ORIGIN AND EVOLUTION OF SATURN'S RINGS

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ABSTRACT

The formation of planetary rings is discussed in the context of formation theories of the gaseous planets. The subsequent evolution of Saturn's ring system, both dynamically and mechanically, is described, and the consequences are compared with observations.

INTRODUCTION

Planetary rings seem to be a rule rather than an exception for the giant planets in our solar system. A few years ago only Saturn was known to have a ring system, now Neptune is the only candidate which may possibly <u>not</u> have a ring system. Terrestrial planets do not have rings.

This systematic, and the fact that the rings lie in the equatorial plane of their respective planet, suggest that ring formation and giant gaseous planet formation are closely linked. In the sense that planets and their moons appear as miniature solar systems, study of planetary rings (in particular the largest system around Saturn) may throw new light on the early history and development of the whole solar system, a fact which was recognised a long time ago (Laplace 1796, Kant 1755).

In this review, we discuss this formation question in the light of our improved knowledge of the giant planets and then describe the subsequent evolution of Saturn's rings (but ignoring the formation of moons) both dynamically and mechanically. Comparison with observations is made wherever this is possible.

ORIGIN OF PLANETARY RINGS

Two scenarios have been proposed for the formation of giant gas planets:

The first one (e.g. Cameron 1978, 1979, Cameron et al. 1982) is the hydrodynamic collapse in a massive protosolar gas and dust disc. In order that the process should operate, this should occur preferentially before too much mass has accreted into the protosun.

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The second one is the formation of a solid core (terrestrial material) with subsequent accretion of gas (e.g. Mizuno 1980, Stevenson 1982). This process must also not occur too late in the solar system evolution (in order to accrete the massive gaseous envelope of Jupiter and for Jupiter to disrupt terrestrial planet formation in the asteroid zone), but the sun cannot "quench" the process.

The two scenarios have advantages and disadvantages, which have been discussed by Lin (1982) and references therein. Recent internal structure calculations by Stevenson (1982) and Hubbard et al. (1980) have been interpreted to favour the accretion model rather than the collapse model. The result of the calculations is that all four gas planets contain "rocky" cores of ~ 10 earth masses (Jupiter and Saturn may contain somewhat more), and the significance of this result is that in the accretion model a critical core mass of roughly that size must be built up before gas accretion becomes effective.

From the point of view of moons and rings, the accretion model is favoured, of course, since it presupposes many solid bodies (planetesimals) to exist. A number of these will end up orbiting the planet - outside the Roche zone they may coalesce to form larger moons, inside they will form a ring system. The coplanarity of the orbits of inner moons and rings, the low orbit inclinations, the small eccentricities and the abundant craterisation are all facts which support an accretion model - although, in fairness, one should say that very little quantitative work has been done in either model regarding this question.

EARLY DYNAMICAL EVOLUTION OF PLANETARY RINGS

Irrespective of the chosen model, it is clear that the early evolution of planetary rings is characterised by the existence of a gas-rich environment. This has two consequences:

1. There will be a radial inward drift due to gas drag (Whipple 1972, Weidenschilling 1977) and small particles will be dragged in towards the planet. This clears up the space surrounding the planets and leads to growth of moons by accumulation.

2. The gas is probably turbulent. By Epstein drag, random velocities are imparted to solid bodies in orbit. The evolution of a planetary ring system can then be described dynamically as if it were a viscous disc, the coefficient of viscosity being defined by

$$\nu = 1/3\ \delta v\ H \qquad (1)$$

where δv is the mean random velocity and

$$H = \delta v/\Omega_k \qquad (2)$$

is the thickness of the disk. Ω_k is the Keplerian angular velocity. Again the net result is a dissipation of angular momentum and a mass flow towards the planet.

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The survival of the planetary ring system then depends on the time it takes to viscously dissipate the system, and on the existence of possible restoring forces.

The dissipation time for a ring of radial extent (from the planet surface) of δR is given by

$$t_d = \delta R^2/\nu. \tag{3}$$

If $t_d > t_G$ = gas accretion time scale ($\sim 10^6$ years) portions of a ring system may survive this early evolutionary period.

At the same time, it is possible for this dissipation to be checked. Whilst larger bodies cannot accrete inside the Roche zone, they may, of course, do so outside. Compaction may lead to fairly strong binding energies of such "moonlets". Growth of the planet by gas (and solid matter accretion) will adiabatically draw orbiting bodies towards it (under conservation of angular momentum). Sufficiently compact "moonlets" may thus find themselves inside the Roche zone at a later time, without breaking up.

The interaction of such moonlets with planetary ring material has been described by e.g. Goldreich and Tremaine (1979, 1980), Lissauer et al. (1981). The physical processes in this early evolutionary phase are identical; the viscous dissipation may be higher. However, a sufficiently big moonlet may still be able to stop the viscous decay of ring material, at the expense of a relatively minor orbit decay. This may be the reason for the survival of relatively narrow rings.

