THE ORIGIN AND EVOLUTION OF PLANETARY RINGS

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Saturn's rings have often been regarded as the uncoagulated remnant of a circumplanetary disk from which the regular satellites formed. In 1847, Roche suggested that they may instead be the fragments of a disrupted satellite. More than a century later, this central issue of whether ring particles are primordial or evolved remains unresolved. In this chapter, I review a number of dynamical processes which act on a gas/solid disk in Keplerian motion: viscous spreading, gas drag, coagulation of particulates, and the effect of further infall of matter from heliocentric orbit onto the planet/disk. From these considerations, I conclude that the survival of a remnant ring is unlikely, and turn to the possibility that rings were created by the disruption of sizable satellites, which were less sensitive to the destructive processes present during planet formation. This hypothesis, while appearing at first more complex than the other one, seems upon closer examination to have fewer unresolved difficulties. It offers a natural explanation for the presence of shepherd satellites (i.e., large collision fragments) coexisting in the same orbital range as ring particles, where coagulation into satellites is apparently not possible. This feature of the hypothesis is particularly attractive with regard to the origin of the Uranian rings.

There is little disagreement that the planetary rings which we see today are basically products of the same formation process that gave rise to the regular satellite systems surrounding each of the ringed planets. The primary issue debated in theories of ring origin is whether they represent a failure of the innermost portion of a circumplanetary disk to accumulate into satellites, or whether they are the result of the disruption of preexisting satellites. The principal difficulty of the former scenario is the matter of survival of such small particles under the conditions of planetary formation. In order to avoid this same difficulty, the latter scenario must provide for a delay from the time of satellite (and planet) formation to the time of disruption of the satellite(s) under more quiescent conditions. Furthermore, a breakup scenario must provide for the radial migration of the satellite(s) from the site of origin to the site of breakup (since satellite formation appears to be impossible at the present ring locations), and for the subsequent grinding and spreading of fragments to the present size and orbital distributions. In spite of the apparently greater difficulties, I favor the breakup scenario, and will attempt to describe and defend one such model in the following sections.

In this chapter I take the Roche limit or Roche zone to mean that orbital range near the planet within which accumulation of a particulate disk into discrete bodies fails to occur on account of the planet's tide. (See the chapter by Weidenschilling et al. for a discussion of tides which can affect a particle's disruption and accretion.) I do not review in detail the broader topic of planet and satellite formation. Such a review is in preparation by Stevenson et al. (1984). Section I of this chapter is a brief overview of the aspects of planet formation that affect ring formation. In Sec. II I consider the various processes operating during planet formation that lead to rapid evolution of small ring particles. The severe constraints imposed by these processes lead me to favor a scenario in which the ring material is preserved in the form of satellites until after the process of planet formation is essentially complete. In Section III I outline such a formation model. In the final section, the interrelation of the various known ring systems, and the implications of my ring formation model for the larger question of planetary formation, are discussed.

I. THE FORMATION OF PLANETS AND SATELLITE SYSTEMS

Models of giant planet formation can be grouped in two categories. If the planets formed by large scale gravitational instabilities in the solar nebula (essentially Jeans instability with rotational energy included), then the entire mass of the planet would collapse into a giant gaseous protoplanet on a time scale on the order of the orbit period (Cameron 1978). Following a time of 10^5 to 10^7 yr, during which the mass would be in hydrostatic equilibrium but in a very distended state, hydrodynamic collapse due to the dissociation of hydrogen would occur in $\lesssim 1$ yr, resulting in a planet not much hotter and larger than at present (Bodenheimer et al. 1980). Pollack et al. (1976, 1977) have extrapolated the cooling histories of Jupiter and Saturn backward in time, assuming hydrostatic equilibrium. Figure 1 shows the time required for Saturn to cool enough to allow ices to condense at various orbital radii. From the later work of Bodenheimer et al. (1980), it appears that the hydrodynamic collapse model merges with the hydrostatic one at $\sim 10^5$ yr, hence that point on the timeline in Fig. 1 should be taken as zero and everything to the left disregarded. The important conclusion with regard to satellite and ring formation is that ices could not condense at the present ring radii for $\sim 10^6$ to 10^7 yr. Therefore the ring mass must have been stored as a gaseous ring for that long,

