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Mapping spiral waves and other radial features in Saturn's rings

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ABSTRACT

We have analyzed the highest-quality images to be obtained by *Cassini* of Saturn's main rings after the Saturn Orbit Insertion (SOI) and before the Ring Grazing Orbits (RGO) and Grand Finale (GF). These images are comparable to those of SOI in fidelity, though not in nominal resolution, due to their high signal-to-noise. We have systematically searched for radial structure in these images by reducing them to a single dimension (distance from Saturn's center) and using the continuous wavelet transform technique. We discuss the resonant theory of spiral waves and discuss the proper method for deriving the local surface mass density from the wavelet signature of a spiral wave. We present 1) individual features of interest found in our data, including several classes of waves that have not previously been reported; 2) a radial profile of surface mass density in Saturn's rings, which is more definitive for the A ring than any previously presented and which corrects some errors in previous profiles; and 3) an atlas of resonant features that indicates whether each feature is or is not expressed in the rings and that is organized graphically by resonance strength.

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1. Introduction

The main rings of Saturn,[2] in addition to being among the most beautiful and enticing structures in the solar system, constitute a dynamic system with a great deal of internal structure. The vast majority of that structure is too fine to be seen in the global-scale views of the rings that are most often seen by the public, while close-up views are often presented without sufficient context to enable viewers to comprehend how the whole is composed of the parts. The purpose of this work is to take a first step towards an "atlas" of Saturn's rings, which presents a global view yet with enough detail to see the fine structure, and which also uses several tools to explicate the fine structure.

Nearly all the fine structure in Saturn's rings is either azimuthally symmetric or in the form of a tightly-wound spiral; moreover, the spiral structures can be understood as phased wavefronts passing through a spatial frequency profile that is azimuthally symmetric. Therefore, a radial profile of the ring is sufficient to account for the basic structure of the ring system. Azimuthally compact structures do exist, such as spokes (Mitchell et al., 2013) and propellers (Tiscareno et al., 2006a; 2008; 2010; Sremčević et al., 2007), but these may be considered as objects moving across a "landscape," while the landscape itself is azimuthally symmetric and is the subject of this work.

This work focuses on the ring's structure as seen in images obtained by the Imaging Science Subsystem (ISS) on board the *Cassini* spacecraft. The ISS images generally have substantially lower resolution than occultation profiles from the VIMS, UVIS, and RSS instruments. However, an occultation is a one-dimensional profile, and as such often has difficulty distinguishing actual radial ring structure from local ring microstructure (e.g., Showalter and Nicholson, 1990). On the other hand, because ISS images are two-dimensional, averages over the azimuthal dimension can reveal very subtle radial structure, especially when exposures are set to take advantage of the camera's sensitivity and obtain optimal signal-to-noise. Therefore, although dozens of *Cassini* occultations can now be combined in order to emphasize radial structure (e.g., Colwell et al., 2009; Hedman and Nicholson, 2016) – a strategy that could also be employed with *Cassini* images, though no one has yet done so – ISS images are potentially the best instrument for detecting a certain class of subtle radial features, as long as their radial extent is not much smaller than the nominal resolution of the images.

The maps and atlases of ring structure presented in this work are innovative and (we hope) useful, but are not yet definitive. They should be improved in the future by incorporating occulta-

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[2] The present analysis is restricted to Saturn's "main rings," namely the A, B, and C rings and the Cassini Division.

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tion data from the *Cassini* RSS, UVIS, and VIMS instruments. They should also be improved by incorporating *Cassini* ISS data that was recently obtained during the Ring Grazing Orbits (RGOs) and the Grand Finale (GF) in 2016 and 2017, during which the spacecraft passed repeatedly very close to the rings and obtained a radially complete series of images at much better resolution than the images presented in this work. The RGO/GF images are better than 0.8 km pixel^{-1} for nearly all locations in the main rings (cp. Fig. 4). They improve upon the data set reported in this work by a factor ranging from 25% to 75%, depending on location, and show a wide range of structures never seen before (Tiscareno and the Cassini Imaging Team, 2017; Tiscareno et al., 2018). A full analysis of the radial structure of the main rings as seen in the RGO/GF images will be presented in future work.

Section 2 reviews relevant portions of the theory of spiral waves, which is at the heart of much of this work. Sections 3 and 4 describe the methods by which the data we present were obtained and processed. Section 5 describes our results, including individual features of interest found in our data, a radial profile of surface mass density in Saturn's rings, and an atlas of resonant features that indicates whether each feature is or is not expressed in the rings and that is organized graphically by resonance strength.

2. Theory

Spiral waves occur at locations in the rings where the forcing frequency from the moon forms a whole-number ratio (the "resonance label") with the orbital frequency[3] of ring particles. *Lindblad resonances* excite the eccentricities of ring particles, leading to spiral density waves (SDWs). *Vertical resonances* excite the inclinations of ring particles, leading to spiral bending waves (SBWs).

