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Corrugations and eccentric spirals in Saturn's D ring: New insights into what happened at Saturn in 1983

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ABSTRACT

Previous investigations of Saturn's outer D ring (73,200–74,000 km from Saturn's center) identified periodic brightness variations whose radial wavenumber increased linearly over time. This pattern was attributed to a vertical corrugation, and its temporal variability implied that some event – possibly an impact with interplanetary debris – caused the ring to become tilted out the planet's equatorial plane in 1983. This work examines these patterns in greater detail using a more extensive set of Cassini images in order to obtain additional insights into the 1983 event. These additional data reveal that the D ring is not only corrugated, but also contains a time-variable periodic modulation in its optical depth that probably represents organized eccentric motions of the D-ring's particles. This second pattern suggests that whatever event tilted the rings also disturbed the radial or azimuthal velocities of the ring particles. Furthermore, the relative amplitudes of the two patterns indicate that the vertical motions induced by the 1983 event were 2.3 ± 0.5 times larger than the corresponding in-plane motions. If these structures were indeed produced by an impact, material would need to strike the ring at a steep angle (>60° from the ring plane) to produce such motions. Meanwhile, the corrugation wavelengths in the D ring are about 0.7% shorter than one would predict based on extrapolations from similar structures in the nearby C ring. This could indicate that the D-ring was tilted/disturbed about 60 days before the C ring. Such a timing difference could be explained if the material that struck the rings was derived from debris released when some object broke up near Saturn some months earlier. To reproduce the observed time difference, this debris would need to have a substantial initial velocity dispersion and then have its orbital properties perturbed by some phenomenon like solar tides prior to its collision with the rings.

1. Introduction

The D ring is the innermost component of Saturn's ring system, extending from the inner edge of the C ring towards the planet's cloud tops. One of the more intriguing structures in this region is a set of periodic brightness variations with a wavelength of ~30 km covering the outermost 1500 km of this ring (see Fig. 1). The intensity of this periodic pattern varies with longitude around the ring, and it becomes rather indistinct near the ring ansa. Such azimuthal intensity variations are characteristic of vertical ring structures, and so Hedman et al. (2007) argued that these periodic patterns were due to a vertical corrugation in the ring. Similar corrugations had previously been identified in Galileo images of Jupiter's rings (Ockert-Bell et al., 1999; Showalter et al., 2011), but the more extensive Cassini images (coupled with an earlier Hubble Space Telescope occultation) revealed that the wavelength of the D-ring pattern was steadily decreasing over time. The observed trend in the pattern's wavelength was consistent with the evolution of a corrugation under the influence of differential nodal regression. This finding not only confirmed that the D-ring pattern included a vertical corrugation, but also suggested that this structure probably arose from some event in the recent past that caused the ring to become tilted out of the planet's equatorial plane.

Later investigations revealed that both Saturn's C ring (Hedman et al., 2011) and Jupiter's main ring (Showalter et al., 2011) contained similarly evolving patterns of vertical corrugations. Furthermore, by extrapolating these trends backwards in time, we could estimate when Jupiter's and Saturn's rings became inclined relative to their planet's equatorial plane. The event that tilted Jupiter's rings happened in the summer of 1994, when the fragments of Comet Shoemaker-Levy 9 were crashing into the planet. It is therefore reasonable to conclude that this cometary debris was responsible for tilting Jupiter's rings. The event that tilted Saturn's

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rings occurred in the early 1980s, but unlike the Shoemaker-Levy 9 collision with Jupiter, this earlier event was not directly observed. Fortunately, some information about the impact is encoded within the corrugations themselves. In particular, the extent of the disturbance in the rings indicates that the ring encountered a dispersed debris field rather than a single compact object. Thus Hedman et al. (2011) inferred that the ring-tilting event at Saturn may have involved an object that was disrupted by a previous close encounter with Saturn, just as Shoemaker-Levy 9 broke apart during its close encounter with Jupiter in 1992.

Here we present a more detailed analysis of the periodic patterns in Saturn's D ring that provides additional information about how the rings were disturbed and how the resulting patterns evolved over time. This investigation focuses on the D-ring structures for two reasons. First, there are extensive Cassini observations available, and suitably high-resolution Cassini images that capture the relevant periodic patterns span nearly a decade (By contrast, the corrugations in Saturn's C ring were only visible for a brief interval around Saturn's equinox in 2009). This data set yields very precise measurements of how the patterns' wavelengths vary over time, and so we can confirm that these structures are evolving at rates consistent with current models of Saturn's gravitational field.

