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SPOKES IN RING GALAXIES

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Catalogues of peculiar galaxies include several galaxies with luminous rings surrounding nearly vacant areas. Although rare compared to normal galaxies, these "ring" galaxies likely comprise between $\sim$ 0.02-0.2% of all spirals (Athanassoula & Bosma 1985). Many of these objects contain other peculiarities. A noteworthy example is the Cartwheel galaxy, designated AM 0035-335 by Arp and Madore. In addition to a dominant outer ring, the Cartwheel has a more compact inner ring near its center which is linked to the outer one by spoke-like features.

Motivated by observations that many ring galaxies have nearby companions, early simulations of ring formation focussed on interactions between large spirals and less-massive companions. These simulations demonstrated that rings can be produced in disks by an intruder when the stars in the primary rebound radially in response to the gravitational perturbation of the companion (Lynds & Toomre 1976, Theys & Spiegel 1977). Recent work has included the effects of self-gravity, which acts to increase the definition of ring structures. But more complex morphologies, such as the Cartwheel, probably cannot be reproduced without considering gas dynamical effects as well.

Indeed, the Cartwheel galaxy appears quite rich in gas. Its outer ring contains $\gtrsim 10^8 M_\odot$ of ionized gas and its nucleus contains $\lesssim 10^{11} M_\odot$ of neutral gas (Fosbury & Hawarden 1977). Moreover, infrared and visual observations suggest that the color of the Cartwheel shifts radially outwards from red to blue, indicating that star formation has occurred during the expansion of the ring (Appleton & Marcum 1992, Higdon 1992).

We examine the response of self-gravitating primary galaxies consisting of dark matter halos and disks containing both stars and gas to collisions with less massive companions. The primaries were constructed using a technique developed by Hernquist (1991,1992a,b) which makes it possible to realize multi-component systems that are stable and virtually in precise equilibrium. A total of 65,536 particles were employed to represent the primary and 4096 to represent the companion. Half the particles in the primary comprise its halo and the other half its disk. Gas makes up 10% of the disk mass and is represented by 8192 of the disk particles. A system of units is used where the gravitational constant, total disk mass, and disk exponential scale length are unity. Scaling to values appropriate for the Milky Way implies that unit time and velocity correspond to $\sim 1.3 \times 10^7$ years and 260km/sec, respectively. The vertical scale thickness of the disks is 0.2; the halo has core radius of 1 and truncation radius of 10. The gas is initially distributed with the same radial and vertical profiles as the stars but with a vertical scale-thickness of 0.057. A companion with a mass of 1 and scale-length of 0.5 engages in a collision along the initial symmetry axis of the disk. The halo has a mass of 2.9 so that the primary is nearly four times as massive as the companion. The center of masses of the disk and companion are initially separated by 15 length units, where tidal effects are negligible, and approach one another at escape speed. Simulations were performed using a hybrid code capable of evolving systems containing both collisionless material and gas (TREESPH; Hernquist & Katz 1989).

The primary motivation of the present study is to determine whether effects associated with dissipation and self-gravity can account for the unusual morphology of the Cartwheel galaxy. Figure 1 shows the evolution of the gas down the rotation axis of the disk for a few significant times. At late times in the simulation, the disk begins to resemble the Cartwheel. As in other studies of the ring phenomenon, the passing of the companion through the disk induces large radial motions in its stellar distribution. These epicyclic oscillations eventually drift out of phase giving rise to a radial density wave whose crest is reminiscent of observed rings. Initially, the gas responds in a similar manner to the stars, sporting an outwardly propagating ring by t=15. Unlike that in the stellar distribution, however, the ring in the gas appears to be a true material structure. This is due both to shock dissipation in the gas, which allows it to accumulate in thin ridges, and self-gravity which temporarily maintains these features.

As the gas is compressed into a thin ridge near the center of the stellar ring, it becomes mildly self-gravitating and is subject to the "bead" instability. By time t=20 the inner parts of the gas ring have already fragmented into amorphous clumps. Since these clumps partly comprise gas from the inner parts of the disk, which has little angular momentum, they eventually begin to fall back towards the center of the disk. Owing to differential rotation and the effects of tidal forces, the clumps do not remain intact as they fall towards the center and are sheared into radial structures having some curvature. During the final stages of the encounter these features are rather similar in appearance to the spokes in the Cartwheel galaxy. In addition, a second ring begins expanding outwards from the center.