2.1. Wave dispersion and unperturbed surface mass density

The linear theory of spiral waves in disks has been described in several classic publications (see review by Schmidt et al., 2009). For our purposes, we only need quote the relation between a wave's spatial frequency $k = 2\pi/\lambda$ (for wavelength λ) and the distance between any radial point r (measured from Saturn's center within the ring plane) and the resonance point $r_{\rm res}$, at which the wave is generated:

$$k(r) = \frac{\mathscr{D}}{2\pi G\sigma_0 r_{\rm res}}(r - r_{\rm res}), \tag{1}$$

where G is Newton's constant, σ_0 is the unperturbed surface mass density at radius r, and the factor $\mathscr{D}$ is given by

$$\mathscr{D} = \begin{cases} 3(m-1)n_{\rm res}^2, & m > 1 \\ \frac{21}{2}J_2\frac{R_{\rm Sat}^2}{r_{\rm res}^2}n_{\rm res}^2, & m = 1 \end{cases} \tag{2}$$

where $n_{\rm res}$ is the orbital frequency (or "mean motion") at radial location $r_{\rm res}$, J_2 is the quadrupole gravity harmonic of Saturn, $R_{\rm Sat} = 60{,}330$ km is the radius[4] of Saturn, and m is the azimuthal parameter[5] of the resonance.

Nearly all spiral waves discussed in this paper are described by the upper branch of Eq. (2). First-order resonances (for which the two numbers in the ratio differ by one) are the strongest for any given moon, and moons as small as Pan and Atlas (but not Daphnis) raise observed SDWs at their first-order resonances. Higher-order resonances can also raise observable waves, if the perturbing moon is relatively massive and has a significant eccentricity (for SDWs) or inclination (for SBWs). Two factors cause SBWs to be much rarer than SDWs, namely that vertical resonances cannot be first-order, and that inclinations for moons in the Saturn system are generally small. Saturn's small, close-in "ring moons" Pan, Atlas, Prometheus, Pandora, Janus, and Epimetheus produce abundant SDWs in the main rings. More massive and more distant moons, such as Mimas, produce higher-order SDWs and SBWs, some of which are more powerful than the first-order waves driven by the smaller moons.

Resonances for which $m = 1$, described by the lower branch of Eq. (2), are those for which the forcing frequency from the moon resonates not with the ring particle's orbital frequency but with its precession frequency (Cuzzi et al., 1981; Rosen and Lissauer, 1988; Tiscareno et al., 2013a). Because precession frequencies are much slower than orbital frequencies, the moons that raise $m = 1$ waves are much farther from the planet than those that raise $m > 1$ waves; in the case of Saturn's rings, observed $m = 1$ waves are raised by Titan, Hyperion, and Iapetus.

The appearance of the unperturbed surface mass density σ_0 in Eq. (1) allows spiral waves to be used diagnostically to measure that parameter at many locations in Saturn's rings. For waves that conform to the linear theory, the surface mass density can be taken as constant over the extent of the wave. Since all other variables in Eq. (1) have known constant values, we can differentiate with respect to r to obtain a constant value for $\mathrm{d}k/\mathrm{d}r$ (see Tiscareno et al., 2007, and references therein). This tells us that linear waves should produce a slanted feature with a constant slope if we plot k against r (see Fig. 1a, which also introduces the *wavelet transform plots* used throughout this work). However, most of the prominent waves that appear in Saturn's rings are significantly affected by inter-particle effects such as self-gravity and collisions, which cause them to deviate from linear theory; instead, the signature produced on a wavelet transform plot by these "non-linear" waves is concave-up, appearing to hang below the straight slope predicted by linear theory (Fig. 1b).

When σ_0 cannot be assumed to be constant across the wave, then an effective value for σ_0 at each point r within the wave can be estimated by drawing a line between the wavenumber $k(r)$ and the wave's "origin" at $r = r_{\rm res}$ and $k = 0$ (the black dashed line in Fig. 2). The concave-up shape of the non-linear wave's trace means that this calculation yields higher values of σ_0 in the middle parts of the wave. This likely reflects a real process by which non-linear waves concentrate ring mass within themselves, but it is important to recognize that it does not reflect a true "unperturbed" surface mass density, which would be the ring's value of σ_0 if the wave were not there. Most *Voyager*-era measurements of σ_0 from spiral waves are analogous to the black dashed line in Fig. 2, and thus are systematically higher than the true unperturbed surface mass density of the ring.

Sometimes a wave extends across a region in which the ring's unperturbed surface mass density naturally varies. A good example of this is the Iapetus −1:0 SBW (Tiscareno et al., 2013a). The long wavelengths of this $m = 1$ wave (see above) mean that it extends over several thousand km before it damps away (Fig. 3a), such that plugging the observed series of slopes $k(r)/(r - r_{\rm res})$ into Eq. (1) yields a complex profile of true unperturbed surface densities $\sigma_0(r)$, which agrees at several points with σ_0 values derived from measurements of smaller SDWs (Fig. 3b). A key factor that makes this possible is that even strong SBWs do not concentrate mass (since their perturbations are perpendicular to the ring plane, rather than within it), so non-linear effects are negligible.

[3] It is actually the ring particle's radial frequency κ or vertical frequency ν that respectively resonates with the forcing frequency to create a SDW or a SBW. However, both κ and ν differ from the mean motion n by a small factor of order J_2, and it is sufficient to think in terms of n when computing the resonance label.

[4] Note that $R_{\rm Sat}$ is not subject to refinement by improved understanding of Saturn's atmosphere, as it is only a conventional value by which J_2 is normalized.

[5] One can determine m from the identity of the resonance, as a first-order resonance is labeled m:(m−1), a second-order resonance is labeled (m+1):(m−1), a third order resonance is labeled (m+2):(m − 1), and so on.

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