Evolution of Planetary Ringmoon Systems

Jeffrey N. Cuzzi
Space Science Division, Ames Research Center, NASA
Moffett Field, California 94035 USA

January 20, 1995

Abstract. The last few decades have seen an avalanche of observations of planetary ring systems, both from spacecraft and from Earth. Meanwhile, we have seen steady progress in our understanding of these systems as our intuition (and our computers) catch up with the myriad ways in which gravity, fluid and statistical mechanics, and electromagnetism can combine to shape the distribution of the submicron-to-several-meter size particles which comprise ring systems [1-5]. The now-complete reconnaissance of the gas giant planets by spacecraft has revealed that ring systems are invariably found in association with families of regular satellites, and there is an emerging perspective that they are not only physically but causally linked. There is also mounting evidence that many features or aspects of all planetary ring systems, if not the ring systems themselves, are considerably younger than the solar system.

Key words: Planetary Rings, Outer Planets, Origin and Evolution

1. Origin and Evolution

The fundamental goals of ring studies are to understand the origin of ring systems, and to use them as dynamical analogs of astrophysical particle disks in general. The origin of rings has challenged theorists for two centuries; in essence, explanations all relate to the effects of planetary tidal forces. However, consensus has shifted repeatedly over the years between the idea that rings come from moons which were torn asunder by the planet's gravity or by impact (dating from Roche), and the idea that rings are primordial remnants unable to accrete within the zone where tidal forces overwhelm the self gravity of growing satellites [6]. Current understanding favors the "destruction" model in which rings are derivative. In either case, to understand ring origin we must peer back through the evolutionary processes that have acted on the rings and their associated ringmoons to bring them to their current state. We seek evidence of the nature of these processes in the current structure of the rings. A basic property of rings is their "optical depth" τ, which measures the extinction of radiation by material in the rings (see [1-5]). Large optical depths may be regarded either as the approximate number of times a photon would encounter a particle while passing normally through the ring; small optical depths approximte the fractional area filled by particles, or the probability a photon would encounter a particle.

Earth, Moon, and Planets **67**: 179–208, 1995.

2. Important processes

Of course, rings are merely an ensemble of individual objects in orbit about their parent planet. Acting on this ensemble are the handful of processes which, in our current understanding, have the major influence on ring structure.

2.1. VISCOSITY

Collisions between ring particles occur on time scales from small fractions of an orbit to many years, depending on the local optical depth of the rings. The orbiting particles attain random *relative* velocities due to a combination of physical collisions with their (differentially orbiting) neighbors and gravitational scatterings by the largest members. These random velocities act in a statistical mechanical sense to provide a viscosity ν; in fact, much of ring structure has been studied in terms of the behavior of a viscous fluid. In principle, reliable estimates of ring viscosity could constrain the physical nature of individual particles (compact ice balls or fluffy, easily fragmented temporary agglomerations of debris) and the variation throughout the rings of the balance between forcing and damping processes. However, even the physical behavior of the viscosity is not yet fully understood. "Particle in a box" statistical mechanics is not completely valid in these systems, due to the coupling of the velocity of a particle (and thus its "random" relative velocity at the point of collision with a neighboring particle) and its position in its orbit. Furthermore, theoretical studies have suggested that, as the particle number density increases, the collective properties of the ring particles can resemble those of a liquid more than those of a gas, and ultimately even "solid" phases may "freeze out" at least in transient regions [7]. Some evidence for this may be found in discrepancies being seen in careful radiative transfer modeling of the rings. Their photometric properties in many cases deviate from those of a layer of low volume density, as if the particles in some regions are more closely packed than in others [8]. Only very recently are the many simplifying assumptions which have characterized these studies being relaxed [9], and realistic collisions, particle size distributions, and gravitational scatterings by the larger particles included. Nevertheless, detailed inferences as to particle properties, energy budgets, and ultimately timescales in the real rings from such a perspective remain elusive. Further background on this general subject may be found in [10].

2.2. GRAVITATIONAL FORCES

Long before the Voyager encounters, it was realized that the relatively tiny gravitational forces of both nearby and remote satellites, with fractional mass $\mu \sim 10^{-8}$ that of the planet (or even less), could lead to significant effects at resonance locations where the orbital frequencies of the satellite and the ring particles are commensurate (integer fractions or multiples) to a precision on the order of $\mu^{1/2}$ (the "width" of the resonance). Initial studies of individual resonances borrowed from galactic dynamics, and emphasized Lindblad resonances - those between the radial oscillation period of the particle and the period of the perturber. These were quickly shown to explain the numerous spiral density waves seen in the rings of Saturn [2,11]. Subsequent studies extended this framework into vertical or inclination resonances, which lead to spiral bending waves or a flapping of the ring sheet [2,12], and corotation (angular motion) resonances [13]. Combinations of Lindblad and corotation types have been explored in the application to eccentric rings such as those of Uranus [14], and may be involved with angular confinement of ring material into arcs and clumps [15]. The general importance of collective effects in the transfer of angular momentum between moons and rings, regardless of the specific form of the effects (viscosity, self gravity, etc.) has been discussed in several very readable articles [16]. Analyses of density and bending wave profiles have been used to infer the ring mass density and viscosity in a dozen or so specific regions [17,2]. Kinematic viscosities are seen to vary throughout the rings, with lower values (probably $\sim (0.1 - 1)\tau$ cm^{2}sec^{-1}) in the C ring, and larger values ($\sim (10 - 100)\tau$ cm^{2}sec^{-1} in the A and B rings. These values are not far from those inferred from theoretical models of density wave damping given the expected particle sizes. Finally, gravitational perturbations in the presence of viscosity are the essence of what has become known as the "shepherding" process by which moons confine ring material, to which we return below.

2.3. METEOROID BOMBARDMENT

Although those who study the surfaces of the airless planets and satellites have long accepted the importance of extrinsic bombardment as a significant geological process, the importance of the neverending cosmic hailstorm has only recently gained its due attention in the context of ring systems. Actually, this process is probably even more important for the evolution of ring structure and composition than in the better studied case of surface cratering, because of the vastly greater surface area to mass ratio for ring systems than for moons. This process will appear several times in discussions below; articles dealing with this general subject are found in [18].

2.4. ELECTROMAGNETIC FORCES

Icy or rocky particles may become charged in the magnetospheres of the giant planets, and then experience Lorentz ($\mathbf{V}\times\mathbf{B}$) forces since their (Keplerian) orbital frequencies are in general different from the rotational frequency of the planetary magnetic field (that of the planet's mantle or deep interior). Because only a very tiny fraction of the mass in any of the main ring systems is in particles sufficiently small to be affected by electromagnetic forces (sizes of a micron or smaller), and such microscopic particles are extremely short-lived, these effects act primarily to redistribute recently generated dust. Nevertheless, these perturbations on the basic state are important for understanding the structure of the Jovian ring halo and Saturn's E ring, at least [19], and, while small, are unceasing and may play a role in long term ring evolution. For instance, it has been pointed out [20] that very fine charged grains, probably no more than molecular clusters, are unstable in Saturn's rings at radii between 1.53 and 1.63 R_S, where R_S is Saturn's radius, depending on their velocity. Interestingly, the 1.63 R_S limit does correspond to an abrupt change in several ring properties - not only optical depth [20], but also photometric behavior, typical radial structural scale, and presence or absense of spokes [21]. Larger charged grains receive a positive or negative torque from the planet's magnetic field, which rotates at a different rate than the ring particles except at "synchronous orbit" in the B ring. Landing at radii different from their source, they convey their new angular momentum to their new host particle which leads to radial drifts, as discussed further below. Further background in this area may be found in [22].

3. Ring Structure

3.1. RINGS AND RINGMOONS

Jupiter's ring system first revealed its presence to Pioneer 11 as a depletion of magnetospheric protons, and Voyager images provided its unambiguous detection (figure 1; [23]). The most recent studies of the Jovian ring reveal it as a relatively flattened belt containing both macroscopic and microscopic particles, transforming into a three dimensional "torus" of primarily microscopic grains inwards of the main ring, and into an extended, flattened, "gossamer" ring of much lower particle density ranging outwards of the main ring to beyond the orbit of Jupiter's innermost classical satellite Amalthea [24]. The presence of the microscopic dust and the inference of the macroscopic material led to the proposal of an ongoing process whereby micrometeoroid bombardment of a population of objects between centimeters and kilometers in size generates the visible microscopic dust, which is then redistributed and removed by a variety of processes on a timescale of $10^2 - 10^3$ years [25]. Searches of Voyager images have resulted in the discovery of at least two small moons orbiting in and around the Jovian main ring; these have now been complemented by groundbased images [1, 26]. One imagines these to be merely the largest of a distribution of objects ranging down to subkilometer size. Even though the orbits of the visible moons are now well determined, the geometry of the ring images is insufficiently accurate to pinpoint the locations of the moons precisely relative to the ring boundaries.

The first suggestion that nearby small moons could significantly influence ring dynamics and structure (dubbed "shepherding" by a member of the Voyager press corps) was in response to the discovery in 1977 of the Uranian rings during a stellar occultation by the planet [27]. For several years, the stability of these narrow, yet

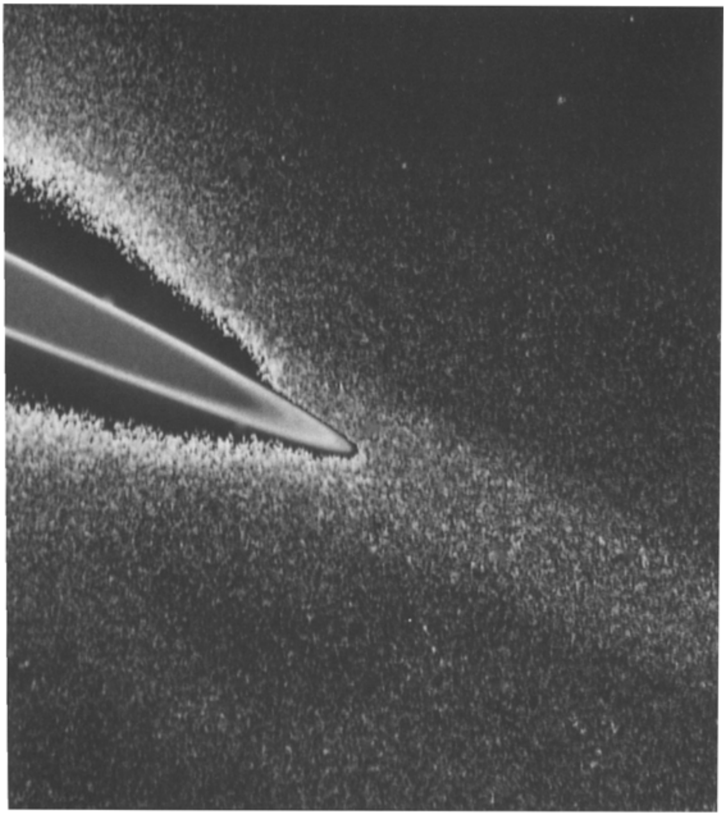

Fig. 1. A wide angle Voyager image, enhanced to display both the main ring and the outward extension, or "gossamer ring", which extends out well beyond the orbit of Jupiter's inner moon Amalthea. The vertical extension or "halo" material inwards of the main ring is also seen. The small moon Adrastea orbits close to the outer edge of the main ring, and its companion Metis lies within the ring. Figure from Showalter *et al.* (1985), in references [1].

quite dense and presumably collisionally active, rings remained a puzzle, because they were expected to spread radially and disperse due to their effective viscosity on a timescale $w^2/\nu \sim 10^5$ yr, where w is the ring width. The concept of shepherding [28, 29] is the transfer of energy and angular momentum between a ring and a more massive external moon (either nearby or remote) which counteracts the viscous spreading tendency. The essence of the Goldreich-Tremaine concept [28] has become generally accepted, although its specifics have evolved with time to keep pace with the observations.

