PLANETARY RINGS: OBSERVATIONAL CONSTRAINTS AND COLLISION DYNAMICS

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Abstract. Since fifteen years, space and ground-based observations have completely renewed our image of planetary rings. Simultaneously, a wealth of theoretical and numerical models have flourished. Collisions between ring's particles and gravitational perturbations of nearby satellites should explain most of the ring's structures. However, important questions are still unanswered. We do not understand why the rings are so dissimilar. We do not know the ring's origin and their stability over billions of years. Most of the ring's complex structures, the existence of arcs, and color and optical depth variations are not yet explained. Among all the ring mysteries, the uniform precession of narrow ringlets and the azimuthal brightness asymmetries should receive a high priority.

The study of planetary rings is probably one of the oldest and more modern problems in astrophysics. At the eve of the XXIst century, like a mountain climber staring at the distant summit, we feel that the journey towards a complete understanding takes longer and longer. Yet, rings have been a subject of discussion, research and controversy for almost four centuries. Many outstanding scientists, including Galileo, Huygens, Cassini, Laplace, Maxwell and Poincaré, have devoted a considerable time trying to understand the physics and the dynamics of rings. A wealth of theoretical and numerical models and space or ground-based observations have flourished since twenty years and our conception of rings has undergone a revolution. However, a number of first order problems is still unresolved. From time to time, papers are published with titles such as "The rings of Uranus: theory", or "Saturn's rings explained", or "An explanation for Neptune's ring arcs" giving the feeling that planetary rings are well understood. Reality is not so simple!

Facing such a complex behaviour, it is tempting to mix a few, well accepted, theoretical ideas and play with a large number of free parameters. It is striking to note that most of the recent models have very few characteristics in common and can barely be compared with one another. It should be probably more fruitful to study with a simple model unexplored fundamental physical mechanisms rather than to *play with parameters*. A more complex model is not necessarily more realistic! We have also to be careful about the results of observations and their interpretation and we have not to be misled by irrelevant or non significant observations. It is sometimes difficult to know if a selected sample of observations is really characteristic of the whole system. If a theoretical explanation is attractive enough, it is accepted even if the observational support is weak or non existent. On the contrary, irrelevant observations detour researchers into dead-end theoretical considerations.

As recently as 1977 we knew only one ringed planet in the solar system and scientists were struggling with the question: "Why does only Saturn have rings?" That question is clearly obsolete now. Instead we turned to ask: "Why are the ring systems so dissimilar? What are the most efficient dynamical processes shaping the rings? Are planetary rings young or old?"

We now realize that planetary rings are not the seemingly smooth, continuous structures one discovers around Saturn in a ground-based telescope. These systems

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rather appear as complex sets of narrow ringlets, which may be sharp-edged, slightly elliptical or inclined, kinky, broken, irregular, "braided",.... At large scale, the rings around the four giant planets are strikingly different, from the tenuous Jovian rings to the spectacularly bright Saturn's system, the narrow sharp-edged Uranian rings and the Neptunian arcs. Yet they present many similarities at a small scale. Up to now, nobody knows if rings are different because they result from different initial conditions or because of different physical parameters such as the chemical composition of the particles, the total mass of material available, the particle-size distribution, the initial angular momentum, the gravitational perturbations by external satellites, the meteoritical bombardment or dust satellite material supply.

For the last twenty years, rings have been challenging theoreticians: they never behave as predicted by the models. Every time a theory seems to bring the solution, a new observation forces us to search in another direction. Gravitation and collisions should make homogeneous planetary rings with smooth edges: they present a wealth of radial structure and they have sharp edges! Collisions and resonances should make circular narrow rings in the equatorial plane of the planet: many are elliptical or inclined and, furthermore, they precess as a rigid body around the planet! Keplerian differential rotation should make rings perfectly homogeneous in the azimuthal direction and rapidly destroy any longitude asymmetry: we observe broken rings, arcs and clumps inside the arcs! There are thousands of unexplained features in planetary rings, but the most mysterious seem to be the survival of azimuthal brightness asymmetries such as arcs, clumps within arcs, broken rings and the slow precession of elliptical rings around the planet.

