Planetary Ring Dynamics [and Discussion]

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Planetary ring dynamics

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The dynamics of planetary rings are reviewed in the light of data derived from the recent spacecraft missions to the outer planets. It is shown that although the ring systems of Jupiter, Saturn, Uranus and Neptune display a great diversity of phenomena and dynamical structures, they have many features and problems in common. The rôle of small satellites in determining ring structure is reviewed, with particular emphasis on the ring system of Saturn. There is mounting evidence that some of the smaller satellites may have densities as low as 0.6 g cm^{-3}. Because Saturn has examples of most of the types of rings seen elsewhere in the Solar System, the forthcoming Cassini mission has particular importance for ring dynamicists. A summary is presented of the critical ring observations that can only be made by a spacecraft orbiting Saturn for an extended period.

1. Introduction

Before the serendipitous discovery of the rings of Uranus in 1977, Saturn was the only planet which was known to have a ring system. The data derived from the successful Pioneer and Voyager missions to the outer planets have been complemented with a variety of ground-based observations and it is now possible to carry out comparative studies of the diverse and complex ring systems of Jupiter, Saturn, Uranus and Neptune. In the course of a decade the two Voyager spacecraft either discovered or provided the first resolved images of 28 new satellites, increasing the inventory by almost 100%. Since the origin and evolution of rings and satellites are known to be closely related, such data is invaluable in attempts to explain the structure of planetary ring systems and provide estimates of their ages.

This paper concentrates on some aspects of the dynamics of planetary rings and their associated satellites. Rather than provide an exhaustive review of the subject, we attempt to highlight recent areas of research which have provided particularly intriguing results, and indicate those questions which can only be answered by the next generation of spacecraft to visit the outer planets.

2. Planetary ring systems

(*a*) *The rings of Jupiter*

The optically thin (optical depth, $\tau < 3 \times 10^{-6}$) ring system of Jupiter was discovered by the Voyager 1 spacecraft in March 1979 and further images were obtained by Voyager 2 later that year (Smith *et al.* 1979*a*,*b*). The set of 25

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Voyager images has been extensively analysed by Showalter (1985) and Showalter *et al.* (1987). The main ring, centred at 129 130 km, is ~ 7000 km wide with a sharp outer edge and a faint 'gossamer' ring extending outwards for a further 850 000 km. At the inner edge there is a toroidal-shaped halo of ring material which is brighter close to the main ring and may extend more than half-way to the planet. The vertical structure extends symmetrically for perhaps 10 000 km above and below the equatorial plane.

Consolmagno (1983) and Burns *et al.* (1985) suggested that the Lorentz force experienced by a charged dust grain could help explain some of the structure of the Jovian ring system. In particular, commensurate relationships between the orbital period of the grain and the period of the electromagnetic force give rise to the so-called Lorentz resonances. One of these occurs close to the transition point between the main ring and the halo (Schaffer & Burns 1987).

(*b*) *The rings of Saturn*

The main ring system of Saturn consists of the broad A and B rings separated by the Cassini division, and the optically thinner C and D rings. Exterior to the main rings lie the narrow, 'braided' F ring and the broader, diffuse E and G rings. It is important to note that the main ring system contains few actual gaps; most of the ring features that appear in the occultation profiles are fluctuations in surface density. However, narrow gaps exist in the C ring, at the inner edge of the Cassini division and in the outer part of the A ring. Gaps in the C ring and Cassini division are known to contain narrow, eccentric rings (Porco 1990) two of which are thought to be subject to forced precession as a result of satellite resonances (Porco 1983; Nicholson & Porco 1988).

The existence of a satellite in the prominent, 325 km wide Encke gap in the A ring had been suspected on the basis of wavy edges detected in Voyager images (Cuzzi & Scargle 1985). Unresolved images of the satellite, Pan, were first detected in Voyager images by Showalter (1991) who determined a semi-major axis of 133 582.8 ± 0.8 km. The Encke gap also contains an incomplete ring, similar in some respects to the ring arcs of Neptune (see below). The coincidence of this ring with the satellite's orbit (Showalter 1991) suggests that Pan is maintaining ring material in horseshoe and tadpole orbits along the lines proposed by Dermott *et al.* (1979) for the rings of Uranus; indeed, the maximum radial width of the ring (20 km) is compatible with the maximum extent of the horseshoe region (30 km) for this satellite (Dermott & Murray 1981*a*). Exchange of angular momentum between Pan and the surrounding A ring material means that Pan also acts to 'shepherd' the edges of the Encke gap according to the mechanism proposed by Goldreich & Tremaine (1979).