PRESENT DYNAMICAL EVOLUTION (SATURN'S RINGS)

The best ring system, in which evolutionary studies may be made, is that of Saturn. We may apply the viscous evolution formalism even today. The processes responsible for random velocity (orbit) perturbations are different (e.g. higher order terms in the planetary gravitational potential, resonant interactions with the moons etc.) and hence the absolute value of ν will be different, too, as well as being more strongly space dependent. Identification of density waves (Cuzzi et al. 1981), slight eccentricities (Smith et al. 1981) and "waves" in isolated ringlets are all testimony for induced velocity perturbations. The value of ν deduced from observations in the Cassini division (Cuzzi et al. 1981) is

$$\nu \approx 200 \text{ cm}^2/\text{sec} \tag{4}$$

If this value is representative for the whole of Saturn's rings, we obtain a viscous life time

$$t_s = \Delta R_s^2/\nu \approx 1.5\text{x}10^{10} \text{ years} \tag{5}$$

(using $\Delta R_s = 10^{10}$ cm as the radial extent of Saturn's rings). This is uncomfortably close to the life time of the solar system itself ($t_{ss} \approx 4.5\text{x}10^9$ years). However, a value of ν as deduced from observations in the Cassini division is probably not representative of the less disturbed regions of the ring system, far away from major resonances. On the other hand, the inner ring system (C and D rings) get progressively thinner optically, the closer the planet. This could be due to viscous evolution over geological times, if perturbations by the planetary gravitational field are important enough or the many higher order resonances with the moons outside the ring system. Of particular interest in this context is the sudden rise in optical depth outside 1.625 R_s (from $\tau \approx 0.8$ to $\tau \approx 2$) which may then be associated with one or more moonlets. It should be mentioned, however, that a mechanical explanation has also been proposed (Northrop and Hill 1982, Ip 1982).

PRESENT MECHANICAL EVOLUTION (SATURN'S RINGS)

The mechanical evolution of Saturn's rings is determined by collisions with interplanetary meteoroids. Such collisions produce particulate ejecta, gas and ions. Using available measurements of interplanetary meteoroid fluxes, their mass distribution and spatial variations (e.g. Schaeffer et al. 1981, Humes et al. 1974, Humes 1976, Southworth and Sekanina 1973) as well as calculations of gravitational focussing, Morfill et al. (1982) have derived the meteoroid environment of Saturn, and the corresponding bombardement of the rings.

A summary of the results is:
Total meteoroid influx: $\dot{M} \approx 1.1\times10^6$ g/sec
Dominant meteoroid size range: $100\mu < a < 1000\mu$
Vapour production rate: $\dot{M}_v \approx 3\times10^6$ g/sec
Dominant vapour species: H, H_2^+, O, O^+, OH, H_2O etc.
H-production rate: $\dot{M}_H \approx 0.4\times10^6$ g/sec
Total mass erosion rate $\dot{M}_E \approx 0.5\times10^{10}$ g/sec

This present mechanical interaction of interplanetary meteoroids with Saturn's rings leads to a number of observable consequences. (It should be borne in mind that the fluxes and rates derived above are very uncertain, as they represent extrapolations across the asteroid belts - hence any observational input from the Saturn system itself is a useful constraint on the original numbers)

1. NEUTRAL RING ATMOSPHERE

Properties of the neutral ring atmosphere are summarised in Broadfoot et al. (1980):

Composition:	neutral H detected
Density:	$n \approx 600$ cm^{-3}
Extent:	$h \approx \mp 1$ R_s (Saturn Radius)
	$r \approx 2$ to 3 R_s
Total mass:	$M \approx 8\times10^9$ g

Using the meteoroid impact rates given earlier, Morfill et al. (1982) obtain a neutral hydrogen ring atmosphere, which in extent as well as density and mass lies within a factor 2 of the observed values.

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2. RING HALO

A ring halo was observed during "edge-on" measurements by Baum and Kreidl (1982).
Its properties are

Thickness: $h \approx \mp 2.5$ km

Perp. optical depth: $\tau_{\perp} \approx 10^{-5}$

The particles responsible are thought to be micron-sized or larger. This ring halo could be related to e.g. the "spokes", but could also be due to continuous ejecta formation by many small meteoroid impacts. Morfill et al. (1982) obtain a mean ejecta velocity of ~ 500 cm/sec, which would lead to a ring halo extending to $\sim \mp 25$ km around the ring plane. The perpendicular optical depth derived from the meteoroid impact source is within a factor 2 of the value deduced by Baum and Kreidl (1982). Taking into account oblique impacts and the fact that heavier ejecta have smaller ejection velocities, it is clear that the ∓ 25 km thickness of the particulate ring halo is too large an estimate. A straightforward reduction by a factor ~ 5 seems possible (in particular if there is a regolith on the larger ring bodies, as this would reduce ejecta velocities).

