An Evolving View of Saturn’s Dynamic Rings


Abstract: The rings of Saturn are composed mostly of water ice but contain small amounts of an unknown reddish contaminant. They exhibit a wide range of structure across many spatial scales. Some of this structure can be traced to the interplay of the fluid nature and the self-gravity of innumerable orbiting cm-m size particles, and the effects of a tribe of peripheral and embedded moonlets, but much remains unexplained. It is actively debated whether the vigorous evolutionary processes to which the rings are subject mean they are much younger than the solar system. Observations of the rings by the Cassini spacecraft over the past five years, combined with key observations from Earth and even the Voyager flybys of decades ago, reveal the dynamic, constantly changing nature of many aspects of ring structure on timescales as short as years, months, and even days. Many processes on view have parallels in protoplanetary disks.

Introduction: Saturn, the jewel of our solar system, is encircled by an extensive ring system that, like the rings surrounding Jupiter, Uranus and Neptune, resides within a Roche zone where tides from the parent planet frustrate aggregation of the ring particles into larger bodies (Canup and Esposito 1995). Moreover, a number of 1-100 km moons are interspersed within, and along, the peripheries of all four systems. Saturn’s rings are distinguished by their far greater mass, and by the purity of their icy particles – inconsistent with the unprocessed primordial mixture of ice, rock, and carbon-rich organics of which the other ring systems seem to be made. A bewildering diversity of structure permeates Saturn’s main rings (Fig. 1)², which include the A ring, separated from the massive B ring by the Cassini Division – itself a ring in all meaningful ways – inwards through the C ring and the nearly invisible D ring. A transition region beyond the A ring contains the wildly complex, multi-stranded F ring, and arrayed yet farther outside the main rings are several diffuse rings composed of minute amounts of rubble and microscopic

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2 The “optical thickness” or “optical depth” τ of a ring of randomly distributed particles is defined as \( \tau = \int n(r) \pi r^2 \, dr \), where \( n(r) \) is the vertically integrated number density per radius increment for particles of radius \( r \), and we have assumed that the ring particles are much larger than the wavelength of light. For small number densities, this is effectively the surface area of particles per unit ring area. Usually this is expressed as the “normal” optical depth, corresponding to rays arriving perpendicular to the mean plane of the rings.
“dust”. Within this diversity can be found structures analogous to most of those present in the other three ring systems.

The Voyager-era (1980s) perspective was that today’s planetary ring systems cannot be primordial, but must be continuously regenerated from their local arrays of moonlets, through vigorous evolutionary processes (Harris 1984, Charnoz et al. 2009b). To create the narrow rings of Uranus, for instance, or the diffuse rings of Jupiter or Neptune, merely requires destroying a 1-10 km-diameter moonlet by impact with a heliocentric interloper. The ongoing evolution suggests that Saturn’s rings, or parts thereof, might be only one-tenth the solar system’s age – a greater challenge given their large mass. Just how Saturn’s rings formed, and when, remain the most basic questions driving their exploration by the ongoing Cassini-Huygens mission (see SOM1). An emerging perspective, after more than five years of study, is that Saturn’s rings also show dramatic variability on much shorter timescales – decades, years, even weeks! The physics driving the evolution of Saturn’s rings and causing its structure has parallels with the processes active in protoplanetary disk evolution.

**Microstructure:** The story of ring structure begins with dynamics at the smallest level – interactions between individual ring particles. Voyager and Earth-based occultations\(^3\) revealed a broad ring particle size distribution extending from centimeters to meters radius, well-modeled by a power-law having equal particle area per decade in radius (see SOM2). Cassini’s three-frequency radio occultations disclose rich radial variability in the abundance of the centimeter-size particles across the system (Cuzzi et al. 2009). Rings B and inner A appear relatively devoid of these small particles compared with the C and outer A rings. Their abundance in the outer ring A increases dramatically with ring radius. The very short lifetimes of particles in this size range to various evolutionary processes suggest that sizes are determined by an active accretion-destruction cycle (Davis et al. 1984, Longaretti 1989) and are not primordial; thus any radial variations indicate ongoing dynamics (Schmidt et al. 2009).

\(^3\) In an occultation, the signal from a star (Cassini observes occultations in ultraviolet and infrared radiation) or the spacecraft (the microwave transmission) is “occulted” when the source appears to pass behind the rings as seen from the observer. The spatial footprint of the source on the rings is the smeared Fresnel-zone size (geometric mean of the wavelength and distance to the observer) and is generally tens of meters, comparable to the size of the largest particles in the rings. Thus stellar and radio occultations are key tools in ascertaining ring microstructure.
Particles closer to Saturn experience stronger gravity and move faster than those further out, generating Keplerian velocity shear across the ring. Collisions between particles, from a few to hundreds of times per orbit, are basic to local ring dynamics (Schmidt et al. 2009). Although the icy particles orbit Saturn at \( \approx 20 \) km/s, impacts occur at merely \( 0.01 - 0.1 \) cm/s. These collisions are inelastic, damping relative motions of the ring particles; this circularizes their orbits and flattens the system towards the planet’s equator plane. Meanwhile, these small random motions are replenished by collisions and gravitational encounters with large particles and clumps of particles, ultimately deriving energy from the overall orbital motion. The vertical excursions of particles out of the plane arising from this small random velocity establish a ring thickness of a few tens of meters at most (SOM2; Schmidt et al. 2009). In low- to medium-tau regions, the ring kinetically behaves like a dense gas of macroscopic particles, with the random velocity corresponding to gas temperature; pressure and viscosity can be assigned to the ring material as well (see SOM2-4 for examples of liquid, or even solid, behavior). Most observed ring structure is created by the interplay between ring fluid dynamics and gravitational forces. Compared to other astrophysical disks (galaxies, protoplanetary disks), Saturn's rings are extremely flat or dynamically “cold” owing to frequent inelastic collisions. Accordingly, the ring’s self-gravity is sufficiently strong compared to pressure forces to foster widespread, small-scale, gravitational instability.

Self-gravity wakes: For decades, the A ring’s brightness has been observed to vary systematically with longitude\(^4\) (Colwell et al. 2009). Motivated by studies of galactic disks, the underlying structure was explained by gravitational instabilities, where ring particles clump under their mutual self-gravity. In the A ring, Saturn’s tides then stretch these clumps into elongated “self-gravity wakes” having a characteristic cant angle of 20-30° to the local orbital motion (Fig. 2; SOM3). This clumping of particles, now studied in detail in Saturn’s rings with Cassini observations, is analogous to planetesimal formation through gravitational instabilities in the protoplanetary disk. However, in the protoplanetary case, the surrounding nebula gas (missing in the rings) has much greater influence, while tidal forces have a lesser effect.

\(^4\) The A-ring quadrants immediately after an observer’s noon and midnight are up to tens of percent dimmer than the other two. The exact amplitudes depend on wavelength and the elevations of the observer and of the Sun as seen from Saturn.
Cassini’s stellar and radio occultations and images (Colwell et al. 2009) have revealed self-gravity wakes to be ubiquitous throughout the A and B rings (but apparently absent elsewhere). For example, light is transmitted through optically thick regions of the B ring even at incidence angles so low that a homogeneous swarm of particles would be predicted to be almost completely opaque. This implies that the rings comprise dense self-gravity wakes packed with particles, situated within less densely populated “gaps” containing isolated particles. The light transmitted through the rings is thus controlled primarily by the gap sizes relative to the wakes, and secondarily by the optical depth of material within the gaps (Colwell et al. 2006, 2007, Hedman et al. 2007c, Nicholson and Hedman 2009, Tiscareno et al. 2009a). In optically thick regions of the B ring, for example, the opaque wakes cover ~80% of the ring surface area, separated by gaps with a normal optical depth of ~0.2. Analysis of occultation data, using simple models for the wake dimensions, suggests a wake height of less than 10 m and in some regions below 5 m - indicating the wakes are flattened relative to their lateral extent and consistent with direct measurements of ring edge thicknesses via occultations. Occultation data have been widely used to derive the ring’s surface mass density, but the bulk of the ring mass may be concealed in ubiquitous, opaque, and inter-fingering wakes (Robbins et al. 2009, Fig. 2).