Most of the structure in the A ring of Saturn can be explained by resonances with the smaller Saturnian satellites. Figure 1 shows part of a Voyager 2 image of the outer region of the A ring with annotation indicating the positions of all the resonances of the form $p+1 : p$ with Pandora and Prometheus which lie within the region. The ring features are caused by a succession of tightly wound, unresolved spiral density waves propagating away from the location of the resonances. There are also two features associated with the 8:5 resonance with Mimas. Although the structure of the B ring is still poorly understood, there has been some progress in explaining some of the C ring structure in terms of resonances with planetary oscillations (Marley & Porco 1993). Recently Hamilton & Burns (1993) have

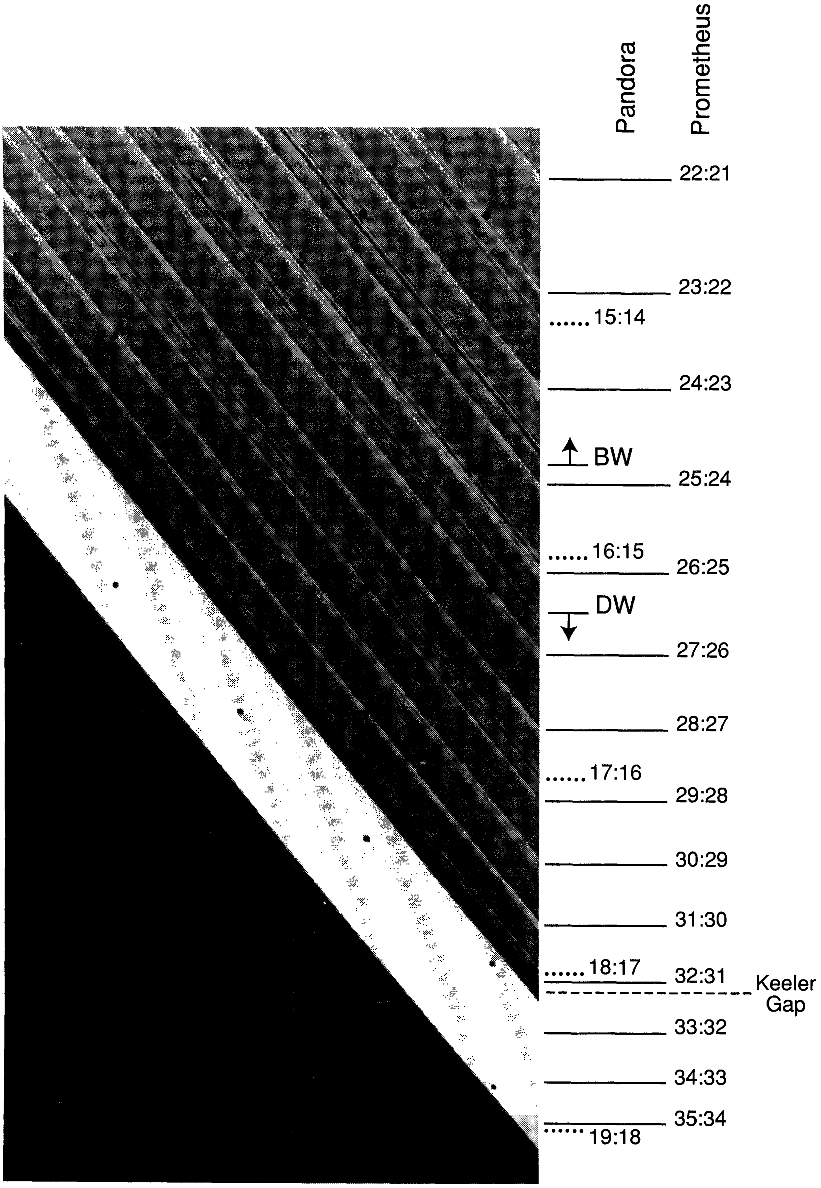

Figure 1. Part of a Voyager 2 image of the outer part of the A ring of Saturn showing the Keeler gap and a series of ring features associated with first-order resonances with the satellites Prometheus (solid lines) and Pandora (dashed lines). The locations marked DW and BW denote the locations of density waves and bending waves associated with the Mimas 8:5 resonance. The regular grid of dark points are reseau marks etched on to the vidicon tube of the imaging system.

attempted to explain the properties of the extended E ring by including the effects of non-gravitational forces on the micron-sized particles.

(*c*) *The rings of Uranus*

Before the Voyager 2 encounter with Uranus in 1986, ground-based stellar occultation experiments had detected the presence of nine, narrow (typical widths of < 10 km) rings around the planet. In order of increasing distance from the planet these are rings 6, 5, 4, α, β, η, γ, δ and ϵ. Voyager images in back-scattered light confirmed the existence of these rings as well as the λ ring orbiting between the δ and ϵ rings, and 1986U2R orbiting interior to ring 6; a 96 s exposure in forward-scattered light revealed the presence of a large number of dust rings.

