THE RINGS OF SATURN AND URANUS

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1. INTRODUCTION

Nature has presented us with two systems of planetary rings. They are not at all similar. Saturn has bright, broad rings separated by narrow gaps. The rings of Uranus are dark, narrow and widely spaced. Presumably both sets of rings lie inside the Roche limit and this is why the ring material has not condensed into satellites.

I will briefly review what is known about each ring system with particular emphasis on properties of significance to dynamical astronomy.

2. SATURN'S RINGS

2.1 Observations

Observations at visual wavelengths reveal two bright broad rings separated by a narrow gap known as the Cassini division. The optical depth normal to the ring plane is of order several tenths (1,2). The thickness of the rings is less than 3 km (1).

Near infrared reflectance spectra show absorption features due to water frost (3). Thus the ring particles are at least coated with ice.

Measurements of the thermal emission at far infrared wavelengths yield brightness temperatures of order 90°K (4). These values are consistent with the equilibrium kinetic temperature for highly reflecting particles at Saturn's distance from the sun.

Interferometric observations at centimeter wavelengths show that the rings are very weak radio emitters, $T_B < 10^\circ$K (5,6). The rings partially block radio emission from Saturn's disk. The optical depth at radio wavelengths is comparable to that at visual wavelengths (6).

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The rings are excellent reflectors of centimeter wavelength radar waves (7). This implies that the ring particles are greater than a few centimeters in size. Incident polarized radar signals are largely depolarized after reflection, presumably the result of multiple reflections (8).

2.2 Basic deductions

The ring particles are probably largely composed of water ice. Consideration of cosmic abundances, the low densities of the inner satellites of Saturn and, above all, the near infrared spectral data all support this view. If ice, the low radio emission implies that the mean particle radius is < 0.1 absorption lengths or perhaps < 10 m. The composition independent lower limit of 1 cm radius is set by the high radar reflectivity.

Silicate particles may be ruled out because the ratio of their emissivity to reflectivity at centimeter wavelengths is much too high to satisfy the radio and radar data.

Metallic particles coated with ice cannot be excluded. They could be of any size greater than 1 cm in radius. However, iron particles would be outside the Roche limit and should have collected into satellites.

2.3 Dynamical problems

The velocity dispersion of the ring particles is determined by the details of their mutual collisions. Collisions give rise to a viscous stress that converts orbital energy into random motions. Since the collisions are not perfectly elastic, the energy in random motions is dissipated as heat. The velocity dispersion adjusts so that the effects of these two processes balance (9,10). For ice particles collisions are likely to be quite inelastic even for impact velocities as low as 10^{-3} cm s^{-1}. This implies that a ring of ice particles would be a monolayer (10).

The outer or A ring shows an azimuthal brightness variation which is asymmetric with respect to the Earth-Saturn center line. Brightness maxima and minima precede and follow conjunctions of the ring particles with this line (11,12). No convincing explanation of this phenomenon exists. Suggestions include albedo variations on synchronously rotating particles and gravitationally enhanced, elongated, particle density fluctuations inclined to the radial direction (13).

The inner edge of the Cassini division is near the position of the 2:1 orbital resonance with Mimas. The problem is to explain how tiny Mimas has managed to clear such a large gap and why the resonance radius lies close to its inner edge. A new mechanism, based on the collective response of the ring particles to the resonant perturbations by Mimas, has been proposed (14). It accounts in a natural way for the size and location of the gap. The principal hypothesis is that Mimas excites a trailing spiral density wave at the position of the 2:1 resonance. The wave carries negative energy and angular momentum and propagates outward. The wave is damped by viscosity (due to collisions) and its negative energy and angular momentum are transferred to the ring particles. Consequently, the particles just outside the 2:1 resonance move inward opening a gap.

3. THE RINGS OF URANUS

3.1 Observations

Uranus is encircled by at least 9 narrow rings. The 5 most prominent rings were discovered during an occultation observation in March 1977 (15,16). Of these, the inner 4 are of order 10 km wide and have eccentricities $< 10^{-3}$. The outermost or ϵ ring is of variable width (20 to 100 km) and has an eccentricity of order 10^{-2}. An additional 4 rings were recognized in a more careful analysis of the March 1977 data and were also detected during an occultation observation in April 1978 (17,18).

Optical detection of the rings is difficult because of their proximity to the much brighter planet. Observations made in methane bands shortward of 1 μm indicate that the albedo of the rings is $\leqslant 0.05$ (19,20). One marginal detection has been reported (21). The stratoscope pictures of Uranus reveal a faint shadow, apparently cast by the rings (19,22).

In May 1978 the rings were successfully mapped at 2.2 μm (23). At this wavelength the rings are brighter than Uranus even though their albedo is only of order 0.05. These measurements cannot resolve the individual rings but they do reveal an azimuthal brightness variation which is plausibly attributed to the variable width of the ϵ ring.

3.2 The ϵ ring

An analysis of all available occultation data reveals the following (24). The width of the ϵ ring varies linearly with radius. Its optical depth profile is remarkably similar at different locations. The edges of the ring are abrupt.

The positions of all the ϵ ring crossings are well fit by a precessing Keplerian ellipse with $a = 51{,}284$ km, $e = 7.8 \times 10^{-3}$ and $\dot{\tilde{\omega}} = 1\overset{\circ}{.}37$ day^{-1}. The linear relation between ring width and radius is consistent with a small spread in the semimajor axes and eccentricities of the ring particles.

