SATURN'S RINGS AFTER CASSINI. J. N. Cuzzi[1], *Jeffrey.Cuzzi@NASA.gov;* [1]*Ames Research Center, NASA, MS 245-3, Moffett Field, CA, USA*.

Cassini has rewritten the textbooks regarding our understanding of Saturn's Rings, a full generation after Voyager first revealed their complex structure. It will be impossible to review all of Cassini's discoveries here (for recent reviews see [1-3]), but we will cover the highlights. Dynamically, the Rings are changing before our eyes; compositionally, they are much younger than the solar system.

Waves and collective dynamics: Spiral density and bending waves were discovered by Voyager. They are driven at orbital resonances with various satellites, blanket the A ring, and are sprinkled throughout the B and C Rings. Improved analysis tools have allowed even the weakest of these features to be studied in detail, and they provide powerful constraints on the underlying, local surface mass density on several-km spatial scales. About a dozen spiral density and bending waves in the C ring have been shown to be caused by gravitational and pressure modes inside the planet, potentially constraining the interior structure of Saturn and its rotation rate.

Ring microstructure on sub-km scales is seen everywhere by stellar and radio occultations, and varies on short timescales. Ubiquitous transient gravitational instabilities called self-gravity wakes arise and are torn apart by differential rotation. These wakes vary in configuration across the rings, and their properties imply a ring vertical thickness of tens of meters or less. An unrelated, axisymmetric kind of microstructure, due more to viscous forces than self-gravity, can also be seen at various places in the denser parts of the rings. Images taken from close orbits, with sub-km resolution, show that fine-scale structure is widespread in optically thick regions, some of it granular and some axisymmetric or streaky. Dense clumps called "straw", each the size of a convoy of aircraft carriers, are seen in between the dense crests of strong spiral density waves, probably compacted as particles pass through the crests, and subsequently broken apart by collisions.

Embedded moonlets: Analysis of Cassini images (including spectacular images of Pan in the Encke gap) have now shown that skirted, embedded 10-km size moonlets are responsible for opening both the Encke and Keeler gaps in the A Ring. In general, the small ringmoons lying within and near to the rings have very low densities and are probably rubble piles, perhaps with dense cores. However, moonlets have *not* been found in similar gaps in the Cassini Division or C ring with the $\sim$1 km sizes previously thought necessary to clear them.

Flocks of smaller "propeller" objects of 100-200m size, detectable only in their disturbance of nearby ring mterial, occupy three radial bands in the A Ring. A dozen or so of the largest of these objects, 0.1-1km in size, wander randomly in semimajor axis because of gravitational scattering by the clumpy ring material they interact with. Discrete km-size objects have also been inferred from disturbances at the outer edges of the A and B rings and in the Huygens ringlet of the Cassini Division. These objects seem to disaggregate and perhaps reaggregate in place, on timescales of months or years, suggesting ongoing recycling of material driven by satellite forcing, self-gravity, and collisions.

Cassini discovered dramatic vertical distortions of the rings, in addition to the well-known spiral bending waves, near Equinox when the sun's illumination was at a grazing angle. The edges of the Keeler gap are noticeably warped, consistent with the small inclination of its central ringmoon Daphnis, but those of the Encke gap are not. The outer edge of the B ring showed alpen-like, spiky peaks and shadows. The outer edge of the A Ring showed a very clumpy structure, lacking distinct peaks but with shadows suggesting vertical relief.

Ring Particle properties: Voyager showed that the main ring particle size distributions tend towards powerlaws ranging between cm-m radii. Cassini has shown that the power-law slope, and the minimum and maximum sizes, all vary across the rings. Enhanced collisions in spiral density waves create blizzards of small particles, which seem to affect the brightness and color of the surrounding region. As shown by comparison of radio and stellar occultations at UV, near IR, and mid-IR wavelengths, and by the ring spectra and color, this effect is especially significant in the outermost A Ring, the region most strongly stirred by spiral density waves.

