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SATURNS RINGS OBSERVED BY THE CASSINI SPACECRAFT (I.S.S.)

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Abstract. After 9 years of observations by the Cassini spacecraft Imaging Sub System (ISS), we review the main discoveries on Saturns rings. We have been able to follow the evolution of the rings as a function of time with variations on time scales as short as days. This exploration provided new information on the structure of the rings, on waves, on resonances phenomena, and on ring - satellites interactions. A detailed study of the rings edges, of the spokes and of the F, G, E and D rings has been performed. The discovery of propellers, meteoroid impacts, and of the opposition effect gave new insights on rings evolution. New ideas about the nature of the particles and the age of the rings have been developed.

Keywords: planetary rings, Cassini ISS observations

1 Introduction

The disc around Saturn is a system of colliding particles submitted to the gravitational influence of Saturn and of small nearby satellites. It can be considered as a natural laboratory of dynamics, cosmogony, granular flow and particle and field physics. The structure of the rings is determined by their origin and by dynamical processes which depend upon the sizes and collisional properties of the ring particles, and on the gravitational effects of the satellites. Electromagnetic processes play a role on the motion of charged particles.

Since they were first discovered by Galileo in 1610, the nature of Saturns rings has been a continuing challenge to observation and theory. From the beginning, observational resolution seemed to be just short of revealing the essential nature of the rings. The effort to understand rings has always attracted outstanding scientific minds. Galileos first detection of something strange around Saturn was open to several interpretations. Huygenss revelation of a disc-like structure did not bring any information about rings nature. Cassini suggested that the rings might consist of a myriad of small particles without being able to prove it. Laplace and Maxwell showed that a solid ring would be unstable. Beginning with Poincar, a general picture of collisional flattening and spreading emerged, with structure governed in part by resonances with the satellites. Dynamical theory was adequately consistent with Earth-based observations of seemingly smooth, continuous rings. Optical and radio properties seemed in good agreement with a swarm of small, icy particles of various sizes. Until 1980, theoretical models seemed in harmony with most observed properties.

The space exploration has completely changed our understanding of rings. In spite of 370 years of telescopic observations from the Earth, no one imagined before 1980 the wealth and the diversity of structures inside planetary rings. In a few years, our conception of rings underwent a revolution. In 1980 and 1981, the Voyager spacecrafts revealed countless detailed features and structures that had never been imagined and, in 1984 and 1985, arcs were detected around Neptune by the author as they occulted a star. After the surprises of the Voyager flybys in 1980 and 1981, the Cassini spacecraft, with considerable improvements in resolution and sensitivity, is revealing a system still more complex than foreseen. I have selected a list of 15 observations which completely change our understanding of rings evolution and I briefly quote the list of these important discoveries, without entering into technical details in this short paper.

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2 The ring structure

Our understanding of the structure of Saturns rings has improved dramatically over the course of Cassinis initial 9-year mission. This has enabled, for the first time, a detailed observation of non-axisymmetric structures as well as vertical structures in the rings. This continuous observation of the rings during almost a decade and comparison with Voyager observations more than thirty years ago reveal changes in ring structure and variations with time with time scales varying from several years to only a few days.

Saturns rings can be broadly grouped into two categories : dense rings (A, B and C) and tenuous rings (D, E, G and the Cassini Division). The lettered rings contain multiple ringlets within them. Several thousands of structures have been observed. Inside the dense rings, typical optical depths are greater than 0.1 while the dusty rings have optical depths of 10-3 and lower.

Different structures can be observed on all scales inside the rings. The most prominent features of Saturns A ring are the multitude of density waves launched at Lindblad resonances with nearby moons and the two gaps (Encke and Keeler gaps) cleared respectively by Pan and Daphnis. The fine-scale texture of the A ring is dominated by self-gravity wakes. Small moonlets can create in their surroundings small disturbances, which have received the nickname of propellers . The microstructure of the A ring has been observed in unprecedented detail thanks to radio and stellar occultations. The optical depth averages around 0.5 in the A ring.