Although we have not attempted to optimize our fit to the Cartwheel, a comparison shows that the spokes in both the Cartwheel and our model are quite clumpy and the material comprising them is not distributed smoothly along their lengths. Moreover, the region between the inner and outer rings in is nearly vacant, aside from the spokes, and both the simulation and the Cartwheel exhibit a secondary inner ring. A failing of the model is the fact that the contrast between the outer ring and the remainder of the galaxy is much greater for the Cartwheel than the simulation. The contrast between the outer ring and inner regions of the galaxy would likely be boosted if the density of gas were to decline less steeply with radius than in the models we constructed.

The simple models used by early investigators reproduce the gross aspects of ring galaxies. The calculation described here, while technically advanced, demonstrates that, for the most part, restricted approaches are adequate to capture most of the essential dynamics. Only if both self-gravity and gas-dynamics are included are the results altered qualitatively. As the gas is compressed in a thin ring, its self-gravity enables it to form transient, but coherent structures which evolve into features which resemble the spokes in the Cartwheel galaxy. Observationally, our models can be further tested by measuring color gradients in the Cartwheel's disk. One might expect the inner regions to be redder than the outer ones since the gas near the center was compressed and fragmented earlier than that in the outer ring. Recent observations suggest that this may in fact be the case. Additional constraints on our models would be provided by detailed observations of gas in the Cartwheel, especially if they establish a physical link between the Cartwheel and one of its neighbors.

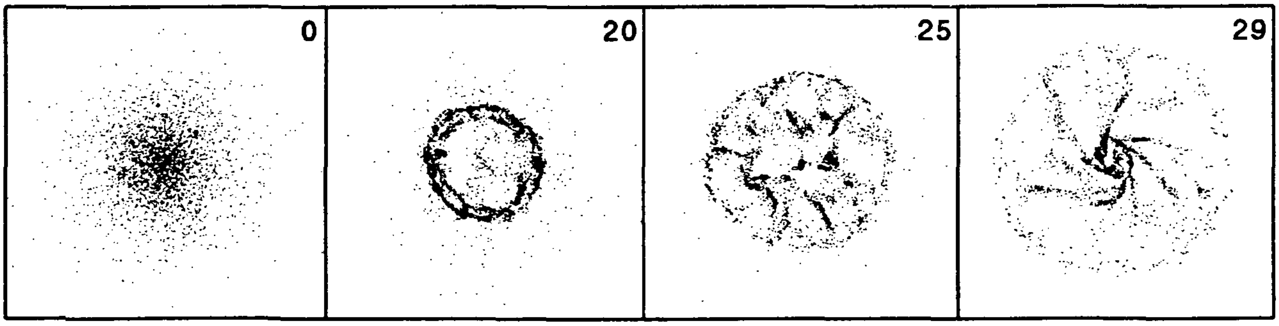

FIGURE 1. Time evolution of gaseous component of primary, seen face-on to the disk plane. Panels measure 15 length units per edge; time is indicated in upper right-hand corner of each.

REFERENCES

Appleton, P.N. & Marcum, P.M., 1992, preprint.

Athanassoula, E., & Bosma, A., 1985. ARA&A 23, 147.

Fosbury, R.A.E. & Hawarden, T.G., 1977. MNRaS 178, 473.

Hernquist, L., 1991. Int. J. Supercomp. Appl. 4, 77.

Hernquist, L., 1992a. ApJ, in press.

Hernquist, L., 1992b. ApJ, in preparation.

Hernquist, L. & Katz, N. 1989. ApJS 70, 419.

Hernquist, L. & Weil, M.L. 1992, in preparation.

Higdon, J.L., 1992, preprint.

Lynds, R. & Toomre, A., 1976. ApJ 209, 382.

Theys, J.C. & Spiegel, E.A., 1977. ApJ 212, 616.