The shepherding satellite model (Goldreich & Tremaine 1979) for narrow rings has had considerable success in explaining the confinement of the ϵ ring by the satellites Cordelia and Ophelia which orbit interior and exterior to the ring. Cordelia has a 24:25 outer eccentric resonance with the inner edge of the ϵ ring and Ophelia has a 14:13 inner eccentric resonance at the outer edge of the ring (Porco & Goldreich 1987). However, despite extensive searches, no other satellites have been found in the main ring system although there is some evidence for their existence (see below).

The ϵ ring is one of several in the Uranian system to exhibit a variable width. Each of these rings can be modelled by two aligned ellipses of different semi-major axes and eccentricities which precess uniformly under the zonal gravity harmonics at a rate determined by the central elliptical path. The two models proposed to explain this behaviour rely on either the self-gravity of the ring (Goldreich & Tremaine 1979) or the effectiveness of a natural 'pinch' mechanism within the ring (Dermott & Murray 1980). The prediction of a mean particle radius of 20–30 cm using the self-gravity model is in conflict with the Voyager observations of sizes > 70 cm.

(*d*) *The rings of Neptune*

The Voyager 2 images show that Neptune has at least three, distinct rings (the Galle, Le Verrier and Adams rings) and that the arcs detected in ground-based occultations are just the optically thicker parts ($\tau \approx 0.04$) of the outermost Adams ring (Smith *et al.* 1989). The three arcs detected in initial observations have been named Liberté, Egalité and Fraternité, although it now appears that there are at least two additional arcs in the same ring. There is also a sheet of dust which extends from between the Adams and Le Verrier rings inwards to a radius of $\sim 38\,000$ km (see figure 2*a*).

Two small satellites were detected in the main rings: Despina orbits ~ 700 km interior to the Le Verrier ring, and Galatea orbits ~ 900 km interior to the Adams ring. Porco (1991) proposed that it was Galatea resonances that produced the radial and longitudinal confinement in the Adams ring necessary to explain the arc structure (figure 2*b*). In particular a 42:43 exterior, corotation inclination resonance would lead to the establishment of 86 equilibrium sites, each with a maximum extent of 4° and a radial width in semi-major axis of 0.6 km. According to Porco, the arcs occupy either all or part of some sites and would be radially confined by the effects of a 42:43 outer Lindblad resonance located 1.5 km interior to the Adams ring.