1. Sharp Edges, Gaps, Narrow Ringlets, Waves and Shepherding.

In an isolated disc made of a gravitating system of colliding particles, the total angular momentum is conserved but the total energy decreases. Inelastic collisions spread out the particles and extend the disc inwards and outwards. The system broadens under the combined effect of differential rotation and of collisions (equivalent to "friction" for a gas). This phenomenon (Brahic, 1975, 1977) is analogous to that described by various authors for an accretion disc around a compact object (Prendergast and Burbidge, 1968; Lynden-Bell and Pringle, 1974). The energy which is continually lost as a consequence of inelastic collisions is obtained at the expense of bodies moving inwards and outwards. This image of a slowly spreading disc is in good agreement with an homogeneous ring system with smooth edges. The discovery of narrow rings and sharp edges indicate either that rings are young or that confinement mechanisms are at work.

In a period of only a few years our best resolution on Saturn's rings improved by a factor 10^4 with the fly-by encounters of Pioneer 11, Voyager 1 and 2. During the same decade, rings have been discovered around Jupiter (Owen *et al.*, 1979), Uranus (Elliot *et al.*, 1977) and Neptune (Brahic and Hubbard, 1989), observed using stellar occultation techniques and explored by the Voyager spacecrafts. This explosion of new data led to a number of surprises. Contrary to what was expected, rings present considerable radial structure. Rather than being the smooth, continuous structures apparent in Earth-based images of Saturn's rings, planetary rings are more commonly characterized on the one hand by sets of narrow ringlets with sharp edges, sometimes slightly inclined or elliptical, sometimes kinky or broken and, on the other hand, by dense rings with density waves or bending waves running through them.

Many narrow rings are approximately 10 kilometers large around Saturn, Uranus and Neptune. Some are extremely narrow. For example the width of the Uranus' δ ring is of the order of 800 meters for a circumference which is larger than 500000 kilometers. The morphology of ring edges varies significantly. Some edges, such as the A ring outer edge, the Maxwell ringlet edges and Encke division edges, are extremely radially sharp. In several cases, the optical depth goes from zero to several tenths on a scale smaller than 100 meters. Several narrow ringlets and gaps can easily be associated with nearby satellites. But, many of them are not apparently linked with observed satellites. There are probably some unseen moonlets embedded in the ring systems. The outer A ring of Saturn and the main Jovian ring have both an abrupt outer boundary with a small satellite orbiting just at the outside of the ring, like a guardian satellite.

Narrow rings and sharp edges require the presence of a confinement or a repulsion mechanism in order to halt the radial spreading. Goldreich and Tremaine (1979) have proposed that the torques exerted by the inner and outer satellites would be sources and sinks of the angular momentum with viscous stresses, arising from interparticle collisions and differential rotation, transport outward through the ring. Depending on the mass and the distance of the perturbing satellite, there are several variants of the shepherding mechanism. Nearby and massive satellites produce wakes, which are perturbations which damp between successive close encounters of the ring particles with the satellite. Smaller and more distant satellites are rather responsible of perturbations which can be described in terms of discrete resonances. A shepherd satellite may have just one resonance near the ring's edge or several resonances within the ring. Planetary rings can support leading and trailing spiral density waves which are controlled by a combination of the Coriolis force and of the ring's self gravity. This phenomenon is similar to density waves in Messier 51. Close to a resonance, the long spiral waves have wavelengths several orders of magnitude greater than the interparticle spacing. These waves can exist only on the satellite side of the resonance and propagate toward and away from the resonance. The satellite excites the long trailing wave at the resonance and this wave carries away all of the angular momentum (positive or negative) which the resonance torque gives to the disc. The wave damps due to non linear and viscous effects close to the resonance. The particles on the satellite side of the resonance move toward the resonance. If the resonance torque is sufficiently large, a gap opens on the satellite side of the resonance.

Goldreich and Tremaine (1980) have calculated the rate at which angular momentum and energy are transferred between a disc of colliding particles and a satellite which orbit the same central mass in order to understand their mutual evolution. They only use the linear approximation and they assume that the satellite has a small eccentricity. A satellite on a circular orbit exerts a torque on the disc in the immediate vicinity of its Lindblad resonances and angular momentum is transferred outwards from the disc to an external satellite or from an internal satellite to the disc. A satellite on an eccentric orbit exerts a torque on the disc both at Lindblad resonances and corotation resonances. In general, torques from Lindblad resonances increase the satellite's eccentricity while those from corotation resonances damp it.