Second, the D ring appears to contain a second periodic structure overprinted on the corrugation. The original analysis of the D-ring patterns by Hedman et al. (2007) revealed that the scatter of the wavelength measurements around the mean trend with time was larger than their individual error bars would predict. Furthermore, observations taken further from the ring ansa appeared to have systematically longer wavelengths, suggesting that another periodic structure was being revealed in certain viewing geometries. Close inspection of additional Cassini images have confirmed this supposition. For example, Fig. 1 shows that periodic brightness variations are visible at the rings' ansa. A vertical corrugation cannot generate brightness variations at this location because the vertical slopes are all nearly orthogonal to the observer's line of sight (see below). Hence the patterns visible close to the ansa likely reflect variations in the ring's surface density rather than its vertical structure. Since there is no obvious change in the pattern's wavelength close to the ansa, the wavelength of these opacity variations must be nearly identical to the wavelength of the vertical

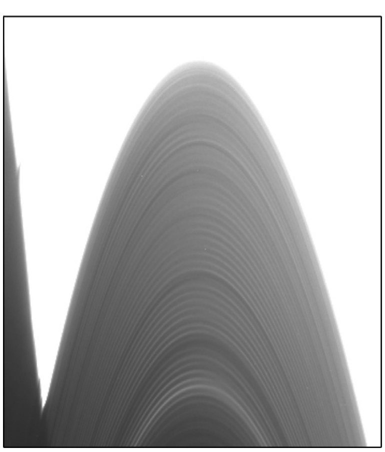

Fig. 1. Image of the periodic structures in the outer D ring (Image name N1571969357 phase angle 26.7°, ring opening angle 2.4°, radius increases upwards, and the surrounding C ring is overexposed). Periodic brightness variations are apparent throughout this portion of the D ring. However, one can also see that the intensity of the pattern varies with azimuth, reaching a minimum near the ring ansa. These azimuthal trends indicate that at least a fraction of these brightness variations are due to vertical structure in the ring. However, periodic patterns are also visible at the ring ansa, where the signal from vertical structures should vanish. Thus periodic variations in the ring's opacity also seem to be present.

corrugations. This suggests that these density variations were generated by the same event that formed the corrugation, and detailed analyses of the two patterns' wavelengths confirm this hypothesis. Furthermore, the relative amplitudes of these two patterns, along with some anomalous trends in the corrugations' wavelength with radius between the D and C rings, yield new information about how the ring was disturbed in 1983.

We begin this investigation by reviewing the theory of how corrugations in the ring are expected to evolve over time, and how similarly time-variable periodic opacity variations could be produced (Section 2). Section 3 then describes the analytical procedures used to isolate opacity variations from vertical structures and to obtain estimates of the relevant patterns' wavelengths and amplitudes. Section 4 lists the images considered for this analysis and summarizes the resulting estimates of the patterns' properties and evolution over time. Based on these results, Section 5 demonstrates that the measured wavelengths and amplitudes are consistent with the expected evolution of patterns generated by a discrete disturbance like an impact that occurred sometime in the past. Section 6 describes how the amplitudes and precise wavelengths of these patterns can provide new information about the pre-impact trajectory of the debris that collided with the rings. The results and potential implications of this analysis are summarized at the end of this paper.

2. Theoretical background

This investigation builds upon the earlier studies of the corrugations (Hedman et al., 2007, 2011) not only by considering additional data, but also by employing image-processing techniques that can isolate signals due to vertical structure from those due to optical depth variations. In order to motivate this effort and justify some of the choices made in the analytical procedures, we first review how an inclined sheet can evolve into a vertical corrugation and the expected observable properties of such a corrugation. In addition, this section will describe how a disturbance in the ring-particles' in-plane motions can produce periodic optical-depth variations with evolving wavelengths very similar to those associated with the corrugations.

Imagine that a portion of Saturn's ring became tilted relative to Saturn's equatorial plane at a time t_i. The particles in such a tilted ring all have a finite inclination I and the same longitude of ascending node Ω, which we can set equal to zero for the remainder of this calculation. However, if the forces exerted on the ring particles deviate from a purely central inverse-square-law, then the node positions will regress at a rate $\dot{\Omega}(r)$ that depends on the particles' mean radial distance from Saturn's spin axis r. Hence if the ring is observed at a time $t_f > t_i$, the node location at a given r will be $(t_f - t_i)\dot{\Omega}(r)$. So long as the nodal regression is predominantly due to Saturn's oblateness parameter $J_2, \dot{\Omega}(r)$ will have negative values everywhere and the absolute value of $\dot{\Omega}(r)$ will decrease monotonically with increasing r. The longitude of ascending node will therefore form a leading spiral that becomes progressively more tightly wound over time. More specifically, the ring's vertical position z at a given radius r and longitude θ can be expressed as the following function of the ring's inclination I and the node longitude:

$$z = rI \sin(\theta - \Omega(r)), \tag{1}$$

The vertical position of the ring at a given θ will therefore oscillate up and down as a function of radius. In the vicinity of any given radial position in the ring r_o, the node position can be approximated using the first two terms of the Taylor series:

$$\Omega(r) = \Omega(r_o) + \frac{\partial \dot{\Omega}}{\partial r}(t_f - t_i)(r - r_o). \tag{2}$$