Planetary Rings

Planetary rings are common to all the giant planets of our solar system. They form a disc of particles following a nearly circular orbit in the equatorial plane of the central planet according to Kepler's laws of motion. Ring discs have various dimensions and radial structure. They have been discovered both from ground-based and spacecraft observations. SATURN'S RINGS were discovered by Galileo Galilei in 1610 but clearly identified as rings by C. Huygens in 1659. They have been the only known planetary ring system for more than three centuries. The developpement of ring knowledge has been therefore tightly linked with their history until the seventies. The discovery of a new ring system around Uranus in 1977, during the ground-based observation of a stellar occultation by the planet, boosted research in this area and quest for new rings. Suspected after the charge particle measurements of Pioneer 11 in 1974, the very faint JUPITER RINGS were finally detected by the Voyager spacecraft in 1979. More extensive observations have been made recently by the Galileo spacecraft. The story of NEPTUNE'S RINGS started when ring « arcs » were detected in 1984 with the same method of stellar occultation. The complete ring system was revealed by Voyager 2 cameras in 1989. The view of ring systems has been completely renewed in this twenty-years-long « golden age » period. Many theories were developped to explain the huge amount of unexpected observations sent back by Voyager probes. Great progress has been made in our understanding but many interrogations on the origin and evolution of planetary rings remain. In the following sections the possible scenarios on their origin are discussed, the main questions raised after these discoveries are developped. Finally open questions and main ring science objectives of the next Cassini mission to Saturn's rings are presented.

Origin

Rings are a common feature in the close vicinity of giant planets. They are located within the Roche limit, an approximate distance where any rock is expected to break up under the tidal effects exerted by the planet. Ring discs in the Roche limit are vertically very thin, a few hundred-meters thick for a radial extent of few ten or hundred thousand kilometers. This is the natural evolution of a cloud of particles in the gravitational field of a central planet which is losing energy in inelastic interparticle collisions while conserving angular momentum. An out-of-plane particle, when crossing the mean plane of the other particles, has its out-of-plane velocity component reduced in each collision and finally reaches the common plane. Meanwhile particle orbits are drifting in the equatorial plane if the planet is even slightly oblate.

Ring particles may have condensed from circumplanetary material when the planet formed and have collapsed into a thin disc. The creation of rings after the disruption of a parent body is another plausible scenario. The parent satellite a captured body, a comet or an asteroid, would have drift into the Roche limit and be disrupted by tidal effects or a large impact. Observations tend to show that planetary rings are evolving on timescales much shorter than the age of the solar system. Then primordial rings should have disappeared already or should be continuously destroyed and replenished over ages. The equivalent mass of a 400 km-sized satellite should be reinjected into the Saturn's rings every 500 Myr. The less massive main rings of Neptune, Uranus and Jupiter might have found enough material in their nearby small satellites to be fed with. An alternative scenario of a recent and widespread ring formation would imply a hardly reconcilable anthropocentric viewpoint.

The origin of dusty and thin rings may be less uncertain. The particles here are typically micron-sized and are consequently removed very rapidly by drag forces. They are most probably replenished with the ejecta produced by the meteroid bombardment of close satellites surfaces. The E ring of Saturn, which extends from 3 to 8 Saturn radii, may be the most illustrative example. Its peak density is correlated with the orbit of the icy satellite Enceladus. The ejected dust would be dispersed around its orbit and further dispersed at large scale nder the action of electromagnetic forces. Recent Galileo observations of Jupiter rings have shown direct evidence of very faint dusty rings associated with small satellites Amalthea and Thebe outside of the main ring system. Spectroscopic measurements tend to confirm the compositional link between Jupiter rings and nearby satellites.

The chemical composition and bulk structure (density, porosity…) of ring particles may provide hints into possible scenarios of formation but relevant spectroscopic data are often lacking. Water ice has been identified as the main constituent on the surface of Saturn’s ring particles. Impurities are also present but not yet identified. The composition of the other ring systems are still unknown but the lack of water ice signature. Conclude for ring origins from current composition is however a tricky task as ring particle surfaces are eroded or polluted on relatively short timescales by meteroid bombardement, high energetic particles sputtering or ejecta of nearby satellites. Clues to origin may be deeper in the surface and then still hard to probe with current data.