These results can provide an explanation for the formation of the Cassini division, due to the influence of Mimas which orbits well outside the rings and the confinement of narrow rings by small satellites which orbit within the ring system. The Encke gap is carved out of the Saturn's A ring by a small satellite which transfers angular momentum from its inner to its outer edge (Cuzzi and Scargle, 1985). Wakes are seen in the ring material adjacent to these edges. The outer edge of Saturn's A ring is located at the 7:6 resonance of the co-orbital satellites Janus and Epimetheus while the outer edge of the B ring is located at the 2:1 resonance of Mimas. The discovery of the Saturn's F ring shepherds (Smith et al., 1981) and of Uranus' ϵ ring shepherds (Smith et al., 1986) were the most spectacular success for the shepherding theory.

Twenty nine clearly discernable wave-like features can be seen in the Voyager I radio occultation profiles of Saturn's rings (Marouf *et al.*, 1986). Many are the signature of spiral density waves and bending waves excited by gravitational Lindblad and vertical resonances with Saturn's satellites. For example, a spiral bending wave excited by the Titan 1:0 nodal inner vertical resonance and a Mimas 4:1 density wave can be recognized in the C ring, while a Janus-Epimetheus 2:1 density wave can be observed in the B ring. Janus-Epimetheus 4:3 and 5:4 density waves propagate in the A ring. But, the source of several wave-like features, in particular within the Saturn's C ring, remains in doubt.

We now understand that a moon exerts coherent periodic perturbations on ring particles which are in orbital resonance with it. These perturbations result in sharp outer edges of the A and B rings, as well as spiral density waves, which are observed propagating outward from dozens of resonance locations within the rings. Nevertheless, there are still many open problems. For many sharp edges and many narrow rings, no shepherd satellite has been observed yet. There are more features still unexplained than features explained by existing satellites! It is always possible to assume the existence of small as yet undetected satellites which are large enough to confine the rings and small enough to have escaped detection. Moreover, the strongest resonances in the Saturnian ring system often do not correspond to the largest gaps. Resonant angular momentum transfer to satellites seems to explain a number of observations, but why some resonances explain abrupt outer edges (for example A and B rings) and nearby resonances of only slightly lesser strength produce mere waves in the disc, with no hint of a gap? Some studies of rings-satellite resonances are just *numerology*. Specially, when there are many close resonances, the coincidence is not really convincing as long as a dynamical study is not done. In addition, there are many structures inside resolved narrow rings which are not yet explained. Furthermore, sharp edges are often too sharp! Borderies, Goldreich and Tremaine (1982, 1983, 1985 and 1989) have introduced a major improvement to the shepherding mechanism: they have discovered that satellite perturbations can produce local angular momentum flux reversals in the direction of the viscous flux of angular momentum. This flux reversal can not only explain the presence of sharp edges, but is an essential feature of the shepherding mechanism. Finally, the shepherding theory needs further refinements, like the introduction of non linear effects or the study of the detailed behaviour of ring particles near a sharp edge.

Saturn's F ring, Pandora and Prometheus seems the best example of the success of the shepherding theory, but a detailed analysis of F ring structure shows at least five components that sometimes seem intertwined. The main component of the mass of this ring has not been detected.Thus, the F ring does not provide yet a precise test of the theory. Cordelia and Ophelia have resonances coinciding with inner and outer edges of the ϵ ring. Goldreich and Porco (1987) have found that Cordelia has a 24:25 outer resonance with the inner edge of the ϵ ring, a 122:123 outer resonance with the λ ring and a 23:22 inner resonance with the δ ring while Ophelia has a 14:13 inner resonance with the outer edge of the ϵ ring and a 6:5 inner resonance with the γ ring. They thus proposed that Cordelia and Ophelia are shepherding the ϵ ring, that Cordelia is the outer shepherd for the δ and λ rings and that Ophelia is the outer shepherd for the γ ring. Apart from the resonances involving these two satellites and the ϵ,δ,λ and γ rings, the fifteen known satellites cannot account alone for the structure of the rings of Uranus. The confinement of 6, 5, 4, α, β and η rings has still to be explained and shepherding satellites have still to be discovered. It is possible that Uranus' rings could be maintained by a large number of small satellites (few hundred meters to one-kilometer sized). Murray and Thompson (1990) have proposed that two nine-kilometer-sized (just below the ten kilometers threshold of detection in Voyager 2 images) satellites act as shepherds to three or more rings.