3. Satellite dynamics

There is now increasing evidence that the masses of some of the smaller satellites of Saturn may have been overestimated; this has important implications for the lifetime of the ring system. Dermott & Murray (1981*b*) showed how accurate orbit determinations of the co-orbital satellites, Janus and Epimetheus, could be used to derive masses of the objects. Combining all the ground-based observa-

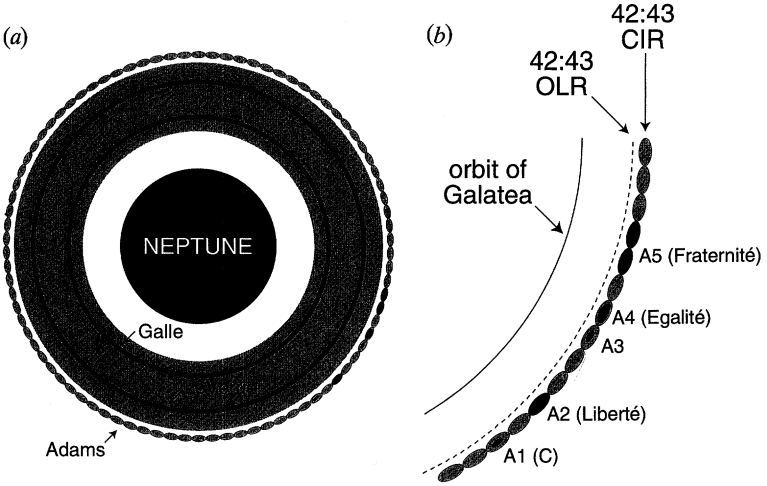

Figure 2. (*a*) A schematic illustration of the ring system of Neptune as viewed from below the ring plane. The radial widths of the Galle, Le Verrier and Adams rings have been exaggerated. (*b*) The relative locations of the orbit of Galatea, the 42:43 outer Lindblad resonance (OLR), the 42:43 corotation inclination resonance (CIR) and the arcs of optically thicker material detected in the Adams ring. The names attached to each arc denote the variety of nomenclature for the arcs.

tions of the co-orbitals with Voyager data sets enabled Nicholson *et al.* (1992) to calculate densities of 0.65 ± 0.08 and 0.63 ± 0.11 g cm^{-3} for Janus and Epimetheus respectively, confirming the earlier work by Yoder *et al.* (1989). There is also independent confirmation for such densities for these satellites and others from an analysis of density waves in the rings by Rosen *et al.* (1991).

Janus (mean radius 90 km) and Epimetheus (mean radius 59 km) execute a peculiar orbital libration (Dermott & Murray 1981*b*). Since the difference in the semi-major axes of their orbits is 50 km, differential Keplerian motion implies that they encounter one another every 4 yr. At encounter the satellites exchange angular momentum leading to a switch in orbits. Viewed in a reference frame rotating at the mean orbital angular velocity, the successive switches in semi-major axis are ±10 km for Janus and ±40 km for Epimetheus. Since the radial location of the density waves that each of these satellites produces in the A ring is determined by their respective semi-major axes, this implies that this too will change by similar amounts with the same regularity.

4. Unseen satellites and ring lifetimes

On observational and theoretical grounds, there is good evidence for the existence of small, unseen satellites orbiting in or near the various planetary ring systems. For example, the short ($\sim 10^{3\pm1}$ yr) lifetimes of particles in the Jovian ring (Burns *et al.* 1984) implies either an extremely youthful ring system or the existence of a ready source of new ring material. There are insufficient observations available to know whether or not the small satellites Metis and Adrastea are capable of providing enough source material from meteoritic bombardment to supply the Jovian ring. However, there is evidence from charged particle absorption signatures that there are small, unseen moons in the vicinity of the rings

(Acuña & Ness 1976). There is also the possibility that dust from the occasional (once per century) passage of a comet will provide an additional source of ring material. The anticipated approach of the dust tail of Comet Shoemaker-Levy 9 in July 1994 could produce a new, temporary dust ring (Horanyi 1993) or provide sufficient new dust to highlight the locations of source bodies in the ring (Hamilton 1993).

Esposito & Colwell (1989) argue that the optically thin dust rings of Uranus are probably examples of part of a steady state process which involves the diminution of larger objects by meteoritic impact. By extension their model would also apply to the dusty ring system of Neptune. Whether or not their model is correct, some explanation of the extensive structure and the confinement (if only temporary) of the narrow rings is still required. The problem becomes even more acute when it is realized that Uranus has an extended hydrogen exosphere which stretches to at least the orbit of the β ring and subjects ring material to the equivalent of an atmospheric drag force. Murray & Thompson (1989, 1990) used the dust ring image to calculate possible radial locations of unseen satellites orbiting in the main ring system. In particular they found that there seemed to be a preference for locations which were already close to first-order resonances with Cordelia. Recently Showalter (1993) has discovered periodic, azimuthal structure in the λ ring and deduced that it is caused by a small satellite at a radial separation of 6700 km.