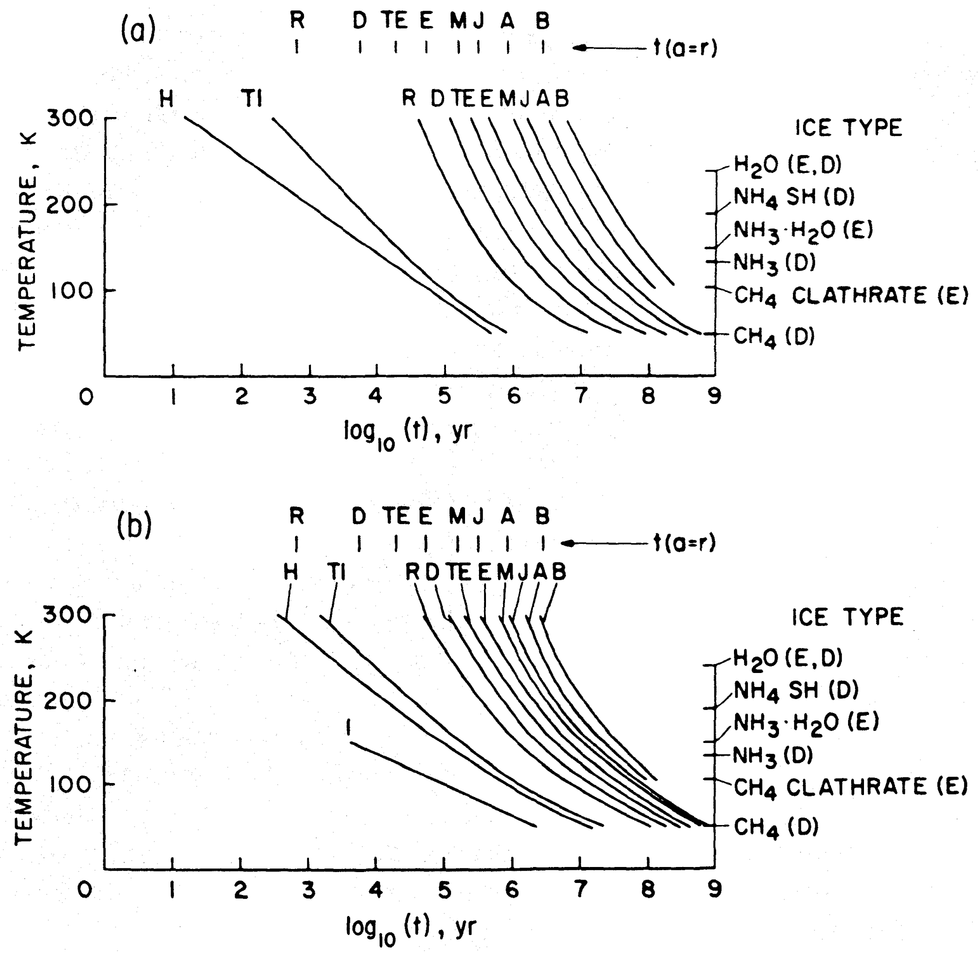

Fig. 1. The temperature within a circumplanetary disk about Saturn as the planet cooled and contracted. The two profiles represent assumed optically thin (a) and optically thick (b) disks. Each curve refers to a constant orbital distance and is identified by the initial of the satellite or ring currently occupying that orbital distance. (J for Janus may be regarded as the distance of the coorbital satellites.) The scales across the top identify the times at which the radius of Saturn equaled the orbital distances indicated. See Pollack et al. (1976) for further details. (Figure from Pollack et al. 1976.)

or else condensed at a larger radius and later transported into the present ring radius.

The second general class of models of giant planet formation require solid cores of 1 to 10 Earth masses which trigger gas accumulation about them (Safronov 1972; Harris 1978*a*; Mizuno et al. 1978; Mizuno 1980). The advantage of these models is that a less massive solar nebula is required, since gravitational instability of the gas phase is not required. On the other hand, nucleated gas accretion only occurs about fairly massive cores, which are likely to require ~10^5 to 10^6 yr to grow from the condensates of the cooling nebula. Even if a core of several Earth masses grew more rapidly, the gas envelope surrounding it would require $\sim 10^5$ yr to cool sufficiently for hydrodynamic collapse to occur (Harris 1978*a*). Following the initial hydrodynamic collapse, further gas accumulation would occur as rapidly as gas could be delivered to the accumulation zone. This time scale could be very short for a vigorously turbulent solar nebula; however, it is unlikely that it was $\lesssim 10^5$ yr, or the solar nebula would have been dissipated before the cores were formed. Unfortunately, thermal history calculations analogous to those discussed above have not been done for a nucleated growth model of planet formation, so it is not clear whether ice could condense about such a protoplanet while it was still growing. Based upon the hydrostatic models (Fig. 1), one might guess that if the time scale of gas accumulation were $\lesssim 10^6$ yr, the protoplanet would be too hot to allow condensed ice to exist as close to Saturn as the present rings, and the ring material would have had to be preserved as a gaseous disk for $\sim 10^6$ yr after formation, or else be transported in from a greater radius after that period of time, as in the previous model. On the other hand, if gas accumulation took $\gtrsim 10^6$ yr, ice may have been stable at the ring radius during the time of planet growth, and the storage problem would not exist.

In summary, it appears that the time scale of planet formation and/or ice condensation is probably $\gtrsim 10^5$ yr, so that one should be concerned about dynamical processes within a gas/solid protoplanetary disk which tend to disrupt it more rapidly than that. Furthermore, it is not clear whether or not the planets were still accumulating matter during the course of satellite/ring formation, so the effect of continuing mass infall onto the disk should be considered.

In order to illustrate (in Sec. II) the possible importance of various dynamical processes present in a gas/solid protosatellite disk, I shall make use of the numerical values given in Table I. For each planet with a known ring, a minimum mass disk is estimated at several orbital radii. The surface density of solids is estimated by smearing out the present ring/satellite masses over the disk area available. The temperature is taken to be the condensation temperature for the dominant solid species present. (Ice is assumed for Uranus since the lower temperature results in more conservative estimates of the importance of the various processes.) The equivalent thickness of the gas disk is (see Safronov 1972, p. 25) $h \approx 1.5\, v_T/\Omega$, where $v_T \approx 10^{-4}\, T^{\frac{1}{2}}$ cm s^{-1} is the thermal velocity of the gas molecules and Ω is the orbit frequency. The gas density is obtained by first estimating the mass of gas of the planet's composition necessary to yield the observed mass of solids in the disk. Others (e.g., Weidenschilling 1982) have assumed reconstitution to solar composition, which implies a more massive protosatellite disk. The assumed reconstitution factors, σ_g/σ_s, are tabulated. The solid surface density is mutiplied by this factor and divided by h to obtain the midplane gas density.

