LOOKING FOR CHANGES IN THE SATURNIAN SYSTEM BETWEEN VOYAGER AND CASSINI

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Abstract. This paper reviews a number of time-dependent phenomena that are relevant to our understanding of the dynamics of planetary rings and that will be investigated using Voyager and Cassini data. A long time baseline may help us decipher the physics of the spokes, understand better the morphology of the F ring and the rigid precession of non-circular ringlets, measure more precisely than has been done so far the satellites' torques and the viscosity of the A ring, and discover small satellites in the Saturnian ring system. Two exciting possibilities are those of determining the recession rates of the small satellites that border the rings, and of observing changes due to viscous diffusion in the irregular structures of the B ring.

Key words: Planetary Rings Dynamics

1. Introduction

The Voyager missions provided the first close look at the rings of Saturn. The numerous and detailed data acquired during the Voyager missions at Saturn have allowed us to increase our understanding of planetary ring dynamics. However, a number of unresolved issues remain. The Cassini mission represents our next chance to look closely at Saturn and its rings and satellites. The two time baselines represented firstly by the interval of time of nearly ten months between the two Voyager missions, and secondly by the interval of time of twenty four years between Voyager and Cassini will allow us to study time-dependent phenomena.

This paper deals with time-dependent phenomena that will be investigated using the Voyager and Cassini data, and the significance of these time-dependent phenomena to our understanding of the dynamics of planetary rings. These phenomena concern spokes, narrow rings, spiral waves, ring's edges, and viscous diffusion. The next sections are devoted to these phenomena. Each section deals with the relevant observations, our state of the knowledge, and the value of a long time baseline.

2. The spokes

The spokes are an obvious example of a time-dependent phenomenon. An observer close enough to see them would see changes occuring.

2.1. OBSERVATIONS

The spokes are narrow, nearly radial markings in the B ring, which were discovered by Voyager 1 (Smith *et al*, 1981). They are observed in the range from 1.72 to 1.94 R_s, where R_s is Saturn's radius. Individual spokes are typically 10,000 km long and 2,000 km wide. They have the shape of a very narrow bow-tie with the narrowest part at the corotation radius. They are nearly radial, tilting away in the direction corresponding to Keplerian motion.

In back-scattered light, the spokes appear darker than the surrounding regions, whereas they appear brighter in forward-scattered light. This implies that the

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spokes consist of very small particles, of the order of a few microns or less (Cuzzi *et al*, 1984).

The spokes are observed to have the largest contrast near the morning ansa, suggesting that their formation is related to the emergence of the rings from the night. However, Grün *et al* (1984) have observed spoke formation along radial lines in the sunlit portion of the ring, reporting that the formation time is typically ≤ 5 minutes for a 6000 km long spoke. In the cases where spokes have been observed in the process of formation, they were nearly radial. In most cases, both spoke's edges revolve with Keplerian speed. However, a few spokes have been found where only one edge revolves with Keplerian speed whereas the other edge stays radial and corotates with Saturn (Grün *et al*, 1984). The lifetime of a spoke is shorter than the revolution period of the ring particles around Saturn.

Porco and Danielson (1982) showed that spoke activity is statistically enhanced when the morning ansa is facing a certain longitude ($\sim 115^\circ$ with respect to Saturn Longitude System, associated with the magnetic rotation period) that is also associated with kilometric radiation and auroral emission. Saturn kilometric radiations (SKR) most often occur when the longitude of the meridian facing the Sun with respect to Saturn Longitude System is $\simeq 100^\circ$ (Kaiser *et al*, 1981). The brightness of the aurora observed by Voyager 1 correlated well with the SKR probability (Sandel and Broadfoot, 1981). Auroras on Saturn are thought to result from the interaction of the magnetosphere and the solar wind.

2.2. STATE OF OUR UNDERSTANDING OF SPOKES

Before we can claim to understand spokes, we must establish their physical properties and the way in which they are formed.

As far as the nature of the spokes is concerned, several pictures have been presented. One possibility is that the spokes are features within the rings contrasting in brightness with the surrounding regions because they consist of aligned, elongated, micron-sized particles. Cuzzi *et al* (1984) discard this idea on the ground that it would lead to the contrast of the spokes being doubly periodic in longitude, which is not observed. Another possibility is that the spokes consist of micron-sized particles which are levitated above and below the mean plane of the rings.

As far as the formation of the spokes is concerned, several researchers (Cuzzi *et al*, 1984; Grün *et al*, 1984; Tagger *et al*, 1991) suggested that the relationship of the spokes with the magnetic field of Saturn indicates that Saturn's magnetic field controls the formation of the spokes. However, none of these theories is yet widely accepted.