The B ring contains much of the total mass of the Saturns ring system, but its higher optical makes the detailed observations more difficult. Many density and bending waves as well self-gravity wakes have been detected in this ring. Large-scale irregular structures have been observed in most of the B ring. In its denser part, a nearly bimodal distribution of ring optical depth has been revealed with much of this ring being essentially opaque and with abrupt transitions in optical depth. This may be due to previously unsuspected instabilities in the rings.

The Cassini Division and the C ring are similar in many ways. The most obvious similarity is their optical depth, which averages around 0.1 for both regions and only rarely exceeds 0.5. There are also several narrow gaps, with five of them within the 18 000 kilometres wide C ring while the Cassini Division has eight within its width of only 4 500 kilometres. In comparison, the A ring has only two empty gaps and the B ring has none.

The F ring, located near the Saturns Roche limit and gravitationally perturbed by Prometheus and Pandora, has a variety of unique features. Faint rings (G and E) extend well beyond the Roche zone.

3 Waves

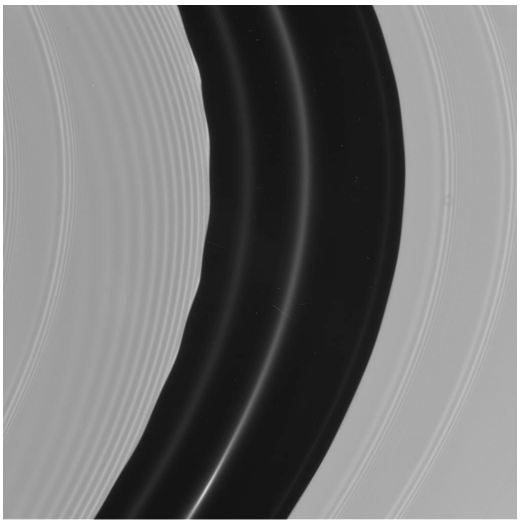

Fig. 1. Waves on the edges of the Encke gap, spiral density waves (on the right) and moonlet wakes (on the left) can be seen in this image. (NASA-JPL / ESA document).

Saturns rings is a waves heaven. Dozens of spiral waves have been observed and five bending waves have been clearly identified. Spiral density waves are densely packed throughout the A ring because a large number of moonlets and satellites are close to this ring and the resulting resonances are closely spaced. These spiral waves are generated at the locations of resonances with perturbing moons, they propagate away from the resonance location in a single radial direction. Spiral waves are compressional waves while bending waves are transverse waves that arise at locations where a ring particles vertical frequency is in resonance with a perturbing moon. These waves serves as an in situ probe, by which local properties of the rings can be obtained. Spiral density waves transfer angular momentum between the rings and the forcing moons; thus, the orbits of the perturbing moons evolve outward, while those of the ring particles decay inward.

4 Ring-satellite interactions

Moons are intimately involved with much of the structure of the rings. The outer edges of the A and B rings are shepherded and sculpted by resonances respectively with the Janus - Epimetheus co-orbital satellites and Mimas. Density waves at the location of orbital resonances with nearby and embedded moons make up the majority of the large-scale features in the A ring. Pan and Daphnis are massive enough to clear gaps in the A ring. Large ring particles, which are not massive enough to clear a gap, can produce localised propeller-shaped disturbances kilometre long. Clumps and strands are observed in the A, B and F rings. Near the Roche limit, accretion and disruption phenomena are competing in the F ring. Clumps and strands form and are disrupted all the time.

The interactions between satellites and rings are not only gravitational. There also exchanges of material between the satellites and the rings. Enceladus is bringing dust to the E ring while Prometheus is regularly taking away material from the F ring.