3. MASS EROSION AND REGOLITH FORMATION

The total mass erosion due to meteoroid impacts over geological times was also estimated by Morfill et al. (1982). It is of the order 10^{27} g, and must be compared with an estimated ring mass of $\lesssim 10^{24}$ g. Clearly, only a small fraction of the ejecta are lost from the ring system. Most of the material is deposited back on the rings, the area over which the deposited material is scattered is a few 10^{4} km^{2}. In this way, all the larger ring bodies should acquire a regolith, the depth of which will become selfregulated by the size distribution of the impacting interplanetary meteoroids. A depth of a few cm would be sufficient to shield the ring body from major erosion and ensure its survival until today.

4. SPOKES

The existence of a regolith, particularly in the densest portion of Saturn's rings, i.e. the B-ring, may be of importance in connection with an intriguing phenomenon observed by Voyager, "Spokes". These are dark patches, sometimes triangular, sometimes narrow and long, which occur frequently in the B-ring (for a recent analysis see e.g. Grün et al. 1982). In forward scattered light, spokes appear bright, an indication of the existence of small, micron-sized dust.

The problem of understanding the formation and evolution of spokes, centres on the mechanism for levitating small dust particles above the ring plane. Another major puzzle is the speed of spoke formation. Grün et al. (1982) show one example, where a spoke of length ~ 6000 km is formed within < 5 minutes (the time difference in the image sequence on Voyager).

Finally, the fact that young spokes appear aligned with the radius vector, and subsequently evolve along Keplerian orbits (sometimes growing in width, too) also places constraints on any formation theory.

A possible model for spoke formation has been proposed by Goertz and Morfill (1982). The central element of that theory is the existence of a dense plasma cloud above (or below) the ring plane. Within the plasma cloud, small charged dust grains are levitated by electrostatic forces from the ring bodies. These grains charge up further once they have been elevated more than one Debye length. The next stage is that of grain-plasma segregation. Grains move along Keplerian orbits, the plasma corotates with the magnetic field. Since the grains are charged, there exists therefore a net azimuthal current out of the plasma cloud. Charge neutrality in the plasma cloud is maintained by a pair of field-aligned current sheets, which close through Pederson currents in the Saturnian ionosphere. The corresponding electric field is azimuthal, it maps back into the equatorial plane and causes a radial $\underline{E} \times \underline{B}$ motion of the plasma cloud. For negatively charged grains, the velocity is away from the corotation radius. Goertz and Morfill (1982) derive

$$v \approx 20.6 \sqrt{\tau R(\mathrm{km})}\, L^{1.75} \left[(L_s/L)^{1.5} - 1 \right]^{0.5} \mathrm{km/sec} \qquad (6)$$

where τ is the perpendicular optical depth of the spokes, R the radius of the plasma cloud in km, L = distance from the centre of Saturn (in R_s) and L_s is the corotation radius (in R_s). Note that the mean size of the particle population making up the spoke does not enter in (6). Speeds in excess of ~ 20 km/sec (using e.g. $\tau = 0.1$, $R = 50$ km) can explain the observed rapid formation of spokes.

The plasma cloud model of Goertz and Morfill (1982) satisfies all the observational constraints known so far. The question remaining is, of course, what is the origin of the plasma cloud? One possibility could be impacts of large meteorites (in the metre size) onto even larger ring bodies. This would again favour the B-ring. Such impacts produce dense plasma clouds (several kg). Plasma cloud evolution has been studied in our own magnetosphere in connection with Barium releases (see e.g. Völk and Haerendel 1971, Scholer 1970). Estimated meteor impact rates are not inconsistent with the rate of spoke occurrence (Grün, priv. comm.), but the numbers here are very uncertain.

CONCLUSION

A brief review of current theories of the origin and evolution of planetary rings has been given. Quantitative estimates have been made for the particular case of Saturn's rings. These show that quite violent processes may be taking place as a result of interactions with interplanetary particulates, and that some of the results of these processes may have been observed. Clearly, a great deal more information is desirable to understand the dynamic evolution of ring systems. This is particularly important, since a number of astrophysical applications involve accretion disc phenomena (e.g. star and planet formation, binary X-ray sources etc.).

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DISCUSSION

McCREA: 1) Do you consider the ring particles to be mainly water-ice? 2) Do you associate ring formation with satellite formation?

MORFILL: 1) The existence of the neutral hydrogen atmosphere and cosmogonic considerations make it very likely that there is a large abundance of "ices", in particular water ice. 2) Yes, certainly formation of the inner satellites which orbit on near-circular orbits in the ring (or equatorial) plane. Rings are formed inside the Roche radius $r_{Roche} = 2.43R\,(\rho_P/\rho_R)^{1/3}$, where R is the planet radius, ρ_P the planet density and ρ_R the density of ring material, simply because they cannot evolve into satellites.