In evaluating the results based on this table, it must be remembered that if satellite formation is an inefficient process, then the disk masses may have

TABLE I

Models of Primitive Circumplanetary Disks

Planet Zone	Type of Solids	Temper-ature (K)	Orbit Radius (10^{10}cm)	Mass of Solids (g)	Surface Density of Solids, σ_s (g cm^{-2})	Equivalent Thickness of Gas Disk (10^{10}cm)	Gas/Solid Ratio, σ_g/σ_s	Mid-planet Gas Density (g cm^{-3})
Jupiter								
rings-V	rock	1000	1.8	10^{22}	10	0.3	100	3×10^{-5}
I-II	rock	1000	7	10^{26}	10^{4}	1.5	100	7×10^{-5}
III-IV	ice	250	20	3×10^{26}	3×10^{3}	3	25	3×10^{-6}
Saturn								
rings	ice	250	1.5	10^{24}	10^{3}	0.1	20	2×10^{-5}
I-V	ice	250	5	5×10^{24}	10^{3}	0.6	20	3×10^{-6}
Titan	(methane)	100	12	1.4×10^{26}	3×10^{3}	3	5	5×10^{-7}
Uranus								
rings	(ice)	250	0.5	10^{19}	10^{-1}	0.1	3	3×10^{-10}
I-IV	(ice)	250	6	3×10^{24}	3×10^{2}	1.5	3	7×10^{-8}

been much greater. On the other hand, if satellite formation was concurrent with slow growth of the planets, then the instantaneous mass of the disk may have been much less. Thus Table I represents a middle-of-the-road model of circumplanetary disks. Also, the low densities in the Jupiter and Uranus ring zones may well be due to loss of solid matter from those zones. If this is the case, then the surface densities of the inner satellite regions may be more representative of the original ring zone densities than those inferred from the amount of solid material presently there.

II. DYNAMICAL EVOLUTION OF A PROTOSATELLITE DISK

There are several dynamical processes which act to dissipate a solid/gas disk about a planet. Most of the same processes would occur in the solar nebula as well, but because of the smaller length scale, generally higher surface density, and shorter orbit period of a circumplanetary disk, the corresponding time scales are very much shorter than for the solar nebula.

A protosatellite disk is subject to viscous shear, just as are the present planetary rings (e.g., see chapter by Stewart et al.). If the gas phase of the ring were not turbulent, then the time scale of viscous spreading would be very long ($\sim 10^9$ yr). However, since even a minimum mass circumplanetary disk, with a surface density $\gtrsim 10^4$ g cm^{-2} (cf. Table 1) would be optically thick, it is likely that the disk would be convectively unstable and hence turbulent (e.g., Lin and Papaloizou 1980). The time scale for an element of gas to migrate a distance of the order of its orbit radius by viscous shear is

$$t \sim \frac{a^2}{\nu_e}\,. \tag{1}$$

The effective viscosity is $\nu_e \sim \Delta \mathrm{v}\delta/\mathrm{Re}$, where Re is the effective Reynolds number. The turbulence velocity $\Delta\mathrm{v}$ is on the order of the product of the eddy scale δ times the radial gradient of the orbital velocity. For Keplerian motion, this is just half of the orbit frequency Ω, so $\nu_e \sim \frac{1}{2}\,\Omega\delta^2/\mathrm{Re}$. If the turbulence is driven by thermal convection in the vertical direction, then δ will be on the order of the vertical scale height: $\delta \sim h \approx \mathrm{v}_T/\Omega$. The effective Reynolds number is expected to be $\sim 10^3$ (e.g., Goldreich and Ward 1973; Lin and Papaloizou 1980). Thus, combining all these dimensional estimates, the time scale in years of viscous spreading of a turbulent disk becomes:

$$t \sim \mathrm{Re}\,\frac{\Omega a^2}{\mathrm{v}_T^2} \sim 10^5 \left(\frac{m_p}{m_\odot}\;\frac{a}{a_\oplus}\right)^{\frac{1}{2}} \left(\frac{100\ \mathrm{K}}{T}\right) \tag{2}$$

where $m_p/m_\odot$ is the mass of the central body in solar units, $a/a_\oplus$ is the orbit radius in AU, and T is the temperature of the gas disk. The dissipation time for the solar nebula itself is thus on the order of 10^5 yr; for a circumplanetary disk about Jupiter or Saturn, t ~ 100 yr. One consequence of this difference in time scales is that, if the giant planets grew by nucleated instability (see e.g., Mizuno 1980), then mass infall onto a circumplanetary accretion disk would occur on a time scale of $\sim 10^5$ yr, whereas viscous dissipation of the disk would occur on a scale of $\sim 10^2$ yr. Thus it is questionable whether a protoplanetary accretion disk could exist as a steady state feature under these circumstances. Regardless of the mode of formation of the giant planets, the above time scale of dissipation imposes a serious constraint on models of condensation and growth of satellites from a circumplanetary disk. It has been argued (see e.g., Coradini et al. 1981) that a circumplanetary disk would not be turbulent and hence the diffusion time scale would be very long. I consider the arguments either for or against turbulence to be poorly developed at present; and the time scale of dissipation of the gaseous disk remains an important problem.