**Overstability:** In the A and B rings Cassini discovered organized, axisymmetric wave-like structures having only a few hundred meters radial length scale (Porco et al. 2005, Thomson et al. 2007, Colwell et al. 2007). These features appear to be periodic and, in contrast to self-gravity wakes, show no measurable cant angle relative to the orbital direction. This axisymmetric structure may arise spontaneously from an oscillatory instability or “overstability” (Schmit and Tscharnuter 1995) if the ring’s viscosity increases rapidly enough with its surface mass density (Fig. 2 and SOM4). Since the requisite density is present across most of the B ring, overstabilities were predicted throughout it (Schmit and Tscharnuter 1995, Salo et al. 2001, Schmidt et al. 2001). However, although Cassini radio occultation data (Thomson et al 2007) identify candidate structures routinely in the B ring, it is not always present. Thus it remains unclear what could make parts of this ring overstable and others (with otherwise similar properties) not. Perhaps strong self-gravity wakes locally prevent overstability (Salo et al. 2001, Schmidt et al. 2009). In any case, the easily visible, so-called “irregular structure” that permeates the entire B ring (Colwell et al. 2009; Fig. 1) has a radial scale ≥ 100 km, far too large to be explained by these overstabilities. Its cause remains unknown (see, however, SOM11).
Spiral density and bending waves: Saturn’s satellites, orbiting beyond the rings or in gaps within the rings, can excite spiral waves at locations where the orbital frequencies of ring particles are commensurate with those of the perturbing moon (see SOM5). At these resonances, ring particle orbits can be perturbed either within or perpendicular to their orbit planes, resulting in compression (density) or transverse (bending) disturbances, respectively. These disturbances are transmitted by the ring’s local self-gravity, propagating as spiral waves until damped by viscous effects (Tiscareno et al. 2007; SOM5). After their prediction by analogy with galactic features, numerous spiral waves were detected by Voyager and Cassini, especially in the A ring (which, being closer to the perturbing moons, contains abundant resonant locations) but also in the B and C rings. Spiral waves in rings are much more tightly wrapped than their galactic counterparts because the mass of the rings is so small compared to the mass of the central planet (Fig. 3). Spiral bending waves (Shu et al. 1983) are excited at resonances with inclined moons, particularly Mimas, causing a vertical corrugation of the ring with amplitudes as large as 1 km.

The local surface mass density – a critical property for understanding ring evolution– is directly inferred from the wavelengths of spiral density and bending waves. Cassini has detected waves much weaker than those seen by Voyager; these better obey the linear theory from which local surface density is most easily derived (Tiscareno et al. 2007; SOM5). The inner-to-mid-A ring is characterized by densities \( \sim 40 \text{ g/cm}^2 \), while densities in the Cassini Division are only a few g/cm\(^2\) (Colwell et al. 2009). Comparing the mass densities with the corresponding optical depths reveals significant regional variations in the particle sizes (e.g., more small particles in the C ring and Cassini division), consistent with radio occultation results (Colwell et al. 2009, Cuzzi et al. 2009). The damping of spiral density waves measures the rings’ viscosity, which arises from interparticle collisions plus Keplerian shear and increases outwards in the A ring (Tiscareno et al. 2007, Colwell et al. 2009), suggesting a gradually increasing contribution of self-gravity wakes to the total viscosity of the ring (Daisaka et al. 2001; SOM2). Viscosity also constrains the vertical thickness of the rings: 3-6 meters in the Cassini division (Colwell et al. 2009) and less than 10-15 meters in the inner A ring (Tiscareno et al. 2007). The amplitudes of spiral density waves as well indicate the masses of the moons that drive them (see SOM5).

The self-gravity wakes (Fig. 2), 40-60 m in the radial length-scale, are much smaller than the spiral density waves propagating through regions where they are common, so all material in the wakes should contribute to the surface mass densities calculated from the waves. Moreover,
the wake length scale itself is diagnostic of the local surface mass density, providing an
independent check. The central B ring contains regions that are too opaque for wake length
scales to be determined, and they are only sparsely sampled by spiral density waves. Thus the
local surface mass density in the central B ring is essentially unconstrained and could be twice
historical estimates, or even more (Robbins et al. 2009).

Spiral density waves transfer angular momentum between the rings and the forcing
moons; consequently, the orbits of the perturbing moons evolve outward, while those of the ring
particles decay inward, at rates that limit the possible age of the ring-moon system. The
magnitude of this effect (Goldreich and Tremaine 1982) suggests that neither the A ring nor the
close-in ring moons could have retained their current configuration for the solar system’s age;
this provided the first indication of youthful main rings. Cassini observations have validated the
gravitational torque theory in the context of several embedded moonlets, where resonances
merge (see below), even while recent work has raised several issues regarding the detailed
dynamics of precisely how the moon Mimas constrains the B ring edge at its isolated 2:1
resonance (see SOM6). Direct measurements of orbital evolution of the ringmoons under
gravitational torques have been complicated by dynamical chaos (French et al. 2003, Goldreich
and Rappaport 2003).

**Embedded moonlets:** Embedded moons can open complete circumferential gaps in
surrounding, nearby ring material by virtue of the gravitational torques transmitted at their
closely spaced resonances (Goldreich and Tremaine 1982, SOM6). This was first demonstrated
when Voyager data revealed the 14-km radius moonlet Pan in the Encke gap, and further
validated by Cassini’s discovery of the 4-km radius moon Daphnis in the Keeler gap (see
SOM6). The equilibrium width of a moonlet-caused gap is obtained by balancing the moon’s
gravitational torque to the ring’s viscous torque (Schmidt et al. 2009). The Encke gap’s measured
width is close to that predicted in this way, and the relative scaling between the widths of the
Keeler and Encke gaps is also roughly correct given the masses of Pan and Daphnis (Porco et al.
2007). These results support and constrain the widespread belief that Jupiter-mass objects can
create cavities in circumstellar disks (Chambers 2009).

However, despite substantial campaigns by Cassini, moons have not yet been found
inhabiting and clearing the other dozen-odd gaps in Saturn’s rings. Perhaps alternate theories
merit consideration. Five of the empty gaps in the Cassini division may be responding to sub-
harmonics associated with the B ring’s distorted edge (Hedman et al. 2009a); that edge, which oscillates in and out by as much as 75 km, appears to undergo unanticipated large angular librations or even circulations5 relative to Mimas’ longitude; the moving, non-axisymmetric ring edge itself might play the role of a perturbing moonlet. Even if this explains the Cassini division gaps, the clearing of other non-resonant, apparently moon-free gaps, most in the C ring, remains baffling.

Particles moving near a gap’s edge are tugged as they pass the perturbing moon; their Keplerian shear, combined with the induced eccentric motion, produces a radial oscillation downstream of the moon whose period reflects the moon’s distance and whose peak-to-peak amplitude measures the moon’s mass. If the moonlet’s orbit is sufficiently eccentric, or very close to the gap edge, nonlinear effects modify this result slightly (Weiss et al. 2009, Lewis and Stewart 2005). Collisions should cause the wavy edges to decay downstream, but the Encke edge’s undulations persist around the full circumference, containing the expected period but several others too (see the figure in Burns and Cuzzi 2006 taken from Tiscareno et al. 2005b). Numerical simulations suggest that synchronization of orbit shapes in the densely packed moonlet wakes associated with these edge phenomena might forestall the expected decay (Lewis and Stewart 2005; SOM6). Cassini observations near Saturn equinox (Fig. 4) have shown that Daphnis’ inclination drives wavy edges which oscillate vertically by 1-1.5 km along the Keeler gap’s perimeters (Weiss et al. 2009), while the Encke gap edges have undetectable vertical relief, consistent with Pan’s lack of a measurable inclination.