The torque due to gas drag associated with the distended Hydrogen atmosphere of Uranus has to be considered at least for the inner Uranian rings such as 6, 5, 4, α and β. There is a problem in keeping α and β rings from collapsing into the atmosphere. They need huge shepherds which have not been observed. The maximum shepherd torques on the ϵ ring from Ophelia and Cordelia is quite close to the minimum viscous torque and to the atmospheric torque. Perhaps, the flux reversal or a more accurate determination of the masses of the shepherds or an accurate calculation of the non linear torque at a ring edge may improve the situation.

In the process of exciting density waves and maintaining sharp edges, moons exert a torque on ring particles, removing some of their angular momentum. Ring particles thus drift inward, while moons move outward. The associated timescales can be calculated (Goldreich and Tremaine, 1982). These timescales are uncomfortably short. There is a major problem: satellites just outside the Saturn's, Uranus' and Neptune's rings should have drift outwards until they fall into a resonance with external satellite like Rhea, Enceladus, Dione, Miranda, Ariel, Triton,....Such a situation is not observed. Are the rings young structures? Or is there any mechanism which prevent the outward drift? For example, the decay of A ring into Cassini division should take about 5×10^8 years. Janus and Prometheus move outward at a velocity of about 3 centimeters per year and 70 centimeters per year respectively. At current speed, Janus was at the outer edge of Saturn's A ring 4×10^8 years ago and Prometheus 4×10^6 years ago.

2. Elliptical and Inclined Rings. Precession of Narrow Rings.

The discovery of narrow rings around the giant planets does not close the list of surprises. Planetary rings should be circular, because differential precession across an eccentric ring would soon lead to particle collisions that would circularize the rings. Nevertheless, some rings are elliptical and have variable widths. Since many rings like the Uranus' α and β rings and several Saturn's narrow ringlets are manifestly eccentric, there must be some mechanism to prevent this rapid circularization. Other rings are normally circular, but they are inclined. The remarkable thing is that the elliptic rings precess slowly around the planet, just as they should, due to the planet's oblateness.

The most striking example of an eccentric ring is the ϵ ring, with an eccentricity of 0.0078 (Nicholson et al., 1978). The boundaries of the ϵ ring can be fit by aligned Keplerian ellipses. Goldreich and Tremaine (1981) have studied gravitational perturbations from a nearby satellite on the eccentricity of a narrow ring. They have studied the relative role of corotation and Lindblad resonances. Whatever is the origin of the ring eccentricities, differential precession due to the quadrupole moment of the central planet should destroy the apse alignment. The Uranus' ϵ ring and the Maxwell gap ringlet precesse, respectively, at a rate of 1.364° and 14.68° per day, both in very good agreement with the rate determined by planetary oblateness alone. Normally, the rate of precession would depend on the distance to the planet: the inner edge of a ring of any width would precess more rapidly than its outer boundary. This differential precession would shear each ring into a circular band in a time scale of only a few tens of years. In fact, each ring precesses as a rigid whole, the eccentric nature of the rings seems to be continually reinforced, either by satellites or by the ring material itself. The profile of the rings looks the same everywhere (Nicholson et al., 1978).

Goldreich and Tremaine (1979) have studied several possible mechanisms for maintaining uniform precession in the ϵ ring. They have investigated whether shepherding satellites could force uniform precession in the ϵ ring. A nearby satellite can lock the ring particles apsides to its own apse, however the required satellite mass is so large that the ring would be rapidly repelled. A lighter satellite and the ring can precess independently, this weakens but does not remove the conflict with the confinement theory. Shocklike phenomena can force uniform precession, however the physics of such a process is very complex and has not been investigated yet. Apse alignment can be maintained by the self gravity of the ring. The required ring mass is then of the order of 5×10^{18} grams which corresponds to a surface density at quadrature of the order of 25 $g.cm^{-2}$.

In fact there are a number of problems not yet solved. For example, Voyager radio occultation data challenge the hypothesis that self gravity is responsible for maintaining apse alignment. In particular, they suggest that this hypothesis leads to underestimate significantly the masses of α and β rings. The close apse alignment of thei inner and outer edges of the α and β rings seems difficult to reconcile with pressure gradients playing a significant role in the prevention of differential precession. The full understanding of ring precession is probably one of the major progress which should be accomplished in a next future.

But, the understanding of the ring's precession will not be the end of the story. Indeed, a detailed analysis (French et al., 1986) shows that none of the Uranian rings is adequately modeled as having elliptical inner and outer edges in a fixed relative orientation: all of the rings have perturbed widths. The narrow eccentric rings 6, 5 and 4 do not have linear width-longitude relations. There is significant scatter in the width-longitude relations for rings α, β and ϵ. The narrow quasi-circular rings γ, δ and η have all large width variations.