Another dissipation process that occurs as solids condense from the gaseous disk is aerodynamic drag (see e.g., Whipple 1964; Goldreich and Ward 1973; Weidenschilling 1977). If a radial pressure gradient exists in the gaseous disk, then the balance between gravitational and centrifugal forces will be altered by an additional gas pressure term, resulting in a slightly different circular orbit velocity for the gas than for solids at the same orbital radius. If the gas pressure gradient is of the order of the pressure divided by the orbit radius, then the difference between the Keplerian orbit velocity and the gas orbit velocity is (see e.g. Goldreich and Ward 1973):

$$\mathrm{v}_w \sim \frac{1}{6}\,\frac{\mathrm{v}_T^2}{\Omega\, a}\,. \tag{3}$$

For a typical circumplanetary disk at the temperature of ice condensation, $\mathrm{v}_w \sim 30$ m s^{-1}. Small particles ($\lesssim$ meter sized) would be carried along with the gas and would experience relatively little radial drift before settling to the midplane (Weidenschilling 1982). If the particulate disk is optically thick (i.e., like the present rings of Saturn), the gas drag is probably best estimated as a shear stress on the surfaces of the disk (see e.g. Goldreich and Ward 1973). The stress per unit area of the disk (both sides) is:

$$S \sim 2\rho_g \mathrm{v}_w^2/\mathrm{Re} \tag{4}$$

where ρ_g is the gas density and Re is the Reynolds number. For laminar flow, the Reynolds number would be $\gtrsim 10^5$; hence it is likely that the shear zone will be turbulent, with an effective Reynolds number Re $\sim 10^3$. The torque per unit area on the disk is $S\,a$. This can be equated to the rate of change of orbital angular momentum as follows:

$$\frac{2\rho_g v_w^2 a}{\mathrm{Re}} = \frac{\sigma_s}{2} \Omega a \dot{a} \tag{5}$$

where σ_s is the surface density of the particulate disk. The gas density can be expressed in terms of the gas surface density σ_g, divided by the equivalent thickness of the gas disk $h \approx 1.5\, v_T/\Omega$ (Safronov 1972, p. 25):

$$\rho_g \approx \frac{2}{3} \frac{\sigma_g \Omega}{v_T} . \tag{6}$$

By substituting this expression, along with the expression for wind speed Eq. (3), into Eq. (5), the time scale $t \sim a/\dot{a}$ for drag decay of the solid ring can be written in a simple form:

$$\begin{aligned} t &\sim \frac{27}{2} \mathrm{Re} \frac{\sigma_s}{\sigma_g} \frac{G m_p}{v_T^3} \\ t &\approx 6 \times 10^4\ \mathrm{yr}\ (\mathrm{Re}) \left(\frac{\sigma_s}{\sigma_g}\right) \left(\frac{m_p}{m_\odot}\right) \left(\frac{100°\mathrm{K}}{T}\right)^{\frac{3}{2}} . \end{aligned} \tag{7}$$

Note that t is not dependent on the actual mass of the disk, nor on its radial extent, but only on the mass ratio of solids to gas. For an effective Reynolds number $\sim 10^3$, the decay time for silicate condensates ($T \sim 10^3$ K, $\sigma_s/\sigma_g \sim 10^{-2}$) is $\sim 10^4$ yr for the solar nebula or ~ 10 yr for a circumplanetary nebula about Jupiter or Saturn. For ices ($T \sim 250$ K, $\sigma_s/\sigma_g \sim 10^{-1}$), the lifetimes are $\sim 10^6$ yr or $\sim 10^3$ yr for solar or planetary nebulae, respectively.

For larger solid aggregates, the disk approximation above may not be appropriate. Rather, one should consider drag about individual bodies. For a circumplanetary nebula, the Reynolds number for a sphere $\gtrsim 1$ m moving at a velocity v_v, given by Eq. (3) through even a thin gas nebula ($\rho_g \sim 10^{-5}$ g cm^{-3}) would be $\gtrsim 1000$, hence the appropriate drag law is (cf. Weidenschilling 1977):

$$F_D \approx 0.7 r^2 \rho_g v_w^2 . \tag{8}$$

The time scale of orbital decay from aerodynamical drag on an isolated sphere of density ρ_s and radius r is thus:

$$t \sim 100 \frac{\rho_s}{\rho_g} \frac{\Omega^3 a^3}{v_T^4} r . \tag{9}$$

For the minimum mass circumplanetary disk about Saturn, the time scale of aerodynamic decay is ~ 200 (r km^{-1}) yr in all zones. For Jupiter, the time scale is also $\sim$200 (r km^{-1}) yr in the ring/Amalthea and Ganymede/Callisto zones, but only $\sim$5 (r km^{-1}) yr in the Io/Europa zone. Weidenschilling (1982) derives considerably shorter time scales because he assumes a higher gas density and a steeper pressure gradient. For Uranus, t $\sim$600 (r km^{-1}) yr in the satellite zone, or $\sim 2 \times 10^6$ (r km^{-1}) yr in the ring zone. The large value in the ring zone is due to the low mass of the present ring system. If the same density is assumed as is present in the satellite zone, then the time scale of decay in the ring zone would be $\sim 10^4$ (r km^{-1}) yr.

If the planet is experiencing infall of matter from the solar nebula, then as a result both the gas and solid components of a circumplanetary disk will experience drag (Harris 1978*b*). The infalling matter is expected to arrive with very little angular momentum with respect to the planet, otherwise the accumulation of such matter would greatly overspin the planet (see e.g., Harris 1977). This being the case, the matter that falls onto the disk will cause it to decay into the planet as it gains mass. The same will be true of satellites in orbit about the planets, even if they do not retain the gas component of the influx of heliocentric matter. Harris (1978*b*) derived the rate of inward spiraling of a satellite, for the case of matter arriving with no preferred angular momentum with respect to the planet, and infalling from the solar nebula with originally negligible velocity relative to the planet. Since the velocity of the infalling matter exceeds that of the satellite (escape velocity versus orbit velocity), Epstein drag was assumed. This assumption is perhaps not perfect for gas infall, but should yield a dimensionally valid estimate. The rate of inward spiraling is

$$\frac{\mathrm{d}a}{a} \approx -3\frac{\rho_p}{\rho_s}\,\frac{r_p^2}{r_s\,a}\,\frac{\mathrm{d}m_p}{m_p} \tag{10}$$

where ρ, r, and m are the density, radius, and mass of the planet (subscript p) or satellite (subscript s). The flux of mass on the satellite is

$$\frac{\mathrm{d}m_s}{m_s} \approx -\frac{2}{5}\,\frac{\mathrm{d}a}{a} \tag{11}$$

hence even if the mass sticks, the infall of the satellite is rapid compared to its growth. Figure 2 is a plot of the evolution of the Saturnian satellites as a function of mass gain of the planet. Since satellites could not survive evolution across neighboring orbits, it can be inferred that the present satellites, particularly the small ones, were formed very near the end of the growth of the planet, if not after the growth was completed.