Most of the moons that lie within or close to the rings – Pan to Pandora– display appreciably non-spherical forms, surprisingly low densities (significantly smaller than the density of solid water ice), and shapes and sizes that approximately match those of their associated Roche lobes, suggesting accretion of loose rubble onto a core significantly denser than the ambient ring material (Porco et al. 2007; Fig. 5; SOM6). This is reminiscent of numerical simulations of local gravitational aggregation of material in Saturn’s rings (Karjalainen and Salo 2004), and is apparent in the shapes of Phobos and Amalthea, close-in moons of other planets. The smooth, equatorial ridges that are so prominent on Pan and Atlas may represent a secondary

5 This terminology follows that for a vertically hanging pendulum, where “libration” refers to oscillations about the stable (minimum energy) locations and “circulation” describes a complete cycle through the stable point.
process in which material flows onto the moons through their libration points (Charnoz et al. 2007).

**Packing in compressed regions:** As ring material gets thrust together, either in the crowded crests of resonantly forced density waves, the wakes of passing moonlets, or perhaps the narrowed periapse regions of eccentric ringlets, changes may occur in the particles’ orbits and even perhaps their physical structures. The finite volumes of ring particles can cause the ring material to “splash” vertically when compressed (see SOM7). Diverse particle orbits can be jammed into synchronized trajectories such that limited radial regions may orbit as units rather than with the normal Keplerian shear, reducing viscous dissipation and differential precession, and perhaps even creating large, clumpy structures (Lewis and Stewart 2005; SOM7). Disaggregation by disruptive collisions or tidal shedding (Davis et al. 1984) may follow. Images and occultations show broad swaths of “straw” in the innermost troughs between crests of strong spiral density waves (Fig. S4) and the Encke gap edge (Porco et al. 2005; Lewis and Stewart 2005). These clumps of “straw”, probably formed by packing in the dense wave crests, are kilometers to tens of kilometers in extent. Whether this process leads to accretion of objects having some permanence remains unknown; propeller objects (see below) are absent from the regions surrounding the strongest density waves (Tiscareno et al. 2008).

**Propellers:** Moons with sizes much smaller than Pan and Daphnis are unable to clear a complete circumferential gap, because their gravitational torques are too feeble to overcome viscous diffusion. However, they do create local disturbances that can be observed (Fig. 6; SOM8). Such disturbances, shaped like “propellers” due to Keplerian shear, were predicted theoretically (Spahn and Sremčević 2000), and subsequently observed by Cassini (Tiscareno et al. 2006, Sremčević et al. 2007, Tiscareno et al. 2008). The central moonlets causing the disturbances remain unseen, but their sizes can be inferred from a model of two azimuthally aligned lobes, with the leading one slightly closer to Saturn, where the radial separation between the two lobes is a few times the central moonlet’s diameter (Schmidt et al. 2009). Although the precise photometric and dynamical interpretations of the observations are controversial (see SOM8), propeller moonlets have radii roughly between 10 meters and 1 km, with a much steeper size distribution than that of the cm-m sized particles that dominate the main rings (Tiscareno et al. 2006, Sremčević et al. 2007, Tiscareno et al. 2008). The total mass in these bodies is therefore relatively small.
Propellers seem to be largely confined to a 3000-km-wide band in the mid-A ring (Sremčević et al. 2007) that is divided into three sub-belts (Tiscareno et al. 2008). Perhaps each sub-belt was produced by the local breakup of a larger object (Tiscareno et al. 2006, Sremčević et al. 2007), or the propeller-rich belts are regions where accretion is enhanced and/or erosion is decreased (Tiscareno et al. 2008). As inferred for Pan and Atlas (Porco et al. 2007), propeller moonlets may have grown to their current sizes by accretion of porous material onto a solid seed until the moonlet’s size fills its own Roche lobe; the ultimate origin of these “seeds” remains unknown. Rarer but much larger propellers have been identified in the outer A ring, allowing individual objects to be tracked over extended times where some display evolving orbits (Tiscareno et al. 2009b). Continued observation of the orbital evolution of these propellers holds the promise of directly observing processes analogous to the complex evolution of a planetesimal through a protoplanetary disk (Chambers 2009). A small moonlet (~300 meters) has been found in the outer B ring (Porco and the Cassini Imaging Team 2009) but it is missing the tell-tale propeller lobes.

The F ring: A dusty band of rubble orbiting 3000 km beyond Saturn's main rings, the F ring contains several narrow strands, tens of km wide, that vary on time scales of hours to decades (Colwell et al. 2009). A fainter dust cloud spanning ~ 1500 km (Murray et al. 2005, Porco et al. 2005) surrounds the strands. Nearby Prometheus causes the primary perturbations, distorting the ring by tens of km at each passage (Murray et al. 2005, 2008). The phenomenon is analogous to the wakes produced by Pan and Daphnis, but is complicated by the large variations in closest approach distance resulting from the orbital eccentricities of the ring and Prometheus. For example, as Prometheus approaches and retreats from the ring each orbital period of 14.7 hours, its gravity repeatedly draws material out from the core to form a streamer, while leaving behind an emptier channel (Murray et al. 2005). The cycle recurs every 3.2° of longitude (i.e., the Keplerian shear over 14.7 hours), producing an obvious quasi-periodic pattern trailing Prometheus (Fig. 7). The strength of these perturbations peaks every ~19 years as differential precession brings the orbits into anti-alignment; the closest approach between the two orbits occurred in late 2009.

Occasionally, more extraordinary events are observed. Within a few days, a ring sector’s brightness can double or triple following a sudden injection of dust (Showalter 2004). In Cassini images these features subsequently shear out to form kinematic spirals and “jets” (Charnoz et al.
2005, Murray et al. 2008) (Fig. 7). Even larger clumps have appeared in Hubble images (McGhee et al. 2001), with orbits that apparently differ slightly from the F-ring’s core. The nearby object S/2004 S6 (Porco et al. 2005) – perhaps a ~ 5-km moonlet enshrouded in dust – is representative of several bodies that seemingly pass through the F ring semi-regularly, and collisionally trigger these events (Charnoz et al. 2005, Murray et al. 2008, Charnoz 2009). A particularly bright and dense structure appeared in late 2007 with properties much like those of the main F ring core but more than 100 km away in places (Albers et al. 2009).

The primary F ring core orbits and precesses smoothly (Bosh et al. 2002, Albers et al. 2009), maintaining its integrity in seeming defiance of the large distortions and variations present, and, like the rings of Uranus, avoiding differential precession as well. Due to the proximity of Prometheus and Pandora, which have numerous overlapping resonances, the dynamics of the F ring and nearby objects are more likely chaotic than “shepherded” (Winter et al. 2007). Stellar occultations have revealed opaque (or nearly opaque) bodies present throughout the ring's core, from 30-1200 m in diameter (Esposito et al. 2008). These may be members of a previously unseen population of larger bodies that serve as dust sources and that provide the mass needed to stabilize the ring's orbit (Cuzzi and Burns 1988).