2.3. VALUE OF A LONG TIME BASELINE

We have yet another clue at our disposal concerning the formation of spokes: contrary to what they expected, astronomers have not succeeded in detecting the spokes from the ground (McMuldroch and Westphal, personal communication). This indicates that at the time of these observations, the spokes showed less contrast than at the time of the Voyager encounters with Saturn. One might speculate that the spoke activity is more intense when the ring opening angle is small (as it was during the Voyager flybys), than when this angle is large (which is the preferred geometry for ground-based observations of the rings). Alternatively, changes in spoke activity could be due to changes in solar activity that affect the UV flux illuminating the rings. Cassini, because it will observe the rings at varying opening angles, will tell us if indeed the visibility of the spokes depends on the ring opening angle. In any case, Cassini will bring us new clues to help us decipher the physics of the spokes.

3. Narrow rings

Narrow rings change over different time-scales. Some narrow rings pulsate with a period of several hours. Elliptical ringlets take tens of days to precess around the planet, while the period of differential precession is a few tens of years. Viscous diffusion across the rings takes thousands of years.

3.1. OBSERVATIONS

This section presents observations relevant to the dynamics of narrow rings, concerning the F ring of Saturn, other narrow rings in the Saturnian system, and the narrow rings of Uranus.

3.1.1. The F ring

The F ring was discovered in 1979 by Pioneer 11 (Gehrels *et al*, 1980). It lies at 3600 km outside the outer edge of the A ring. Voyager 1 discovered the two shepherd satellites of the F ring, each about 200 km in diameter, moving on eccentric orbits on either side of the F ring. The F ring was also found to be eccentric. Neither the satellites' orbits nor the F ring are inclined.

The F ring appears different depending on the technique of observation. On the high resolution images acquired by Voyager 1, the F ring has three components, each about 20 km wide. On one of the images, the outer two components seem to be braided (Smith *et al*, 1981). In addition, the F ring contains kinks and clumps. Voyager 2 found the same kinky and clumpy appearance as Voyager 1, but did not observe any braided appearance (Smith *et al*, 1982). Burns *et al* (1983) applied image processing techniques to Voyager 2 images, which revealed additional faint components of the F ring, and even ring material inward of the F ring, all the way to the A ring. The stellar occultation tracked by the Voyager 2 photopolarimeter observed a 50 km wide ring with a dense core 2 km wide. The Voyager 1 radio occultation profile showed a 2.4 km wide ring with a 300 m wide inner core. Empty lanes in the charged particles observed by Pioneer 11 testify to the presence of unseen clumpy ring material in the region of the F ring (Simpson *et al*, 1980; Van Allen *et al*, 1980; Van Allen, 1982).

The F ring appears brighter at high phases angles, indicating a significant portion of micron-sized particles (Smith *et al*, 1981). Observational evidence for the presence of large particles (1–10 km) has also been found (Smith *et al*, 1982).

3.1.2. Other ringlets in the Saturnian system

Isolated ringlets have been found in the C ring, in the Cassini division, and in the Encke Gap. In the C ring, the ringlet located at 1.29 R_s is associated with an apsidal resonance with Titan (Porco *et al*, 1984), while the Maxwell ringlet, at 1.45 R_s, does not correspond to any known resonance (Esposito *et al*, 1983). An elliptical ringlet was found in the Cassini Division at 1.95 R_s, outside the outer edge of the B ring, which is itself controlled by a 2:1 resonance with Mimas. Voyager 1 photographed two kinky, apparently incomplete ringlets in the Encke gap (Smith *et al*, 1982).

3.1.3. The narrow rings of Uranus

The narrow rings of Uranus have been extensively observed from the ground and thus are better known than the Saturnian narrow rings. For this reason, they play for us the role of prototypes of narrow rings.

The ϵ ring is the largest of the narrow rings of Uranus. The shepherd satellites of the ϵ ring have been discovered by Voyager (Porco and Goldreich, 1987). Some of the ring's edges are remarkably sharp. Rings 6, 5, 4, α, β, and ϵ are eccentric. Rings 6, 5, 4, α, and β are inclined. There is a linear relation between the width and the radius of each ring ϵ, α and β (Nicholson *et al*, 1978; Elliot *et al*, 1981; Nicholson *et al*, 1982). Deviations from the linear relation are few kilometers in radius, thus appearing more important for the rings α and β which are narrower. These deviations indicate that the structure is more complicated than a simple model can account for (Elliot and Nicholson, 1984).

