pre-cooling of the beam before transferring it to the second ring, the accumulator.

The accumulator sits inside the debuncher and looks like an irregular hexagon with three long sides and three short ones where the corners of the debuncher are. Its job is to stochastically cool and store successive pulses of antiprotons arriving from the debuncher. After about two hours of running, the stored antiproton beam contains about $2 \times 10^{11}$ particles. It turns out that the precooling in the debuncher is a key to reducing the cooling time in the accumulator. The reduced beam size due to precooling permits higher frequency operation and hence a shorter cooling time.

From the dense core of the stored beam, antiprotons are extracted to form one of the three bunches in the collider. This bunch is first accelerated to 150 GeV in the old synchrotron ring and then injected into the Tevatron. The process is repeated three times to obtain three antiproton bunches, which are then accelerated together with three proton bunches to the final beam energy.

Fermilab scientists hope to demonstrate this scenario in its entirety during the current test period, which lasts to the end of this month. Peoples says there is about a 50 percent chance of accomplishing this. If it does occur, one of the two major detectors will be partially completed and in place to record the world's highest energy, man-made proton-antiproton collisions.

Obtaining collisions would be a tremendous psychological boost to carry the scientists through a long shutdown scheduled from October until next summer to accommodate two major civil construction projects related to the detectors. It would also provide useful data for tuning up the antiproton source, the collider, and the detector over the shutdown, so that everything will be ready for the first real run next year.

—ARTHUR L. ROBINSON

**References**


1. M. M. Waldrop, *Science* **225**, 490 (1984).
2. A. L. Robinson, *ibid.* **213**, 191 (1981).
3. ——, *ibid.* **217**, 814 (1982).


# Making Better Planetary Rings

## *Particles colliding in Saturn's rings appear to be ice balls, not snowballs, acting like molecules of a gas, a liquid, and perhaps even a solid*

Saturn's rings have seemed stranger and stranger of late, as spacecraft have made revealingly close inspections. The new observations have uncovered a stunning number of variations on the few, broad rings expected by researchers and have even suggested that the rings formed only recently, a most unpalatable prospect to astronomers. However, there are new signs that theory could be catching up with the observations.

Theorists have had no trouble explaining how particles could orbit a planet in a disk so thin that, if scaled down to the size of the United States, it would be no thicker than a few centimeters. Some theorists argue that it must be even thinner. And they had little or no trouble coming up with some ways of sculpting what would otherwise be a single, featureless disk into broad rings, narrow ringlets, ripples, and spiraling waves. But Saturn's rings stayed far ahead of the theorists with their mysterious razor-sharp inner edges, narrow gaps, wavy edges, thousands of ring subdivisions, and other oddities (*1*).

One group of theorists believe that they now have a handy new tool for developing and testing explanations of the rings' bizarre appearance: a mathematical description of how ring particles orbiting a planet behave as they nudge neighboring particles. The model has passed a crucial test and has yielded some interesting initial insights.

The new model takes one of several available approaches to describing a cloud of particles in which collisions are far less frequent than those of molecules in a liquid but far more frequent than any considered in plotting the motions of planetary bodies. Accounting for collisions is crucial because they mediate the transfers of energy that shape rings. The model was developed by Frank Shu of the University of California at Berkeley and Glen Stewart, who is now at the University of Virginia (*2*). They borrowed from plasma physics the 30-year-old Krook equation, an approximate mathematical description of colliding particles, and modified it so that some of the kinetic energy of a collision could be lost to the deformation and heating of the particles. Without such inelasticity, the model's particles would be unrealistically bouncy. Put to its first test, the Krook model results compared well with other models of a ring unperturbed by external forces.

The new model has since done well on a second, more challenging test (*3*). Shu and Luke Dones of the University of California at Berkeley and Jack Lissauer, Chi Yuan, and Jeffrey Cuzzi of the National Aeronautics and Space Administration's Ames Research Center at Moffett Field, California, used the disturbance due to the periodic gravitational pull of a satellite to create a spiral density wave in the model ring. This is a wave of bunched ring particles that spirals outward from the disturbance, called a resonance, in the form of a watch spring. The Voyager spacecraft discovered dozens of them in Saturn's rings.

The model's simulation of a spiral density wave, one in the A ring due to a resonance of the satellite Mimas, bore considerable resemblance to the real thing. In a radial cross section of model and observed waves, the peaks of ring opacity are sharp, the troughs between are broad, and, most impressive, the distance between crests is inversely proportional to the distance from the resonance. The resemblance is "striking," the authors conclude, suggesting that the model's inelastic collisions are dissipating energy and damping the wave much as happens in the A ring.

The good fit to reality comes only if ring particles are assumed to be solid ice. Despite the spacecraft flybys, researchers have only been able to speculate whether ring particles are hard ice through and through, are coated with a cushioning layer of collision-produced chipped ice, or are a loose agglomeration of many particles.

The highly elastic particles required by the model bear a strong resemblance to the clean, hard ice balls studied by Frank Bridges, A. Hatzes, and Douglas Lin of the University of California at Santa Cruz (*4*). In the lab they collided two ice balls chilled to 165 K at speeds between 1.5 centimeters per second and a few tenths of a millimeter per second. Like cars racing around a track, ring particles jostle their neighbors at these low relative speeds despite their hurtling about the planet at several kilometers per second. Bridges and his colleagues could use the high elasticity of the balls measured at low collision speeds in calculations of ring properties, such as the determination of a ring thickness of less than 5 meters, but they could not know if such results with hard, crystalline ice had anything to do with Saturn's rings.