3. Azimuthal Brightness Asymmetries. Arcs, Broken Rings and Irregular Rings.

Keplerian differential rotation should quickly erase any clump or local inhomogeneity inside the rings. Surprisingly, stable azimuthal brightness asymmetries are visible at different scales in the planetary rings. The more striking example is given by the arcs of Neptune: *Liberté, Egalité* and *Fraternité.* A detailed analysis of Voyager images reveals that many azimuthal brightness variations are visible at different scales: the arcs themselves appear to be made of small clumps of particles embedded in a more continuous and fainter ring.

Large scale brightness asymmetries are visible in Jupiter's and Saturn's rings. Azimuthal asymmetries have been found by Camichel (1958) in Saturn's ring A and later observed from many ground-based observatories as well as from Pioneer 11 and Voyager 1 and 2 spacecrafts. In Saturn's ring A, the first and the third quadrants (as measured counterclockwise from superior geocentric conjunction) are 10% to 15% dimmer than the second and fourth quadrants. This azimuthal asymmetry is far from uniform in the A ring and it preserves the same orientation to the observer, no matter where he is located with respect to the Sun and Saturn. This phenomenon has not been entirely explained, but is widely attributed to mutual shadowing of ring particles in the density *wakes* of larger ring members (Colombo,Goldreich and Harris, 1976). Azimuthal brightness asymmetries have also been found in both the main ring and in the nearby surrounding halo of Jupiter. On close-up views of Jupiter main ring, the far arm appears to be about 10% brighter than the near arm. Because a complete high resolution view of the whole Jupiter's ring is not available, it is impossible to know if it is a quadrant asymmetry similar to that observed for Saturn's A ring. Anyway, the mutual shadowing of ring particles cannot be an explanation in this case of Jupiter's diaphanous ring system: the particle density is too low! So, the cause of this asymmetry remains mysterious (Showalter et al., 1987).

At a much smaller scale, brightness asymmetries have been found in narrow ringlets. Some, like the Uranian ϵ ring, are the result of the ringlet's variable width (Svitek and Danielson, 1987). Others, like the Adams ring, are due to arcs or clumps of particles embedded in a continuous ring. From two stellar occultations by Uranian ring system observed by the Voyager 2 photopolarimeter, Lane et al. (1986) claim that the nearly circular γ and δ rings exhibit different spatial distributions of material at the different occultation longitudes measured by the occultations and that the narrow component of the η ring may be discontinuous. They also claim that low optical depth, incomplete rings or arcs with widths around 1 to 16

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kilometers exist around Uranus. Those results have to be considered with care: an accurate statistical analysis of stellar occultation data should be done before any confirmation of a phenomenon. Spurious events are so frequent that it cannot be claimed that Uranus is surrounded by incomplete rings before a complete statistical analysis of the data be published.

Neptune arcs are the more striking example of azimuthal brightness asymmetries in narrow rings. Whereas the Le Verrier ring seems rather constant at the resolution of Voyager 2 images, many azimuthal brightness variations are visible in the Adams ring at different scales: the arcs appear as small clumps of particles embedded in a continuous and faint ring.

The Voyager 1 and 2 spacecrafts found that the F ring of Saturn contains a remarkable diversity of features like kinks, clumps and braids with typical longitudinal spacings estimated to range from 5000 to 130000 kilometers (Smith et al., 1981, 1982). The F ring's peculiar structure has been widely attributed to the gravitational perturbations from its two adjacent shepherding satellites Pandora and Prometheus. Cuzzi and Burns (1988) have re-analyzed the five abrupt depletions in the flux of trapped magnetospheric electrons observed by Pioneer 11 within a 2000 kilometers wide band surrounding Saturn's F ring. Two of the five observed decreases are probably due to absorption by the F ring. However, none of the other three are likely to be caused by Pandora, Prometheus, or the F ring. They infer that the observed depletions of charged particles are caused by clumps of material with low optical depth ($\tau \sim 10^{-4}$ to 10^{-3}). This hypothetical belt of colliding objects could partly explain the observed structure of the F ring. This hypothesis raises the possibility that the F ring is not necessarily *shepherded* by Pandora and Prometheus over millions years, but is merely one of a series of transient events occurring at the very edge of the Saturn's Roche zone. Such moonlet belts could play an important role in order to explain ring arcs seen around Saturn, Uranus and Neptune.