The F ring dramatically documents the difficulty of living near the edge of the Roche zone, where accretion and disruption are in continual combat (Canup and Esposito 1995, Karjalainen and Salo 2004). Its many peculiarities are likely produced by the ongoing competition between these two processes (Cuzzi and Burns 1988, Barbara and Esposito 2002). Understanding the evolution of the ring bodies, and their interactions with Prometheus, should furnish a good grasp on the more general problem of protoplanets perturbing a disk of bodies from which they are also growing.

**Diffuse rings:** Saturn possess several other low-optical-depth rings primarily containing microscopic grains (Horanyi et al. 2009). Collisions happen infrequently in such systems, allowing non-gravitational forces to be influential (Burns et al. 2001; *SOM9*). These faint rings, and their analogs in the Jupiter, Uranus, and Neptune systems, may have parallels in protoplanetary debris belts, whose apparently confined edges are considered to signify unseen planets (Carpenter et al. 2009).

Cassini observations have clarified the origins of many faint rings. Plumes of micron-sized grains emerge from warm fissures near Enceladus’s south pole, and are likely the principal
supplier of the extensive E ring (Porco et al. 2006, Horanyi et al. 2009, Postberg et al. 2009). More commonly, dusty rings are fed by mutual collisions among, or meteoritic erosion of, various parent bodies (Burns et al. 2001). Most of the small moons (including Pan, Janus/Epimetheus, Pallene, Methone and Anthe) interior to Enceladus’s orbit generate faint rings or resonantly confined arcs of material in their orbits (Horanyi et al. 2009). The G ring is supplied from a resonantly trapped population of objects (including the 500-m Aegaeon) located near its inner edge (Hedman et al. 2007b). These dynamical configurations testify to the ubiquity of resonant trapping in faint debris disks.

The D ring itself has changed appreciably since Voyager’s visit (Hedman et al. 2007a); the D ring and inner C ring display a vertical corrugation that is thought to have been generated only twenty-five years ago (Hedman et al. 2009b). Images taken with the Spitzer infrared telescope reveal a system-encircling dust ring with radial and vertical structure matching Phoebe’s orbit (Verbiscer et al. 2009), providing support for the longstanding idea that dust from Phoebe coats Iapetus’s dark orbitally-leading hemisphere.

Ring composition: The A and B ring particles are composed of >90-95% water ice, based on decades-old near-infrared spectra and radio/radar observations (see SOM10). Particles in the C ring and Cassini division are known to be dirtier, compatible with models of extrinsic pollution by carbon-and-silicate-rich meteoroids over the rings’ lifetime (Cuzzi and Estrada 1998). Cassini near-infrared observations have ruled out any CO₂, CH₄, or NH₃ ices at the percent abundance level, yet all of these species have been detected on Saturn’s moons (see SOM10). At wavelengths < 520 nm, the A and B rings are much redder than any of Saturn’s icy moons; the UV absorber responsible for this remains a puzzling clue to the rings’ origin. For instance, Cassini identifies no infrared C-H spectral feature in the rings, which might preclude some large, reddish, organic “tholins” as possible absorbers (Poulet et al. 2003). Two new candidates have been recently suggested: small clusters of carbon rings (PAHs) and/or Fe³⁺ compounds such as nanoparticles of hematite (iron oxide, which gives Mars its red color). The idea of “rusty rings” was inspired by Cassini’s discovery of the rings’ oxygen atmosphere and their spectral dissimilarity to supposedly organic-rich reddish icy solar system objects (Cuzzi et al. 2009). The degree of visual redness is highly correlated with water-ice band strengths as a function of radius (Nicholson et al. 2008) – with redness and ice band depth increasing together in the more massive ring regions, suggesting that the UV absorber is distributed intrinsically,
within the ice grains in the regolith of the ring particles, rather than as a distinct, or extrinsic, component.

**Big Open Questions** – Arguments that the rings may be only a tenth of the solar-system’s age are (a) mutual repulsive density wave torques between (primarily) the A ring and the nearby ring moons and (b) meteoroid restructuring and pollution of the ring material (see SOM11). These short lifetimes are problematic because the generation of the entire ring via disruption of the Mimas-size (or larger) parent is unlikely on this timescale (Lissauer et al. 1988, Dones 1991, Harris 1984). Producing only the A-ring’s relatively small mass may be easier if smaller parent bodies are more frequently disrupted (Harris 1984, Lissauer et al. 1988).

The gravitational torque theories on which (a) relies have now been validated by observations of moonlets clearing gaps. Some flexibility in their implications for ring age may emerge if ring moons periodically interact and perhaps temporarily destroy each other (Poulet and Sicardy 2001) or are held up by much-sought-for, but as-yet-unidentified, resonances with exterior massive moons (Goldreich and Tremaine 1982). Pollution contaminates the entire system, but models rely on the poorly known incoming mass flux and ring mass. Cassini has plans to measure the incoming meteoroid mass flux indirectly, with a technique which, used at Jupiter, obtained a mass flux in accord with interplanetary measurements (Sremčević et al. 2005; SOM11).

Recent models link a delayed onset of solar-system-wide dynamical chaos to a time when Jupiter and Saturn evolved into resonance. This chaos induces an episode of intense cratering 700 Myr after the solar system began (the so-called Late Heavy Bombardment), thereby postponing the rings’ origin to a slightly more recent era; nonetheless, it remains temporally remote (Charnoz et al. 2009). Moreover, current pollution age estimates assume the present bombardment flux, so that if the rings were instead created during an interval of enhanced overall influx of potential parents, they would also be subject to a simultaneously increased abundance of polluting debris.

Any substantial increase in the rings’ mass could make them better able to withstand the effects of meteoroid bombardment. Firm density-wave mass measurements now blanket the A ring, and extend across the Cassini division, inner B ring, and C ring; moreover, significant mass cannot be carried by the sparse propeller objects lying in these regions. However, it is hard to gauge the mass within most of the B ring; perhaps its murky depths contain significantly more
material than generally believed. Plans call for Cassini to measure the ring mass directly (by tracking the ring’s gravitational effects on the spacecraft) during its last close orbits before plunging into the planet (SOM11).

We remain unsure whether the propeller objects (or even the visible gap-moons Pan and Daphnis) are residual shards from a creation event or locally grown, even though huge “straw-like” packed clumps suggest that some form of accretion can occur where trajectories of ring particles are kinematically forced together. Are the large peripheral ring moons (at least Prometheus and Pandora) examples of ring precursors, or were they grown within the A ring and repelled outwards by their own torques? Regardless, these large ring moons represent only a fraction of the main rings’ mass, and they may be encapsulated in a rind of accumulated ring-rubble, meaning that their true composition, if different, might never be discerned. Is the F ring the detritus of some more recently destroyed member of this tribe, and/or does accretion continue there as well? The composition of the main rings, and its variation with radius, might yet be the best clue as to the provenance of their predecessor(s); however, one must first unravel the various evolutionary processes affecting composition (the ring atmosphere, incoming pollution, etc.) and structure.

We have learned a great deal about the rings in the decades since Voyager, from ground-based observations and theoretical modeling, and in particular during Cassini’s five years at Saturn. Far more, however, remains to be done. By mission’s end, Cassini will return hundreds of times more data than Voyager, and careful examination of this dataset is still in its early stages. We remain puzzled regarding the cause of the irregular structure that blankets the B ring, of the crisp, symmetrical, banded structure of the C ring (Colwell et al. 2009), or why a Cassini division exists at all. Explanations for the origin of Saturn’s rings will remain unconvincing until we have understood the powerful dynamical processes that have formed, and continue to shape, these elegant structures on timescales from yesterday to millions of years.