Shu and his colleagues, on the other hand, used spiral density waves as a natural probe of the physical state of the rings and its particles, the character of the waves depending on the properties of the colliding particles within them. "We have obtained in this investigation a strong suggestion that the ring particles are indeed composed of crystalline ice . . . we believe that this result rules out models of ring particles as extremely fragile as dynamic ephemeral bodies," the loose agglomerations of various sized particles hypothesized to populate some parts of the rings (*5*).

The model's apparent success with the A ring wave would also imply that there is no easy means of explaining away the youthful appearance of the rings. Planetary dynamicists abhor youthfulness in the solar system; everything is much tidier if the general arrangement of planets, satellites, and rings was determined early on as formation processes petered out and violent collisions became rare. Theorists would have no problem with a broad, featureless disk surviving the 4.5 billion years since the early days of the solar system, but features such as spiral density waves are clear evidence that satellites, including the profusion of small ones found near the rings, are draining angular momentum from the rings. The satellites should be spiraling outward into ever larger orbits as they gain angular momentum, and the A ring should collapse inward into the B ring in just 100 million years as its particles lose angular momentum.

The results of the Krook model establish "beyond the shadow of a doubt that powerful gravitational torques are at work shaping the structure of Saturn's rings" and draining angular momentum from them as rapidly as theorists had feared, according to Shu and his colleagues. Either the rings formed a short while ago or both the rings and the inner satellites are somehow being buttressed. The inner satellites may indeed be anchored to the more massive outer satellites through a chain of resonances (*6*), but no obvious means of shoring up the A ring has been proposed.

Not everyone is as confident about the Krook model's success as Shu and his colleagues. Peter Goldreich of the California Institute of Technology and Scott Tremaine of the Canadian Institute for Theoretical Astrophysics in Toronto, who are also noted ring theorists, remain unconvinced that the Krook model, or their own for that matter, is realistic enough yet. "The agreement is encouraging," says Tremaine, "but it doesn't necessarily mean that the model is right. We're not confident that either model has all the relevant physics."

**Satellites are draining angular momentum from the rings as rapidly as theorists had feared.**

Both models consider only smooth, spherical, spinless particles, but what makes Tremaine and Goldreich most uneasy is the assumption that ring particles act like molecules of a thin gas all of the time. Both groups agree that ring particles do become so tightly packed in some parts of the rings that gaslike models break down; the groups disagree on how commonly that might happen. Shu and his colleagues see evidence of this nonideal behavior only at the density peaks of a spiral density wave in the already dense B ring. A Krook simulation of one such wave, induced by a resonance of Saturn's two co-orbital satellites, duplicates neither the wavelengths nor the amplitudes observed by the Voyager spacecraft. Apparently, the gaslike particles become so compressed in the crests that the gravitational pull between particles condenses them into a liquid that the model cannot properly describe. Nicole Borderies of the Observatory of Pic du Midi and Toulouse, Goldreich, and Tremaine have also concluded on the basis of more quantitative calculations that tightly packed rings will condense into liquids (*7*).

Suguru Araki of the Massachusetts Institute of Technology and Tremaine have used a 60-year-old theory of dense gases and liquids to study ring behavior and found that not only condensation to a liquid but also "freezing" into a rigid, solid-like body may occur in the dense B ring. Rigid rings were a popular idea from the mid-17th century until theory and observation seemed to eliminate the possibility late in the 19th century. A rigid ring could not span the breadth of the B ring, for instance, because not even a truly solid ring with strong bonding between its particles could be strong enough to hold together inner and outer edges that would tend to orbit at greatly differing speeds.

But Araki and Tremaine suggest that the myriad of alternately lighter and darker narrow ringlets that mark most of the B ring may be adjacent solid and liquid phases of the ring, in which particles in the solid phase no longer slip by their inner and outer neighbors. They find no evidence in their model of diffusive instability, which thin-gas models had supported as the favored mechanism for generating the B ring structure. Whichever model is correct, says Tremaine, it is almost certain that the B ring does not act like a thin gas.

Shu counters that there are several indications that the Krook model applies not only to the less dense A ring but also to much of the B ring. Light passes through much of the rings, he notes, suggesting that particles are not tightly packed everywhere. The Krook model properly damps the energy of spiral density waves in the A ring through inelastic collisions even though damping is inversely proportional to the eighth power of the measure of particle inelasticity. The trade-offs between the damping required by observations and the physical limitations of ice are so finely balanced, Shu says, that only relatively hard particles can work. And the model predicts that damping of spiral density waves in rings like A will be rapid but, in dense rings like B, waves will propagate great distances. In fact, the A ring wave damps beyond detectability within about 10 cycles while the B ring wave continues to propagate after 90 cycles.

There appears to be no insurmountable obstacle to a consensus on how far ring models can be pushed. When generally accepted models are available, which will probably happen first in the case of the less dense A ring, their application will include not only planetary ring systems but also other systems of colliding particles: condensing liquids, the nebula that formed the solar system, and the dust, stars, and gas clouds of galaxies.—**RICHARD A. KERR**


**References**

1. R. A. Kerr, *Science* **218**, 141 (1982).
2. F. H. Shu and G. R. Stewart, *Icarus* **62**, 360 (1985).
3. F. H. Shu, L. Dones, J. J. Lissauer, C. Yuan, J. N. Cuzzi, *Astrophys. J.*, in press.
4. F. G. Bridges, A. Hatzes, D. N. C. Lin, *Nature (London)* **309**, 333 (1984).
5. D. R. Davis, S. J. Weidenschilling, C. R. Chapman, R. Greenberg, *Science* **224**, 744 (1984).
6. R. A. Kerr, *ibid.* **221**, 449 (1983).
7. N. Borderies, P. Goldreich, S. Tremaine, *Icarus*, in press.