A similar pair of equations can be derived for the rate of mass gain and orbital evolution of an optically thick ring (subscript r) subject to mass infall (Harris 1978*b*):

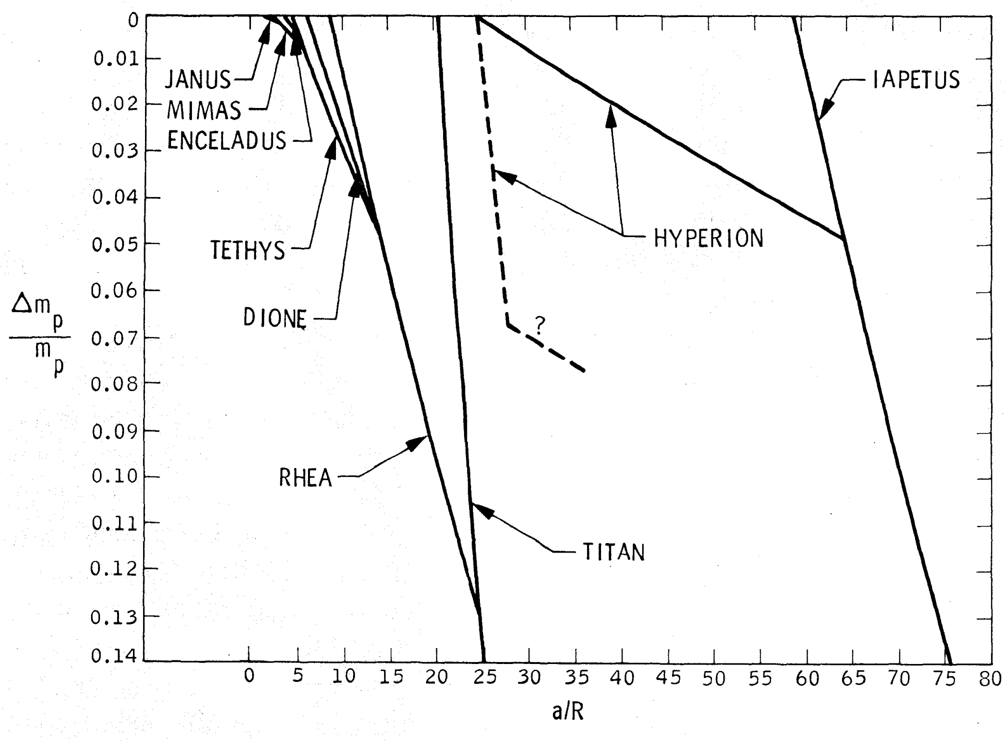

Fig. 2. Evolutionary tracks of the satellites of Saturn due to the growth of the planet. $\Delta m_p/m_p$ is the mass remaining to be accumulated and a/R is the orbit radius in current Saturn radii. The end points of the tracks ($\Delta m_p/m_p = 0$) are at the present orbital radii. (The track labeled Janus may be regarded as that of the coorbital satellites.) Hyperion may have been carried along with Titan for some time after the establishment of the present resonance (dashed line). (Figure from Harris 1978*b*.)

$$\frac{\mathrm{d}m_r}{\mathrm{d}m_p} \approx 1 \tag{12}$$

$$\frac{\mathrm{d}a}{a} \approx 2\,\frac{\mathrm{d}m_r}{m_r} \approx 2\,\frac{\mathrm{d}m_p}{m_r}\,. \tag{13}$$

If such a ring existed throughout the growth of the planet, then approximately half of the total planet's mass would have arrived via ring infall. This mass would have arrived with orbital angular momentum, which would greatly overspin the planet. Thus the scenario of a growing planet continuously surrounded by an optically thick ring is contradictory to the observed spins of the planets. From Eq. (13), it is clear that disks of the mass of those outlined in Table I would be extremely sensitive to decay by infall of heliocentric matter. Even the "reconstituted" masses of the disks are $\sim 10^{-3}$ of the planet masses, hence such disks would not survive even the last 1% of growth of their respective planets.

TABLE II

Coagulation Time Scales in Model Circumplanetary Disks

Planet/Zone	Time scale (yr) (r_s km^{-1})
Jupiter	
Rings/V	3
I-II	0.05
III-IV	0.3
Saturn	
Rings	0.02
I-V	0.2
Titan	0.3
Uranus	
Rings	100
I-IV	2

One last time scale which should be compared with the above ones is that of coagulation of the solid particles through mutual collisions. The time scale of growth, assuming all particles stick on contact, is (Safronov 1972, ch. 9):

$$t \sim \frac{m_s}{\dot{m}_s} \sim \frac{2\rho_s r_s}{\sigma_s \Omega} \; . \tag{14}$$

The coagulation time scales in the various zones of the disk models of Table I are given in Table II. In general, these time scales are very much shorter than any of the preceding ones, hence one should expect the particulates in a circumplanetary disk to coagulate into $\gtrsim$100 km bodies before any of the other processes are effective.

