are initially in virial equilibrium.

It will be obvious that, for impact velocities much larger than the typical internal velocity dispersion of an individual galaxy (external kinetic energy much larger that internal energy), the galaxies will continue their path almost undisturbed. The passage is so fast for the individual stars that they haven't had time to react to this sudden impulse before they have moved significantly within the stellar system. In such cases an analytical approximation known as the impulsive approximation can be used to estimate mass and energy loss of the galaxy.

On the other hand, for impact velocities much lower than the internal velocity dispersion, the galaxies will merge, since the total binding energy was negative to begin with. It is the low and intermediate ranges of impact velocities which need modeling through expensive N-body calculations, because no analytical treatment of the theory is possible.

We kept the physical parameter space one dimensional in order to study the effect of a number of computational parameters. The recently developed treecode (N-body integrator) can simulate a much larger number of stars, necessary for a reliable description of realistic galaxies (highly concentrated elliptical galaxies, multicomponent thin disk galaxies with bars/spiral arms). A few tests of the code have now been undertaken and published, but within the framework of a project like this the dependancy of the computational tuning parameters must be understood.

The following tuning parameters can be indentified:

(1) N, the number of particles the system is represented by,

(2) DT, the timestep of the individual particles. Currently all particles are advanced with the same timestep using a leapfrog scheme. Due to the rather coarse form of the force field, it is not necessary to invoke more expensive higher order integration schemes. The timestep must be chosen small enough so that individual particles do not travel more than the smallest interparticle distance. Furthermore, the energy conservation must be monitored.

(3) EPS, the potential-softening length. The point masses are not really point masses, but it is as if their mass has been extended over a size of order EPS in radius. The modified potential reads:

$$\mathrm{pot}(r) = -\frac{G \bullet M}{(\mathrm{EPS}^2 + r^2)^{1/2}}$$

For EPS=0 the exact point mass potential is reproduced. The softening length cannot be made too small, as one needs to avoid close encounters between stars (apart from the problems the time integrator will have with energy conservation); neither can it be made too large because it would introduce artificial non-interaction. The physical reason behind the introduction of a softening length is relaxation. In real galaxies (as opposed to a globular cluster), where the number of stars is of order 10^{11}, close encounters between stars do not occur in practice, and must be avoided because they introduce physical changes to the system.

(4) TOL, the tolerance in this particular N-body code. It is the opening angle (in radians) in the treecode which determines the degree of clumping of particles used to compute forces. For a TOL=0 no clumping is applied, and an exact expensive N-squared calculation is done to compute all the forces. For increasing TOL the forces become less time consuming to compute but introduce (sometimes systematic) errors. Typically TOL must be set not larger than 1.0 radians to exclude relaxation effects. A second parameter which handles the direct accuracy of the computed forces is the inclusion of quadrupole corrections.

Throughout the integration the full state of the system (positions and velocities of all particles) must be stored fairly frequently (about every crossing time) to get a reliable estimate of the evolution: merger or escaper. This results in a fairly large amount of data storage: typically 10Mb for a collision between two systems of 8k particles each. The analysis of the data is not done during the time integration; only conservation of energy and momentum are monitored. This allows us to run more expensive (high N, low TOL, low DT) runs on a faster computer. The analysis is done with the NEMO package on a SUN workstation. The N-body integrations for experiments up to N=2k particles per system are still possible on a SUN workstation, although they take a few CPU days to finish. A CYBR 205-type CPU runs about a factor of 100 faster for this particular program, and can be completed in about 40 CPU minutes.

A SUN workstation has been used to do a variety of experiments with N=128 and N=512 particles per system, the CYBER 205 with 2k particles per system and the ETA10 with 8k particles per system.

The analysis is done as follows. The centroids of the two systems determine whether the systems merge. For a non-merger an estimate of the relative velocity of a remnant is made, because the remnant must be analyzed in its own rest frame. In this frame of reference we can determine the mass loss (stars with binding energy larger than zero), and new internal structure of the remant galaxy. Due to the finite number of stars the center of the galaxy and its center of mass are not identical, and the outcome of a collision is not symmetric. This however will give an indication of the errors due to a finite number of particles. By repeating the same experiment a few times with a different seed of the random number generator, an even better estimate is obtained.

A number of experiments with varying impact velocity and reasonable settings of the tuning parameters have been performed to determine the critical merger velocity. This (relative) velocity was found to be in good agreement with previous studies, expressed relative to the internal velocity dispersion of the galaxy: $V_\infty/\sigma \sim 1.49 \pm 0.02$.

The loss of internal and orbital energy has been calculated as a function of impact velocity. The ETA10 experiments (with 8k particles per system) will allow us with reasonable accuracy to analyse the internal structure of the prolate remnant of a complete merger. Galaxies with 2k particles per system are too noisy to determine internal structure with reasonable accuracy.

Another interesting observation was made in the ETA10 results, which were not seen in the CYBER 205 experiments with 2k stars per system. The escapers form an expanding spherical cloud which has about the same initial velocity as the parent galaxy. The mass of the escaping particles is 15-20% near the critical merging-velocity.

To date a few full N-body calculations have been done to study merging galaxies. In a study by van Albada and van Gorkom (1977) the mass loss found was of order 1%, which is significantly lower than what we found here. Although they used a different N-body integrator (an axisymmetric fourier decomposition of the mass distribution, which directly transforms to the forces), it is hard to imagine that this explains the large difference. It may be that their distribution function was slightly different, but a few experiments with King models (which have a finite cutoff radius) showed that the mass loss in the near-merger range remained in the 10-20% range. Although Roos and Norman (1979) found a larger fraction of mass loss, their results may be subject to large errors due to the very low number (20-30) of particles per system.

Use of ETA Resources:

Most of our experiments with 2k particles per system were done on the CYBER 205, and take 40 minutes to 2 hours per experiment (depending on choice of parameters). We decided to use the ETA10 to run a few experiments with 8k particles per system. In a small comparison test run we got a factor 1.2-1.6 speed increase. For a more thorough comparison of the two CPUs, see Makino and Hut's paper - page 35 in this volume.