

DISSIPATION, MEMORY, AND RESERVOIRS: THE RINGLETS OF SATURN

Charles E KenKnight, 3819 Lake Drive, Robbinsdale, MN 55422

The Voyager 1 images revealed that the rings of Saturn were divided into at least 1000 ringlets when viewed with linear resolution poorer than 10 km. The Voyager 2 occultation experiment improved the linear resolution of ring details to 0.1 km. Analysis [1] revealed that radial structure existed even to 0.1 km. The rings resemble Fig. 1 in appearance. The star measures gave the projected area of solid grains per unit area of the disk (optical depth, OD) as in Fig. 2, which is an average along the ringlets in Fig. 1. Histograms of the optical depths [2] in each region were not Gaussian, but triangular as in Fig. 3. Spatial correlations of the OD's were given as power spectra, which declined about as $1/f$. Finding a spectrum that is a power law is evidence that no special scaling length exists for the transport process that maintains the variance in OD in spite of the tendency to smooth it away. We have 2 unexplained effects: 1) triangular histograms; 2) power spectra that declined as $1/f$.

I have done simulations that gave Figures 1-3. The programs are related to the cellular automata used by Per Bak and colleagues [3,4] and others [5] to mimic earthquakes and those used by Schulman and Seiden [6] to discuss galactic structure in response to star formation. They assumed that nearest neighbor cells influenced each other according to some rules, including the value of some random number. The "quakes" were a response to stress exceeding a threshold. Release in one cell caused some increase in several neighbors, which put some of them above the threshold and caused a cascade of arbitrary size.

I assumed both short and long range transfers of mass induced, for example, by meteoroid bombardment [7]. In a time step, a random number was generated for each cell, representing a projectile mass P coming from a distribution in which large masses are rare. For P larger than the cell mass, chips in proportion to P were extracted from the target and scattered everywhere over the array of cells. Newton's 3rd law assures great difficulty for chips to stop where no mass impedes them, so I made the probability of stopping proportional to the mass already present: ringlets grew. That growth of slopes will occur from short range transfers may be seen from Fig. 4. The mass decrease from the center bin is to be divided between the adjacent bins according to the mass already present there. The greater mass collects most of the transfer. After all transfers were made, each ringlet was smoothed a little by a 1D diffusion routine. Such diffusion could arise from the phase mixing of differential rotation. I included rotation between the ringlets at each time step, so the nearest neighbors changed with time. That increased the rate of variance growth.

Long range transport was used alone in special studies. The histogram of masses per bin grew to a triangle provided that the mass transfers per time step were large enough. We are not integrating a differential equation, where steps half as large taken twice should give almost the same values unless the method is failing. Our central intent here was to make the variance grow.

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We are modelling systems having a variety of characteristic times for transport. The memory for radial movement in rings is much greater than that for azimuthal transfer. Large radial movement is slower than the short range. It is this memory that is analogous to the physical system.

I sought out run conditions for which low spatial frequencies in the radial power spectrum persisted for many time steps. Without short range transfers the system always decayed toward a white spectrum. I added a variety of schemes for short range transfers. Most of them worked too well at a small distance: the power spectrum became steeper than $1/f$, especially at the highest spatial frequencies. The curve in Fig. 2 is too smooth. Cascades of short transfers triggered by a large P event has interest, but it cannot be more than a correction. In every case a longer run turns a Saturn-like view like Fig. 1 into isolated ringlets like those at Uranus. One ringlet eats all others.

Looking ahead, the flare-like events giving chondrules in the solar nebula may be an extreme temperature event in which diffusion-slowed radiation cannot cool a density fluctuation of the gas until and unless the opacity is locally decreased by transfers from dust to chondrules. We expect a variety of gas fluctuations to be stirred by the infalling gas. Orbital sloshing through the central plane should cause a long memory. Such a simulation would require following events in the gas, dust, and radiation distributions. But given any means by which most dust reaches a few μm in at least one dimension and given gradual loss of gas, the solids will settle into a disk where solid-solid interactions become dominant over gas-solid forces. We now expect ringlets in that disk. Such ringlets may deserve to be called the "reservoirs" that gave the variety of final bodies, because transport between them was suppressed by the large energy requirement for change in semi-major axis or inclination.

References. [1] Esposito et al, *Icarus* 56(1983)439 [2] Esposito et al, *J Geophys Res* 88(1983)8643 [3] P Bak et al, *Phys Rev Lett* 59(1987)381; *Phys Rev* 38A(1988)36 [4] P Bak & C Tang, *J Geophys Res* 94(1989)15635 [5] L Kadanoff et al, *Phys Rev* 39A(1989)6524 [6] L S Schulman & P E Seiden in *Percolation Structures and Processes*, *Annals Israel Phys Soc*, Vol 5 (Adam Hilger, 1983) p 251 [7] R H Durisen in *Planetary Rings* (U of AZ, 1984) p 416.