The various time scales discussed above are summarized in Table III. If the disk is turbulent, coagulation may be stalled, but viscous spreading will dissipate both the gas and the solids rapidly. Even if the gas is quiescent, aerodynamic drag would quickly remove a particulate disk from inside the Roche limit, while small particles outside the Roche limit would probably coagulate into satellites on an even shorter time scale. Thus it seems unlikely that solid particles as small as those of the present Saturnian or Uranian rings could have survived either within or outside the Roche zone for as long as $\sim 10^5$ yr, as required by the arguments in Section I. For this reason I favor a model of ring origin in which the ring mass is preserved in the form of satellites until after planet growth is complete and any gaseous disk has been dissipated. In Sec. III, this scenario is outlined.

TABLE III

Summary of Dynamical Time Scales in a Gas/Solid Circumplanetary Disk

Process	Time Scale (yr)
Viscous spreading (gas)	$\gtrsim 100$
Gas drag on particulate disk	10-1000
Gas drag on satellites	$\sim 200\ (r_s\ \mathrm{km}^{-1})$
Infall of circumsolar matter on disk	$\gtrsim 10^{-3}$ (planet growth time)
Infall of circumsolar matter on satellites	$\gtrsim r_s/r_p$ (planet growth time)
Coagulation/fragmentation	$\sim 0.1\ (r_s\ \mathrm{km}^{-1})$

III. A SATELLITE BREAKUP MODEL OF RING FORMATION

The primary motivation for this scenario of ring formation is to avoid the difficulty presented by the very short orbital decay times of small particles during planet/satellite formation. Since the time scale of coagulation of particles outside the Roche limit is shorter than their orbital decay times, it is unlikely that rings were formed farther out and then evolved inward without first coagulating into satellites. Therefore, I suggest that satellites formed rapidly, or were captured, into orbits about the giant planets, and then spiraled inward due to the processes discussed in the previous section. When planet growth was completed, and/or any circumplanetary gas was dissipated, the inward migration ceased, leaving the presently observed satellite systems, plus additional small satellites in the regions presently occupied by rings. Such satellites would not necessarily be tidally disrupted (see e.g., Jeffreys 1947; Aggarwal and Oberbeck 1974), but may have persisted intact for some time, much as is the case for Phobos today (Dobrovolskis 1982). However, if subsequently disrupted by large meteoritic collisions, these satellites would be unable to reaccumulate into satellites, due to the planetary tides, and could instead evolve collisionally into the presently observed ring systems.

The first critical test of this hypothesis is whether the rate of infall of satellites into the planet poses an inconsistency. If the planets formed by hydrodynamic collapse, then circumplanetary gas disks must have persisted for $\sim 10^6$ yr in order to deliver satellites into the Roche zone after the planet had cooled enough to allow them to survive there. The persistence of a gas disk for so long itself poses difficulties due to the level of turbulence likely to have been present (cf., Table I). Ignoring this difficulty for the moment, the relevant time scale of decay is that of grown satellites in response to gas drag. Note that this time scale is $\sim 10^4$ yr for Saturn's ring parent body at its present radius. Thus, in the course of $\sim 10^6$ yr ~ 100 such bodies (comparable in size to a typical inner satellite) should have been lost in order to assure that a ring parent body would have a high likelihood of being left behind in the Roche zone. This is $\sim 10^{26}$ to 10^{27} g, not an impossible amount of solid mass to have been lost into Saturn.

The alternate hypothesis, that satellites were both created and driven inward by the infall of matter from heliocentric orbit during the course of slow planet growth, also leads to plausible limits (cf. Fig. 2 and Eq. 10), of several times the present masses of the satellite systems. Thus either mode of planet/satellite formation might lead to one or more satellites being left within the Roche limit of a planet after the conclusion of planet/satellite formation.

The next step in the scenario, collisional disruption, was probably accomplished by the same meteoritic bombardment which left a record of large craters on some of the older surfaces of Callisto and most of the Saturnian satellites. By extrapolating the crater density on Iapetus to the innermost satellites and rings of Saturn, Smith et al. (1982) estimate that these bodies have experienced enough collisions to have disrupted them several times over. Indeed, if a problem exists at all, it is one of an embarrassment of riches: it might be difficult for a satellite, once inside the Roche limit, to avoid disruption for the requisite time until formation processes have ceased.

Once a single ring parent body has been disrupted, further disruptions will occur as a result of mutual collisions between large fragments. The time scale of this process is given by Eq. (14), where r_s should be taken to be on the order of that of the parent body ($\sim$200 km for Saturn or $\sim$10 km for Jupiter and Uranus), and σ_s the value for the respective ring zones from Table I. The time scales are $\sim$ 30 yr, 4 yr, and 1000 yr, respectively, for Jupiter, Saturn, and Uranus. This process is limited in that as the fragments become smaller, the collisions become more gentle and less effective in causing further fragmentation. Since the impact velocity between two particles is at least on the order of the surface escape velocity of the larger fragment, the kinetic energy of such an impact can be equated with the limiting energy for fragmentation (Harris 1975; Greenberg et al. 1977) to define the size to which the largest fragments will be reduced:

$$r \sim \left(\frac{3E_c}{4\pi G}\right)^{\frac{1}{2}} \approx 20 \left(\frac{E_c}{\rho_s}\right)^{\frac{1}{2}} \quad \text{meters} \qquad (15)$$

where E_c is the critical specific energy for fragmentation in ergs g^{-1}. Greenberg et al. (1977, 1978) suggest values for E_c of $\sim 10^7$ and 2×10^5 for solid rock and ice, respectively, but also suggest that values as low as $\sim 10^5$ to 10^6 may be appropriate for hydrated mineral assemblages that may have been prevalent in the outer solar system during formation (i.e., Uranian ring material). For these values of E_c, rapid collisional fragmentation should cease in an ice ring when the largest fragments are $\sim$5 km in radius, and for a rocky ring, fragments should be no larger than $\sim$40 km, but probably much smaller, perhaps $\lesssim$ 10 km.