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References:


Figure 1. An overview of Saturn’s main ring system: top: radial profile of ring optical depth from stellar occultations\(^1\); bottom: true color image (Porco et al 2007). The B ring – especially its dense central and outer portion, is filled with irregular structure that remains puzzling. The outer C ring contains a series of plateau features that are also not understood. The dark gap in the outer A ring is the Encke gap, and the very narrow gap near the A ring outer edge is the Keeler gap (figure 4). The identifiable sharp features in the A ring are spiral density and bending waves (figure 3). Figure from Esposito (2009).
Figure 2: Simulations of how ring microstructure changes with optical depth (vertical axis) and the strength of the ring's self-gravity (relative to the planet’s tides), which increases with distance from the planet and/or internal density of the particles (horizontal axis). Identical particles (R=1m) are assumed, having coefficient of restitution 0.5. The relative strength of self-gravity is parameterized by the ratio $r_h$ of the mutual Hill radius of two particles divided by the sum of their radii; here $r_h = 0.82 \left( \frac{\rho_p}{900 \text{ kg/m}^3} \right)^{1/3} (a/100,000 \text{ km})$ where distances $a$ (times 1,000 km) corresponding to a particle density $\rho_p = 900 \text{ kg/m}^3$ are given. Each snapshot has a dimension of roughly $600 \tau r_h^3$ particle radii (i.e. four times the dimension of the self-gravity wakes) - ranging from 40m (lower left) to 140-280 m (upper left, lower right). Clumping can lead to discrete objects at distances greater than $r_h \sim 1.2$ (near the F ring). The inset indicates ranges of $\tau$ and $r_h$ where random velocities are dominated by (i) physical impacts, (ii) gravitational encounters, and (iii) self-gravity wakes. It also indicates where overstabilities (parallel structures in the upper left corner of the main plot) and aggregates can form. From Salo et al. 2008; see OSM3.
Figure 3 A montage made from Cassini ISS images, showing part of the outer A ring, containing prominent spiral bending waves (left) and density waves (center), as well as the 320-km wide Encke gap (right) which contains several ringlets – one associated with the 10km radius embedded moonlet Pan that orbits in the center of the gap and causes the wavy inner edge of the gap. The fan-shaped disturbance inside the inner edge is a direct result of the wavy edges produced by Pan. Note that, by comparison with spiral waves in galaxies, the spiral density and bending waves are very tightly wrapped, like watchsprings.

Figure 4: Cassini ISS image of the 30km wide Keeler gap at the very outer edge of the A ring, showing its 3km radius embedded moonlet Daphnis and the wake it creates in ring material at the gap edges. The image was taken very close to Saturn’s equinox, with the sun at very low elevation, so that the vertical relief of the wake casts shadows (from Weiss et al 2009). The other horizontal features include spiral bending waves, which also have some vertical component as indicated by their bright/dark appearance.
Figure 5a Detailed closeups of Atlas (left) and Pan (right), showing their smooth, elongated, flattened equatorial bulges, which probably arise from a subsequent stage of accretion of ring material leaking in through their gaps. The ring material lies in a sheet that is much thinner than the diameter of these moonlets. From Porco et al (2007).

Figure 5b A model illustrating the likely structure of all of Saturn’s close-in ringmoons: a possibly solid central shard (red), deeply buried in loose icy rubble with a much lower density, which can assume the shape of a strengthless object. The view is from the north, with the leading hemisphere at the bottom and Saturn to the right. (From Porco et al 2007).

Figure 6: This model calculation illustrates a “propeller” structure (the dark, mainly empty regions on either side of a 20 m-size object). The slanted bright structures all around are self-gravity wakes. Objects causing propeller structures are too small to detect directly, but statistics on their sizes and distribution can be determined from detections of the disturbed regions on either side. From Sremčević et al (2007).
Figure 7 A mosaic of reprojected Cassini ISS narrow-angle images of the F ring obtained at low phase angle. The radial offset is relative to a precessing elliptical model of the F ring (Bosh et al. 2002, Albers et al. 2009), and the horizontal axis is the longitude (in degrees) at the epoch of 12:00 UTC on 2007 January 1. The mosaic is annotated to show the more prominent jets and spirals, thought to be due to recent impacts with a number of different crossing bodies, and the radially extended channels, which are caused by Prometheus and Pandora. As seen in the inset, most of the short-wavelength features in the bright core are due to perturbations from Prometheus (Charnoz et al. 2005, Murray et al. 2008; Colwell et al. 2009). Image credit: NASA/JPL/Space Science Institute; obtained 2005 April 13 (ISS-006RI-LPHRLFMOV001-PRIME).
SOM1: The Cassini-Huygens flagship mission is a cooperative undertaking by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and the Italian space agency (Agenzia Spaziale Italiana, ASI), with NASA supplying the Cassini Orbiter, ESA furnishing the Huygens Titan Probe, and ASI providing hardware systems for the Orbiter as well as instruments for both the Orbiter and Probe.

Cassini-Huygens arrived at Saturn on July 1, 2004 (UTC), roughly two years after the northern winter solstice. It has been in orbit around Saturn through spring equinox (August 2009), to date completing its 4-year Prime Mission and more than half of its 2.25-year Equinox Mission. Through September 2009 Cassini had executed 115 Saturn orbits, whose size, inclination and orientation were controlled using 58 Titan-gravity-assist flybys and numerous propulsive maneuvers.

Science requirements shape Cassini’s orbital tour (Fig. S1). For example, special orbits to accomplish ring science were designed to perform radio science occultations at a variety of tilt angles, from maximum ring openings near the beginning of the tour to much smaller ring openings near equinox. Most of these geometries are, of course, unobservable from Earth. High inclination orbits are particularly well suited for ring studies; three separate periods of inclined orbits have occurred during the last five years, including a high-inclination sequence (inclinations reaching 75 degrees) in the last year. A key opportunity for ring science began just after completion of the Saturn Orbit Insertion (SOI) burn, which slowed the spacecraft for capture into Saturn orbit. The SOI burn occurred earlier in time than optimum for minimizing propellant usage so the burn could end, and ring science begin, near closest approach to Saturn (0.3 Rs, 18,000 km above Saturn’s atmosphere). A number of unique observations were made during this period, including sampling the ring atmosphere and plasma wave effects in situ, and observing ring properties remotely at the highest spatial resolution (~100 m/pixel) to date.

Cassini-Huygens supports 18 scientific instruments, 12 on the Orbiter and 6 on the Huygens Probe. The Orbiter carries two types of instruments, in-situ and remote-sensing. The six in situ instruments, mounted at various places on the spacecraft, are CAPS, CDA, INMS, MAG, MIMI and RPWS (see Table S1). The four optical remote-sensing instruments (CIRS, ISS, UVIS and VIMS) are mounted together on a separate pallet and make measurements from ultraviolet to sub-millimeter wavelengths. Two other remote-sensing instruments (RADAR and
RSS) use the high-gain antenna. Many instruments have multiple detectors or whole instrument systems. Key ring techniques include stellar occultations (UVIS, VIMS), radio occultations (RSS), composition measurements (CDA, CIRS, INMS, UVIS, VIMS), two-dimensional high-resolution color images (ISS), thermal emission measurements (CIRS, Radar), and magnetospheric signatures (CAPS, MAG, MIMI, RPWS).

The Cassini Project recently completed tour planning for an additional 7-year phase informally called the Cassini Solstice Mission (CSM) that will, if approved by NASA, extend the mission’s lifetime through Saturn’s northern summer solstice, including another 160 orbits of Saturn, with 56 more Titan flybys. This extension would permit observations of temporal and seasonal change across nearly half a Saturnian year.

For more information, see http://saturn.jpl.nasa.gov.