The presense or prediction of "ringmoons" in and around the rings of Jupiter and Uranus was quickly echoed at Saturn during the Pioneer 11 and Voyager encounters of 1979 - 1981. Five substantial new moons were discovered skirting the edge of the main rings, and the classical satellite region is replete with debris. Lagrange point objects are seen in the orbits of Tethys and Dione [30]; in addition, unseen dispersed material is inferred in the orbits of these moons and those of Mimas, Enceladus, and Rhea as well as in regions devoid of any known moons of significant size [31].

The narrow, multistranded, kinky F ring lies between two of the five new inner moons; although this configuration has been referred to as the archetype of the shepherding process, it is not actually a particularly satisfying one. Most significantly, the ring may not be in torque balance; it is closer to the larger "shepherd" [32]. The lack of a good explanation for the presence of the F ring, and the presence of certain anomalous depletions of the inner magnetosphere surrounding it which do not correspond to any known rings or moons, has led Cuzzi and Burns [33] to suggest that the F ring is embedded within a much wider (1-2000km), but much more transparent (optical depth $\sim 10^{-3} - 10^{-4}$) ring or belt of asteroid-sized moonlets. This ensemble of objects is expected to interact collisionally to produce sporadic clumps of material; the F ring may be no more than an unusually large, rare collisional remnant. Recent analysis of azimuthal structure ("kinks" and "clumps") in the F ring appears to contain evidence for the presence of several members of the hypothesized moonlet belt population [34].

Inverting the original shepherding idea of Goldreich and Tremaine [28], it was suggested that the empty gaps in Saturn's rings were due to embedded small moonlets repelling ring material [35]. Initial attempts at direct detection of these objects were unsuccessful [36, 2], but indirect evidence for one such moonlet in the Encke gap of Saturn's A ring was accumulated [37], which allowed the object to be directly detected in fairly low resolution Voyager images [38]. Other gaps have been studied for indirect evidence of a similar nature, but the search has not been exhaustive and has not as yet met with comparable success [39].

The Voyager encounters with Uranus and Neptune completed the family portrait of the four ring systems (figures 2 and 3). The nine opaque rings of Uranus were found to be accompanied by about a hundred dusty bands of low optical depth (about 10^{-5}), and by ten new moonlets [40] of which one is embedded within the nine main rings. Similarly, Voyager found Neptune to have an extensive, low optical depth, ring system containing diverse elements with opacity ranging from 10^{-1} in the arcs, through 10^{-2} in two complete but narrow rings, to $10^{-3} - 10^{-4}$ in a broad, diffuse system about 30,000 km in width. Moonlets were also found in and around the Neptunian ring system with a radial distribution highly reminiscent of that found orbiting the other three gas giants. That is, they are found distributed throughout the observed ring material, both inside and outside of the Roche limit. Actually, the mass of the Neptunian ringmoons far exceeds that of the observed Neptunian rings, as seen in the Jovian ring-moon system. The orbits of two of the ring-related moonlets lie just about 1000 km inwards of the two major narrow Neptunian rings. This is probably not a coincidence, but as yet no one has grasped the significance of this configuration. It would be consistent with resonance trapping of inwardly drifting material (e.g., [41])

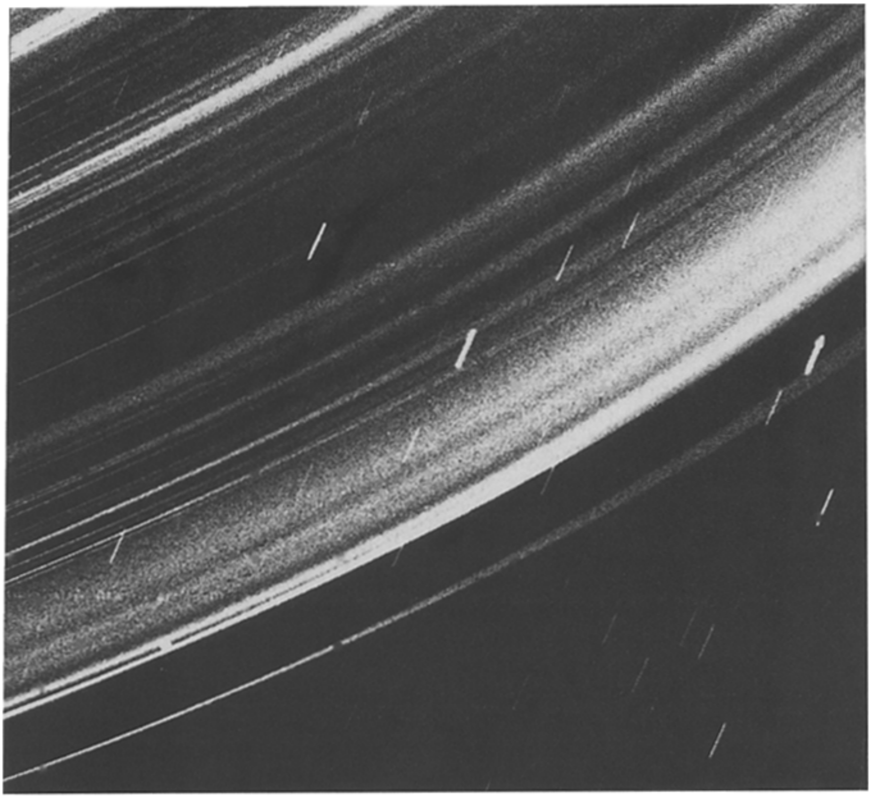

Fig. 2. Voyager wide angle image of the Uranian ring system, obtained looking nearly directly back towards the sun. This "forward scattering" geometry highlighted microscopic particles even of extemely low optical depths, and revealed for the first time that the nine known opaque, narrow rings were embedded in an extensive, structured, low (about 10^{-4}) optical depth system covering the entire region. The features in this image are about 50 km wide. Figure from Smith *et al.* (1986), in reference [97].

So, in the broadest perspective, we see a definite family similarity between the four ring-moon systems (figures 4 and 5). Each lies mostly within the Roche "zone" of its parent planet. The rings mingle with 1 - 10 embedded and outlying ringmoons, of tens to roughly a hundred km diameter, which themselves merge into the less numerous, larger "classical" moons further from the planet. The inner ring-moon systems are all prograde and equatorial - certainly not a foregone conclusion in the case of Neptune, which lacks a well-behaved classical satellite system.

Unfortunately, the Roche zone concept is actually not very well studied, as its applications lie in that messy regime so common in planetary science where realistic material properties strongly influence behavior and "spherical elephant" assumptions are glaringly inappropriate. The assumption of a liquid, or even self-gravitating, object is simply not adequate for irregular 10-100 km fragments, and

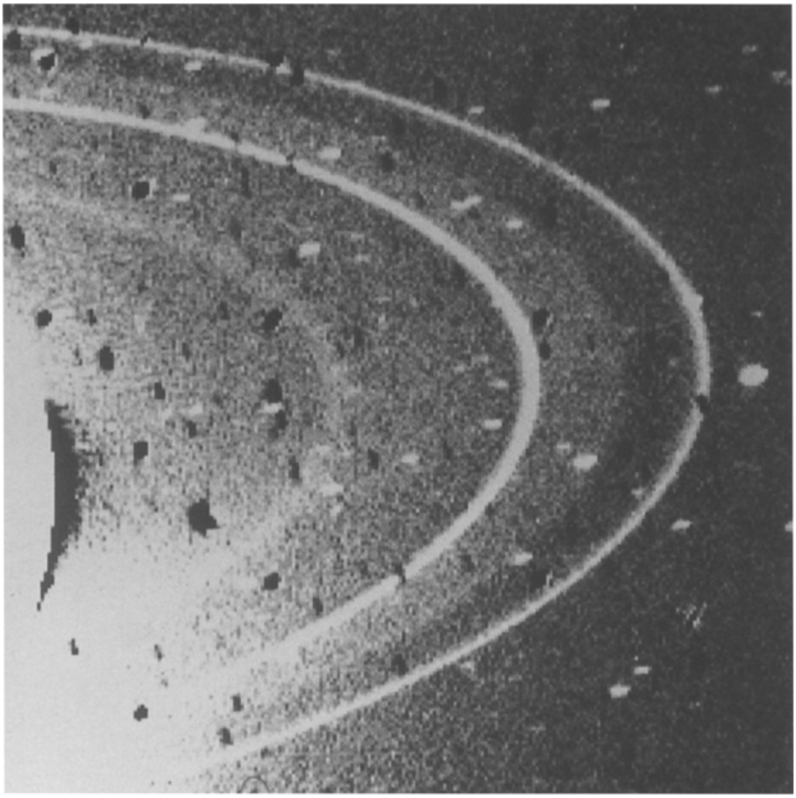

Fig. 3. **Voyager wide angle, long exposure (about 10 minutes) image of the Neptunian ring** system. This image is of fairly low resolution but shows the global structure of this optically thin ($10^{-4} - 10^{-2}$ except for the arcs which are $\sim 10^{-1}$) ring system. Several distinct components are visible, each having slightly different morphology and particle size distribution.

their actual properties, including internal strength in the presence of fractures and possible ice-rock boundaries, are not really known. Smoluchowski [42] pointed out that accretion of small particles onto the surface of larger ring particles of density ρ_{rp} becomes impossible at an "inner accretion limit" of $1.44(\rho_{pl}/\rho_{rp})^{1/3}R_{pl}$, where R_{pl} is the planet's radius and ρ_{pl} is its density; this is the location where (for characteristic particle spins) the combination of planetary tidal force, particle gravity, and centrifugal force just balance. This radius corresponds very well to the inner limits of all four ring systems (figure 4); one infers from this that particle histories in rings must result from a balance between accretion and erosion processes, since rings cannot long survive in the face of size-dependent removal processes where particles are no longer able to accrete, and thereby preserve, their smaller neighbors.

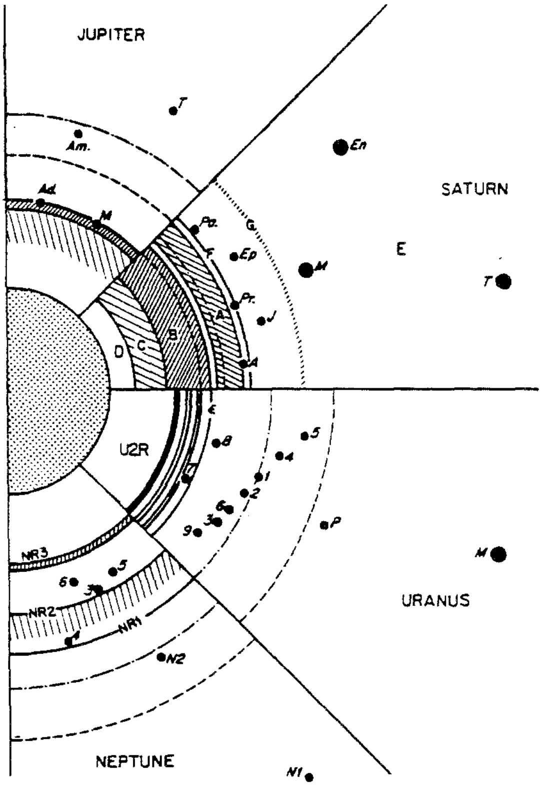

Fig. 4. A rendition of the intermingling of rings and ringmoons in the four systems, with radii scaled to the radius of the parent planet. The density of cross-hatching suggests the relative optical depths of the different rings. In each case, synchronous orbit is shown as a dashed line, and the Roche limit (for satellite density of 1 g cm^{-3} is shown by a dot-dashed line. (from Nicholson and Dones 1991, in reference [5].

