C. NUMERICAL EXPERIMENTS

70. NUMERICAL EXPERIMENTS IN SPIRAL STRUCTURE

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Abstract. Results of an *n*-body calculation, containing about 120000 particles, were shown as a motion picture. Some of the particles are treated as 'gas', obeying a special dissipative dynamics, the rest as 'stars'. The system was started as pure 'gas', and 'stars' were made out of the 'gas' in a manner closely mimicking real galaxies. Spiral density wave patterns appear in the 'gas', and last for about 3 'galactic rotations' without substantial change of form. Various experiments are described that have been undertaken in an attempt to learn the roles of various parts of the system in the maintenance of spiral patterns.

The large *n*-body calculation based on the 'game' described earlier (Miller and Prendergast, 1968) has shown spiral patterns which are demonstrated by showing a motion picture of their evolution. This calculation exactly incorporates the essential feature of being microscopically reversible; a feature which corresponds to the very long relaxation times expected in all parts of a galaxy.

Earlier calculations led to very 'hot' stellar populations. In order to look for spiral patterns, a much 'cooler' system seems necessary. We first tried sudden 'cooling'. Immediately after the cooling', gravitational collapse 'heated' the system back to the 'hot' condition it had been in before. Repeated 'coolings' did not help. A continuous 'cooling' scheme that conserves linear and angular momentum while reducing the random velocities in all the particles at each configuration space location at each integration step led to a general mess. The material which is treated this way is something like a 'gas'; it has dissipative properties. The next scheme for 'cooling' is a gradual scheme in which 'stars' are formed from the 'gas'. In this version of the calculation, two populations are represented, that being 'cooled' as in the continuous 'cooling' scheme, being called 'gas', the other, which is not so 'cooled' being called 'stars'. 'Stars' are created at each integration step by changing a certain number of 'gas' particles into 'stars' – shifting them from one constituent population to the other. The number changed is proportional to the square of the number of 'gas' particles at a particular configuration space location. When a model is started, all particles are 'gas'. The constant of proportionality, the 'star creation coefficient', is an important parameter that strongly influences the early evolution of the system.

We have conducted several experiments in an attempt to discover which features of the system are most important to the maintenance of spiral patterns. The value of the computer model is that it gives us a spiral system that may be modified in any way we wish. The problem is to design experiments that will delineate the essential features of systems showing spiral structure; that will show the role of each of the constituent parts. All details of the system are available; we routinely compute all of

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the usual galactic parameters such as mean velocities, circular velocity, force, epicyclic frequency, Oort constants, and components of the velocity ellipses at each radius in the system.

Spirals can be made in self-gravitating systems. The additional complications of magnetic fields are unnecessary.

The spiral patterns look like real galaxies. They are similar to real galaxies in that the spiral patterns are delineated in the 'gas' while the 'stars' form a background that shows much less structure. The models differ from real galaxies in that the peculiar velocities of the 'stars' are quite large – of the same order as the circular velocity. The 'star' system is pressure-supported, but the 'gas' moves with nearly the circular velocity. The spiral patterns have some features that agree with expectations from current ideas about spirals: individual mass points move through the patterns, and the patterns extend inward to the inner Lindblad resonance. The patterns become indistinguishable at about the co-rotation point, because of lack of particles.

Several experiments were run to try to determine the role of this 'star' background and the extent to which it is involved in the spiral patterns.

(1) 'Stars' of small peculiar velocity (velocity near the circular) were selected and a density plot was made for one integration step. A pattern was discernible although much less pronounced than in the 'gas'. As 'stars' of larger peculiar velocity were included, the patterns became more difficult to distinguish. These 'stars' show the local minima of the potential field.

The remaining experiments were carried out on a slightly modified system, using a stage of the regular calculation at which the spiral pattern is readily distinguishable as the starting point for a new integration.

(2) The entire 'gas' population (some 16000 particles) was turned into 'stars'. Separate density plots were made for this new 'star' population and for the other particles that were already 'stars' at this integration step. The spiral pattern began to dissipate – it was clearly discernible as a spiral pattern for about one revolution (20 integration steps), but became less and less so as more and more of its 'stars' acquired the large peculiar velocities of the background 'stars'. In a similar experiment in which the 'gas' was turned into 'stars' at an earlier stage, the new 'stars' rather rapidly settled down into patterns reminiscent of barred spirals. A 'bar' formed and 'stars' trailed off its ends to form open spirals. As more and more 'stars' trailed off, the spiral became tighter – a few of the 'stars' fell back toward the 'bar', the 'bar' became smaller and the spiral pattern less distinct. This entire process required about 2–3 revolutions of the bar (40–60 integration steps). These experiments show that the different dynamics of the 'gas' population leads to a somewhat different form for the spiral pattern and helps the pattern to last for longer times.

(3) The 'star' background was frozen into place. This produced a force field that did not evolve further, but was approximately that of a self-consistent static model because of the way in which it was obtained. The 'gas' continued to move in this unchanging background potential. Spiral patterns persisted – perhaps even a little better than they did with the actual 'star' background. In another version of the

experiment, the 'star' background potential was symmetrized (in angle). With this modification, the patterns did not persist as well. These experiments show that the moving structure of the actual 'star' background is not essential to the maintenance of the spiral pattern, but that a grainy or asymmetrical potential is.

(4) A static background potential like that of (3) was obtained from the mass of both the 'gas' and the 'stars'. The 'gas', now treated as having no-self-gravitation, continued to move in this background. The spiral pattern dissipated rather rapidly. This shows that the self-gravitation of the 'gas' is essential to the maintenance of spiral patterns, as might have been expected. When the background potential was symmetrized in angle, as in the second part of (3), the pattern dissipated quickly, showing that while the grainy static background is a little harmful to spiral patterns, an unsymmetrical part is necessary to drive the spiral.

(5) The static background of (3) was once more set up, but now all the mass points that were treated as 'gas' in (3) were treated as 'stars' for this experiment. Again, the spiral pattern persisted about as well as it did in (3). This shows that the special dynamics of the 'gas' component is not necessary to maintain spiral patterns at this stage of evolution. Again, the symmetrization in angle of the second half of (3) caused the patterns to die out.

Taken together, these experiments indicate that: (a) the 'stars' provide a background potential in which the 'gas' moves and must have an asymmetric potential to 'drive' the spiral, but otherwise do not play an essential part in the maintenance of the spiral pattern. High-velocity 'stars' can provide such a potential field without danger of a gravitational collapse. The excess velocity despersion above that necessary to prevent collapse is probably an artifact of our computer model and of the way in which the system was created. (b) Self-gravitation is essential to the maintenance of spiral patterns. The extra dissipative effects in the 'gas' component also help the patterns to survive for a longer time, when the subsystem that shows the spiral pattern can interact with a dynamic background. It helps to 'cool' the population. With a static background, this dissipative effect is less important, but that background cannot be symmetrized.

The method used to establish conditions in which spirals might occur is appealing because of the close analogy with the processes thought to be important in real galaxies, and because it stresses those properties that make spiral patterns stand out in real galaxies.

While we are not yet satisfied with all aspects of the calculation, the fact that spiral patterns have been obtained means that we are on the right track.

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Reference

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