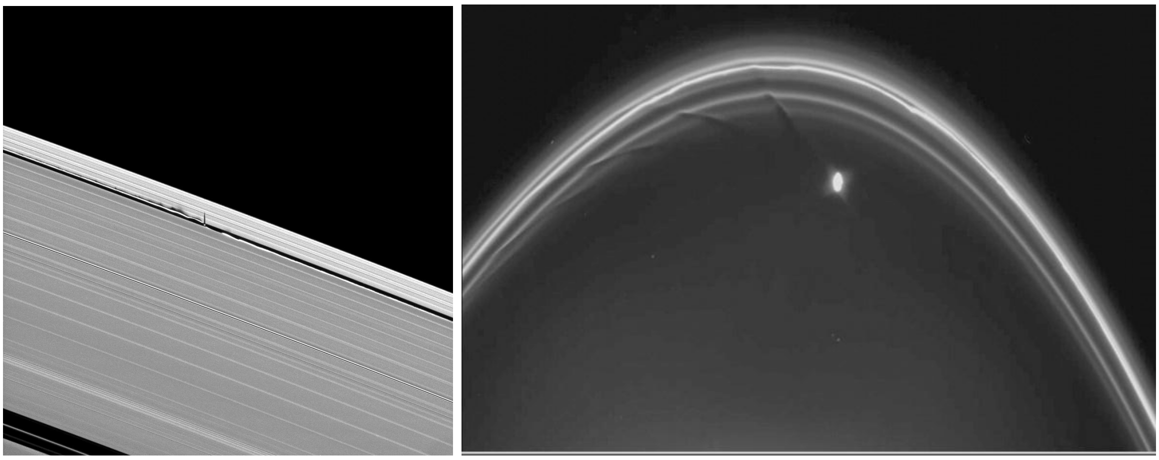

Fig. 2. On the left, the moon Daphnis clear a gap in the A ring and sculpts the edge into waves that have both horizontal and vertical components. On the right, at each close passage, the shepherding moon Prometheus triggers the formation of channels with clumps at the edges. (NASA-JPL / ESA document).

5 Resonances

Resonances in Saturns rings create waves, gaps, wavy edges, vertical structure, material confinement and several other phenomena, making the rings a laboratory of physics and dynamics. Several different types of resonances are at work in Saturns rings, including orbital resonances, mean-motion orbital resonance, secular resonances, Lindblad resonances, vertical resonances, Kozai resonances, etc.

The outer edges of the A and B rings both occur at strong resonances. At the outer edge of the A ring, the ring particle orbital period is equal to 6/7 Janus orbital period while the ring particle orbital period at the outer edge of the B ring is equal to 1/2 Mimas orbital period. The perturbations from the moons cause the edges to move in and out.

Different resonances produce different waves, which can be observed for example at the location of the 5/6 Janus, the 12/13 Pandoras or the 18/19 Prometheus orbital periods. These localised disturbances can even lead to changes in the apparent brightness of the ring, which can be observed for example at the location of the 3/4 Janus, the 4/5 Janus, the 3/5 Mimas orbital periods.

6 Ring edges

Unusual mottled-looking narrow region, with a radial width varying with longitude from 5 to 10 kilometres, have been seen for the first time about 60 kilometres inside the outer edge of Saturns A ring. The mottled regions are probably caused by particle clumping brought about by gravitational disturbances. The outer A ring edge is sculpted into a seven-lobed pattern called a Lindblad resonance by the co-orbital satellites Janus and Epimetheus. The resonant perturbations in this region are complicated by the presence of these two moons whose orbits are within 50 kilometres of each other.

Other kinds of new features like ropy structures have also been found. For example, at the outer edge of the Encke gap, rope-like features can be seen between the first two wakes nearest the gap edge. Theses ropy features appear to be a product of the enhanced gravitational disturbances that occur when the particles pass through the wakes caused by Pan and consequently are squeezed close together. These disturbances obviously persist even outside the wakes, as is evident in the presence of the ropy structures in the bands in between the wakes.

The inner edges of the A and B rings are remarkably similar morphologically. The A ring edge is confined by the 7:6 Lindblad resonance with the co-orbital moons Janus and Epimetheus. Cassini mapping of the edge reveals complex structure, with a time-variable component which may be due to changes in Janus and Epimetheus orbits.