Accretion of 10-100 km size objects from, say, a preexisting disk of small ring particles is unlikely anywhere in the rings due to the ability of such an object to repel surrounding material quite effectively. Objects this large must accrete outside the Roche limit. Once grown, reasonable material strength can allow moons of these sizes to survive within the outer Roche zones of their parents [43]. The implication is that moons form outside the Roche limit, and migrate into it. Occasional breakup of one of these objects can then provide ring material, and even entire rings, to replenish that which is continually lost. Source bodies could also be passing transients torn apart by planetary gravity [44]. A third possibility is that impact with preexisting ring material pulverizes an incident object, leading to capture of a larger amount of debris. One imagines that these processes recur throughout the ringmoon systems of the outer solar system.

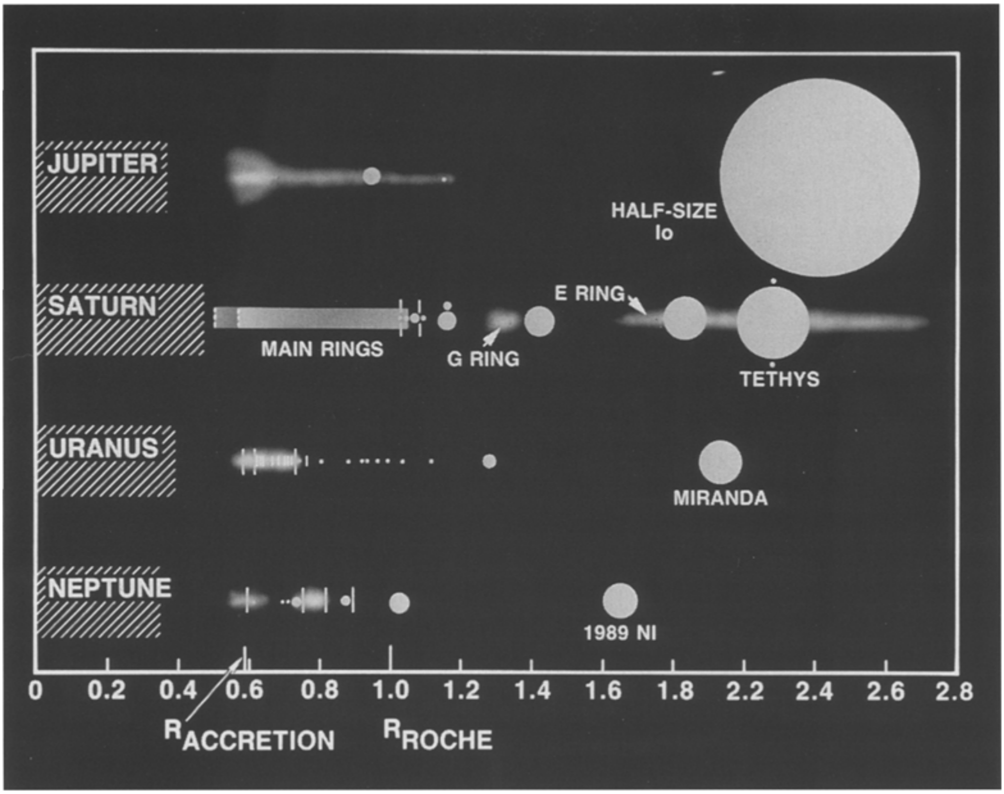

Fig. 5. **A different rendition of the inner ring**moon systems of the four **gas giant planets, with** locations scaled by the "equivalent" radius $R_{eq} = (\rho_{rp}/\rho_{pl})^{\frac{1}{3}} R_{pl}$. In these units, the classical Roche limit lies at 2.44. The inner accretion limit is at 1.442 and is fairly closely related to the observed inner edges of all four ring systems (ref 38). The outer edges of most rings are in the vicinity of the classical Roche limit. Generally, the numbers of moons increase and their sizes decrease as the planet is approached in all cases.

3.2. SHEPHERDING

The ability of nearby moonlets to counteract the tendency of ring material to spread radially under viscosity has been a central theme of ring studies for nearly two decades now. The most cited early hypothesis [28] envisioned *local* satellites having numerous, overlapping resonances in the ring material. This concept, while containing the essential physics of angular momentum transfer, ignored the effects of the moonlet perturbations on the transport process. The torques involved are of the form

$$\mathcal{T} = \nu \overline{\nabla \overline{v}},$$

where ν is the viscosity and $\overline{\nabla v}$ is the velocity shear tensor, of the form $(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i})$ where (i, j, k) denote radial, angular, and vertical coordinates. In early theories, the velocity shear was merely assumed to be Keplerian. That is, the interacting particles were assumed to lie on nearly circular orbits with velocity varying with radius due only to the planet's gravity. However, we now know [45] that the very perturbations caused by the moons alter the form of the velocity shear as a function of orbit longitude to the extent that at longitudes where the compression of material is the greatest, and the collisions are the most frequent, the *local* velocity gradient $\frac{\partial v_\theta}{\partial r}$ reverses from the Keplerian one and becomes positive over a restricted angular region. Overall, this causes the azimuthally averaged angular momentum transport and energy dissipation to be significantly decreased, and the ring material spreads much less rapidly in the presence of satellite perturbations than when unperturbed [45]. It is therefore much easier to "shepherd" ring material in this way than previously thought, especially narrow rings where the entire ring may lie in the perturbed region. The failure of Voyager to detect large embedded moons in some of the gaps in the rings of Saturn and Uranus is slightly less worrisome for this reason; however, there is fair agreement between the mass of the Encke moonlet Pan and the expected width of the Encke gap within current uncertainty in current parameter estimates. Consequently, unseen shepherds may yet be found in the Uranian system, but some concern remains about gaps in wide rings, such as at Saturn.

A slightly different "remote" shepherding process emerged when it was realized that two of the moonlets discovered by Voyager within the Uranian system have individual resonances at the edges of the largest Uranian (ϵ) ring [46]. The ability of isolated resonances to maintain ring edges had been previously discussed in the context of how Mimas delineates the outer edge of Saturn's B ring [47] and, in principle at least, in the context of the Uranian ring system itself [48]. Although no other moons have been found to provide confining torques for the other eight Uranian rings, exhaustive searches of the data to the level needed to approach the new lower masses required are difficult and time consuming, and remain to be done. There are locations from which several as-yet-undiscovered moonlets could influence the edges of several of the rings simultaneously; some of these are close to low-order resonances with known moons [49]. This implies that the unseen, locally controlling "shepherds" could be locked to larger objects.

The fact that partial "arcs" of ring-like material surrounded Neptune was first revealed by groundbased stellar occultations, and subsequently by Voyager images (figure 6, [50]).

Because of the differential orbital velocity across the width w of an arc at radius a from the planet, material with a spread w in orbital semimajor axes would ultimately spread to encircle the entire planet uniformly in a time roughly equal to a/w orbit periods - a matter of years. These arcs have been explained in terms of corotation resonance trapping by Galatea [51]. Jupiter's Trojan asteroid family is a

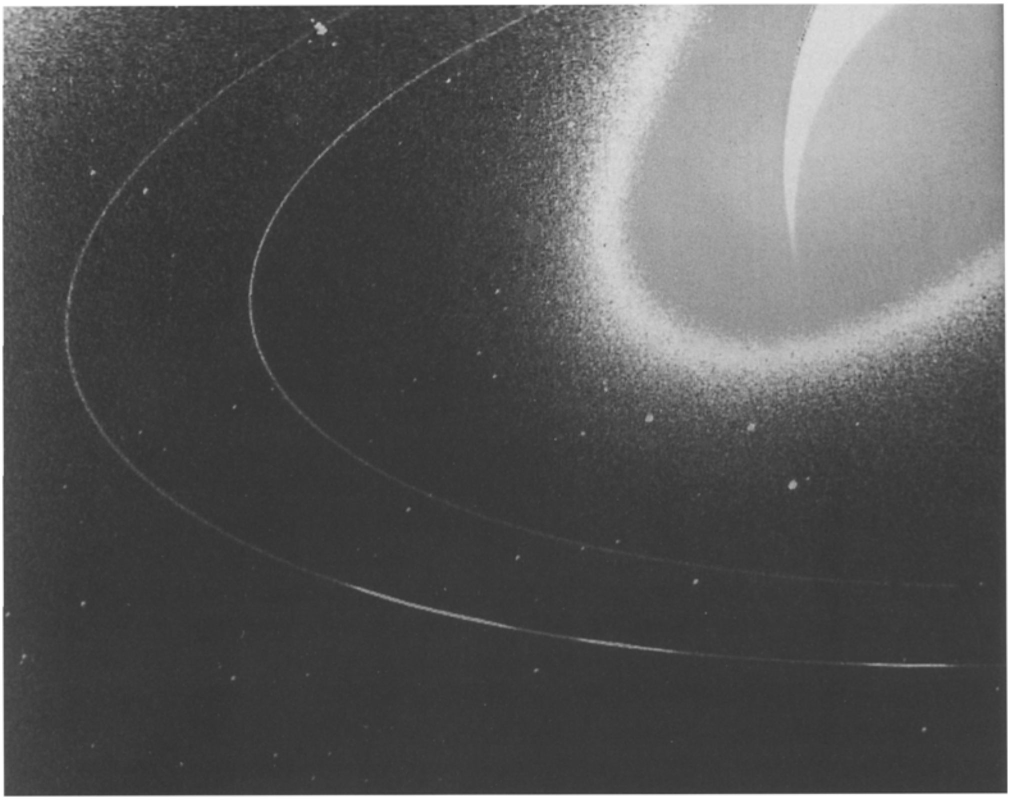

Fig. 6. Wide angle image of the Neptune rings showing the three main arc features Liberté, Egalité, and Fraternité. These arcs can explain all of the groundbased detections of ring material around Neptune to date; one such observation actually detected a small moonlet (1989N1). Figure from Smith *et al.* (1989), in reference [97].

good example of a dissipationless system "confined" in the angular direction in the rotating frame of their prime perturber. The several arc confinement hypotheses which have been advanced thus far are variations on the theme of Lagrange point stability of (dissipationless) objects as coupled with some means of resupplying the energy lost by the colliding particles in the arcs [52]. Although the fundamental identification with the Galatea corotation resonances is probably secure, the Neptune arcs remain somewhat problematic - the observations are consistent with azimuthal confinement, but only if the spread in orbital semimajor axes is much smaller than the observed radial width of the arc material. It might be difficult to reconcile this situation with the expected level of collisional interactions, which excite random velocities [52]. Nevertheless, configurations have been proposed which minimize such spreading [53], and might be of relevance to the even smaller "clumps", with azimuthal scale of merely hundreds of km, which have also been found within the Neptune arcs [54]. An alternative possibility, dubbed "creationist" by one ring scientist, is that arcs in general might merely be transient, as suggested for the smaller clumps in Saturn's F ring region [33].