**Figure S1:** Cassini’s nominal mission orbital tour (2004-2008). Left: Polar view; sun is to the right. Right: equatorial view. Units are Saturn radii ($R_S$). Dotted circles: orbits of Titan ($20 R_S$), and Iapetus ($60 R_S$). SOI and the initial probe orbits are in white; an early set of orbits optimized for ring occultations are in orange. A series of equatorial orbits with large apoapses are shown in green, designed to explore Iapetus and the magnetosphere. The blue paths represent orbits with high inclination (up to 70 degrees) that flip the apoapse to the sunward side of the planet. The yellow lines sketch another series of equatorial orbits. The red orbits are the nominal end-of-prime-mission orbits with low periapse and high inclination (up to $78^\circ$). Orbit changes are accomplished primarily by close Titan flybys.
### Cassini Orbiter Instruments

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Table S1.
**SOM2: Ring particle sizes and ring local vertical thickness:** Ring particle sizes are strongly constrained by Voyager radio occultations (Marouf et al. 1983, Zebker et al. 1985), with important augmentation by Voyager stellar occultations (Showalter and Nicholson 1990) and ground-based stellar occultations (French and Nicholson 2000). The analytical model of particle size evolution by Longaretti (1989) has been refined through improved estimates of the size at which gravitational binding can occur (Ohtsuki 1993, Salo 1995, Karjalainen 2007); physical sticking and grazing impacts probably play a larger role than the tidal effects originally envisioned by Davis *et al.* (1984). Physical collisions and gravitational deflections stir the particles into a layer that is not much thicker than the size of the largest particles, with the smaller particles stirred into a somewhat more extended band (*Fig. S2*) (Goldreich and Tremaine 1978a, Cuzzi *et al.* 1979, Stewart *et al.* 1984, Ohtsuki 1993, 1999, 2000; Salo 1992c; Salo and Karjalainen 2003). The viscosity due to interparticle effects has been extended to include nonlocal effects in dense collisional layers (Shukhman 1984, Araki and Tremaine 1986, Wisdom and Tremaine 1988) and stirring by self-gravity wakes (Daisaka *et al.* 2001, Tanaka *et al.* 2003). The fluid nature of ring material and its evolution under several different processes can be best appreciated in movies made from numerical simulations, as described below.

*Figure S2:* Side view of a ring simulation (Salo and French 2009) with a power-law distribution \((q = 3)\) of sizes between 0.2 m and 5 m. Self-gravity is not included in this simulation of optical depth \(\tau = 1\) using a velocity-dependent coefficient of restitution obtained in experiments (Bridges *et al.* 1984). The curves on the right indicate the vertical distributions of the particle centers, divided into three logarithmic size bins, \(R < 0.58 \text{ m}, \ 0.58 \text{ m} < R < 1.72 \text{ m}, \ 1.72 \text{ m} (\text{each bin contributes equally to the total optical depth}): \) the effective vertical thicknesses are \(H = 22, 15, \) and 10 m, respectively, from smallest to largest particles. When such a ring is viewed from the top, the observer sees more of the dense mid-plane layer of particles with a volume density near
D=0.29 (see Salo and Karjalainen 2003). At shallow viewing geometry, however, the line-of-sight cuts a long path through the low volume density layers away from the midplane. This might account for the tilt effect of the B ring, where brightness increases significantly with the observer’s elevation angle (Lumme and Irvine 1976, Salo and Karjalainen 2003).

**SOM3: Self-gravity wakes:** The A-ring’s non-axisymmetric structure was originally suggested by Camichel (1958), followed by Lumme and Irvine (1976) and Reitsema et al. (1976). The first theoretical proposal (Colombo et al. 1976) that these structures were due to self-gravity wakes drew on analogies from galactic dynamics (Julian and Toomre 1966). Fig. S3 gives a high-resolution visualization of self-gravity wakes. The radial wavelength of the wakes is proportional to the local surface mass density, providing an independent estimate to complement inferences from spiral density waves (SOM5; Colombo et al. 1976; Shu 1984). The cant angle of the wakes from the orbital direction varies significantly with location in the rings, from only 10-15° in the inner B ring to 20-30° or even larger in the A ring (Colwell et al. 2007).

Figure S3: Ring-patch simulation of the mid-A ring at 128,000 km after more than 12 orbits (from Porco et al. 2008a). The simulation cell is 626 m in the orbital dimension (horizontal here) and 250 m in the radial (vertical in this plot). The surface mass density of the patch is 43 g/cm² while the particles have an internal density of 0.4 g/cm³. The optical depth is 0.6 and particle radii follow a power-law radius distribution from 0.3 m to 3 m with a power-law index of ~2.75. In this model, the normal coefficient of restitution follows the model of Andrews et al. (1930, cf. Borderies et al. 1984) with v*=0.001 cm/sec; the tangential coefficient of restitution is 0.9.
Franklin et al. (1987), French et al. (2007) and Porco et al. (2008a) conducted other studies. A number of simulations and visualizations of self-gravity wakes have been conducted by Salo and collaborators. For instance, Salo (1992a) described the formation of self-gravity wakes, with and without particle size distributions, at different locations in the rings. An animation of the B ring (http://spacescience.arc.nasa.gov/users/cuzzi/salo_SGwakes.mpg; Salo 1992b) is viewed normal to the ring plane, with the radial direction running from left to right. The frame moves with the orbital motion of material at the frame’s radial center; thus material radially inwards moves faster (ahead) and material radially outwards moves slower (behind); this is the so-called Keplerian shear. The particles range up to 5 m radius and have internal density of 0.5 g/cm$^3$. The caption of Figure 1 of Salo (1992a) contains a detailed description of the simulation parameters. Figure 2 of our main paper, from Schmidt et al. (2009), and the associated studies by Salo (1995) and Salo et al. (2001), shows the dependence of the appearance of self-gravity wakes on optical depth and the relative strength of gravity and tidal force. Self-gravity becomes more important at greater distance from the planet or for larger internal density of the ring particles. At larger distances, the wake structure becomes less coherent and eventually the inclined wakes are replaced by gravitationally bound aggregates of particles. Viscous overstability appears at large optical depth if the self-gravity is not too strong (i.e. close to the planet or at small internal particle density).

**SOM4:** Viscous overstability: The first allusion to what is now called viscous overstability was by Borderies et al. (1985) (cf. Borderies et al. 1983b and Longaretti and Rappaport 1995) who also pioneered the concept of vertical “splashing” in regions where kinematics drives particles together. Goldreich and Tremaine (1978b) pointed out the possibility that density waves might become overstable. Schmit and Tscharnuter (1995, 1999) studied the spontaneous viscous instability of a dense ring and Mosqueira (1996) verified the condition for viscous overstability, as derived by Borderies et al. (1985), in local simulations of a perturbed planetary ring. Self-gravitating local simulations by Salo et al. (2001, see also Daisaka et al. 2001) demonstrated how overstable waves can spontaneously develop in an unperturbed dense planetary ring. The animation http://spacescience.arc.nasa.gov/users/cuzzi/salo_viscous_overstability.mpg shows examples from these simulations, i.e. radial oscillations and vertical splashing caused by a viscous overstability in a standing wave mode. The model corresponds to a particle internal
density of 0.3 g/cm³ and displays the evolution over six orbital periods. Note that the vertical scale is exaggerated (actual radial width = 583 m, vertical range ± 10 m in the animation). The simulation uses meter-sized particles, an optical depth $\tau = 1.4$, surface mass density $\sigma = 84$ g/cm², and Saturnocentric distance 100,000 km. The particles collide inelastically (Bridges et al. 1984). Salo et al. (2001) have studied different combinations of surface mass density and particle size. In the top panel of the simulation, the rings are viewed normal to the ring plane; in the lower panel, the system is viewed in the equatorial plane. In both cases, radius runs from right to left. Over longer times, the dominant behavior evolves into what is expected to be a more common “traveling wave” mode (Schmidt and Salo 2003) that moves radially one wavelength per orbit period. Such nonlinear traveling wave systems usually expose a rich dynamical behavior in a pattern-forming system (Aranson and Kramer 2002), and overstable wave trains might decay radially in segments of alternating inward-, and outward-, traveling waves, possibly with amplitude variations on much longer scales than the basic underlying 100 m oscillations (Latter and Ogilvie 2008, 2009). At a fixed location, a traveling mode would appear as a simple oscillation at the orbital period. Whether this behavior can be actually observed is unclear – successive stellar occultations closely spaced in time (less than an orbit) are warranted. For example, see http://spacescience.arc.nasa.gov/users/cuzzi/salo_visc_overstab_traveling.mpg, in which the top two panels show normal (xy) and equatorial (xz) views, whereas the lower two panels display the x- and y- velocities, respectively.