At least seven of the gaps in Saturn's rings have a narrow, sharp-edged, eccentric ring orbiting within them. The precession of two of these rings is known to be caused by resonant forcing and there is speculation that small satellites may be involved in the motion of the others, as well as creating the gaps in the first place (Porco 1990).

The technique of detecting satellites by looking for waves, or periodic azimuthal structure, on surrounding ring material is now well established, following the discovery of Pan (Showalter 1991). The passage of a satellite of mass, m, at a radial separation, δa, from a ring of semi-major axis, a, will create a wave of wavelength,

$$\lambda = 3\pi\,\delta a \tag{4.1}$$

and amplitude,

$$A = 2.24(m/M)(a/\delta a)^2 a \tag{4.2}$$

where M is the mass of the central planet (see, for example, Dermott 1984). Cooke (1991) has described wave phenomena on the edges of the 35 km wide Keeler gap in the outer part of Saturn's A ring (see figure 1) which may be caused by nearby satellites, although the interpretation is not as simple as in the Encke gap. Similarly, a Fourier analysis of a sequence of low-resolution images of the F ring led Kolvoord *et al.* (1990) to propose a satellite at a radial distance of 1180 km from the ring.

There is now good evidence that the F ring and its immediate environs contain a number of small (radius < 10 km) satellites and that the ring itself can evolve on time-scales of ~ 1 yr. Strands visible in some of the Voyager 2 images cover > 260 km in radius, extend over $\sim 45°$ in longitude and cannot be explained by resonances with the known satellites (Giuliatti-Winter & Murray 1993, and in preparation). One possible explanation is that this region contains several small satellites (radii ~ 5 km) which have acted to clear dust from their orbits. There is independent evidence from charged particle data for the existence of a moonlet belt in the vicinity of the F ring (Cuzzi & Burns 1988).

Probably the most difficult problem facing ring dynamicists concerns the lifetime of Saturn's rings (Borderies *et al.* 1984; Nicholson & Dones 1991). The excitation of density waves in Saturn's A ring (see figure 1) by satellites such as Atlas, Prometheus, Pandora, Janus and Epimetheus, involves an exchange of angular momentum which results in a mutual repulsion of the A ring and the satellites. An optimistic time-scale for collapse of the A ring to its inner edge is $\sim 10^8$ yr (Nicholson & Dones 1991). However, Borderies *et al.* (1984) point out that the secular evolution could be curtailed if Pandora was itself involved in an angular momentum exchange with Mimas by means of a 3:2 resonance which lies ~ 60 km beyond the orbit of Pandora. Since Mimas contains almost twice the mass of the entire ring system, even a temporary exchange mechanism might extend ring lifetimes to a value approaching the age of the Solar System (4.5×10^9 yr). However, we note that Pandora lies in the middle of six, second-order resonances associated with the Mimas 6:4 commensurability and that since the orbits of Pandora and Mimas are receding from Saturn due to ring and tidal torques, it is likely that resonance passage has occurred or will occur at some time in their dynamical evolution.

5. Future prospects

There are a number of general, dynamical observations of the Saturn system which can only be made *in situ* by a spacecraft orbiting the planet. These include (i) a complete inventory of rings and satellites, (ii) shape, mass and accurate orbit determination of the satellites and (iii) observations of the time evolution of the ring system on a variety of time-scales. There are also several unique events which will occur in the period between 2004 and 2008 when the Cassini spacecraft will be orbiting Saturn. A switch in the orbits of Janus and Epimetheus will occur on February 1, 2006 and Cassini will have the opportunity to refine the orbits and masses of these objects as well as observe the response of their density waves to the sudden change in resonant radius.