Other clumpy, azimuthally incomplete arcs are found in Saturn's F ring strands, the orbit of Neptune's ringmoon Galatea (1989N4), and also in Saturn's Encke gap. The Encke arcs are of somewhat larger angular extent than those of Neptune [2], and their longitudinal structure and relationship to the Encke moonlet have not been studied. Another new narrow, dusty, clumpy ring was discovered at Uranus, reminiscent of Saturn's F ring (λ; originally 1986U1R; [55]). Thus, while the main Neptune arcs are apparently confined in some way, others may be transient byproducts of interactions between local moonlets.

3.3. LOCAL STRUCTURE - MODES, WAVES, AND WAKES

Prior to Voyager encounter in 1986, several of the rings of Uranus were known to exhibit unexplained sub-km radius and/or width residuals from smooth, elliptical, inclined orbits. These residuals were identified [56] as patterns with low azimuthal wavenumber - an $m = 0$ or an axisymmetric "breathing" mode, and an $m = 2$ pattern such as excited along the outer edges of Saturn's B ring [47]. These patterns have a characteristic angular velocity for each m that, when included in the fits, reduce the residuals considerably. The possibility of free or excited modes in planetary rings was first suggested by Borderies and coworkers [57], who suggested that stable modes would be most likely to occur in rings where the material was extremely closely packed, with viscous properties more like those of a liquid than the gas-kinetic type viscosities more commonly adopted for sparser rings. The essence of the idea, as for favored modes in many other bounded systems (drumhead modes, for example) is that certain patterns of oscillation are stable due to the combination of their spatial and temporal scales of oscillation, and a balance between energy production and dissipation. Since the primary energy loss mechanism in rings is viscous coupling across the radial gradient in orbital velocity, normal modes are most stable in narrow rings, where this gradient can be most easily suppressed by the mode itself. The existence of elliptical modes which are stabilized by viscous forces might supercede the older idea that the elliptical shape of narrow rings is stabilized by the self-gravity of the ring; the self-gravity idea has led to some inconsistencies with observations [56]. In fact, all of the nine main rings of Uranus and several ringlets in Saturn's rings [2, 3, 39] show unexplained eccentricities ($m = 1$) which could be excited modes. Both the eccentricities and inclinations of the Uranian rings show a significant radial dependence [56, 58] which is not understood.

It is impossible to adequately address the full complexity of the structure in Saturn's ring system [2] in a brief article. In general, the three major ring regions (A, B, and C) exhibit different stucture (figure 7). The A (outermost) ring is characterized by a multitude of identified spiral density and bending waves, separated

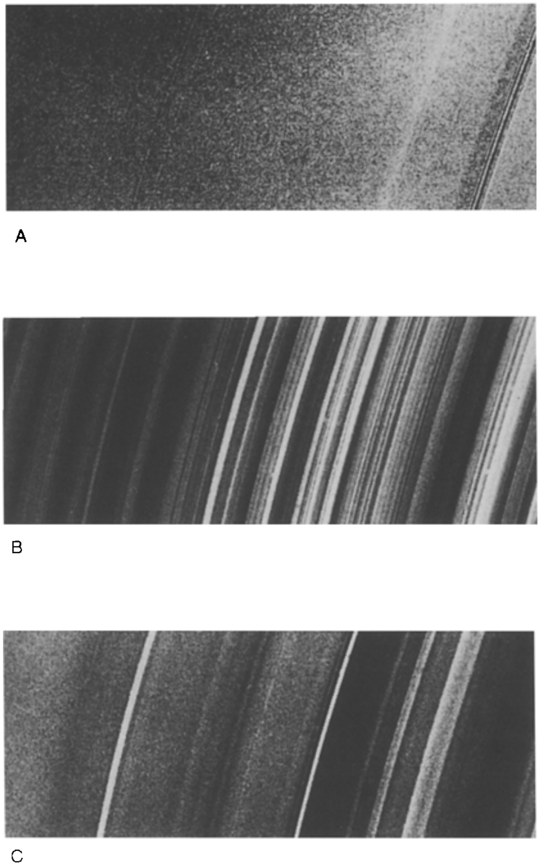

Fig. 7. Typical structure in Saturn's rings varies between the classical ring regions. The panels each display a region about 4000 km wide. The outermost (A) ring is generally featureless, but is punctuated with well separated and clearly identifiable trains of spiral density and bending waves excited at resonances with external moons. The middle panel shows the "irregular" structure filling the B ring. The lower panel displays the broad "plateau" stucture which characterizes not only the C ring shown, but also the Cassini division. The C ring and Cassini division are also the location of practically all of the empty gaps in the rings. Figure from Lissauer and Cuzzi (1985), in reference [5].

by regions which are featureless on short radial scales but exhibit a quadrupole azimuthal brightness asymmetry that has been ascribed to wake patterns which are on the scale of the ring thickness in horizontal scale [59]. One generally ascribes this behavior to the proximity of the A ring to the planet's Roche limit, where tidal effects weaken and coherent wakes are more easily generated. Salo [60] has shown that transient clumpings of particles occur on the tens-to-hundred meter scale even in the B ring, and long-lived agglomerations of several tens of meters radius can form in the A ring. The B ring, containing the bulk of the ring material, is filled with "irregular" radial structure on length scales of about 100 km. The characteristic length scale of this structure varies from $\sim$ 100 to $\sim$ 300 km; very

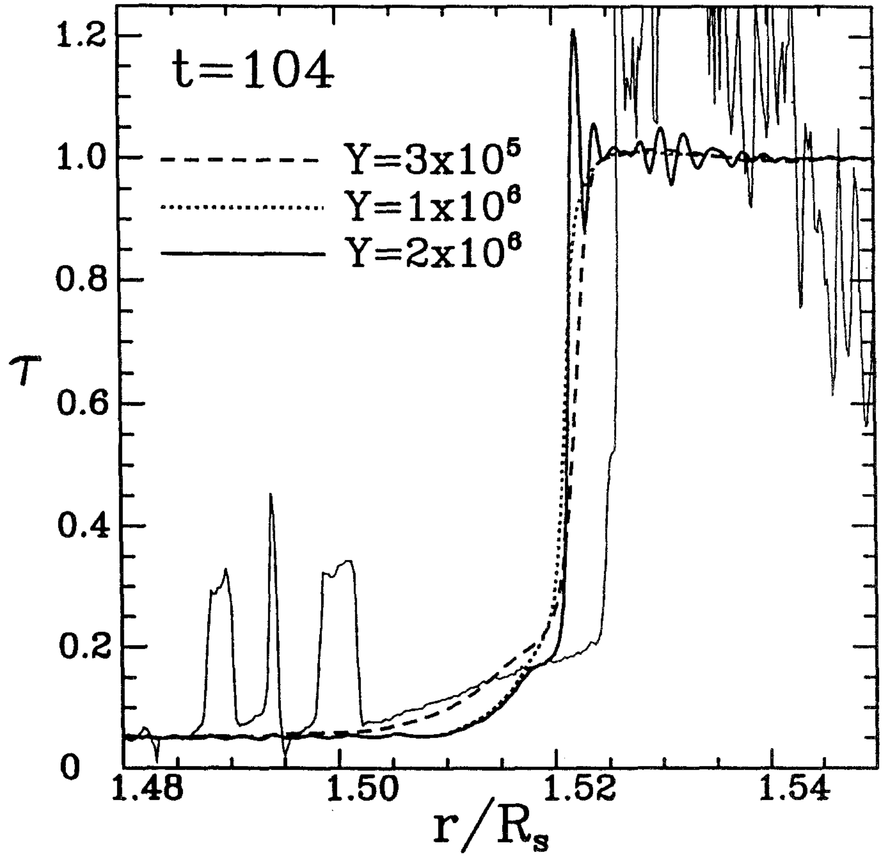

Fig. 8. Structure generated at and near the inner edge of a step in optical depth similar in magnitude to that founud at the inner edge of Saturn's B ring, for three choices of a parameter Y that combines projectile flux and ring viscosity (heavy curves). The observed optical depth profile is shown by the lighter solid curve. The runs began with a smooth edge and cover a duration of 104 "gross erosion times". The gross erosion time is the time in which the incident flux generates a surface mass density of ejecta equal to that of the B ring (roughly 10^5 years for an ejecta yield of 10^5 times the projectile mass). Note that (a) ballistic transport maintains the edge in the face of the tendency of viscosity to make it spread, (b) a "ramp" forms inwards of the edge much like seen inwards of the observed A and B ring inner edges, and (c) "irregular" structure grows outwards of the edge, much as seen in the inner B and A rings. (from Durisen *et al.* 1992, in reference [65]).

fine scale structure ($\sim$ 10 km), some of which appears to be azimuthally variable, appears primarily in the outer 1000 km of the B ring [61, 2]. The lowest optical depth regions, the C (innermost) ring and Cassini division, are characterized by plateau-type structures with 100-1000 km radial scale, and empty gaps which often contain narrow ringlets. No explanation for the plateau-like structure of these regions is at hand.

Several hypotheses have been advanced to explain the B ring irregular structure. Some early ones invoked either very small moonlets, too small to completely clear gaps [35, 2], or viscous or collisional instabilities of various types, similar to those responsible for traffic jams [62, 2]. The viscous instability has encountered difficulties explaining the existence of characteristic length scales much larger than the ring thickness. Furthermore, it has now been realized that an important contribution to ring viscosity had been omitted from the early work: that due to finite particle size effects which are, in fact, dominant at large optical depth and probably prevent the instability [63]. On the other hand, others [64] suggest that stable eccentric features or "overstabilities" arising in large optical depth regions may produce azimuthal asymmetries, as in the case for isolated eccentric rings, on the scale of the finest structure

Two other explanations for the irregular structure have been advanced which are both related to transport of meteoroid ejecta. Durisen and coworkers [65] have shown that the optical depth dependence of the ability to release and absorb meteoroid ejecta may lead to growth of optical depth fluctuations with widths on the scale of the throw distance. The equilibrium amplitude of these fluctuations is given by a balance between ejecta yield and throw distance, and viscosity (which tends to diffuse the structure); observed structure is consistent with reasonable values of all parameters (figure 8). Goertz and coworkers [66] suggest a similar process, but relying on the electromagnetic torques incurred by grains temporarily charged in impact plasma clouds (discussed further below). Due to the more limited mass fraction of active carriers, this process creates structure only if viscosities are $\sim 10^{-2}$ (cgs). This is smaller than current estimates in the C ring, where the optical depth and particle size are both small compared to the rings in general; current estimates in the A ring are more in the 10-100 (cgs) range [17]; we have no observational viscosity constraints in the B ring, which is the location of nearly all of the irregular structure, but it is probably at least as large as in the A ring.

4. Ring particle properties

4.1. COMPOSITION

In light of the vast amount of spatial structure under study in ring systems, surprisingly little is known about ring composition. The Pioneer and Voyager cameras carried only broadband, visual wavelength filters, and had no capability for reflectance spectroscopy. Naturally, groundbased observations are of lower spatial resolution; however, they are still capable of providing many important compositional constraints.

