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Supercomputer Simulations of Disk Galaxies

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The time evolution of models for an isolated disk of highly flattened galaxies of stars is investigated by direct integration of the Newtonian equations of motion of $N = 30,000$ identical stars over a time span of many galactic rotations. Certain astronomical implications of the simulations to actual disk-shaped (i.e. rapidly rotating) galaxies are explored as well.

KEY WORDS Galaxies kinematics and dynamics galaxies structure–instabilities

One can learn much about the properties of stellar systems of disk galaxies experimentally by computer simulation of many-body systems. We analyze the evolution and stability of structures in N-body models of isolated, rapidly and nonuniformly rotating, and spatially inhomogeneous stellar disks of galaxies by direct integration over a time span of Newtonian equations of motion of identical particles. Use of concurrent computers has enabled us to make long simulation runs using a sufficiently large number of particles. The essential difference between the present and previous simulations is the comparison between the results of N-body experiments and the stability theory as developed by Griv and Peter (1996), Griv *et al.* (1997, 1999a, 1999b, 2000) and Griv (1998).

At the start of the N-body integration, our similation initilizes the particles on a set of concentric circular rings with a circular velocity $\mathbf{V}$ of galactic rotation in the equatorial plane; the system is isolated in vacuum. Then the position of each particle was slightly perturbed by applying a pseudorandom number generator. The Maxwellian-distributed random velocities $\mathbf{v}$ were added to the initial circular velocities $\mathbf{V}$, and $|\mathbf{v}| \ll |\mathbf{V}|$. Finally, slight corrections have been applied to the resultant velocities and coordinates of the model stars so as to ensure the equilibrium between the centrifugal and gravitational forces and to preserve the position of the disk center of gravity at the origin.

In Figure 1 we show a series of face-on view snapshots from a three-dimensional simulation run of the so-called cold disk, in which the initial dispersion of random velocities of stars was chosen to be less than the critical Toomre's (1964) dispersion.

Figure 1. The time evolution (face-on view) of a Jeans-unstable cold disk of $N = 30,000$ stars. Notice how rapidly the small-scale Jeans instability grows with time. At the final stage the pair of strongly interacting M51 type galaxies consisting of the main massive galaxy and a minor one is developed. Note the resemblance of the structures seen here at times $t = 0.8 - 2.6$ to ones which were usually classified (and included in the Atlas of Interacting Galaxies) by Vorontsov-Velyaminov (1977a, 1987) as the "nests" and "chains." Vorontsov-Velyaminov considered these objects as compact fragmenting systems, giving birth to young galaxies. Based on the present simulations, a new mechanism for the formation of definitely interacting galaxies in close pairs and groups may be suggested through the fragmentation of a Jeans-unstable (Toomre-unstable) disk of an original giant galaxy.

Figure 2. Higher resolution plots (edge-on view) for the simulation run shown in Figure 1. The striking resemblance of the chain structures seen in the N-body model at times $t = 1.4 - 2.6$ and ones revealed by Vorontsov-Velyaminov (1977a, 1987) (see also Zasov *et al.*, 2000) probably confirms our suggestion that these structures in strongly interacting close galaxies is indeed produced by the Jeans instability that develops in the dynamically cold Toomre-unstable disk of stars. Earlier, Vorontsov-Velyaminov (1974, 1977b, 1987) already presented observational evidence of the fragmentation of galaxies at the present epoch. The latter represents a factor of quantitative importance in the general evolution of galaxies themselves and of the intergalactic medium (e.g. the density in intergalactic space becomes higher).

The time was normalized so that the time $t = 1.0$ corresponds to a single revolution of the initial disk; the rotation was taken to be counterclockwise. It is seen that the system is violently unstable to small-scale gravity perturbations of the Jeans type. During the first rotation, such unstable perturbations break the system into several macroscopic fragments of stars. At the end of the second rotation, we see a quasi-stationary binary system of strongly interacting galaxies. According to Vorontsov-Velyaminov (1987), the average estimate of the number of such strongly interacting pairs is 14% of single galaxies.

In Figure 2 we show the time evolution of the cold disk in the direction normal to the plane. From an initial very thin model, a fully three-dimensional disk develops immediately at $t \approx 0.2$ with a mean height above the plane, corresponding to the force balance between the gravitational attraction in the plane and the "pressure"

due to the velocity dispersion (i.e. "temperature") in the vertical direction. At a time $t \approx 1.4$, in Figure 2, one can see a small chain system consisting of interacting galaxies. At the same time a bending firehose type instability develops in each fragment. See Griv and Chiueh (1998) for a discussion of the bending instability. This instability essentially increases the disk thickness of compact fragments.

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