Another event involves Prometheus and the F ring (Borderies *et al.* 1983). Figure 3 shows the orbital radius as a function of orbital longitude for the F ring, Prometheus and Pandora at the time of the Voyager 2 encounter in August 1981. The ring and satellites orbits are eccentric and precess at different rates under the zonal gravity harmonics of the planet. Although the individual precession rates are large ($\sim 3^\circ\ \mathrm{d}^{-1}$), the differential precession rates are ~ 50 times smaller, implying that the pericentre of the F ring will be aligned with the apocentre of Prometheus once every 16.9 yr (Giuliatti-Winter & Murray, in preparation). However there is an uncertainty of ± 1.6 yr in the time of the next alignment caused by the poorly determined longitudes of pericentre of the orbits (indicated by the bars on figure 3); the next approach should occur between February 2008 and April 2011, with an optimum date of September 2009. Giuliatti-Winter & Murray (in preparation) have studied the effect of the repeated encounters of F ring particles with Prometheus at the apocentre of its orbit. At each apocentre passage Prometheus creates a gap in the ring caused by the gravitational scattering of ring particles (see figure 4). If such an encounter takes place Cassini will

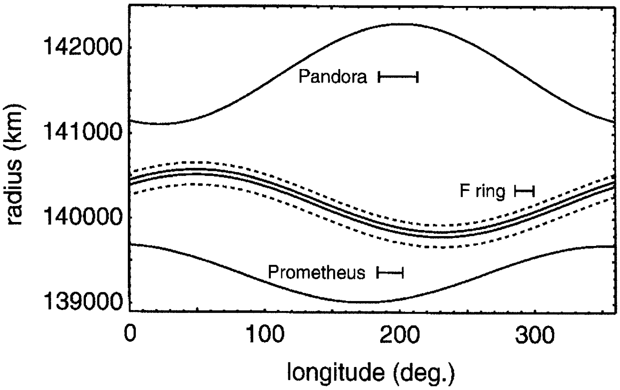

Figure 3. A plot of orbital radius as a function of orbital longitude for Prometheus, Pandora and the F ring at the time of the Voyager 2 encounter in August 1981. The two solid lines for the F ring indicate the possible positions taking account of the ±30 km uncertainty in its semi-major axis. The dashed lines on either side of the F ring indicate the extent of the faint rings detected in some Voyager 2 images. The bars associated with each plot indicate the 1σ uncertainty in the pericentre position of each orbit.

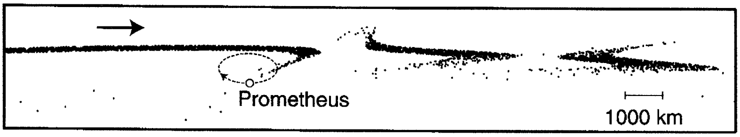

Figure 4. The results of a numerical simulation of the effects of an encounter between Prometheus and the F ring. The path of Prometheus in the frame rotating with its mean motion is shown as a dashed ellipse. The arrow denotes the direction of motion of the particles in the rotating frame.

have the opportunity to observe at first hand the response of a narrow ring to the disrupting perturbations of a close satellite. This will yield information about the dynamical properties of the F ring in particular and narrow rings in general.

There is also the possibility that Cassini images will allow a direct determination of the secular evolution rate of the ring system, and hence an estimate of the lifetime of the Saturnian ring system. Lissauer *et al.* (1985) estimate that Prometheus should have an acceleration of $-5.4 \times 10^{-20}\ \mathrm{s}^{-2}$ implying an increase in its semi-major axis of ~ 3 m, or equivalently a lag of $\sim 0.02°$ in longitude over the orbiting lifetime of the Cassini mission. In order to be able to make such an observation it is essential to have a complete understanding of all the relevant perturbations that Prometheus will experience, and accompanying astrometric data on the satellite throughout the course of the mission. This is likely to be one of the most challenging observations for the Cassini imaging system.

