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JSPAM: A restricted three-body code for simulating interacting galaxies☆

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ABSTRACT

Restricted three-body codes have a proven ability to recreate much of the disturbed morphology of actual interacting galaxies. As more sophisticated n-body models were developed and computer speed increased, restricted three-body codes fell out of favor. However, their supporting role for performing wide searches of parameter space when fitting orbits to real systems demonstrates a continuing need for their use. Here we present the model and algorithm used in the JSPAM code. A precursor of this code was originally described in 1990, and was called SPAM. We have recently updated the software with an alternate potential and a treatment of dynamical friction to more closely mimic the results from n-body tree codes. The code is released publicly for use under the terms of the Academic Free License ("AFL") v. 3.0 and has been added to the Astrophysics Source Code Library.

1. Introduction

Soon after galaxies beyond the Milky Way were first observed, it was noticed that some of them appeared to be in close proximity to one another. Many of these close pairs and groups contained disturbed morphologies, the cause of which was debated for much of the middle part of the twentieth century. Speculation as to the source of the peculiar features included gravitational and magnetic interactions. One of the first papers to demonstrate that tidal distortions caused by gravity could produce the thin tails and bridges seen in interacting galaxies was Pfleiderer and Siedentopf (1961). The researchers used a simple model for the particles of the primary galaxy in the interaction. It was treated as a point mass and was surrounded by a disk of massless test particles. The secondary galaxy was represented by a point mass with no resolved disk. The particles in the primary disk were influenced by the gravity of both point masses, but not each other. This is allowed for a relatively easy set of calculations to determine the forces felt by each particle at each time step in a simulation.

Later researchers such as Toomre and Toomre (1972) would add a disk of test particles around the secondary galaxy and attempt to simulate models of major mergers. The authors of that work were able to produce credible models of four well-known pairs of interacting galaxies. This seemed to answer conclusively that it was possible to recreate the general morphology of interacting systems, especially the tails and bridges, with gravitational tidal disturbances. These models are referred to by several names, but they will be called restricted three-body methods in this work. The results from these models showed that the more dramatic features of interacting galaxies are produced by slow, close passages along parabolic or elliptical orbits. Faster passages usually result in smaller features being generated.

This paper announces the public release of a specific restricted three-body software implementation. The precursor to the JSPAM code presented here was first presented in Wallin (1990) as SPAM.[1] It has been used since then for parameter studies (Wallin and Stuart, 1992) and to model specific systems (Smith and Wallin, 1992; Wallin and Struck-Marcell, 1994; Smith, 1994; Smith et al., 2010). The "J" in JSPAM indicates the software was ported to the Java™ language. This paper presents details of significant enhancements to all language versions of the code. The code has been added to the Astrophysics Source Code Library (Wallin et al., 2015).

Though more sophisticated n-body models with gas dynamics and stellar feedback have been developed, restricted three-body

☆ This code is registered at the ASCL with the code entry ascl:1511.002.

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[1] SPAM is the Stellar Particle Animation Module.

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codes remain useful. They can generate a rough match for a wide range of morphologies. Finding this match by manually varying the orbit parameters can be a time consuming process, especially when running full n-body codes. Automating the search by connecting a restricted three-body code to an optimization routine is a much quicker approach. Follow-up simulations can then be performed using self consistent, n-body codes. In the last decade, several researchers have attempted this approach, see Smith et al. (2010) for a brief summary of methods. The most common optimization approach is to use a genetic algorithm or similar evolutionary code to run thousands of models in order to converge on best-fit parameters. This multi-method modeling technique benefits from the existence of a fast, restricted three-body code. We have implemented our code in multiple languages to assist with integration into larger systems. For example, the FORTRAN code can be compiled as a library and linked directly to other FORTRAN and C/C++ codes. The Java™ version was integrated with a Citizen Science project called *Galaxy Zoo : Mergers* that used an Applet running in the browser of each of the volunteers that contributed (Holincheck et al., 2010).

2. Methods

2.1. Gravity in restricted three-body problem

The restricted three-body model has been used to model interacting galaxies since the early 1970s. The seminal models by Toomre and Toomre (1972) using this method first demonstrated that observed tidal features could be reproduced using simple gravitational interactions without the need to invoke more complicated physical processes.