**SOM5: Spiral density waves:** Spiral density waves in Saturn’s rings were predicted by Goldreich and Tremaine (1978b); pioneering work on deriving the torques associated with these waves was presented by Goldreich and Tremaine (1980). A number of waves were discovered and analyzed by Voyager (see Cuzzi et al. 1984, Esposito et al. 1984, and Shu 1984). Shu et al. (1985) discuss the damping of these waves by ring viscosity. Far more waves have now been identified by Cassini (reviewed by Colwell et al. 2009a), including new waves in the Cassini Division (Colwell et al. 2009b), giving a mass density there that requires the particle size to decrease smoothly from the A ring inwards into the division. Ideally, the mass of the perturbing moons can also be inferred from the amplitude of the waves, although attempts (Rosen et al. 1991) to do so for moons whose masses can also be determined more accurately through orbital perturbations have thus far been inconsistent (Jacobson and French 2004). Two of Saturn’s
moons, Janus and Epimetheus, share nearly the same orbit and “trade places” every four years. A history of the variable orbits of these moons is recorded in the spiral density waves that they raise in the rings (Tiscareno 06b). Recent analyses enable strong, nonlinear waves to be analyzed (Rappaport et al 2009), revealing radial variations in surface mass density underlying the radial trajectory of a given wave – often hundreds of km.

**SOM6: Embedded moonlets and wavy edges:** Thirty years ago theory (Goldreich and Tremaine 1982) and observations (Smith et al. 1981, Cuzzi et al. 1984) demonstrated that spiral density waves driven by moons exert profound influences on a ring’s structure through their transport of angular momentum. Rings can be confined: the B-ring’s outer edge lies at Mimas’s 2:1 resonance and the A ring terminates near the 7:6 resonance with Janus/Epimetheus (Porco et al. 1984). More recent work suggests that the shepherding of the B-ring edge is not yet entirely understood (Hahn et al. 2009) and that the B ring edge is not a simple $m = 2$ structure following Mimas’ longitude, but has higher order azimuthal structure and varies both in radial amplitude and in angular position relative to Mimas (Hedman et al. 2009a, Spitale and Porco 2009, Esposito et al. 2009). In a similar way, narrow rings, such as Uranus’ ε ring, can be constrained by single resonances with shepherd satellites on either side (Porco and Goldreich 1987, Goldreich and Porco 1987). Conversely, a moonlet embedded in a sheet of ring material can clear an empty gap around itself in a regime where resonances overlap (Lissauer et al. 1981, Henon 1981, Goldreich and Tremaine 1982). This identical process was very early realized to be associated with “tidal truncation” of protoplanetary gas disks by embedded planets or protoplanets (Papaloizou and Lin 1984, Hourigan and Ward 1984, and numerous other studies since then). As the massive gas disk evolves by its own viscosity, the entrapped protoplanet is carried along. This has been called “Type 2” planetary migration. The gap-clearing theory was physically realized by the discovery of Pan in the Encke gap (Cuzzi and Scargle 1985, Showalter et al. 1986, Showalter 1991). Many improvements have been accomplished since the Voyager era, due to detailed numerical studies of moonlets in gaps (Lewis and Stewart 2000, 2005). Cassini discovered Daphnis (Porco and Cassini Imaging Team 2005a) and imaging scientists suspect that the Keeler-gap’s inner edge is distorted by Prometheus’s 32:31 resonance (Tiscareno et al. 2005a, Torrey et al. 2008), complicating the story further.
The kinematic effect of a moonlet on ring material at some distance was first seen in the wavy edges of the Encke gap in the A ring (Showalter and Burns 1982, Cuzzi and Scargle 1985, Showalter et al. 1986). Cuzzi and Scargle (1985) give a simple heuristic derivation of the torque resulting from these perturbations. The wavy structure can be thought of as similar in behavior to a ripple forming downstream of a rock in a stream. A ripple structure (with fluid particles moving through it) remains stationary relative to the rock. If the “rock” moves, however, the ripple’s morphology will be correspondingly changed in time. The narrow Keeler gap in the outer A ring contains a moonlet that has orbital inclination and perhaps eccentricity (Daphnis; Weiss et al 2009) so its wavy edge structure varies in time, as simulated by Lewis and Stewart (2005, cf. http://www.cs.trinity.edu/~mlewis/Rings/KeelerGap2005/).

Regarding the rubble-pile nature of the ringmoons, their low density has been noted over the years (Rosen et al. 1991, Nicholson et al. 1996) before being confirmed by Cassini results. Note that the profiles of Pan, Atlas, Prometheus, and Pandora are in good agreement with the expected shapes of their Roche lobes (Porco et al. 2007). The Roche Lobe is the volume in space that is stably bound to an object by its own gravity, incorporating the effects of its orbital motion and the tides from the parent planet. This supports their growth -- at least to some degree-- by accretion of loose rubble atop a denser “seed” (Porco et al. 2007), and thus perhaps to accretion within the main rings and expulsion by torques as speculated upon by Goldreich and Tremaine (1982). Nonetheless, the coorbital satellites Janus and Epimetheus do not share this property: Epimetheus, in particular, is discernibly irregular and insufficiently oblate (Porco et al. 2007, cf. Tiscareno et al. 2009c). This might argue in favor of a more traditional initial formation, and fragmentation, of a larger, more cohesive parent and limited subsequent accretion.

**SOM7: “Straw” and other kinematic compaction effects:** As edge waves are carried downstream from the moon, a radial wake of significant density appears to propagate into the rings (Showalter et al. 1986). These dense crests, like those of spiral density waves (Porco et al. 2005b), can pack particles together; this is strictly a kinematic effect but nonetheless may lead to “straw”-like clumps, as seen in some of the simulations at http://www.cs.trinity.edu/~mlewis/Rings/Icarus2004/; in particular, the reader is encouraged to view http://www.cs.trinity.edu/~mlewis/Rings/Icarus2004/DetailGravity2high.mov, which has the surface density thought to represent the middle A ring. Note as dense wave crests traverse the
region (upper left panel), “straw”-like structures are created in the regions that they move through, which are then dissipated by Kepler shear and mutual collisions as time progresses. See also Fig. S4 (Porco et al. 2005b).

Figure S4: A high-resolution Cassini SOI image (~ 300m/pixel) of a spiral density wave in the A ring, as viewed from the unlit face of the ring (Porco et al. 2005b); the dark bands are dense wave crests which transmit little light. In the brighter troughs between the crests can be seen a granular structure with a preferred trailing orientation; the granules are dense clumps several km long and have been named “straw”. They are less prominent or absent in the shorter-wavelength and lower-amplitude wave-cycles that lie radially outwards downstream. These dense clumps probably are created when particles are driven together kinematically in the dense crests of the waves that they pass through.