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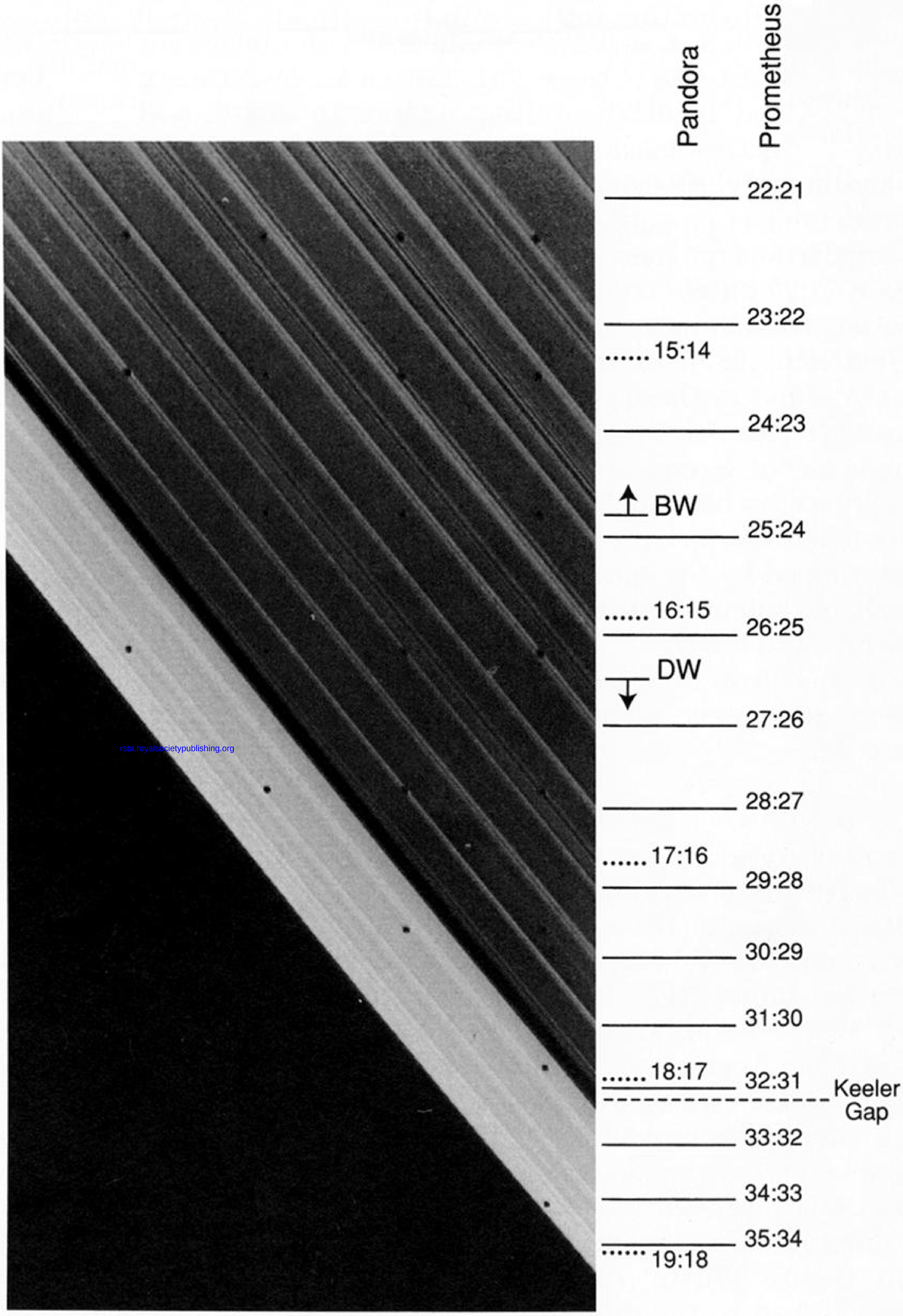
Discussion

P. H. FOWLER (*Physics Department, University of Bristol, U.K.*). In the Saturnian ring system many high-order resonances are involved. Some appear to yield gaps and many others appear to give enhancements. What is happening here?

C. D. MURRAY. Almost all the enhancements in the A ring are due to spiral density waves arising from first-order resonances with the small satellites that orbit just beyond the main rings, whereas most of the B ring features do not correlate with known resonances. There are few genuine gaps in the ring system. Some are likely to have been swept clear by the local action of small satellites, as in the case of the Encke gap and Pan. Although other gaps are known to be associated with resonances the situation is further complicated by the presence of narrow rings orbiting within the 'gaps'. Results from Cassini should help us to understand the observed differences.