Groundbased reflectance spectroscopy of Saturn's rings long ago demonstrated that the rings contain large amounts of water ice and a small admixture of (probably) silicate and (possibly) other non-icy material [2]. Groundbased radar and radio observations, even before Voyager encounter, required the particles to have a very high microwave reflectivity and a very low microwave emissivity [67]. Combining these properties with particle sizes allows *bulk* material refractive indices to be estimated. The particle size distributions inferred by these studies have been confirmed by Voyager [68, 69], and the non-icy component is thus constrained to make up less than about 10% of the rings [67], and perhaps no more than 1% [70] by mass. Other constraints on the makeup of *surficial* material have been obtained from analysis of Voyager photometry. In order for the macroscopic ring particles in the A and B rings to have a Bond albedo of about 0.5, the individual grains making up the surface must be nearly devoid of non-icy impurities, to a level of a few percent [71].

This is not easy to explain in light of the large amount of meteoritic material the rings must have absorbed (section 2) - primitive material consists of intimate mixtures of carbonaceous, silicaceous, and icy grains and is probably extremely dark, like the nucleus of comet Halley. The highly reflective classical satellites of Jupiter and Saturn presumably grew sufficiently large and hot during their formation to melt, allowing the lighter icy material to separate from denser, more refractory material, and form an icy outer shell of typically hundreds of km thickness. Early processing of Saturn's ring material through a large, differentiated satellite is consistent with the presence of compositional variations on both local and global scales in Saturn's rings, inferred from preliminary Voyager color and photometric data [2]. Catastrophic breakup of a differentiated moon would generate a compositionally inhomogeneous population of moonlet-sized fragments which might provide the source for the observed ring material. More systematic study of the observed variations is just beginning, and considerable analysis and modeling remains to be done. It does appear that local radial color variations are most prominent in the opaque regions of the B ring. Elsewhere, global color and albedo variations are fairly smooth and consistent with meteoroid infall and ballistic transport [72].

The Uranian ring particles are known to be extremely dark and essentially colorless, reminiscent of primitive materials such as comet nuclei or carbonaceous chondrites [73]. The reflectivities and colors of the nearby ringmoons are similar, but their reflectivities drop abruptly towards the planet. Laboratory experiments [74] suggest that, if the primordial composition of these objects included significant amounts of carbon-bearing ices, millenia of bombardment by trapped magnetospheric protons and electrons may have stripped the associated Hydrogen and/or Oxygen, leaving behind more complex, and highly absorbing, hydrocarbons. On the other hand, these objects may merely (or primarily) preserve the composition of primitive non-differentiated material, or be so thoroughly saturated with infalling meteoroidal material as to have lost their primordial composition. These latter explanations would not help explain the abrupt albedo drop with decreasing albedo, just where the magnetosphere might be expected to become important, in the case of Uranus.

In the case of the rings of Jupiter and Neptune, uncertainties as to the net amount of material present (optical depth) prevents determination of the absolute particle brightness; for Jupiter, relative spectral reflectivity measurements [2] show the ring material to be reddish, in contrast to the Uranian ring material. However, the entire inner Jovian system is polluted with reddish material ejected from the volcanoes of Io. In the case of the Neptune rings, color measurements are nonexistent. Preliminary photometric modeling [75] implies that the particles are quite dark, like those of the Uranian rings.

Taking the current results at face value, Saturn's rings appear unique in their high reflectivity as well as in their sheer abundance of material. The old question of "why is Saturn the only giant planet with rings" now becomes "why is Saturn the only giant planet with big, bright rings"? The new question is not much less puzzling than the old one. We return to this issue in the next section.

4.2. SIZE DISTRIBUTION

The physical nature of the individual particles is of interest primarily through its relationship to ongoing local dynamical processes. In general, the largest "typical" particles in rings are on the order of meters to tens of meters in size. The size of the largest typical particle varies dramatically with location [69]. Averaged over large radial regions in Saturn's rings, this largest size is typically seen as a cutoff in a powerlaw distribution of the form $n(r) \propto r^{-s}$, with s in the range between 2.5 and 3.5 [2, 68]. For these distributions, most of the mass of the rings lies near the upper size cutoff. However, the tiny fraction of mass residing in the microscopic dust is of great interest because dust is extremely short lived due to a variety of removal processes [1, 25] and is thus a diagnostic of relatively vigorous local dynamics.

The exception, Saturn's E ring, contains a quite narrow size distribution of micron-radius particles which was originally thought to be realted to unusual geological processes on the surface of the moon Enceladus [2, 19, 76] but now seems more likely to be a self-supported configuration [77]. The concept is that continual erosion of Enceladus is driven by a population of eccentric, charged, micron-radius grains which are highly selected for by the combined action of solar radiation pressure and electromagnetic forces.

The fraction of micron-sized dust in moderately opaque rings ($\tau > 0.1$) is quite low - in the main rings of Saturn and Uranus it is probably on the order of one percent or less in general [78]. This recent result, which was not anticipated in preliminary post-Voyager review articles [2] will require changes in several hypotheses of ring structure which adopted now outdated dust fraction estimates on the order of 10%. From the very limited photometry done so far of the low optical depth rings of Jupiter and Neptune, and of the Uranian dust bands, the fraction of dust appears to be higher: 50% or greater. Furthermore, Saturn's F ring [79] and Encke gap ringlets, the Uranian λ ring, and the Neptunian ring arcs are examples of rings of moderate optical depth (~ 0.1) which have an even larger dust fraction, indicative of vigorous ongoing creation.

Modeling which includes the sporadic creation of debris by collisions and meteoroid impacts, and the continual removal of debris by sweepup, demonstrates the diminished capacity of nearly transparent rings to sweep up the dust into the surfaces of their macroscopic ring particles compared to opaque rings. In the case of the Uranian and Neptunian dust bands and rings, ongoing collisions in belts of meter-to-kilometer-sized moonlets can generate the dust and sweep it up again sufficiently rapidly to confine it to the region of creation [80].

The macroscopic ring particles seem to be fairly sturdy, at least where their properties can be inferred. It has been suggested that the 5 to 10 meter "particles" that we observe with various techniques [68, 69] have no long term integrity but are merely passing clusters of smaller fragments, accumulating and collapsing on an orbital timescale. These objects, dubbed "DEBS", or dynamic ephemeral bodies, in one hypothesis [81], would have little or no strength or elasticity. Although ring particles might well be shattered and reaccreted on $1 - 10^4$ year timescales, difficulties arise with the DEB idea in its original form, which advocates extremely fragile objects with a strength several orders of magnitude lower than granular ice or snow in order that tidal forces alone may disrupt particles as small as 10 m in radius. However, photometric analysis in both unperturbed regions and nearby regions perturbed by spiral density waves has shown that, contrary to previous beliefs, optically thick rings are *not* dusty, either with or without relatively vigorous collisions, as one might expect if the particles are so easily and so often disintegrated and reassembled. Instead, Dones *et al.* (1993, in [78]) have shown that the particle surfaces are made smoother as they collide more vigorously, much like well-packed snowballs. Although the radiative transfer models being used to interpret ring brightness are still somewhat idealized and are currently being improved [8], the fractional optical depth of dust appears to be no more than about 1% on the average in any of the main rings of Saturn or Uranus [78]. In addition, the damping of most observed spiral density waves requires a viscosity typical of a particle random velocity of $10^{-2} - 10^{-1}$ cm $\sec^{-1}$, which is comparable to the velocity shear across a 1 - 10 m radius ring particle, and can only be maintained if the corresponding particles are fairly elastic. A slight variation on the "DEBS" idea, with the destruction mechanism working entirely by collisions and not by tidal breakup, would appear to allow the particles to be of moderate strength while yielding sizes consistent with these observations [82]. As mentioned earlier, "DEB"-like objects of much larger size (several tens of meters in radius) are seen to form in numerical simulations which include a realistic hard-sphere size distribution up to 5 meters in radius. Some of these are really not even genuine aggregates but only temporary "wakes".

5. Short timescales

The first study of ring particles with short lifetimes came in relation to the Jovian ring. All of the (observed) particles tend to be microscopic and are removed or destroyed by various processes in 100 years or so, leading to a model characterized by ongoing creation (by meteoroid bombardment of a population of more massive, long lived parent objects; [1]). Shortly after spiral density waves were identified in the rings of Saturn, it was realized that the transfer of angular momentum between the rings and the nearby satellites in these waves was so rapid that neither the moons nor the rings could maintain their present positions for more than about 10^7 years [83]. A related dynamical argument involves Saturn's pair of moons known as the "coorbital satellites", Janus and Epimetheus. These objects are in such close orbits that they cause each other to shift back and forth across the orbital distance of their relative center of mass. In the frame of the larger, the smaller executes a "horseshoe" orbit of a particular angular amplitude. The amplitude of this angular excursion, or libration, depends on the energy of the configuration, and it has been shown that the energy will be damped by density wave interactions to yield a very small amplitude for the libration, if the configuration is as old as the solar system [84]. Most possible loopholes in these dynamical arguments have been closed by improvements in our understanding of the angular momentum transfer process [16]; however, there may be other possible ways out involving as-yet unknown ways to transfer angular momentum and energy from the planet to the rings (eg. [85]), or to resonantly lock the moons at or near their current locations.

An independent short timescale argument comes from the icy purity of Saturn's rings, discussed earlier. The rings are bombarded by a constant infall of interplanetary debris, as is well documented for the Earth at the present time and manifested on the cratered surfaces of airless planets and satellites for eons into the past. The meteoroid population is quite primitive, abundantly endowed with carbonaceous and silicate material. There is, of course, an uncertainty in the flux of this material at Saturn. The best flux estimate comes from experiments on the Pioneer 10 and 11 spacecraft, which suggest a nearly constant volume density out as far as Saturn [86]. It is then possible to estimate that the mass flux of this material into the rings over the age of the solar system as roughly equal to the current mass of the rings, far more than permitted in light of the allowed impurity content of the ring material. In addition to the flux uncertainty, one needs to worry about the persistence of absorbing properties of the infalling material after impact at tens of kilometers per second. If the non-icy material is all dissociated into atoms and lost to the planet, or recombined into nonabsorbing forms (e.g. pure C, Si, Mg, etc. oxides), then timescales may be lengthened somewhat. However, even assuming only 10% of the infalling impurities retain their absorbing nature in the rings, a ring age of only 10^8 years has been inferred by Doyle *et al.* [71].

The generally assumed value of meteoroid flux has some support from the depletion of electrons in the Saturnian ionosphere. This unusual situation has been ascribed to influx of charge-scavenging water vapor molecules from the rings [87], and the only mechanism capable of generating sufficient water vapor is meteoroid impact [18]. This process implies a loss rate of water ice from the rings of about 10^{-15} g cm^{-2} sec^{-1}, comparable to the currently estimated meteoroid mass flux into the rings (which amounts to about a ring mass in the age of the solar system). Impact produced vapor is usually estimated as comparable in mass to the impactor, so this crude agreement is not unreasonable. The ionized fraction of this vapor is subject to immediate loss along magnetic field lines to the planet, and for mass fluxes about an order of magnitude larger than current estimates, a lifetime of $10^7 - 10^8$ years has been derived for the inner B ring due to this process [88].