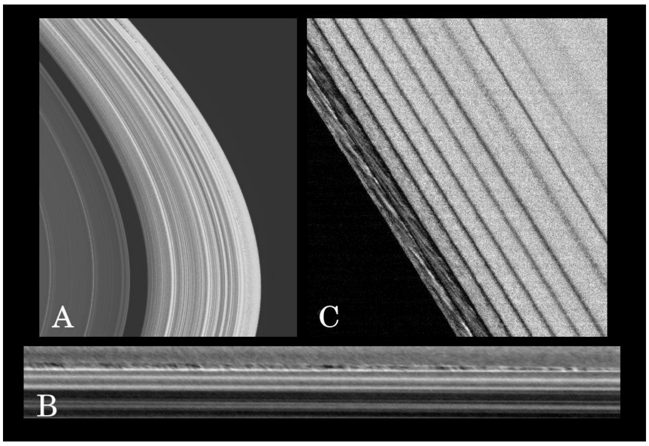

Fig. 3. Image A displays, at the edge of the A ring, a mottled-looking narrow region which have never be seen before. The image B is a close-up of the region. Image C shows the outer edge of the Encke division and the region exterior to it. The wakes of Pan are clearly seen. A different example of mottled structure is seen in the eight Pan wake from the edge, as well as ropy structure within the first two bands exterior to the gap. (NASA-JPL / ESA document).

7 Propellers

Moonlets with sizes much smaller than 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. The propellers provide the first direct observation of the dynamical effects of moonlets of about 100 meters in diameter. Such unseen size-class of particles can be detected indirectly. Such disturbances, shaped like propellers due to Keplerian shear, were predicted theoretically and subsequently observed by Cassini.

The radial separation between the two lobes is a few times the moonlet's diameter.Many propellers seem to be confined in the mid-A ring. Variations of propellers' orbits have been observed.

The outer A ring contains swarm of 100-meters size objects, just large enough to disturb nearby ring material into propellers. A handful of extremely large propellers was discovered and tracked. It was found that their orbits were changing with time. This seems to be mainly due to librations in the gravity well of the channel they create.

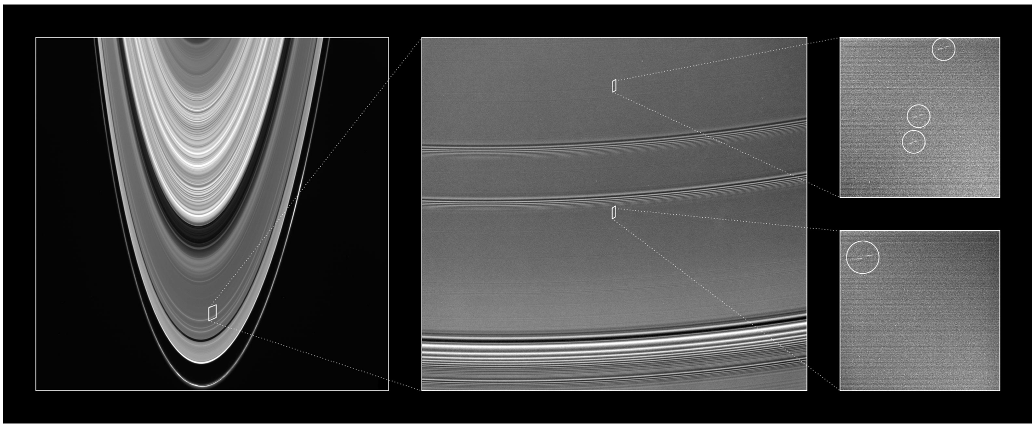

Fig. 4. This zoom shows the first discovered propellers. The centre image is a close view of the A ring, showing the radial locations were where propellers features were spotted. At the right, the propellers appear as double dashes and are circled. The unseen moonlets lie in the centre of each structure. (NASA-JPL / ESA document).

8 Opposition effect

The Cassini cameras captured the opposition effect in Saturns main rings with a fine radial resolution at extremely small phase angles. When Saturns rings are viewed with the Sun directly behind the observer, this opposition effect can be seen. The opposition effect is a sudden nonlinear rise in the reflectance with decreasing phase angle that occurs as the phase angle approaches zero.