French *et al* (1988) found that the δ ring contains an $m = 2$ mode. This ring is elliptical, with the planet located at the center of the ellipse rather than at the focus. They also found that the γ ring contains both modes $m = 0$ and $m = 1$. The mode $m = 1$ corresponds to an elliptical shape, with the planet located at one of the foci. The mode $m = 0$ corresponds to radial oscillations of the entire ring with the epicyclic period (7.5 hr). The amplitude of this oscillation is 5.2 km.

3.2. STATE OF KNOWLEDGE OF THE DYNAMICS OF NARROW RINGS

The dynamical problems posed by narrow rings are related to their structure, their shape, and their confinement. A summary of the state of knowledge concerning these issues is given below.

3.2.1. Structure

Because of the gravitational interactions between the F ring and its inner shepherd, the latter approaches, and may even penetrate, the F ring every 18 years (Borderies *et al*, 1983a). The disturbances exerted on the motion of the large particles must persist for many years and may be responsible for many of the unusual features of the F ring.

3.2.2. Shape

The first problem is to explain the persistence of narrow rings around Saturn and Uranus. The most promising model to explain this phenomenon is the self-gravity model (Goldreich and Tremaine, 1979a). The basic idea is that self-gravity compensates for the tendency towards differential precession, allowing an eccentric ring to maintain its shape and to precess as a rigid unit. Such a balance requires a precise relation between the shape of the ring and its mass. Borderies *et al* (1983c) showed that viscous dissipation would lead to this precise configuration. A similar mechanism works for inclined ringlets (Borderies *et al*, 1983b).

The self-gravity model leads to predictions (width-radius relation for instance) which are, in a first approximation, confirmed by the observations. However, this model encountered difficulties when detailed data on the Uranian rings were analyzed (Marouf *et al*, 1987). Borderies *et al* (1988) have performed a preliminary analysis which eases the problem with the ϵ ring: deviations of the observed shape from the shape predicted by the self-gravity model can be explained by the perturbations exerted by the shepherd satellites. Nevertheless, difficulties remain with the self-gravity model (see Goldreich, this issue).

Over a long period of time, the eccentricity of these ringlets tends to be damped by viscous interactions between the particles. Goldreich and Tremaine (1981) showed that satellites perturbing the rings can excite their eccentricity and Borderies *et al* (1984a) showed that similarly, perturbing satellites can excite ring inclinations.

3.2.3. Confinement

Viscous dissipation leads to the spreading of an unconfined ring. Goldreich and Tremaine (1979b) predicted that the gravitational torques exerted by the satellites orbiting on each side of each narrow ring of Uranus would confine them. As noted above, both the shepherd satellites of the F ring and the shepherd satellites of the ϵ ring of Uranus have been discovered by Voyager. Shepherd satellites for other narrow rings have not yet been seen by the cameras of Voyager, although the shepherd satellites of the ϵ ring are also involved in resonances with other Uranian rings (Porco and Goldreich, 1987).

3.3. VALUE OF A LONG TIME BASELINE

With a long time baseline of observations, the following studies can be performed.

3.3.1. F ring

What has made the F ring difficult to study so far is that we do not know where the mass of the ring is. This is related to the fact that the F ring appears so different when observed by different means. Detailed observations over a long time baseline will help us overcome this difficulty by allowing us to determine the particle size distribution in the main ring and to detect large particles orbiting in the region of the F ring. Tracking of bright features over time will enable us to distinguish large bodies from transient clumps of small particles. In addition, a long time baseline will allow us to observe the gravitational interaction of the F ring with the shepherd satellites, and to understand better how the morphology of this ring is controlled by its shepherd satellites.

3.3.2. Other ringlets

A long time baseline will allow us to precisely determine the shape of the ringlets embedded in the Saturnian system. We can expect to find other modes than the elliptical $m = 1$ mode. We may also find rings consisting of particles in horseshoe orbits about a satellite, as was suggested by Dermott and Gold (1977). This could be the case of the incomplete ringlets in the Encke gap. The new observations will help us understand why different modes develop in different rings. A long time baseline will also allow us to precisely determine the precession rate of eccentric ringlets. This new, detailed information could lead to a resolution of the self-gravity model problem.

4. Spiral waves

Two types of spiral waves can be found in Saturn's rings: density waves, and bending waves.