If meteoroid bombardment does proceed at these rates, yet one more effect shortens the lifetime of material in all ring systems. Whereas relatively small particles ($r < 1$ cm) are easily destroyed by magnetospheric sputtering (at Jupiter), gas drag (at Uranus), or catastrophic impacts (generally), they can be replaced by new ejecta from larger objects. However, even meter-sized objects suffer from orbital decay due to absorption of the meteoroidal mass flux. If the infalling mass has an essentially isotropic orbital distribution (such as the well-known Oort cloud comets), as suggested by the Pioneer 10 and 11 results, it has no preferred direction and thus conveys zero net angular momentum to the rings. If its mass is primarily absorbed by the rings, as seems reasonable, the ensuing decrease in angular momentum per unit mass results in orbital decay. Particles with a centimeter-to-meter size distribution like those in the main rings of Saturn and Uranus drift inwards at a rate of about a centimeter per year [89]. There do not appear to be any moonlets in these regions capable of absorbing this amount of angular momentum [90]. Thus, the entire C ring of Saturn, and the inner rings of Uranus, would be expected to fall into their planets in about 10^8 years. This effect (which depends, of course, on the poorly known meteoroid flux) dominates the widely discussed gas drag torque on the Uranian rings for particles larger than about one centimeter, and applies equally to all four giant planets.

Additional evolutionary processes, involving electromagnetic loss mechanisms, also follow from the presence of microscopic particles (which are the only particles significantly affected by electromagnetic forces) in the rings. It is generally accepted that the radially extended "spokes" seen flickering across the face of the B ring result from temporary enhancements of the fractional abundance of microscopic dust particles from undetectable levels to about one percent [71], and that these enhancements derive from an electrostatic charging process possibly related to meteoroid impacts [91]. An alternative hypothesis for subsequent rapid radial motion of the charged plasma, responsible for levitating the grains from the regoliths of their parent particles over radial distances of 10^4 km in only a few minutes, has been suggested (m=1 electrodynamical instability; [92]).

Generally, the presence in, at least, the spokes, of charged 0.1 - 1 micron sized grains is fairly well accepted. These charged grains receive a net torque from the differentially rotating magnetic field during their lifetime, which is conveyed to the ring region in which they ultimately come to rest. This process is also said to lead to radial drifts on timescales much shorter than the age of the solar system, but suffers from uncertainties due to the poorly known spoke optical depth, dust particle size distribution, and equilibrium particle charge [93].

It might be said that there really are three independent arguments in the set above - dynamical ones relating to ring-moon torques, extrinsic ones related to meteoroid bombardment, and an electromagnetic one based on observed spoke properties. It is possible that, say, the meteoroid flux and the torque models are independently off by an order of magnitude or so in the right direction. However, many workers in the field now look at rings as systems which can not survive for longer than 10 -100 million years, and, unless we live in "the age of rings", must be created and recreated many times over the age of the solar system.

6. Ring origins

The weight of the current evidence does not *prove* the youth of any particular ring, much less that of all ring systems; however, it is highly suggestive and worthy of attention. Within the context of ongoing creation, a scenario for ring origin may be drawn that enjoys a certain plausibility in spite of its speculative nature. The general thread follows that of Harris ([94]).

The formation of the giant planets occurred at a time when particulate and gaseous phases coexisted in the nebula. It has been suggested several times in the past that the process of gas accumulation and collapse of the giant planets themselves may lead to the spinning off of a prograde, equatorial disk of (gaseous and embedded particulate) material (e.g. [95]). It has been claimed that accreting gaseous material prefers prograde circumplanetary orbits; on the other hand, incoming planetesimals show little preference for the prograde direction [96]. Universally prograde satellite-ring systems then imply that these objects probably accreted from an in-situ circumplanetary nebula. No solid material can survive the gas drag in this dense subnebula for long, unless it grows to a size of roughly 100 km or more. We still do not know the details of planetary growth between meters and moonlets, but it clearly has occurred. So, one presumes that near the end of the "nebular" phase of planetary formation, the giant planets were surrounded by a retinue of moons, possibly with a bias toward radii of at least 100 km, and, after a brief period during which the surrounding primordial gas/debris disks were dissipated by (as yet unknown) processes, little else. The smaller of these moons might be of uniform primordial composition, and the larger might be differentiated by the heat of their own formation. This ensemble of moons probably extended all the way in toward the planet due to ongoing radial evolution throughout the entire nebular stage.

The lifetime of a moon to catastrophic disruption is dependent on its size and on the bombarding flux. Moons larger than 100 km radius are especially resistant to breakup, because of their gravitational binding energy. Smaller moons are held together primarily by their material strength, and are destroyed by smaller meteoroidal projectiles which are considerably more numerous. However, this increasing flux is offset by the smaller target cross sections to a degree which depends on the projectile size distribution. The bombarding flux has varied greatly over the age of the solar system, and is smaller at the current epoch than during the period recorded on the surfaces of airless planets and satellites. From (admittedly uncertain) extrapolations of the number densities of large craters on the surfaces of the satellites of the giant planets, it has been shown [97, 98] that moons as large as 100 - 200 km radius receive impacts sufficiently large to destroy them at least several times during the period over which the observed cratering occurred (thought to be primarily in the first billion years of the solar system, based on age dating of lunar geologic features).

The fate of the fragments depends on the location of the parent bodies, and on the energy of the disruptive event. Far from the planet, tidal forces will not prevent the fragments from reaccumulating into a single (probably smaller) satellite. Thus, the five inner classical moons of Saturn may each have reaccumulated several times over in the early years of the solar system. In general, the energy of accumulation seems to have softened the moons sufficiently to allow them to relax into spherical shapes. Hyperion, an unusually irregular fragment, probably escaped this fate due to the gravitational dispersal of other fragments of its parent by Titan before reaccretion could occur [99]. Close to the planet, the interplanetary flux is focussed by the planet to a degree which depends on the relative velocity, given by the orbital distribution of outer solar system objects which contribute to the flux. Current estimates assume a mix of short- and long-period comets captured directly from the Oort cloud [97]. These have fairly large eccentricities and are not concentrated significantly. However, the presence of a large population of inwardly diffusing, low inclination and eccentricity, objects has been suggested [100] to account for the origin of (generally prograde) short period comets. This population, if present, is strongly gravitationally focussed by the planets because of its low relative velocity, and would overwhelm current estimates of the bombarding flux, especially within 2-3 R_{pl}. Some evidence against this population, at least as reflected in the small particle population which most strongly drives ring evolution, is provided by photochemical models of the water and carbon content of the stratospheres of Uranus and Neptune [101]. Consequently, it is difficult at this time to attach great confidence to lifetimes of moons of small and intermediate sizes in this region. However, taking our best current estimates at face value [97, 98], the average lifetime of a 10 km diameter moon at 2 planetary radii (at Neptune) is a few times 10^8 years, and the lifetime of a 100 m object is about ten times shorter. Lifetimes are about ten times longer at Saturn and three times shorter at Uranus, with Saturn's larger mass not quite compensating for the larger projectile flux at Uranus [97]. These lifetimes should be compared to the estimated lifetimes of $10^7 - 10^8$ years being currently estimated for the inner Uranian and Saturnian rings, as mentioned above.

The general case of the Saturn ring system is especially difficult to explain, as noted above, because of its large mass and compositional purity. The mass of Saturn's rings is about equal to the mass of Mimas. The expected lifetime against disruption for such a large object is close to the age of the solar system, making the creation of Saturn's rings in the last 10^8 years an improbable event [98]. A similar alternative (dating back to Roche), involving tidal disruption of a large "comet" suffering a close encounter with the planet, has recently been discussed in the light of current knowledge [102]. It appears to be about equally (un)likely, but doubles the probability that one or the other event actually occurred. Of course, the parent object would have had to have been significantly differentiated, and the bulk of the non-icy material would have to be preferentially removed or hidden from view, but these do not seem to be impossible difficulties. The fact that localized and regional scale compositional differences *are* seen in Saturn's rings is consistent with such a concept. In interesting recent developments, the densities of Saturn's inner ringmoons seem to be significantly less than that of solid water ice [103], suggesting that they may be merely rubble piles of loosely consolidated fragments of prior disruptions. Clearly, considerable effort needs to be devoted to these lines of evidence.

7. Comparative planetology

Practically all of the structural and compositional properties of planetary ring-moon systems can probably be explained by the *same* processes acting under slightly different boundary conditions; this makes them ideal for comparative study. Several successes of the past have been described above. In the future, several other aspects are worthy of study:

The question of transience *vs* confinement for any and all ring features should be approached objectively. Clumpy features which may help clarify this distinction are found in the systems of Saturn, Uranus, and Neptune, and few have been studied in detail. Comparing their structures and, in some cases, subsequent evolution, could tell us which are really transient or lead to new understanding about confinement.

If rings are transient, their creation and re-creation relies on impact disruption of small moons, and the rates at which this happens in the different systems are strongly tied to the projectile populations in the outer solar system. A better understanding of these objects (number densities and orbital configurations, from submillimeter to kilometer sizes) is greatly needed. This might be garnered from more extensive studies and interpretation of crater counts on the surfaces of the satellites. Stratospheric photochemistry might also provide constraints. Variation of this population between Jupiter and Neptune might provide new understanding to questions of the evolution of the Kuiper belt and the origin of short-period comets.

Improved theoretical modeling of viscous transport in particle disks, including realistic size distributions and all important processes, is required; a better understanding of viscosity may help us resolve many of these uncertainties regarding the B ring fine structure. Considerable information remains to be extracted from realistic radiative transfer modeling of regions in the rings of Uranus and Saturn;

it may be possible to infer their volume density, with important implications for local dynamics. Because different ring systems vary in particle size, optical depth, and state of excitation, a complete theory will only be developed by relating to all known ring systems.

Groundbased spectral reflectivity measurements of all planetary rings are needed to understand their origin and evolution. In the years to come, these should be feasible as far as Uranus. In the case of Saturn's rings, regional variations in important constituents can be mapped out. The stability and compositional purity of Saturn's rings for times longer than $10^7 - 10^8$ years remains an issue of special concern, due to the difficulty of avoiding contamination and the improbability of creating such a massive system so recently. Comparisons of these spectra with those of better studied objects will help trace the evolution of rings - are they dominated by infall? What is the nature of the reddish material in Saturn's rings and how does it differ from the reddish colorant in the Jovian rings?

In the long term, one expects the Cassini orbiter mission to remove most of the uncertainties currently besetting us in the area of inferring ring origin. Nevertheless, a considerable amount of preparatory work, both theoretical and observational, remains to be done in the next decade.

Acknowledgements

I owe a great debt to Dr. James B. Pollack, who was a stimulating and supportive mentor and colleague during the years in which I became deeply involved in studies of planetary rings. Although rings, of course, were only one of Jim's wide-ranging interests, he personally made several key creative contributions to the subject. His insight led to the realization that wavelength-sized ice particles could resolve the "radio-radar paradox" which had everyone else stumped 20 years ago. No doubt, Jim will be often and fondly remembered in the Cassini era for these and his many other contributions.