A combination of 10-400μm thermal emission and scattering, and 2.2 cm radiometry, suggests that ring particles probably have a very low density mantle — *ie,* are porous aggregates - but may also have more dense cores. The rings' thermal emission suggests a regolith of pure water ice grains of 10-100 μm size. Cassini 2.2cm radiometry detects a fraction of a percent of non-icy material, with little variation, through the A and B rings, improving on pre-Cassini microwave observations which claimed that the total non-icy material could not represent more than a few percent relative abundance. However (when combined with spiral density wave surface densities/opacities), 2.2cm radiometry has also revealed what looks like a buried silicate-rich rubble belt in the mid C Ring.

VIMS spectra show that A and B ring composition is nearly pure water ice without any other identifiable ices (CO, CO_2, NH_3, CH_4) but there is a strong and still-undefined UV absorption that varies in strength from place to place; the red color of the rings is strongest where the water ice absorption bands are deepest, suggesting that the red material resides within the icy regolith grains, and increases steadily inwards, having a different radial distribution than more "neutral" non-icy material. The very low mass fraction of nonicy material (except in the C Ring rubble belt) provides our strongest constraint on the age and origin of the Rings, as discussed below. The rings' red color in the UV-visible region may be explained by fragments of carbon-bearing tholins (perhaps similar to material blanketing the surface of comet CG as observed by Rosetta), or (some argue) by tiny iron-rich particles, embedded in the dominant water ice. HST-STIS observations favor the organics.

New *in situ* data from CDA and INMS on the ring-grazing and grand finale orbits have greatly enriched the ring composition story. Abundant, Fe-poor silicates and organic molecules are associated with the innermost D and perhaps C Rings. Evidence for organics is also found outside the rings, and INMS also sees CH_4 both outside and inside the main rings. Reconciliation of these *in situ* results with remote sensing is only beginning.

Ring variability with time: The outer edges of the dense A and B rings vary in complex ways with both longitude and time, indicating the combined effect of multiple free or "normal" modes, and the expected satellite-driven forced modes; the actual cause of the free normal modes remains a subject of debate. The outer 100 km of the B ring shows complex, fine-scale brightness variations possibly caused by these deformations. Gravitational effects of the modes might even play a role in sculpting the narrower gaps in the Cassini Division, so far found to be free of small moonlets.

Channels open and close in Saturn's stranded F ring, in response to close approaches by Prometheus, and change in strength as the orbits of Prometheus and the F ring mutually precess. Kinks and "mini-jets" come and go in the F ring core, excited by small unseen objects at low relative velocities, and more dramatic jets of material lasting months are triggered by objects eccentric enough to crash through the ring at high relative velocities. One of these objects was tracked in 2006-2008 as it collided with the F ring several times, but has not been seen since, while two similar objects have just appeared.

These violent collisions continue because the entire F ring region is dynamically chaotic, mostly because of Prometheus, and for this reason the long term stability of the F Ring core has been problematic. The F Ring has a narrow "true core" of large particles, as characterized best by RSS, confined and stabilized by a specific new kind of dynamical trapping due only to Prometheus. This arrangement must constantly make small adjustments, given leakage of particles and occasional chaotic changes in Prometheus' orbit to which the clumps must readjust. The fine dust seen in images and stellar occultations is a tiny fraction of the F Ring total mass. Clump activity has varied dramatically between Voyager and Cassini.

Impacts have warped the C and D rings: Vertical ripples or warps covering the inner part of the rings suggest that Saturn's inner main rings were tipped relative to its equator several times over the last millennium, and as recently as a few decades ago. Impacts by rubble streams produced by disrupted objects are the most likely cause. Several impacts by individual m-size projectiles have actually been seen and catalogued.