The Encke gap does contain two narrow, discontinuous ringlets which appear kinked and clumpy in the Voyager images, with morphology and particle size reminiscent of Saturn's F ring. The similarity of the Encke ringlets led to a suspicion that a moonlet (or more), embedded within the gap, could produce the observed ringlet structure and also keep the gap clear by gravitational torques (Cuzzi and Scargle, 1985; Hénon, 1981, 1984; Showalter et al.,1986).

A systematic quantitative analysis of the azimuthal brightness variations has been made by Ferrari (1992) for a number of narrow ringlets. Liberté, Egalité and Fraternité arcs have been observed over one week by the Voyager 2 spacecraft. They are respectively 4400, 5500 and 11000 kilometers long. They have sharp edges in the longitudinal direction and their structure does not depend on the phase angle of observation. There are made of clumps, which are 4 to 7 times more opaque than the ring in which they are embedded. A fourth arc lies just before Liberté arc and many other clumps are also visible between the arcs.

A detailed analysis of the Uranian λ ring, of the Saturnian F ring, the two Encke ringlets and the Huygens and Fresnel ringlets shows that arcs and clumps are also present around Saturn and Uranus. Adams, λ, Huygens, Fresnel, F and Encke ringlets share many similarities: they hold arcs which are typically 4000 to

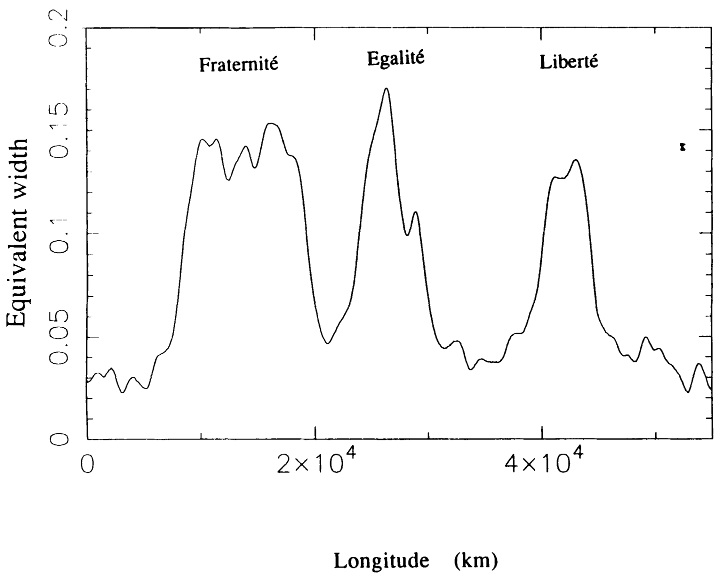

Fig. 1. Mean profile of the Neptunian ring arcs. The equivalent width (in kilometers) is represented as a function of the azimuthal distance

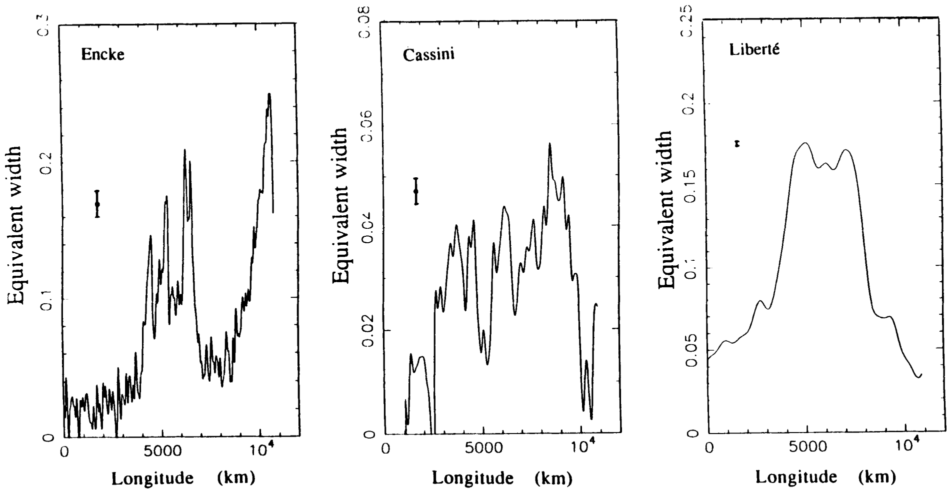

Fig. 2. Mean profile of Encke ringlets, Cassini ringlets and Liberté arc. The equivalent width (in kilometers) is represented as a function of the azimuthal distance