Studies of this effect are useful to constrain a number of the properties of ring particles, such as their size and spatial distribution. The observations of this phenomenon are under analysis.

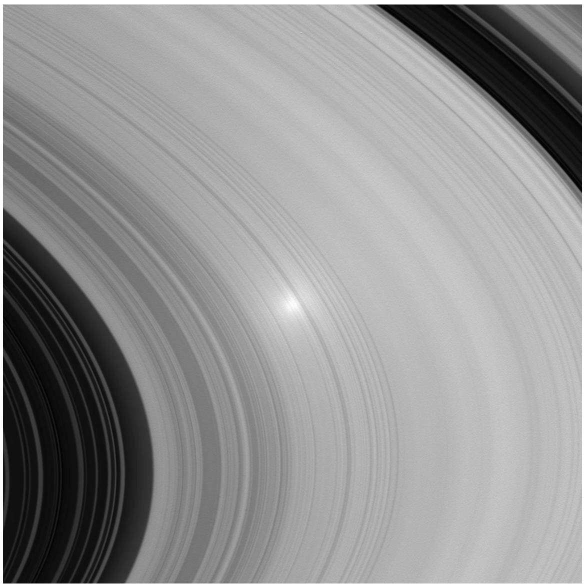

Fig. 5. The opposition effect : The bright spot occurs where the angle between the spacecraft, the Sun and the rings is near zero. (NASA-JPL / ESA document).

9 The Cassini Division

There are many similarities, both in particle properties and structure, between the C ring and the Cassini Division. The location of the Cassini division corresponds to a 1/2 resonance with Mimas. This division, separating the A and B rings by about 4 500 kilometres, is may be the signature of the past orbital evolution of Mimas. A large diversity of structures can be observed in the Cassini division : gaps, ringlets, plateaux, ramps, etc. The inner edge of 6 gaps are eccentric. Near the A ring, outside 120 400 kilometres, the Cassini Division takes a very different aspect, with no gaps and with a smoothly-varying optical depth with a monotonic increase towards the inner edge of the A ring.

10 The D ring

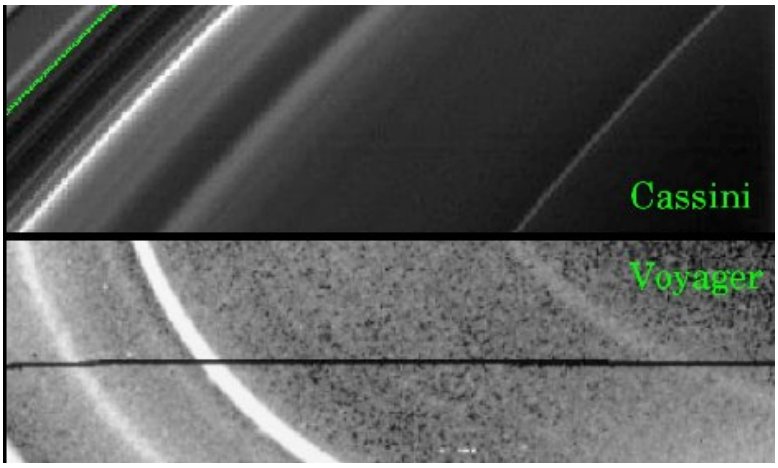

Fig. 6. As seen in the above images, structural evolution has occurred in Saturns D ring during the 25 years separating the Voyager and Cassini missions. The lower image, taken by Voyager 1 in 1980, shows from left to right, the bright inner edge of the C ring and three discrete ringlets: D 73, D 72, and D 68. The upper image, obtained by Cassini, shows the same region from a similar viewing geometry, but there have been some very significant changes in the appearance of the D ring. The green line marks the inner edge of the C ring. The D 72 ringlet has decreased in brightness by more than an order of magnitude relative to the other ringlets. It has also moved inward bout 200 kilometres relative to the others. With a much higher resolution than was possible for Voyager, Cassini revealed surprising fine-scale structures between the C ring and D 73 (inset). (NASA-JPL / ESA document).