Dense packing of particles as they are kinematically forced together in the narrow periapses of dense ringlets, such as the Uranian $\epsilon$ ring, were suggested as a way to keep the ring from destroying its own structure by differential precession (Dermott and Murray 1980). This mechanism, attributed to the enforcement of synchronicity by close packing, has more recently been applied in detail to Saturn’s rings (Lewis and Stewart 2005). Alternate suggestions that self-gravity kept narrow, elliptical rings from precessing differentially (Borderies et al. 1983) are problematic (Borderies et al. 1988, cf. Chiang and Goldreich 2000, Mosqueira and Estrada 2002). Particles having initially porous or jagged surfaces may physically stick together and effectively merge into a solid “phase” (Tremaine 2003); this was originally suggested to arise ubiquitously, triggered by overstabilities, but would probably be more plausible in actively compacted regions.
SOM8: Propellers: First predicted by Spahn and Sremčević (2000), the structure of “propeller” objects was discussed in detail by Sremčević et al. (2002) prior to their discovery by Cassini. Simulations showing the fluid flow around “propeller” objects in the rings can be viewed at http://www.cs.trinity.edu/~mlewis/Rings/Moonlets2006/; as one example, see http://www.cs.trinity.edu/~mlewis/Rings/Moonlets2006/L1/fullL1.gif. The material is viewed normal to the ring plane with Saturn toward the bottom and orbital motion to the right. The frame moves at the orbital rate of the propeller object in the frame’s center. The actual propeller-gap that it carves out can be easily seen. One complication of propellers is that the observed brightness contrast, as observed in both lit face and unlit face geometries, is inconsistent with a simplistic dynamical model having only depleted and compacted regions (Tiscareno et al. 2006a, Sremčević et al. 2007, Tiscareno et al. 2008, Lewis and Stewart 2009). It may be that self-gravity wakes, which locally depress the observed optical depth per unit mass, are disrupted by the propeller-creating moonlets, as suggested by Tiscareno et al. (2006a, 2008) and explored in more depth by Tiscareno et al. (2009a). Alternatively, more vigorous collisions in the perturbed regions might lead to release of small pieces of rubble from the surfaces of large ring particles (Sremčević et al. 2007).

SOM9: Diffuse rings: The production of diffuse or debris rings has been discussed by Burns et al. (1984, 2001) and Porco et al. (1995). Cassini (Porco et al. 2005b, Porco and Cassini Imaging Team 2006, 2008b) has sighted several new ones. In the middle of an arc of rubble that spreads to form the G ring resides its likely parent, the newly discovered moon Aegeon (Hedman et al. 2009b). Other small moons are also known to be associated with tenuous rings and/or arcs (Hedman et al. 2009c). Within and adjacent to the main rings are several unique features in addition to those described in the main body of the paper. Tenuous rings are found in the Roche Division, the region between the A and F rings (Hedman et al. 2009d). Sheets of material in the D ring close to Saturn and in the Roche Division between the A and F rings display periodic structures that seem to be driven by resonances connected with Saturn’s rotation (Burns et al. 1985, 2001; Hedman et al. 2009d). Some faint rings embedded within the main rings are inclined and/or elliptical; in the latter circumstance, curious (heliotropic) alignments with the Sun are visible (Burt et al. 2008).
SOM10: Ring composition: The main rings have long been recognized as dominated by water ice, both from their near-IR spectra (Clark et al. 1980) and from their peculiar combination of very small microwave emission along with their strong radar reflection at the same wavelengths (reviewed by Esposito et al. 1984; see also Grossman et al. 1989 and van der Tak et al. 1999). Their visual redness has long been a puzzle, however. Based on an analogy with the well-known redness of outer-solar system objects, this hue was thought to arise from organic tholins such as those that color Titan’s atmosphere (see Cruikshank et al. 2005). The rings’ coloration was modeled using this assumption by Cuzzi and Estrada (1998) in the visual, and by Poulet et al. (2003) in the visual and near-IR. Cassini observations enable more sensitive searches for other ices and organic materials, such as are found in small amounts in the surfaces of some of Saturn’s moons (Clark et al. 2005, 2008; Cruikshank et al. 2007, 2008). None of these materials are apparent in the rings to a limit of less than a percent or so.

SOM11: Meteoroid bombardment: Saturn’s rings have (at least) Mimas’s mass but an area 10^5 times as large. The rings are thus highly susceptible to an incessant hail of interplanetary meteoroids; this affects their mass, angular momentum, and composition. Based on the best present estimates of the current meteoroid mass flux into the rings (Landgraf et al. 2000, Sremčević et al. 2005), the rings should absorb their own mass in meteoroids over 4.5 Gyr. Doyle et al. (1989) first postulated that the rings’ composition— and the particles’ albedos— would change significantly over this interval, and concluded that the current bright ring particle albedos suggested a ring exposure age much shorter than 4.5 Gyr. In a series of papers, Durisen, Cuzzi and coworkers (see Durisen 1984, Durisen et al. 1989, 1992 and 1996) showed that the rings’ radial structure would evolve as mass ejected by incoming projectiles, redistributed by so-called “ballistic transport”, altered the mass and angular momentum of different regions in the rings; nonintuitive structures emerged which bore a resemblance to still-unexplained structure in the rings (Fig. S5). Cuzzi and Estrada (1998) extended the meteoroid bombardment / ballistic transport process to compositional evolution, showing that the optically thinner regions of an
Figure S5: Comparison of model results showing radial restructuring (heavy solid, dashed, and dotted lines) into an abrupt inner ring edge, with the actual structure (light solid line) at the inner B ring edge (Durisen et al. 1992). The parameter $Y$ is a scaled ejecta yield that depends on ring viscosity and the ratio of optical depth to surface mass density. The time $t$ is given in units of the so-called “gross erosion time” which for standard parameters translates to exposure times of 0.7 – 4.5 Myr for the three cases shown. Note, besides the abrupt edge itself, the fine-scale oscillations starting to develop in the B ring, and the developing “ramp” between 1.50–1.52 $R_S$. Some models also show development of potential plateau-like features interior to the ramp. For comparison, Fig. 1 of our main paper exhibits the intriguing similarity between the inner A and B ring edges, extending to the structure of the optically thin regions interior to the edges. No common dynamical (resonance) mechanism is available to explain this similarity, making restructuring by ballistic transport appealing. However, the details remain to be completed.

Initially uniform composition ring would naturally end up darker and more neutral in color if the bombarding material had these properties, as is believed. The global color and albedo properties of the main rings are in good agreement with this theory in its current crude form; intriguingly, both these compositional evolution models, and structural evolution models (Durisen et al. 1992, Fig. S5) point to ring exposure ages in the few-hundred-Myr range. The incoming mass flux assumed by Cuzzi and Estrada (1998) and Durisen and coworkers is in reasonable agreement (factor of order unity) with the more recent determination by Landgraf et al. (2000) and Sremčević et al. (2005). Considerable additional progress can now be made using Cassini data,
such as the correlations of water ice band depth and visual color found by Nicholson et al. (2008), and the wealth of new information regarding local surface mass densities now available. Cassini will measure two critical parameters during its extended mission (Spilker et al 2009): the incoming mass flux of meteoritic projectiles (by flying through and measuring the density of the halo of trapped meteoroid ejecta surrounding Rhea) and the mass of the rings (by tracking the spacecraft near closest approach in several of its penultimate orbits with periapse lying inside the D ring). The ring mass measured in this way is expected to have only a few percent uncertainty – tiny compared to current estimates, which can be at least twice Mimas’ mass (Robbins et al 2009).

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**N. B.** The SOM list of references does not include the following, which may be found in the reference list for the main paper.


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