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10000 kilometers long and have abrupt edges (in the longitudinal direction); The arcs are 3 to 7 times brighter than the rest of the ringlet, there are many clumps and substructures within them, the clumps are typically 500 to 1700 kilometers far apart and the arc's morphology does not depend on the phase angle of observation. Arcs and clumps have only been observed during few days when the Voyager spacecraft was flying by the planet. A continuous set of observations should be particularly useful in order to have some idea of the stability of these structures. Neptune's arcs have been observed at least during 6 years using ground-based observations (Sicardy, Roques and Brahic, 1991), but there is no data on the stability of the arcs' substructure.

Differential rotation due to Keplerian motion should quickly destroy the arcs and clumps: the time required to spread over 360° an azimuthal structure that is 20 km wide in the radial direction, is only about 5 years. Stable, non transient ring arcs would obviously require a longitudinal confinement mechanism. Lissauer (1985) and Goldreich, Tremaine and Borderies (1986) have proposed that small satellites embedded in the Neptunian ring system can confine arcs. Observed Neptunian arcs and satellites do not verify their model constraints. Transient arcs should require the continuous creation, destruction and replenishment of local concentrations of ring material. Porco (1991) has done a careful kinematical study of the rings and satellites of Neptune and has proposed that the Neptunian arcs are azimuthally confined by a resonant interaction with the nearby satellite Galatea. She found that the 42:43 corotation resonance associated with the satellite inclination, which falls within the Adams ring, can explain the confinement of the Liberté, Egalité, and Fraternité arcs. In fact, a complete dynamical study has to be done before the understanding of arc's confinement. In particular, the strength of this resonance should be calculated in order to understand if it can explain the particularly sharp edges of the arcs. If this Galatea 42:43 resonance is responsible for the arc stability, it is not understood why some corotation sites should be populated while most of them are empty and why the arc's abrupt edges do not correspond to the corotation sites boundaries. It is still not known why some resonances should lead to strongly confined arcs while some other resonances which have apparently a strength of the same order of magnitude do not correspond to observed arcs. Even if these corotations resonances can maintain already formed asymmetries, an explanation of the origin of such structures has still to be provided.

4. Open Problems.

In order to fully understand rings' physics, there are many additional problems which would have to be solved before a significant progress be made. The particle size distribution and the ring thickness should be well known in order to have reliable dynamical models. The stability of tenuous and ethereal rings should be understood in order to check if they are ephemeral structures or if they are permanently linked with the main ring systems. Small particle effects and electromagnetic interactions should be studied in order to clearly separate dynamical effects which affect all particles and radiation and magnetic effects which affect only small particles. We just list below a short list of open problems.

4.1. Ring thickness

The local vertical thickness of a ring is an important dynamical parameter which characterizes the particle velocity dispersion. The controversy over the vertical structure of the rings, whether it is a single layer in thickness, a few layers or many layers thick, is not merely an academic exercise: it has implications for the dynamics and evolution of the rings. The *apparent* Saturn's rings thickness has been measured by Brahic and Sicardy (1981) from ground-based observations made during the transit of the Earth through the ring plane in March 1980. The observed brightness includes the warping of the disc, the contribution of large chunks and condensations, and the contribution of the E ring. Locally, the rings are extremely thin – perhaps as little as ten meters – (Marouf and Tyler, 1982; Porco et al., 1984; Zebker and Tyler, 1984, Rosen and Lissauer, 1988). Dynamical arguments (Brahic, 1977; Brahic and Hénon, 1977; Brahic and Sicardy, 1981; Cuzzi et al., 1979) imply that a characteristic thickness of a ring is a few times the diameter of the largest particles: dynamically, rings can be regarded as monolayers. But, for a true monolayer, there is no mutual shadowing by neighbouring particles unless the ring is observed edge-on. It seems that Saturn's ring is both a dynamical and an optical monolayer for the sub-system of the largest particles. But, if most of the mass resides in large particles which form an effective monolayer, most of the area, which play the major role for optical observations, reside in a many-particle-thick layer of smaller particles (Brahic,1977; Weidenschilling et al., 1984).