The D ring, which is between the inner C ring and the top of Saturns clouds, is among the most complex of the faint rings. It has significantly changed since Voyager. For example, the ringlet located at 72000 kilometres from Saturns centre, called the D72 ringlet, is now much fainter than it used to be, and its centre of light has shifted of about 200 kilometres inwards relative to the other features in the D ring. We see new ringlets exterior to the D73 ringlet. There no longer appears to be any wave-like structure in the diffuse material.

Cassini has observed the D ring at much higher resolution than was possible for Voyager, revealing surprising fine-scale structures with a periodic wave-like structure with a wavelength of 30 kilometres. This complex pattern can be decomposed into multiple series of alternating bright and dark bands tilted relative to the local radial direction.

11 The F ring

Saturns F ring is a narrow, eccentric, inclined ring with unusual, time varying structure. The F ring is located near the Roche limit. Accretion and disruption phenomena are competing. The F ring contains a long-lived core and several narrow peripheral strands, tens of kilometre wide, that vary on time scales of hours to decades. A fainter dust belt spanning about 1 500 kilometres surrounds the strands. Nearby Prometheus causes the primary perturbations, distorting the ring by tens of kilometres at each passage. The phenomenon can be compared 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.

Fig. 7. In this image of the F ring, taken shortly after its ring particles encountered the shepherd moon Prometheus, the disruption to the ring caused by the moon is evident. The bright core of the ring and its neighbouring faint strands show kinks where the moon's gravity has altered the orbits of the ring particles.(NASA-JPL / ESA document).

12 The G and E rings

The E ring is the most extensive planetary ring in the solar system, enveloping many Saturns satellites from Mimas to Titan with Enceladus, Tethys, Dione and Rhea. The maximum edge-on brightness occurs near Enceladuss mean orbital distance, suggesting that this satellite is the source of the E ring. Cassini spacecraft has identified a geologically unique and presently active province at the South pole of Enceladus. This 505-kilometres diameter bright icy moon is active. Cassini imaging, thermal and other data indicate clearly that this satellite is presently heated by some mechanism. Tidal heating associated with the eccentricity of Enceladus orbit, forced by its 2:1 mean motion resonance with Dione, has long been suspected.

The E ring has been extensively imaged by the Cassini spacecraft. In addition, in-situ measurements during passages through the rings, have provided a complementary view of the E ring. We have a better understanding of the E ring thanks to two Cassini discoveries, i.e. the active dust-producing geysers in Enceladus s south polar regions and the fact that the E ring has a large radial span and reaches Titans orbit. Enceladus is filling Saturns entire magnetosphere with dust and particles are transported outwards due to plasma drag and they lose mass via sputtering.

The G ring is a tenuous ring outside the main ring system. It is not clear why the outer part of the G ring is brighter than other parts. Arcs are visible in some images of this ring. However, their existence might hold clues about how this ring was formed and where the material which makes up this ring comes from. Arcs of material confined by corotation resonances with Mimas have been found at the orbits of the small moon Anthe and Methone.

13 Meteoroid impacts

A spectacular collision between the rings and a large asteroid should lead to the escape of many particle, to waves formation and also to a large amount of material out of the Saturn equatorial plane. An inclined ring should appear and collisions between particles should reduce the inclination. Material which has not escaped Saturns system after the asteroid collision should come back to the main rings system in the equatorial plane of Saturn.

ISS has observed several impacts in the rings. They are thought to be the results of bombardment by meter-or-smaller size meteoroids. Observed ripples in the C and D rings are probably due to an asteroid collision. Something tilted the ring plane slightly in spring 1984. Saturns oblateness caused inclined orbits to wobble, inner orbits moving faster than outer ones. Twenty-five years later, ripples are still visible.