4.1. RELEVANT OBSERVATIONS

Goldreich and Tremaine (1978) predicted that density waves are excited in Saturn's rings at the locations of resonances with satellites and demonstrated that, if the resonance is strong enough, the outward transport of negative angular momentum opens a gap. Many density waves have been found in Saturn's rings (Cuzzi *et al*, 1981; Lane *et al*, 1982; Holberg, 1982; Holberg *et al*, 1982; Esposito *et al*, 1987). Bending waves are vertical warps associated with resonances involving the inclination of the ring particle's orbits. They were found by Shu *et al* (1983) and by Rosen and Lissauer (1988).

4.2. STATE OF THE THEORY

The theory of density waves was first developed by Lin and Shu (1964) to explain the spiral structure of galaxies. Goldreich and Tremaine (1978) developed the theory of density waves for planetary rings. Their theory was linear, valid only in principle if the perturbations are small. Actually, most density waves found in Saturn's rings are nonlinear. The theory of nonlinear density waves was developed by Shu *et al* (1985a, 1985b), and Borderies *et al* (1985, 1986). These theories predict that the damping of the wave is less efficient than that it is observed to be. The theory of bending waves was developed by Shu *et al* (1983).

Analysis of spiral waves provides a measurement of the ring's surface density in the region of the wave (Cuzzi *et al*, 1981; Lane *et al*, 1982; Holberg *et al*, 1982; Shu *et al*, 1983; Longaretti and Borderies, 1986). The damping of the waves also contains information on the ring viscosity, but the determination of ring viscosity from the analysis of the amplitude of the waves is more uncertain, especially in the case of nonlinear density waves.

One interesting issue is that of the short time scale of orbital evolution for the satellites orbiting near the rings. The gravitational torques exerted by the rings on these satellites should make the satellites move away from the ring on a time scale of a few tens of millions of years to a few hundred of millions of years (Goldreich and Tremaine, 1982; Borderies *et al*, 1984b). This suggests that the satellites are young.

4.3. VALUE OF A LONG TIME BASELINE

The waves associated with the coorbital satellites must change as the satellites move on their horseshoe orbits. The changes should occur over a length-scale of $\simeq$ 50 km, and with a libration period of 8 years (Yoder *et al*, 1989; Nicholson *et al*, 1990). Observing these changes will help us understand the response of the rings to the gravitational perturbations of satellites in the vicinity of resonances. We may be able to measure more precisely than has been done so far both the satellite torques and the viscosity of the A ring.

An exciting possibility is that we may be able to observationally determine the recession rates of the small satellites that border the rings of Saturn. A back of the envelope calculation can elucidate this point. We write the mean longitude of a satellite in the form $l = a + bt + \frac{c}{2}t^2$, and we suppose that it is computed in the form $l' = a' + b't$. We consider three times: the time $t_0 = 0$ (corresponding to 12 November 1980) of the closest approach of Voyager 1 with Saturn, the time $t_1 = 2.5 \times 10^7$ s (corresponding to 26 August 1981) of the closest approach of Voyager 2 with Saturn, and a time $t_2 = 8.2 \times 10^8$ s (corresponding to 26 years after t_0) within the Cassini orbital tour. Using t_0, we compute $a' = a$. Using t_1, we compute $b' = b + \frac{c}{2}t_1$. Next, we find $\mid l'(t_2) - l(t_2) \mid = \frac{c}{2}(t_2 - t_1)t_2$. This deviation in longitude can be detected if it is greater than 1.5×10^{-4} rd (Synnott, personal communication). We infer that the recession rate can be measured if it occurs over a time scale $\dot{a}/a < 2 \times 10^{10}$ years.

5. Edges

Some, and maybe all, of the ring edges are controlled by satellites, so that satellite orbital evolution must result in time-dependent edges.

5.1. RELEVANT OBSERVATIONS

We have already mentioned that the edges of narrow rings can be maintained by shepherd satellites. Edges of wide rings can be maintained by the same mechanism. Indeed, the outer edge of the B ring is associated with a 2:1 Lindblad resonance with Mimas, while the outer edge of the A ring is associated with a 7:6 Lindblad resonance with the coorbital satellites. The edges of the Encke gap are maintained by a satellite orbiting in the gap. This satellite was discovered from the wake it produces in the material at the outer edge of the gap (Cuzzi and Scargle, 1985; Showalter *et al*, 1986). Afterwards, it was observed by Showalter (1991) in Voyager images. All the above-mentioned edges are sharp. The inner edges of the wide rings A and B are less sharp. We do not know what causes these inner edges.

5.2. STATE OF THE THEORY

One can distinguish two types of confinement, depending on whether the edges correspond to isolated or overlapping resonances (Borderies *et al*, 1984b). Overlapping resonances occur when the satellite responsible for the confinement orbits close enough to the ring. Borderies *et al* (1982, 1983d, 1989) have shown that sharp edges can be explained in both cases by the reversal of the viscous flux of angular momentum. This reversal arises from the perturbations exerted by the satellite perturbing the edge.