Following the rapid reduction of the rings to particles no larger than $\sim$10 km, the gentle bumping of particles should continue to result in slow erosion, much as rocks in a stream bed are slowly eroded by frequent collisions which are individually much too gentle to cause large scale fracturing. Borderies et al. (see their chapter) estimate that the time scale of this erosion is $\sim 10^5/\tau$ yr, where τ is the normal optical thickness of the ring. Weidenschilling et al. (see their chapter) argue that as particles develop a regolith erosion will not occur in the usual sense; however, they agree that mass exchange between ring bodies will occur on a time scale very short compared to the age of the solar system, so that in any case the particle size distribution should be highly evolved to an equilibrium state.

What is the equilibrium particle size, and why haven't they ground themselves to dust? Weidenschilling et al. (see their chapter) suggest that ring particles may in fact be gravitationally bound aggregates, which grow as large as they can before tidal stress disrupts them. I would suggest instead the following hypothesis. Aggregation is only favored as long as the collision velocity is less than the surface escape velocity of the particles, which in turn is the case if $\tau \gtrsim 1$ (Goldreich and Tremaine 1978). As particles aggregate, τ becomes less and the dispersion velocity increases, which hinders further aggregation. Thus the equilibrium that may be established is not a specific particle size, but rather whatever size results in $\tau \sim 1$. A tantalizing observational fact favoring this hypothesis is that both the Saturnian and Uranian rings have $\tau \sim 1$, in spite of the apparent difference of 2 to 3 orders of magnitude in ring particle size (cf. chapters by Elliot and Nicholson and by Cuzzi et al.). Furthermore, one would expect a tendency at increasing ring radii toward lower τ and larger particles, until finally aggregation wins even at zero optical depth and accumulation into satellites becomes possible.

In order for the above hypothesis to be tenable, ring particles must somehow evolve in size, by erosion and/or reannealing of dust onto larger particles, to achieve the above defined equilibrium, and eventually achieve the high degree of elasticity required by the dynamical constraints (see e.g., Goldreich and Tremaine 1978). The latter requirement is a difficulty for both this model and that of Weidenschilling et al.

Returning to the problem of the early evolution of collision fragments, a disrupted satellite should be reduced, on a time scale of a few years or less, to a swarm of debris in which the largest few fragments are ~ 10 km in diameter, but much of the mass is contained in much smaller fragments typical of comminution outcomes (see e.g., Dohnanyi 1969; Fujiwara et al. 1977). Subsequent erosion should occur on a much longer time scale, $\sim 10^5$ yr. Before this could happen, the narrow ring of fragments would be altered by viscous spreading, and possibly also by tidal truncation of the fluid ring by the largest fragments. Consider first viscous spreading. After a time t a narrow ring should diffuse to a width Δa (e.g., see chapter by Borderies et al.):

$$\Delta a \sim \left(\nu t\right)^{\frac{1}{2}} \gtrsim \left[\tfrac{1}{2}\, \Omega t \left(\frac{\tau}{1+\tau^2} \right) \right]^{\frac{1}{2}} r_s \tag{16}$$

where the viscosity $\nu \approx 0.5\, v^2 \tau / \Omega(1+\tau^2)$ and the random velocity is at least that due to Keplerian shear for a body of radius r_s, $v \gtrsim \Omega r_s$. In the few years required for rapid fragmentation, the debris ring should spread to only ~ 100 times the size of the characteristic particle size, r_s. However, on the time scale of further erosion, $\sim 10^5$ yr, spreading should occur to $\sim 10^4$ times the width of the characteristic particle size. Thus if $\sim 10^5$ yr is really the appropriate time scale for reduction of the largest particles in Saturn's ring from ~ 10 km to the present size, then spreading to the present radial extent may have occurred in the same amount of time. In any case, radial spreading to the current width from an initially narrow debris ring would appear to be an expected outcome, even for the very low interparticle collision velocities in the present ring.

If the dispersion velocity were to become low enough while some large fragments remained, then those fragments might clear gaps in the rings. If this were to occur, then the large fragments would not suffer continued erosion from mutual collisions and might persist for a much longer time. The condition for tidal truncation is that the torque transferred to the disk by the large fragment (satellite) must exceed that of viscous spreading, out to a distance from the satellite at least as great as the distance to the Lagrange points L_1 or L_2 (see e.g. Lin and Papaloizou 1979):

$$\frac{8}{27} \frac{G^2 m_s^2 a\, \sigma_s}{x^3} \gtrsim \pi a^2 \sigma_s v^2 \frac{\tau}{1+\tau^2} \tag{17}$$

where $x = (m_s/3m_p)^{\frac{1}{3}} a$ is the minimum half-width of the gap (distance to the Lagrange points) for truncation to occur. Equation (17) can be rearranged to define the minimum particle size for which truncation occurs:

$$\frac{m_s}{m_p} \gtrsim \frac{9}{8} \pi \left(\frac{v}{\Omega a} \right)^2 \frac{\tau}{1+\tau^2} . \tag{18}$$

For the present rings of Saturn, $v \sim 1$ cm s^{-1}, hence $m_s/m_p \sim 10^{-12}$, corresponding to a minimum diameter of an icy satellite of ~ 10 km. Thus if an initially narrow debris ring spreads radially, so that the dispersion velocity can fall below ~ 1 to 10 cm s^{-1} more rapidly than erosion reduces the largest fragments below ~ 10 km in diameter, then those fragments may open gaps in the ring. In an extreme case of many large fragments, clear gaps may be the dominant feature of the ring system, as in Uranian-type rings.