3.3 Dynamical problems

Narrow rings tend to spread due to particle collisions. The lifetimes of the Uranian rings are probably comparable to the age of the solar system because diffuse rings are not seen and there is very little inter-ring material. In the absence of confining forces, these considerations would imply that the sizes of the ring particles were less than one centimeter. However, over the age of the solar system the Poynting-Robertson effect would produce a substantial decay of the orbits of sub-centimeter size particles. Thus, the presence of confining forces seems likely (25,26).

Attempts to relate the 5 original rings to a series of orbital resonances with the Uranian satellites have not been successful (27,28, 29). The discovery of 4 additional rings makes this approach less attractive.

My guess is that each ring contains a small satellite and that the ring particles are debris from its surface. However, I have yet to investigate the stability of such a configuration.

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BIBLIOGRAPHY

1. Bobrov, M.S.: 1970, in A. Dollfus (ed.), "Surfaces and Interiors of Planets and Satellites," Academic Press, New York, p. 377.
2. Cook, A.A. and Franklin, F.A.: 1958, "Smithsonian Contrib. Astrophys." 2, p. 377.
3. Pilcher, C.B., Chapman, C.R., Lebofsky, L.A. and Kieffer, H.H.: 1970, "Science" 167, p. 1372.
4. Murphy, R.E.: 1974, in F.D. Palluconi (ed.), "The Rings of Saturn," NASA, Washington, D.C., p. 65.
5. Berge, G.L. and Muhleman, D.O.: 1973, "Astrophys. J." 185, p. 373.
6. Briggs, F.H.: 1974, "Astrophys. J." 189, p. 367.
7. Goldstein, R.M. and Morris, G.A.: 1973, "Icarus" 20, p. 260.
8. Goldstein, R.M., Green, R.R., Pettengill, G.H. and Campbell, D.B.: 1977, "Icarus" 30, p. 104.
9. Brahic, A.: 1977, "Astron. Astrophys." 54, p. 895.
10. Goldreich, P. and Tremaine, S.: 1978, "Icarus" in press.
11. Reitsema, H.J., Beebe, R.F. and Smith, B.A.: 1976, "Astron. J." 81, p. 209.

12. Lumme, K. and Irvine, W.M.: 1976, "Astrophys. J. Lett." 204, p. L55.
13. Colombo, G., Goldreich, P. and Harris, A.W.: 1976, "Nature" 264, p. 344.
14. Goldreich, P. and Tremaine, S.: 1978, "Icarus" in press.
15. Elliot, J.L., Dunham, E. and Mink, D.: 1977, "Nature" 267, p. 328.
16. Millis, R.L., Wasserman, L.H. and Birch, P.: 1977, "Nature" 267, p. 330.
17. Elliot, J.L., Dunham, E., Wasserman, L.H., Millis, R.L. and Churms, J.: 1978, submitted to Astron. J.
18. Persson, E., Nicholson, P., Matthews, K., Goldreich, P. and Neugebauer, G.: 1978, "IAUC" No. 3125.
19. Sinton, W.M.: 1977, "Science" 198, p. 503.
20. Baum, W.A., Thomsen, B. and Morgan, B.L.: 1977, "Bull. Am. Astron. Soc." 9, p. 499.
21. Smith, B.A. and Reitsema, H.J.: 1977, "Bull. Am. Astron. Soc." 9, p. 499.
22. Colombo, G.: 1977, "Sky Telesc." 54, p. 188.
23. Matthews, K. and Neugebauer, G.: 1978, private communication.
24. Nicholson, P., Persson, E., Matthews, K., Goldreich, P. and Neugebauer, G.: 1978, submitted to Astron. J.
25. Brahic, A.: 1978, paper presented at IAU Symp. No. 81., Tokyo.
26. Goldreich, P. and Nicholson, P.: 1978, in preparation.
27. Dermott, S.F. and Gold, T.: 1977, "Nature" 267, p. 590.
28. Aksnes, K.: 1977, "Nature" 269, p. 783.
29. Goldreich, P. and Nicholson, P.: 1977, "Nature" 269, p. 783.

DISCUSSION

Van Flandern: Elsewhere in the solar system, we tend to find other satellites, rather than gaps, at resonance positions. Would you comment on the possibility that the Cassini gap is actually cleared by a small Saturnian satellite?

Goldreich: The Cassini gap may be cleared by a small satellite. However, our mechanism would lead to an accumulation of material just inside the 2:1 resonance with Mimas. Thus, if a satellite could form in the rings that is where we would expect it to.

Van Flandern: Isn't it possible to explain the unusual optical and dynamical properties of the Uranian rings, particularly the "precession," if each ring is caused by a single satellite diffusing material, similar to the sodium-hydrogen torus in the orbit of Io?

Goldreich: The ring particles must be at least a few microns in size. However, they might have come from a small satellite.

Marchal: How do you explain the stability of the asymmetric ring since the precession rate decreases with increasing radius?

Goldreich: We are looking for the explanation; the motions are likely forced with numerous collisions.

Kozai: What do you mean when you say that ε-ring of Uranus is precessing? Do the apsides move as if the ring is a solid body?
Goldreich: We think so.

Brahic: In your model of Cassini's division, are the density waves trailing or leading?
Goldreich: Only a trailing wave is excited.

Scholl: Can your theory about the formation of the Cassini division be applied to the Kirkwood gaps? Why?
Goldreich: It cannot because the density in the belt is too low for cooperative gravitational effects to be of importance.