5.3. VALUE OF A LONG TIME BASELINE

A long time baseline will allow us to discover other edge wakes which will reveal the presence of satellites that are small, hence very difficult to detect in images. A long time baseline may also help us discover what maintains the inner edges of the A and B ring.

6. Viscous diffusion

Viscous diffusion arise from inelastic collisions between particles.

6.1. RELEVANT OBSERVATIONS

Viscous diffusion occurs over such a long time-scale that it has not been observed so far. However, we see the signatures of viscosity in several ring's features, and especially in the damping of spiral waves, and most likely in the irregular structures of the B ring (Lin and Bodenheimer, 1981; Lukkari, 1981; Ward, 1981).

6.2. STATE OF THE KNOWLEDGE

The radial distance L over which particle diffusion occurs during an interval of time Δt is $L = \sqrt{\nu \Delta t}$, where ν is the viscosity of the ring material.

Ring viscosity is related to the physical thickness of the ring. A long standing question in ring dynamics is: is there much enhanced vertical thickness in the regions where there is a lot of dissipation? For instance, over a radial distance of ~ 70 km just inside the outer edge of the B ring, all the angular momentum and half of the energy flowing out through the B ring is taken away by Mimas. The other half of the energy is dissipated. Theoretical considerations (Borderies *et al*, 1982) indicate that this comparatively enormous dissipation rate of energy should be accompanied by an enhancement of the thickness of the B ring in this region.

6.3. VALUE OF A LONG TIME BASELINE

Using occultation profiles obtained at low and high opening angles will allow us to uniquely determine the thickness of edges.

We evaluate L over the Cassini mission and over the interval of time between Voyager 1 and Cassini. The only problem is that the viscosity in Saturn's rings is uncertain.

Estimates of the viscosity are obtained in several ways. One method is to use the damping of density waves as a diagnostic of viscosity (Cuzzi *et al*, 1981; Lane *et al*, 1982; Longaretti and Borderies, 1986). However, Shu *et al* (1982) noticed that this method overestimates the viscosity, and proposed to use bending waves as a diagnostic of the viscosity. The advantage of the bending waves is that they remain reasonably linear, which is not the case for most density waves. Their analysis of the bending wave excited by a 5:3 inclination resonance with Mimas in the A ring produced a value of 260 $\mathrm{cm}^2\ \mathrm{s}^{-1}$ for the viscosity. More recently, Rosen and Lissauer (1988) analyzed a bending wave in the C ring associated with a Titan nodal resonance, and obtained an upper bound on the viscosity of 0.24 $\mathrm{cm}^2\ \mathrm{s}^{-1}$.

Another approach consists of using the theoretical equation

$$\nu = 0.46\tau v^2/[\Omega(1+\tau^2)]$$

derived by Goldreich and Tremaine (1982) from the resolution of the Boltzmann equation. Replacing the optical depth τ by 2, the velocity dispersion v by 0.5 cm s^{-1}, and the Keplerian angular velocity Ω by 2×10^{-4} rd s^{-1}, we obtain $\nu = 230$ $\mathrm{cm}^2\ \mathrm{s}^{-1}$.

A viscosity of 230 $\mathrm{cm}^2\ \mathrm{s}^{-1}$ gives rise to a diffusion of 1.7 km in the 4 years of the Cassini mission, and of 4.4 km in the 27 years between Voyager 1 at Saturn (Nov. 80) and the end of the Cassini mission (Dec. 2007). Viscous diffusion in the B ring could be easily detected with a radial resolution of 1 km.

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Discussion

S.F.Dermott – When will the shepherd satellite enter the F ring and when will Cassini arrive at Saturn? If the F ring contains small satellites, why hasn't the shepherding satellite destroyed these satellites?

N.Borderies – As far as I remember, the inner shepherd satellite of the F ring came in close contact with the F ring few years before Voyager I fly-by of Saturn. If this is correct, this should not happen during the Cassini tour. Maybe it is the collision of the inner shepherd with the big particles – small satellites inside the F ring and its neighborhood – which gave rise to the small particles of the F ring.

H.Salo – What is your opinion about the cause for inner edges of rings, especially that of A ring?

N.Borderies – We do not know the cause for inner edges. The inner edge of the A ring is less sharp than its outer edge. Maybe the inner edge of the A ring is a result of the initial conditions when the ring formed.