Evolution

Interparticle collisions in the ring plane even more disperse particles radially. The final disk is uniform with smooth edges. The most remarkable discovery in the past 30 years has been the unexpected and extreme diversity of structures in planetary rings, like divisions, sharp edges, spiral waves, narrow ringlets or azimuthal asymmetries like arcs and clumps in narrow rings or spokes in Saturn's rings. Most of them are common to all ring systems. Any narrow ring should be dispersed radially because of collisions and differential motion (the orbital velocity decreases with increasing distance to the planet). Any longitudinal asymmetry should be also slowly stretched along the ring and erased on timescales of years by this differential motion. These structures are therefore either young or confined radially or azimuthally

Among the processes proposed to explain the observed structures, the resonant gravitational interaction of ring particles with nearby satellites is certainly the most important. Theories of radial confinement of a ring, or « shepherding » mechanism, proposed by Goldreich and Tremaine in the 80s, estimate the torque exchange between ring particles and satellite. The transfer of angular momentum takes place at resonant locations where satellite and ring particle orbital frequencies are commensurable, with mean motions in a ratio of m:m+1 for example. The resonant perturbation of an outer satellite removes angular momentum from ring particles which drift inwards while an inner satellite adds angular momentum to outer ring particles which drift outwards. Both protagonists tend to move away from the resonant orbit. This interaction result in various structures depending on satellite mass and distance. A close and massive outer satellite creates a wake in the ring and repels particles along a sharp edge. The main Jupiter ring edge is maintained by the close satellite Adrastea (km sized). The outer edge of the B ring is located at the 2:1 resonance with Mimas and corresponds to the Huygens gap in the Cassini division. The massive Mimas is then able to remotely open a gap. The outer edge of the Saturn’s A ring is located at a 7:6 resonance with the coorbital satellites Janus and Epimetheus (sizes). Gaps with sharp edges can also be opened in rings by embedded moonlet. The Encke gap is carved out of the Saturn's A ring by the 10-km sized moonlet Pan. The satellite was suspected because of wakes detected on gap edges and later discovered in Voyager images. Density waves or bending waves are driven by smaller and distant satellites at high order resonance locations. The amplitude of waves depend on satellite mass and distance and on the local viscosity of the disc. Few km-wide waves driven by Prometheus, Pandora, Janus or Mimas are visible in the Saturn's rings. Because of these interactions, the orbit of particles drift a few cm to one meter per year due to these kind of interactions. The outer A ring is expected to fall onto the Cassini division in few hundred Myr !

Two shepherding moons on each side of a ring repel the same way particles and can confine the ring radially. The discovery of Saturn's F ring shepherds Prometheus and Pandora and of Uranus ε ring shepherds Cordelia and Ophelia were the most spectacular success of the Goldreich and Tremaine theory. The singularity of URANUS RINGS at the time of their discovery was their extreme narrowness of a few kilometers. Dermott and Gold had proposed in 1977 another confinement theory involving a single satellite. In a frame corotating with the moon, a ring particle of nearly same semi-major axis describes an « horse shoe » trajectory and is then confined into a narrow ring. But this kind of orbit is not stable against collisions. No shepherding moons were discovered around nor within the eight narrow rings of Uranus left. But resonance relationship were found between the sharp edges of δ, λ and γ Uranus rings and Cordelia and Ophelia satellites. The radial confinement of 6, 5, 4, α, β and η rings remains unexplained.

The discovery of Neptune's arcs set the new fundamental question of azimuthal confinement. From 1984 to 1989, a campaign of stellar occultation observations led to the conclusion that Neptune "rings" were in fact a family of longitudinally discontinuous rings, called "arcs", one of which was a few hundred kilometers long. Lissauer i n 1985 formulated a model where an arc could be confined at the Lagrangian L_4 or L_5 points of a 200-km-sized satellite. An inner satellite was added to prevent the radial spreading due to collisions. Goldreich, Tremaine and Borderies in 1986 proposed that a single nearby inclined satellite would confine azimuthally the whole family of arcs in several resonance sites. Voyager 2 images in 1989 showed that arcs were in fact surdensities embedded in a same narrow ring, the Adams ring. No coorbital massive satellite was found but clumps, may be embedded km-sized objects, were discovered in the arcs themselves. After ground-based observations and Voyager 2 data were compared, the arcs appeared to be stable over 5 years despite keplerian shear due to differential motion. Porco detected in Voyager 2 images a wavy radial distortion in the Adams ring that she attributed to the excitation of the ring by a 42:43 resonance with nearby satellite Galatea. Arcs had thersfore to be confined in 4.2°-long azimuthal sectors along the ring. But some arcs did not respect properly confining sites. Thanks to recent first direct imaging of Neptune's arcs from Earth with the Hubble Space Telescope, the mean motion of arcs has been measured much more accurately. The orbit is unambiguously outside the 42 :43 resonance with Galatea. The role of this satellite and the azimuthal confinement of arcs have to be studied again. Other arcs and clumps have been detected in F ring, in the Encke gap ringlets around Saturn or in Uranus λ ring. Their temporal evolution is still poorly known but recent ground-based and HST images of the F ring arcs obtained during 1995 Sun and Earth ring plane crossings suggest that the structure of the F ring evolves on weeks timescale. This result appears to be compatible with Voyager observations. Observing heterogenous rings is certainly a key towards the understanding of the close relationship between rings and satellites, the radial and azimuthal confinements of ring material and then the origin and evolution of rings.