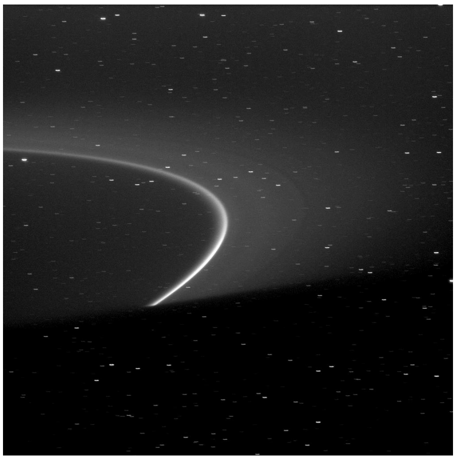

Fig. 8. The G ring has a sharp inner edge and a much smoother outer edge. The bright arc of material is trapped by the 7:6 corotation resonance with Mimas. (NASA-JPL / ESA document).

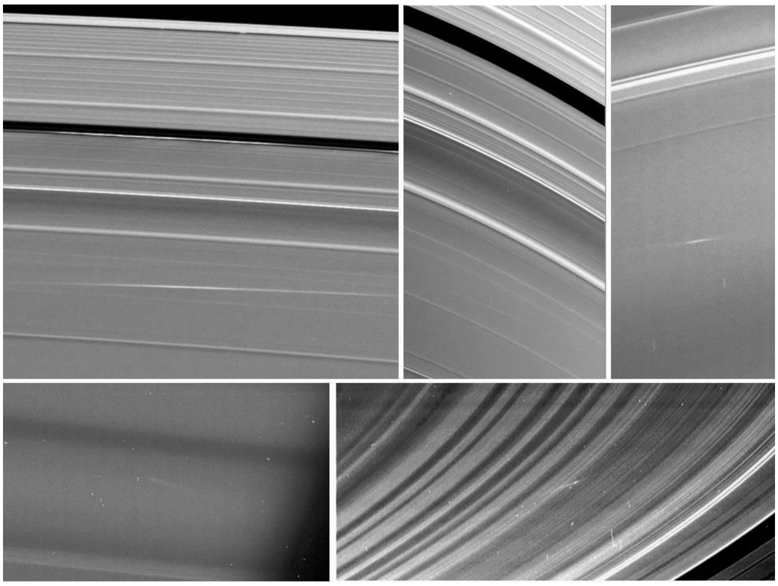

Fig. 9. Meteoroid impacts : The scratches are due to meteoroid bombardment. (NASA-JPL / ESA document).

14 Spokes

Spokes are intermittent, approximately radial markings on Saturns B ring. Cassini ISS saw no spokes until the solar elevation angle dropped below about 10 because of a solar flux related ring charging effect. These ephemeral features are still believed to be caused by sudden releases of micron-size dust particles across a wide radial extent, where the extent and tilt of the spoke change with time until it fades. The typical periodicity of spoke abundance is close, but not equal, to a number of planetary magnetic and ionospheric periods, which themselves are varying with time.

15 Nature of the particles

Saturns rings are composed of myriad individual particles which continually collide. It seems that a number of particles are in fact agglomerates of smaller elements temporarily stuck together. Competing processes lead to both growth and fragmentation. The balance between these processes yields a distribution of particle sizes and velocities. Some particles are temporary rubble piles. The size of Saturns ring particles extends from fine micron-size dust to kilometre size moonlets.