Diffuse rings are affected by sunlight and magnetic fields: The source of the E Ring particles has been confirmed as the south polar jets of Enceladus. Several new arcs and ringlets are associated with erosion of small embedded moons. The E Ring and other diffuse rings and ringlets (such as those in the Encke gap) are affected by radiation and electromagnetic forces as well as by gravity, and thus show seasonal variations in their structure. Some diffuse rings, notably the D Ring and the faint material between the A and F Rings, are modulated by azimuthal variations in Saturn's magnetic field.

The duration and behavior of the "spokes" Voyager discovered in the B ring has been further constrained, though their ultimate cause or trigger remains unknown. Cassini found that they seasonally appear and disappear, probably due to variable photocharging, and their temporal periodicities span the entire range seen for rotational periodicities in Saturn's atmosphere, ionosphere, and magnetic field.

Origin and Age of the Rings: The strongest constraint on ring age is provided by the gradual darkening and restructuring of the rings with time by infalling meteoroids. Inferring the actual ring age requires knowledge of both the incoming meteoroid mass flux and the total mass of the rings.

The Cassini Dust Analyzer experiment has determined, cumulatively over the entire mission, the infalling meteoroid mass flux and dynamical population. The mass flux far from the planet is not too different from pre-Cassini estimates. However, the dynamical population is like that of Kuiper Belt objects, so has a lower encounter velocity and is more strongly focussed by Saturn's gravity than thought previously.

Voyager-era estimates of the ring mass were roughly 0.7-0.8 Mimas masses. It was since realized that the breakdown of the ring layer into opaque clumps (the self-gravity wakes), separated by nearly empty gaps, allows a lot of mass to be "hidden" in the clumps. Modeling of dozens of spiral density and bending waves over the last decade had constrained the mass of the A, C, and inner B rings, so any hidden mass had to reside in the densest parts of the B ring. In the Grand Finale Orbits, the Cassini RSS team carefully tracked the spacecraft to constrain the ring mass by its perturbation on Cassini's orbit. It turns out that the ring mass is not, indeed, much larger than our Voyager-era expectations. Combined with the CDA-determined meteoroid mass flux, pollution-based estimates lead to a ring exposure age of 100-200Myr, even a little younger than Voyager-era "young-ring" scenarios.

The associated puzzles of "Why is Saturn the only giant planet with rings?" and "Is the ring system young?" have been, if not yet explained, at least illuminated by an emerging hypothesis involving a closely-coupled tidal evolution of the mid-sized icy moons leading to a Saturn-specific dynamical instability of the inner satellite system, with possible disruptions and reaccretion, on the order of 100Myr ago. Constraints from satellite surface geology will need to be folded in to evaluate the plausibility of the scenario.

Many Big Unknowns Still Remain: Most of the big picture is still a puzzle! The irregular B Ring structure, C Ring plateaus, and sharp optical-depth jumps (but not to empty space) within the B ring remain unexplained. The inner edges of the A and B rings, and the edges of the C Ring plateaus, are sharp only in optical depth, and their mass density profiles are much more gradual; this is not understood. The red color of the A and B Rings, and its dramatic increase inwards across the B Ring, remain a puzzle, but new CDA and INMS observations are contributing insight. Regional color and brightness variations have been interpreted as small-scale, optical-depth dependent regolith grain size variations, but models capable of treating the tough ring radiative transfer problem have yet to be deployed in compositional analyses. There may be cyclic, self-limiting processes of growth and disruption of small planetesimal-sized objects, especially in the outer A and F Rings. The stable eccentricity of the F Ring remains unexplained. Cassini has answered many of the questions raised by Voyager, and leaves us with a largely untapped reservoir of data with which to answer the rest.

References: [1] Cuzzi J.N. et al (2010); Science, 327, #5972, 1470 - 1475 [2] Dougherty M.K., Esposito L.W., and Krimigis S.M., eds, (2009); "Saturn from Cassini-Huygens"; Springer. ISBN 978-1-4020-9216-9 [3] Cuzzi J. N., Filacchione G., and Marouf E.A. (2018) Saturn's Rings; a chapter in "Planetary Rings": M. Tiscareno and C. Murray, eds. (Cambridge)