One final process which continues to reduce shepherd satellites even after gaps have been cleared is meteoritic bombardment. If the meteoritic bombardment of the ring zone was sufficient to cause the disruption of a ring parent body, then it probably was great enough to cause further disruptions of the largest fragments. Consider a power-law number density of bombarding particles $N(>m_1) \propto m_1^{1-q}$. The power-law index q is expected to lie in the range 1.5 to 2.0 (Dohnanyi 1969; Fujiwara et al. 1977; Shoemaker and Wolfe 1982). The total number striking a satellite is proportional to the cross-sectional area, r_s^2. The probability of disruption of a satellite is thus

$$P \propto r_s^2 N\,(>m_1) \propto \left(\frac{m_1}{m_s}\right)^{1-q} r_s^{5-3q}\,, \tag{19}$$

where m_1/m_s is the projectile/target mass ratio required to disrupt a body of mass m_s and radius r_s. If the collision strength E_c is constant with respect to size, then m_1/m_s is constant. However, E_c may decrease with increasing size due to greater material imperfections contained in larger bodies, but eventually will increase again due to gravitational compression. Neglecting for a moment these uncertainties, note that for $q < 5/3$, the probability of disruption (i.e., the collision lifetime) actually increases with decreasing size. Even for $q = 2$, it is proportional to r_s^{-1}, and this proportionality may be largely canceled by E_c increasing with decreasing size. Hence the collision lifetime does not become drastically less with decreasing particle size. Indeed, since a single large particle is reduced into many smaller particles ($n \propto r^{-3}$), then the probability that at least one collision fragment larger than r will survive further disruption becomes proportional to $r^{5-3q}\,\ell n\,(r_s/r)$. Thus it appears that even if the total meteoritic bombardment was considerably greater than that required to disrupt the original parent body, some large fragments may have survived the bombardment subsequent to the disruption event.

IV. CONCLUSION

During the growth and/or cooling of the giant planets, the dynamical processes which would be expected in a gas/solid circumplanetary disk would remove small particles very efficiently. I therefore conclude that the planetary rings that we see today are the remnants of preexisting satellites, which evolved inward from their sites of origin but were spared infall onto the planet by the conclusion of planetary formation. The tidal forces of the respective planets were too weak to disrupt the already formed bodies, but following a meteoritic disruption of such satellites the planet tides were sufficient to prevent reaccumulation. The subsequent competing processes of viscous spreading, disk truncation by large fragments, erosional griding among colliding particles, and perhaps further catastrophic breakups of shepherd satellites, have led to different configurations in each of the presently known ring systems.

Jupiter's ring is perhaps a case of shepherds without sheep. The presently visible ring particles must be very short-lived, and are undoubtedly replenished by meteoritic erosion of the two satellites orbiting within the ring. Burns et al. (see their chapter; also 1980) suggest that there may be many more smaller satellites which are collisionally isolated from each other, and which provide an even larger collective surface area as a source of erosion of the visible particles. These satellites may be the remnants of the breakup of a single parent satellite. The smaller collisional debris, the sheep, may have been lost through a combination of further meteoritic erosion and Poynting-Robertson drag on the small particles (see Mignard's chapter). If tidal truncation within such a ring occurred, then the inner or imbedded shepherds may have been carried in with the ring debris. Some of the larger fragments which were not quite large enough to truncate the disk would be partially carried along by viscous spreading and/or Poynting-Robertson drag, and thus may have become collisionally isolated from one another, as are the two known satellites in the ring.

Saturn's rings appear to be a case of the opposite extreme: essentially all the mass has been reduced to fragments below the size limit for tidal truncation, so that the ring system is mainly broad, with only a few narrow gaps and confined ringlets caused by imbedded satellites large enough to truncate the disk. The weaker strength of ice in comparison to most rocky materials, with the result that the first generation of fragmentation would end with smaller largest bodies (cf. Eq. 15), may account for the difference in outcomes between Saturn's rings and the others. Also, the greater mass leads to higher viscous torques, so that the satellite mass required to truncate the disk is greater. Finally, the meteoritic erosion flux at Saturn may have disrupted most of the shepherds, even if they once existed.

The Uranian rings can be explained as a system dominated by shepherds (see chapters by Demott and by Elliot and Nicholson). The population of smaller fragments (primarily the ϵ Ring) appears to be overwhelmingly truncated by interstitial satellites, to the extent that the gaps are much wider than the ringlets. The persistence of this configuration may indicate that there has not been much further meteoritic activity following the disruption of the parent body of the rings. The above brief scenarios of origin of each known ring system are not intended to be definitive or unique, but only to indicate that the variety of known ring systems can be plausibly accommodated by differences in parent body mass, composition, and the environment of the various planets in question.

Ever since Saturn was discovered to be encircled by a ring, such structures have been regarded as a key to understanding the formation of the planets and their satellite systems. They have definitely earned this status in the sense that ring systems have motivated critical thinking on dynamical processes relevant to planetary origin: the tendency for an orbiting, collisionally interacting system to flatten into a disk, to spread by viscous shear, and perhaps to be truncated by large imbedded bodies. The dynamical processes of coagulation and fragmentation, density wave generation and propagation, and gravitational instability all have received much study because of their relevance to planetary rings, and all this work has contributed to a greater understanding of the processes of planetary formation.

However, in another sense, planetary rings have failed to provide a key to planetary formation. As I have argued in this chapter, it is unlikely that the present rings are remnants of primordial accretion disks about planets; rather, they are highly evolved structures and their presence cannot be regarded as unambiguous evidence for one mode of planet formation or another. Ring formation appears to be a subsidiary event to satellite formation. Thus, an important constraint on planetary origin is the nature of the various satellite systems of the planets, rather than just the rings that also happen to be present in some cases.

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