4.2. Particle Size Distribution

The particle size distribution is also one of the main parameters which drives the ring's dynamics. Several estimates have been done using Voyager data as well as stellar occultation data and radar measurements of the reflection cross section of the rings. Observations of microwave opacity and near forward scatter from Saturn's and Uranus' rings at wavelengths of 3.6 and 13 centimeters from the Voyager 1 ring occultation experiments give constraints regarding particle size distributions of the range of about one centimeter to a few meters (Marouf et al., 1983). A power-law-type model with an index of the order of 3.3 to 3.4 is consistent with the data assuming an uniformly mixed set of particles in a many-particle-thick vertical profile. It seems that the main Saturnian rings are made of a larger number of smaller particles compared to the main Uranian rings which are populated of a smaller number of larger particles. It should be particularly important to know what is the distribution of ten meter- to one kilometer-sized objects in the rings.

4.3. Tenuous and Ethereal Rings

Rings are often embedded in halos or "atmospheres" and additional extremely faint rings extend well outside the Roche limit. Plasma drag and the dominant destruction process, sputtering, should eliminate the tiny grains of this "gossamer" ring in a few thousand years. In order to remain visible today, ring material must be continually replenished from some source, either ejecta from Amalthea and Thebe or unseen bodies. Saturn's E ring shows a density peak near the orbit of Enceladus.

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Continued replenishment of the E ring by volcanic eruptions on Enceladus seems plausible. The ten known Uranian rings are embedded in a highly structured dust disc. These faint rings share many properties in common: they have low optical depths, they are immersed in a magnetospheric plasma and they contain a significant fraction of micron-sized particles. Since dynamical evolution times and survival lifetimes for micron- to millimeter-sized grains are quite short, some replenishment mechanisms have to be found to explain the ethereal rings. Single-particle dynamics, rather than collective effects, most likely govern their form, and the majority of their particles have quite limited lifetime.

4.4. Unseen Material

We do not know how many one kilometer- to ten kilometer-sized objects are within or around the rings. We do not know either how much material lies within the orbit of Mimas (or Amalthea, or Miranda, or Triton) and how much material share the orbits of the main satellites. A belt of large moonlets should have a very small optical depth and should be hard to detect, but should play an important dynamical role. Nearby satellites seem to play such an important dynamical role that a good knowledge of their number, mass and position should avoid the abusive use of "as yet unseen bodies" to explain the unexplained.

4.5. Ring's Origin

It is not known if ring particles are satellitesimals which never accreted into a moon due to tidal forces from the central planet or if they are the remnants of a disrupted satellite? For a long time, it was believed that the planetary rings which we see today are basically products of the same formation processes that gave rise to the regular satellite system of the giant planets or to the planets of the solar system. In fact, no one knows if planetary rings are primordial or are much more recent objects. No crucial observation can tell us if rings represent a failure of the innermost portion of a circumplanetary disc to accumulate into satellites inside the Roche limit or whether they are the result of the disruption of pre-existing satellites. Even if rings are young objects, the physical mechanisms they exhibit have a primordial importance for a better understanding of cosmogonical problems. Even if there are several dynamical processes which act to dissipate a solid/gas disc around a planet, confinement and stability mechanisms can help a ring to survive over the age of the solar system.

4.6. Temporal Changes

It should be particularly important to know which features are time-variable within ring systems and to detect any temporal change. That can be done for Neptune's arcs by a continuous set of ground-based occultation observations before a come back to Neptune. The Cassini mission to Saturn should provide a good opportunity to compare the Saturn's ring observations with Voyager data and to detect any change in the distribution of ring material. Variable satellite perturbations, pulsations, diffuse instability,... can produce changes in the morphology of those rings.

5. Conclusion and Future Studies.

Planetary rings are both more common and more complex than suspected only twenty years ago. These planetary ring systems, interesting in their own right, also serve as prototypes for more massive disc systems such as the proto-planetary nebula, accretion discs around compact stars and spiral galaxies occurring elsewhere in astronomy. It is why their study is so important! But, for now, we have many more questions than answers. The confinement of arcs and the *rigid* precession of elliptical ringlets are probably among the main problems to solve today. Our best hope is the development of models studying simple fundamental mechanisms and continuous observations using each stellar occultation opportunity and space exploration like the Cassini mission and future missions to Neptune and Uranus. A real progress in our knowledge on rings will be made when we receive in the ground-based laboratories some individual ring particle samples in order to analyze them. Only then, we will be able to tell: *Give me one particle and I will explain the world!*

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