Other processes at play in planetary rings can also severely reduce their lifetime. Erosion mechanisms due to interpaticle collisions, meteroid bombadrement, sputtering by cosmic rays, etc…, supply new molecules into a gaseous ring atmosphere or new small particles in the ring system while removing others. The meteroid bombardment appears to be the most efficient at work with an erosion rate evaluated at 10^{-3} cm/year. These outstanding rates for cm-to-m-sized particles still depend on poor data. The size distribution and density of particles are also controlled by interparticle collisions. But collisional erosion, fragmentation or accretion rate of particles are very uncertain as restitution factor and bulk properties of particles are unknown and difficult to constrain. Ring particles immersed in the surrounding magnetospheric plasma are charged. Within the planetary magnetic field, sub-micronsized grains can experience significant Lorentz force compared to gravity. Particles are driven out of the ring plane. This process is certainly involved in the creation of Saturn’s B ring spokes, in the spatial distribution of the Saturn’s E ring or the halo of Jupiter ring. Small particles are also sensitive to drag forces like Poynting-Robertson or plasma drags. The Poynting-Robertson effect due to solar radiation induces an orbital decay and reduces the lifetime of dusty particles in the system to less than 1Myr. The plasma drag is due to collisions with electrons and ions or long-range charge interactions. Dust charged particles inside or outside the synchronous orbit (where particles and magnetic field rotation speeds are equal) will spiral inwards or outwards respectively. The related lifetime may be as short as few hundred years in Jupiter and Saturn systems.

Future

Planetary rings are complex systems. They apparently evolve on timescales much shorter than the age of the Solar System but are also a common component in a planet system. The different processes at play transfer angular momentum between ring and satellites, confine ring material at some places and push other material onto the planet, feed with or remove particles. Many important ring structures are still not understood. The question of the origin is difficult to solve. Many evolution timescales rely on still poorly known data. The Cassini spacecraft has been launched in October 1997 and will be placed into orbit around Saturn in 2004. Observations on an uniquely large spectral range will give decisive constraints on Saturn’s rings composition, on the bulk properties of particles, the compositional relationship between ring and satellites or the nature and flux of incoming material onto rings. Temporal evolution of structures will be carefully observed over years to better understand ring-satellite interactions and confinement mechanisms. This 4-year-long mission will provide major advances in the answers on origin and evolution of Saturn’s rings. Meanwhile technical progress will provide always richer ground-based data on the other ring systems to constrain their physical properties and short evolution timescales. Until a new generation of spacecraft is launched to Uranus and Neptune.

Bibliography

Greenberg R and Brahic A (eds) 1984 *Planetary Rings* (The University of Arizona Press, Tucson, Arizona).

Esposito L, Cuzzi J N, Holdberg J B , Marouf E A, Tyler G L and Porco C C 1984 Saturn's rings : structure, dynamics and particle properties, In : Gehrels T and Matthews M S (eds) *Saturn* (The University of Arizona Press, Tucson, Arizona) pp 463-545.
French R , Nicholson P D, Porco C C and Marouf E A et al. 1991 Dynamics and structure of the Uranian rings, In : Bergstrahl J T, Miner E D and Matthews M S(eds) *Uranus* (The University of Arizona Press, Tucson, Arizona) pp 327-409
Esposito L, Brahic A, Burns J A and Marouf E A et al. 1991 Particle properties and processes in Uranus' rings, In : Bergstrahl J T, Miner E D and Matthews M S(eds) *Uranus* (The University of Arizona Press, Tucson, Arizona) pp 410-465
Porco C C, Nicholson P D, Lissauer J J, Cuzzi J N and Esposito L W 1995 Neptune's rings In : Cruikshank D and Matthews M S (eds) *Neptune and Triton* (The University of Arizona Press, Tucson, Arizona) pp 703-806

CECILE FERRARI