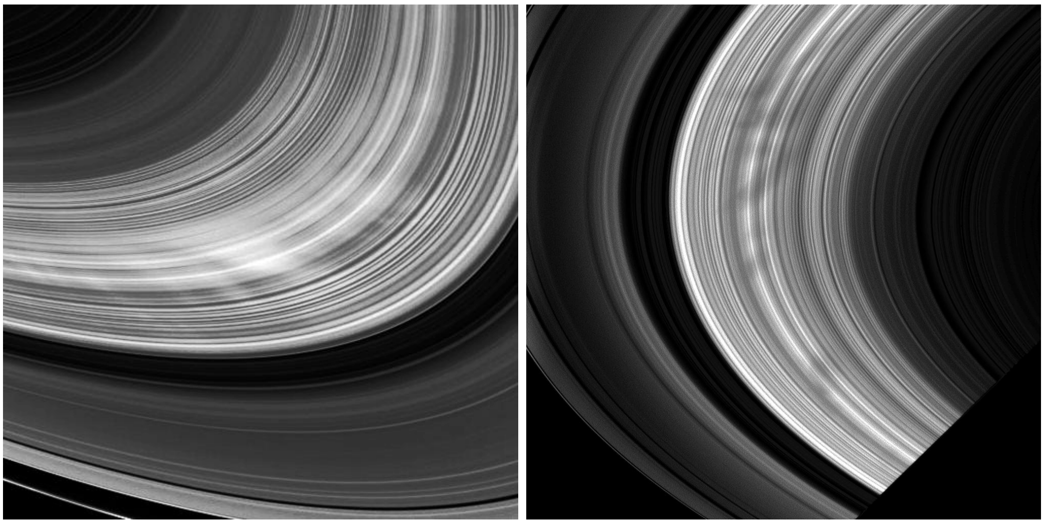

Fig. 10. The spokes are seen in reflected light (left) and diffuse light (right). (NASA-JPL / ESA document).

Reflection spectra and colour give some indication of particle composition. Saturns rings are bright and predominantly water ice. Colour variations, indicating varying composition, may be due to the effect of interplanetary dust that bombards the rings and darkens the particles. Saturns ring particles have rough, irregular surfaces resembling frost rather than solid ice.

The primary composition of the rings is water ice. Ring composition varies from place to place. The A and B rings contain 90 to 95% of water ice. The C ring and the Cassini division contain more dust, they are more contaminated by non-icy material than the A and B rings. The composition of this pollution remains uncertain. Saturns extensive ring system is exposed to the ambient photon radiation field, the magnetospheric plasma and the meteoroid flux. As a consequence, ejection of surface material fill up a gaseous envelope around the rings. In this ring atmosphere, scattered atoms and molecules extend form Saturn s atmosphere to beyond Titan orbit.

16 Rings origin and age

The origin and age of Saturns rings is still an unsolved problem. There are so many destructive mechanisms identified (spreading of the rings due to collisions, meteoroid bombardment, momentum transfer, etc.) that the rings should have been destroyed for a long time if they were formed at the same time than the planet. In addition, rings should be much darker if they are old. But, renewal mechanisms can be at work. We dont know if the rings are old or young and if the rings been formed with the planet Saturn or if they appeared later? Several scenarios have been developed by various researchers. The main rings can be remnants from the Saturns nebula. They can be remnants from a destroyed satellite, for example during the Late Heavy Bombardment. They can also be remnants from a tidally split comet. Cassini observations gave us new constraints and new information for a better understanding of rings origin. More sophisticated models have to be developed and compared to Cassini data. In particular, an estimation of the meteoroid flux at Saturn, a better knowledge of individual particles and a good measurements of the B ring mass should be particularly useful to solve the question of rings origin.

The rings are probably constantly formed and destroyed. Like an old roman building, the monument is old, but several stones have been exchanged.

17 Conclusion

A wealth of new observations need to be explained. The study of Saturns rings which is one of the oldest problem in astronomy should last in the future during several additional centuries. Future observations by new spacecrafts should bring new discoveries. The words of Maxwell in his seminal Adams Prize essay of 1856 are still particularly well adapted to the study of rings: *I am not aware that any practical use has been made* *of Saturns Rings, either in Astronomy or in Navigation . But when we contemplate the Rings from a purely scientific point of view, they become the most remarkable bodies in the heavens .*

18 Bibliography

Several thousands of articles have been published about Saturns rings since their discovery. A presentation of the main properties of planetary rings as well as a discussion of dynamical processes can be found in the book Planetary Rings edited by Richard Greenberg and Andr Brahic and published by The University of Arizona Press in 1984 after the Voyager flybys of Jupiter and Saturn.

The first results of the Cassini mission have been presented in the number 5713, volume 307 of Science on February 25, 2005 and in the pages 375 to 575 of the book Saturn from Cassini-Huygens edited by Michele K. Dougherty, Larry W. Esposito and Stamatios M. Krimigis and published by Springer in 2009.