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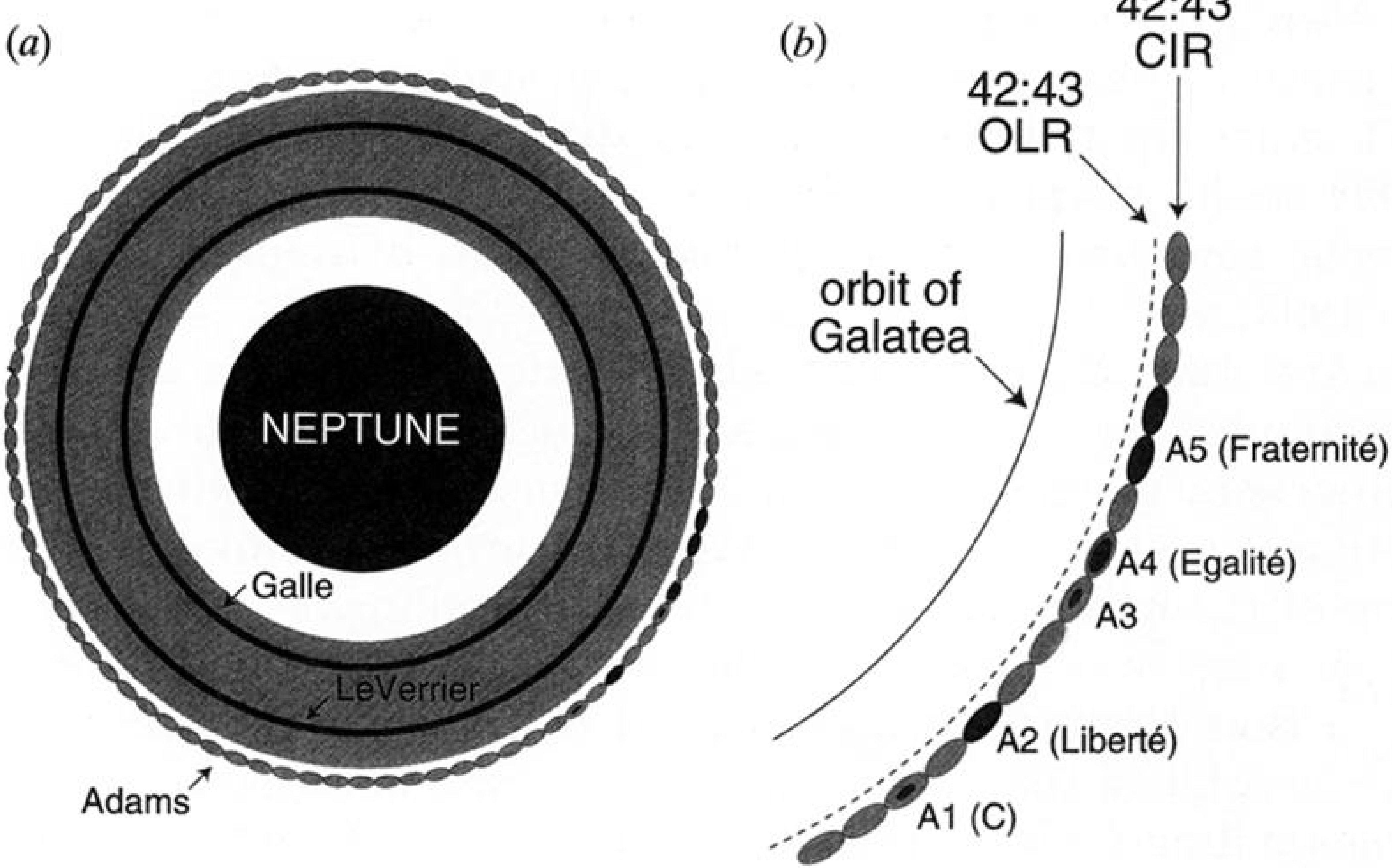

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