Bibliography

1. Jupiter: J. A. Burns, M. R. Showalter, and G. E. Morfill (1984), in "Planetary Rings"; Univ. of Arizona Press; J. A. Burns, M. R. Showalter, J. N. Cuzzi, and J. B. Pollack (1980), Icarus, 44, 339-360; M. R. Showalter, J. A. Burns, J. N. Cuzzi, and J. B. Pollack (1985); Nature, 316, 526-528; M. R. Showalter, J. A. Burns, J. N. Cuzzi, and J. B. Pollack (1987); Icarus, 69, 458-498

2. Saturn: J. N. Cuzzi, J. J. Lissauer, L. W. Esposito, J. B. Holberg, E. A. Marouf, G. L. Tyler, and A. Boischot (1984), in "Planetary Rings"; Univ. of Arizona Press; L. W. Esposito, J. N. Cuzzi, J. B. Holberg, E. A. Marouf, G. L. Tyler, and C. C. Porco (1984), in "Saturn"; Univ. of Arizona Press

3. Uranus: J. L. Elliot and P. D. Nicholson (1984) in "Planetary Rings"; Univ. of Arizona Press; R. C. French, P. D. Nicholson, C. C. Porco, and E. A. Marouf (1990), in

"Uranus"; Univ. of Arizona Press; L. W. Esposito, A. Brahic, J. A. Burns, and E. A. Marouf (1990), in "Uranus"; Univ. of Arizona Press. J. N. Cuzzi and L. W. Esposito, Scientific American, July 1987

4. Neptune: Porco, C. C., P. D. Nicholson, J. N. Cuzzi, J. J. Lissauer, and L. W. Esposito (1994) in "Neptune and Triton", University of Arizona Press, D. Cruikshank and M. S. Matthews, eds.; *cf* also J. Geophys. Res. 96, Supplement, October 30 1991; E. Stone and E. Miner (1989), Science, 246, 1417-1421; B. A. Smith *et al. ibid.*, 1422-1450; A. L. Lane *et al. ibid.*, 1450-1454

5. General review articles: P. Goldreich and S. Tremaine (1982), Ann. Revs. Astron. Astrophys., 20, 249-283; J. J. Lissauer and J. N. Cuzzi (1985), in "Protostars and Planets II", University of Arizona press; P. D. Nicholson and L. Dones (1991), Revs. Geophys., Supplement, U. S. National Report to the I.U.G.G., April 1991, 313-327; L. W. Esposito (1993) Ann. Revs. Earth Planet. Science; 21, 487-523; C. C. Porco (1995) Revs. Geophys., Supplement, U. S. National Report to the I.U.G.G., in press

6. Pollack, J. B., A. L. Summers, and B. Baldwin (1973), Icarus, 20, 263-278; J. B. Pollack (1975), Space Sci. Revs., 18, 3-93; J. B. Pollack and J. N. Cuzzi, Scientific American, November 1981

7. Araki, S. and S. Tremaine (1986), Icarus, 65, 83-109; J. Wisdom and S. Tremaine (1988), Astron. J. 95, 925-940; N. Borderies, P. Goldreich, and S. Tremaine (1985), Icarus, 63, 406-420; F. H. Shu, L. Dones, J. J. Lissauer, C. Yuan, and J. N. Cuzzi (1985), Astrophys. J., 299, 542-573

8. Dones, L., M. R. Showalter, and J. N. Cuzzi (1989), in "Astrophysical Disks, J. Sellwood, ed., p. 25-26; Cambridge. Univ. Press

9. Salo, H. (1991) Icarus, 90, 254-270; (1992a) Icarus, 96, 85-106; (1992b) Nature, 359, 619-621; Richardson, D. C. (1994) Mon. Not. Roy. Astron. Soc., in press

10. Stewart, G. R., D. N. C. Lin, and P. Bodenheimer (1984), in "Planetary Rings", University of Arizona press; R. Greenberg (1988), Icarus, 75, 527-539; *cf.* also G. R. Stewart and G. Wetherill (1988), Icarus, 74, 542-553

11. Franklin, F. W., M. Lecar, and W. Wiesel (1984), in "Planetary Rings", University of Arizona press; F. H. Shu (1984), *ibid.*

12. Shu, F. H., J. N. Cuzzi, and J. J. Lissauer (1983), Icarus, 53, 185; S. K. Chakrabarti (1989), Mon. Not. Roy. Ast. Soc. 238, 1381-1394

13. Goldreich, P. and S. Tremaine (1980) Astrophys. J., 241, 425-441; Sicardy, B. (1991), Icarus, 89, 197-219

14. Borderies, N., P. Goldreich, and S. Tremaine (1983), Astron. J., 88, 1560 - 1568; S. F. Dermott (1984), in "Planetary Rings", University of Arizona press; P. Goldreich and C. C. Porco (1987), Astron. J., 93, 730-737

15. Lissauer, J. J. (1985), Nature, 318, 544-545; P. Goldreich, S. Tremaine, and N. Borderies (1986), Astron. J. 92, 490; D. N. C. Lin, J. Papaloizou, and P. Bodenheimer (1987); M. N. R. A. S. 227, 75; Porco, C. C. (1991) Science, 253, 995-1001

16. Meyer-Vernet, N. and B. Sicardy (1987), Icarus, 69, 157-175; R. Greenberg (1983), Icarus, 53, 207-218;

17. Lissauer, J. J., F. H. Shu, and J. N. Cuzzi (1984), in "Anneaux des Planetes", Cepadues Editions, Toulouse; L. W. Esposito (1986), Icarus, 67, 385-392; S. K. Chakrabarti (1989), Mon. Not. Roy. Ast. Soc. 238, 1381-1394; P. A. Rosen, G. L. Tyler, E. A. Marouf, and J. J. Lissauer (1991), Icarus, 93, 25-44

18. Morfill, G. E., H. Fechtig, E. Grün, and C. K. Goertz (1983), Icarus, 55, 439-447; W.-H. Ip (1983), Icarus, 60, 547-552; R. H. Durisen (1984), in "Planetary Rings", University of Arizona Press; E. Grün, H. A. Zook, H. Fechtig, and R. H. Giese (1985) Icarus, 62, 244-272; J. N. Cuzzi and R. H. Durisen (1990), Icarus, 84, 467-501

19. Burns, J. A., L. E. Schaffer, R. J. Greenberg, and M. R. Showalter (1985), Nature, 316, 115-119; J. A. Burns and L. E. Schaffer (1989), Nature, 337, 340-343; see also refs 77.

20. Northrop, T. G., and J. R. Hill (1982), J. Geophys. Res. 87, 6045; W.-H. Ip (1983), J. Geophys. Res. 88, 819-822

21. Smith, B. A., *et al.* (1982); Science, 215, 504-537; Doyle, L. R., L. Dones, and J. N. Cuzzi (1989), Icarus, 80, 104-135; L. A. Horn and J. N. Cuzzi (1994), Icarus, submitted; Estrada, P. and J. N. Cuzzi, Icarus, in press, 1994.

22. Grün, E., G. E. Morfill, and D. A. Mendis (1984), in "Planetary Rings", University of Arizona Press; C. K. Goertz (1989), Revs. Geophys. 27, 271-292

23. Acuna, M. H., and N. F. Ness (1976), J. Geophys. Res., 81, 2917-2922; T. Owen, G. E. Danielson, A. F. Cook, C. Hansen, V. L. Hall, and T. C. Duxbury (1979), Nature, 281, 442-446; B. A. Smith *et al.* (1979), Science, 204, 951-971; B. A. Smith et al. (1979), Science, 206, 927-950

24. Showalter, M. R., J. A. Burns, J. N. Cuzzi, and J. B. Pollack (1985); Nature, 316, 526-528; Showalter, M. R., J. A. Burns, J. N. Cuzzi, and J. B. Pollack (1987); Icarus, 69, 458-498

25. J. A. Burns, M. R. Showalter, J. N. Cuzzi, and J. B. Pollack (1980), Icarus, 44, 339-360; Burns, J. A., M. R. Showalter, and G. E. Morfill (1984), in "Planetary Rings"; Univ. of Arizona Press

26. Nicholson, P. D. and K. Matthews (1991) Icarus, 93, 331-346

27. Elliot, J. L., E. W. Dunham, and D. J. Mink (1977), Nature, 267, 328-330; Millis, R. L., L. H. Wasserman, and P. Birch (1977), *ibid.*, 330-331

28. Goldreich, P. and S. Tremaine (1979), Nature, 277, 97-99; N. Borderies, P. Goldreich, and S. Tremaine (1984), in "Planetary Rings", University of Arizona press.

29. see, e.g Dermott, S. F., C. D. Murray, and A. T. Sinclair (1979), Astron. J., 84, 1225-1234; Dermott, S. F. (1984) in "Planetary Rings", G. Greenberg and A. Brahic, eds, Univ. of Arizona Press, for a different viewpoint

30. Gehrels, T. *et al.* (1980), Science, 207, 434-439; B. A. Smith *et al.* (1981), Science, 212, 163-191; B. A. Smith *et al.* (1982), Science, 215, 504-537; J. J. Lissauer and J. N. Cuzzi (1985), in "Protostars and Planets II", University of Arizona press

31. Simpson, J. A. *et al.* (1980), J. Geophys. Res. 85, 5731-5762; J. A. Van Allen (1982), Icarus, 51, 509-527; J. A. Van Allen (1984), in "Saturn", University of Arizona Press

32. Showalter, M. R., and J. A. Burns (1982), Icarus, 52, 526-544; *cf.*, however, J. J. Lissauer and S. Peale (1986), Icarus, 67, 358-374

33. Cuzzi, J. N., and J. A. Burns (1988), Icarus, 74, 284-324

34. Kolvoord, R. A., J. A. Burns, and M. R. Showalter (1990) Nature, 345, 695-697

35. Lissauer, J. J., F. H. Shu, and J. N. Cuzzi (1981) Nature, 292, 707-711; M. Henon (1981) Nature 293, 33-35; also (1984) in "Anneaux des Planetes", Cepadues-Editions, Toulouse, 365-384

36. Smith, B. A. *et al.* (1982); Science, 215, 504-537

37. Cuzzi, J. N. and J. D. Scargle (1985); Astrophys. J. 292, 276-290; M. R. Showalter, J. N. Cuzzi, E. A. Marouf, and L. W. Esposito (1986) Icarus, 66, 297-323

38. Showalter, M. R. (1991) Science, 351, 709-713

39. Flynn, B. C. and J. N. Cuzzi (1989) Icarus 82, 180-199; E. A. Marouf and G. L. Tyler (1986) Nature, 323, 31-35

40. Owen, W. M. and S. L. Synnott (1987) Astron. J. 93, 1268-1271

41. Weidenschilling, S. J., and D. R. Davis (1985) Icarus, 62, 16-29; Weidenschilling, S. J., and A. A. Jackson (1993) Icarus, 104, 244-254

42. Smoluchowski, R. (1979) Nature 280, 377-378

43. Dobrovolskis, A. R. (1990) Icarus, 88, 24-38

44. Dones, L. (1991) Icarus, 92, 194-203; Boss, A. P., A. G. W. Cameron, and W. Benz (1991) Icarus, 92, 165-178; Sridhar, S. and S. Tremaine (1992) Icarus, 95, 86-99; Asphaug, E. and W. Benz (1994) Nature, in press.