Since the late 1980s, hierarchical tree codes have been commonly used to model interacting galaxies. By reducing the n-body problem's computational complexity from $\sim O(n^2)$ to $\sim O(n \log n)$, problems that would be intractable have become possible. Of course, Moore's Law has also played a critical role in the evolution of models. The inclusion of other physics beyond gravity, including gas dynamics, star formation and feedback processes, and even radiative transfer have made these models commonly used to understand processes in interaction and cosmology (Robertson et al., 2006).

In many cases, it helps to have a detailed numerical model of a particular interacting galaxy system. Being able to match dynamical time to stellar population, for example, can bring a better understanding of the evolutionary processes. Even with these advances, modeling an observed interacting galaxy is a time consuming process. For self-consistent tree code runs, you need large numbers of particles to represent the halo, disk and bulge of each galaxy. Even a modest ($<100k$ particle) model can take hours or even days on a workstation to run a single model. In general, dozens to even thousands of models are needed to match a single interacting galaxy system. Prototyping systems such as IDENTIKIT (Barnes and Hibbard, 2009), have been created to help make this process easier.

Restricted three-body models have computational advantages over full n-body models. In these models, the gravitational field is represented with a static potential around two moving masses. Stars are represented by non-interacting test particles that are initially orbiting within these potentials. As the two potentials pass each other, the tidal forces create the features seen in interacting systems. With modern computers, a modest resolution run with thousands of particles can execute in just a few seconds using this method. By using the restricted three-body method, it is possible to easily produce hundreds of thousands numerical models in a single day. Although humans cannot easily look at this many models, automatic optimization systems such as genetic algorithms can be used converge on the best fit model for particular systems, (e.g., De Jong, 2006).

In many older codes, the gravitational potential in restricted three-body codes was represented with a softened point mass. Although the models produced with these codes had similar tidal features to those seen in nature, using the results from the code to move to high resolution model with a self-consistent n-body code was difficult due to the large differences between a softened point mass potential and a self-consistent n-body code. Dynamical friction during the interaction also causes the trajectories and resulting tidal features to differ.

In the code we are releasing, we include a new potential in addition to the softened point mass. This potential is derived by using the initial conditions for a self-consistent n-body model. Details are described in Section 2.2.2. We have also included a parameterized version of dynamical friction in this code. Some researchers have included an analytic evaluation of more realistic potentials based on the Hernquist and NFW mass distributions. Simulations run by Dubinski et al. (1999) and Petsch and Theis (2011) also combined these potentials with dynamical friction following a similar prescription to this code. Our key innovation is to make the simulations run almost as fast as the traditional softened point mass by sampling a "unit" mass distributed according to the Hernquist distribution and then use fast interpolation to look up central force acceleration.

With this code, it is possible to rapidly prototype galaxy collisions and then use the results to create high resolution self-consistent n-body models of interacting galaxies.

2.2. Potentials

The restricted three-body problem considered here is that of a set of massless test particles in a system with two massive bodies. Each of the massive bodies represents the center of mass of a galaxy. The massless test particles are distributed around the centers of mass to represent the disk material. The test particles do not interact with each other. The sum of the gravitational potentials from the massive particles determines the dynamics of the system.

JSPAM provides two different potentials. The corresponding acceleration for the softened point mass potential has an analytic expression. The acceleration due to the new potential is made from sampling the potential from a full n-body model of a three-component disk galaxy containing a halo, disk, and bulge.

2.2.1. Softened point mass potential

The softened point mass used is based on the original SPAM code described by Wallin (1990). In this approach, we soften the acceleration of the massless particles using the form:

$$\vec{a} = -\frac{GM}{(r^2 + \epsilon^2)}\hat{r}. \quad (1)$$

Giving a resulting potential of the form:

$$\phi(r) = \frac{GM}{\epsilon}\left[\frac{\pi}{2} - \tan^{-1}\left(\frac{r}{\epsilon}\right)\right]. \quad (2)$$

To model the more extended potential of a galaxy, simulations using the original SPAM code used a softening length typical about 0.3 times the radius of the disk galaxy. Later in Section 4.3, we will show how this potential compares to the n-body interpolated potential and full n-body tree code runs.

2.2.2. N-body interpolated potential

In order to create a more realistic potential, we have adapted a modified three-component model of the mass distribution of