45. Borderies, N., P. Goldreich, and S. Tremaine (1983), Astron. J. 88, 1560-1568; also (1983) Icarus, 55, 124-132; also (1984), in "Planetary Rings", University of Arizona Press; also (1985) Icarus, 63, 406-420

46. Porco, C. C. and P. Goldreich (1987), Astron. J. 93, 724-729; Goldreich, P. and C. C. Porco (1987), ibid, 730-736

47. Borderies, N., P. Goldreich, and S. Tremaine (1982) Nature, 299, 209-211

48. Fridman, A. M. and N. N. Gor'kavyi (1989) Sov. Sci. Rev. A. Phys., 12, 289-346

49. Marouf, E. A. *et al.* (1988), B. A. A. S. 20, 845; Gresh, D. L. (1990), Thesis, Stanford University; Murray, C. and R. P. and Thompson (1990) Nature, 348, 499-502

50. Reitsema, H. J. *et al.* (1982), Science, 215, 289; C. E. Couvault *et al.* (1986) Icarus, 67, 126; W. B. Hubbard *et al.* (1986) Nature 319, 636; Smith, B. A. *et al.* (1989), Science, 246, 1422-1449

51. Porco, C. C. (1991) Science, 253, 995-1001

52. Porco, C. C., P. D. Nicholson, J. N. Cuzzi, J. J. Lissauer, and L. W. Esposito (1994) in "Neptune and Triton", University of Arizona Press, D. Cruikshank and M. S. Matthews, eds.; Sicardy, B., and J. J. Lissauer (1992) Adv. Sp. Res. 12, 81-95

53. Gor'kavyj, N. N. (1991) Sov. Astron. Lett 17, 428-432; Gor'kavyj, N. N. and T. A Taidakova (1991) Sov. Astron. Lett 17, 462-645; Gor'kavyj, N. N. T. A Taidakova, and N. M. Gaftonyuk (1991) Sov. Astron. Lett 17, 457-461

54. Smith, B. A. *et al.* (1989), Science, 246, 1422-1449; Ferrari, C. and A. Brahic (1994) Icarus, in press

55. Ockert, M. E., J. N. Cuzzi, C. C. Porco, and T. V. Johnson (1987) J. Geophys. Res. 92, 14969-14978; also (1988), B. A. A. S. 20, 854; J. E. Colwell *et al.* (1990) Icarus, 83, 102-125; Showalter, M. R. Icarus, submitted (1994)

56. French, R. C., J. A. Kangas, and J. L. Elliot (1986) Science, 231, 480-483; French, R. C., P. D. Nicholson, C. C. Porco, and E. A. Marouf (1990), in "Uranus"; Univ. of Arizona Press

57. Borderies, N., P. Goldereich, and S. Tremaine (1983), Astron. J. 88, 1560-1568; also (1983), Icarus, 55, 124-132; also (1985) Icarus, 63, 406-420

58. French, R. C., J. L. Elliott, and D. A. Allen (1982), Nature 298, 827-829

59. Colombo, G. P. Goldreich, and A. W. Harris (1976) Nature 264, 344-346; N. N. Gor'kavyi and T. A. Taydakova (1989), Pic'ma V. AZh, 15, 547-553 (in Russian, translation available; NASA TT-20576); L. Dones and C. C. Porco (1989) B. A. A. S., 21, 929

60. Salo, H, (1992) Nature, 359, 619-621

61. Horn, L. A., J. Hui, and J. N. Cuzzi (1989) B. A. A. S. 21, 928; L. A. Horn and J. N. Cuzzi (1994), Icarus, submitted

62. Lin, D. N. C. and P. Bodenheimer (1981), Astrophys. J., 248, L83; W. R. Ward (1981) Geophys. Res. Lett. 8, 641

63. Wisdom, J. and S. Tremaine (1988), Astron. J. 95, 925-940; Richardson, D. C. (1994) Mon. Not. Roy. Astron. Soc., in press; Borderies, N., P. Goldreich, and S. Tremaine (1985) Icarus, 63, 406-420

64. Borderies, N., P. Goldreich, and S. Tremaine (1983), Astron. J. 88, 1560-1568; also (1985) Icarus, 63, 406-420

65. Durisen, R. H., N. L. Cramer, B. W. Murphy, J. N. Cuzzi, T. L. Mullikin, and S. E. Cederbloom (1989) Icarus, 80, 136-166; Durisen, R. H., P. W. Bode, J. N. Cuzzi, S. E. Cederbloom, and B. W. Murphy (1992) Icarus, 100, 364-393

66. Goertz, C. K. and G. E. Morfill (1988), Icarus 74, 325-330; Goertz, C. K. (1990) Personal communication

67. Pollack, J. B., A. L. Summers, and B. Baldwin (1973) Icarus, 20, 263-278; J. N. Cuzzi and J. B. Pollack (1978) Icarus, 33, 233-263; J. N. Cuzzi, J. B. Pollack, and A. L. Summers (1980) Icarus, 44, 683-705; F. P. Schloerb, D. O. Muhleman, and G. L. Berge (1980) Icarus 42, 125-135; E. E. Epstein, M. A. Janssen, and J. N. Cuzzi (1984) Icarus, 58, 403-411

68. Marouf, E. A., G. L. Tyler, H. A. Zebker, and V. R. Eshleman (1983) Icarus, 54, 189 - 211; Zebker, H. A., E. A. Marouf, and G. L. Tyler (1985) Icarus, 64, 531-548

69. Showalter, M. R. and P. D. Nicholson (1990) Icarus, 87, 285-306

70. A. L. Grossman, D. O. Muhleman, and G. L. Berge (1989), Science, 245, 1211 - 1215.

71. Doyle, L. R., L. Dones, and J. N. Cuzzi (1989), 80, 104-135; L. Dones, personal communication (1990) (*cf.* also A. Grossman, Ph. D. Thesis, Caltech, 1988; A. Verbischer, P. Helfenstein, and J. Veverka (1990), Nature, 347, 162-164)

72. Estrada, P. and J. N. Cuzzi (1994), Icarus, in press; Cuzzi, J. N. and P. Estrada (1995) in preparation

73. Cuzzi, J. N. (1985) Icarus, 63, 212-215; M. E. Ockert, J. N. Cuzzi, C. C. Porco, and T. V. Johnson (1987) J. Geophys. Res. 92, 14969-14978; C. C. Porco, J. N. Cuzzi, M. E. Ockert, and R. J. Terrile (1987) Icarus, 72, 69-78; T. Svitek and G. E. Danielson (1987), J. Geophys. Res. ,92, 14979-14987

74. Strazzulla, G., L. Calcagno, and G. Foti (1983), M. N. R. A. S., 204, 59; L. J. Lanzerotti, W. L. Brown, and R. E. Johnson (1985), in "Ices in the Solar System", Reidel, Dordrecht; W. R. Thompson, B. Murray, B. N. Khare, and C. Sagan (1987), J. Geophys. Res. 92, 14933

75. Ferrari, C. and A. Brahic (1994), Icarus, in press; Porco, C. C., P. D. Nicholson, J. N. Cuzzi, J. J. Lissauer, and L. W. Esposito (1994), in "Neptune and Triton", University of Arizona Press.

76. Pang, K. D., C. Voge, J. W. Rhoads, and J. M. Ajello (1984) J. Geophys. Res. 89, 9459-9470; Showalter, M. R., J. N. Cuzzi, and S. M. Larson (1991), Icarus, 94, 451-473

77. Horanyi, M., J. A. Burns, and D. Hamilton (1992) Icarus, 97, 248-259; Hamilton, D. and J. A. Burns (1994); Science 264, 550-553.

78. Ockert, M. E., J. N. Cuzzi, C. C. Porco, and T. V. Johnson (1987) J. Geophys. Res. 92, 14969-14978; Dones, L., Cuzzi, J. N., and M. R. Showalter (1993) Icarus, 105, 184 - 215; D. L. Gresh, E. A. Marouf, G. L. Tyler, P. A. Rosen, and R. A. Simpson (1989), Icarus, 78, 131-168; Doyle, L. R., L. Dones, and J. N. Cuzzi (1989), 80, 104-135

79. Showalter, M. R., J. B. Pollack, M. E. Ockert, L. R. Doyle, and B. Dalton (1992) Icarus, 100, 394-411

80. Esposito, L. W. and J. E. Colwell (1989), Nature, 339, 605-607; J. E. Colwell and L. W. Esposito (1990), Icarus, 86, 530-560; also (1990), Geophys. Res. Lett, 17, 1741-1744

81. Weidenschilling, S. J., C. R. Chapman, D. R. Davis, and R. Greenberg (1984), in "Planetary Rings", Univ. of Arizona Press.

82.. Longaretti, P.-Y. (1989) Icarus, 81, 51-73

83. Goldreich, P. and S. Tremaine (1982), Ann. Revs. Astron. Astrophys., 20, 249-283

84. Lissauer, J. J., P. Goldreich, and S. Tremaine (1985), Icarus, 64, 425-434

85. Marley, M. R., and C. C. Porco (1993) Icarus 106, 508-524

86. Humes, D. H. (1980), J. Geophys. Res. 85, 5841-5852

87. Connerney, J. E. P. and J. H. Waite (1984) Nature, 312, 136-138

88. Northrop, T. E. and J. E. P. Connerney (1987) Icarus, 70, 124-137

89. Ip, W.-H. (1983) Icarus, 60, 547-552; Lissauer, J. J. (1984) Icarus, 57, 63-71; Cuzzi, J. N. and R. H. Durisen (1990), Icarus, 84, 467-501

90. Esposito, L. W., A. Brahic, J. A. Burns, and E. A. Marouf (1990); In "Uranus", J. T. Bergstralh, ed. University of Arizona Press

91. Goertz, C. K. and G. E. Morfill (1983) Icarus 53, 219-229

92. Tagger, M., R. N. Henriksen, J. F. Sygnet, and R. Pellat (1990) Astrophys. J. 353, 654-657; also M. Tagger, R. N. Henriksen, and R. Pellat (1990) Icarus, 91, 297-314

93. Goertz, C. K., G. E. Morfill,W. Ip, E. Grün, and O. Havnes (1986), Nature, 320, 141-143

94. Harris, A. W. (1984) in "Planetary Rings", University of Arizona Press

95. Pollack, J. B. (1985) in "Protostars and Planets II", University of Arizona Press; Korycansky, D., P. Bodenheimer, and J. B. Pollack (1991), Icarus, 92, 234-251

96. Nishida, S. (1983) Progr. Theor. Physics, 70, 93-105; Lissauer, J. J. and D. M. Kary (1991), Icarus 94, 126-159

97. Smith, B. A. *et al.* (1981), Science, 212, 163-191; B. A. Smith *et al.* (1982), Science, 215, 504-537; B. A. Smith *et al.* (1986), Science, 233, 43-64; B. A. Smith *et al.* (1989), Science, 246, 1417-1421

98. Lissauer, J. J., S. Squyres, and W. R. Hartmann (1988) J. Geophys. Res. B, 93, 13776-13804; Colwell, J. E., and L. W. Esposito (1992) J. Geophys. Res. E (Planets), 97, 10227-10241; Colwell, J. E., and L. W. Esposito (1993) J. Geophys. Res. E (Planets), 98, 7387-7401

99. Farinella, P., A. Milani, A. M. Nobili, P. Paolicchi, and V. Zappala (1983) Icarus, 54, 353-360

100. Duncan, M., T. Quinn, and S. Tremaine (1988) Astron. J., 328, L69-L73

101. Moses, J. J. (1992) Icarus, 99, 368-383; Lyons, J. R. (1994) B.A.A.S. 26, 1093; also GRL, submitted

102. Dones, L. (1991) Icarus, 92, 194-203

103. Rosen, P. A., G. L. Tyler, E. A. Marouf, and J. J. Lissauer (1991) Icarus, 93, 25-44; Nicholson, P. D., D. P. Hamilton, K. Matthews, and C. Yoder (1992) Icarus, 100, 464-484; Yoder, C. F., S. P. Synnott, and H. Salo (1989) Astron. J. 98, 1875-1889