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Noncircular features in Saturn's rings II: The C ring

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ABSTRACT

We present a comprehensive survey of sharp-edged features in Saturn's C ring, using data from radio and stellar occultation experiments carried out by the *Cassini* spacecraft over a period of more than five years. Over 100 occultations are included in the combined data set, enabling us to identify systematic radial perturbations as small as 200 m on the edges of ringlets and gaps. We systematically examine all of the noncircular features in the C ring, refine the eccentricities, precession rates and width variations of the known eccentric ringlets, identify connections between several noncircular gap and ringlet edges and nearby satellite resonances, and report the discovery of a host of free normal modes on ring and gap edges. We confirm a close association between the Titan (or Colombo) ringlet ($a = 77878.7$ km) and the Titan 1:0 apsidal resonance: the apoapse of the ringlet is nearly aligned with Titan's mean longitude, and the pattern speed closely matches Titan's mean motion. Similar forced perturbations associated with the Titan resonance are detectable in more than two dozen other features located throughout the inner C ring as far as 3500 km from the Titan resonance. The inner edge of the Titan ringlet exhibits several strong outer Lindblad resonance (OLR-type) normal modes, and scans of the outer edge reveal inner Lindblad resonance (ILR-type) normal modes. The Maxwell ringlet ($a = 87{,}510$ km), in contrast, appears to be a freely-precessing eccentric ringlet, with post-fit RMS residuals for the inner and outer edges of only 0.23 and 0.16 km, respectively. The best-fitting edge precession rates differ by over 10 times the estimated uncertainty in the rate of the inner edge, consistent with a slow libration about an equilibrium configuration on a decadal timescale. Using self-gravity models for ringlet apse alignment, we estimate the masses and surface densities of the Titan and Maxwell ringlets. The Bond ringlet ($a = 88{,}710$ km), about 17 km wide, shows no free eccentricity but lies near two strong resonances: the Mimas 3:1 inner vertical resonance (IVR) at 88702.2 km and the Prometheus 2:1 ILR at 88713.1 km. We find no measurable perturbation from the Mimas IVR, but a clear $m = 2$ signature of the appropriate phase and pattern speed for the Prometheus ILR on the outer edge of the ringlet, along with free ILR-type normal modes with wave numbers $m = 3,4,5,6$ and 7. The Dawes gap, located at 90,210 km, and its associated embedded ringlet, also show both free and forced perturbations, and as in the case of the Maxwell gap, the outer edge of the Dawes gap appears to be sympathetically forced by the nearby ringlet. The pattern of newly identified normal modes coexisting on the sharp edges of ringlets and gaps is in excellent agreement with theoretical predictions, with ILR-type modes on outer ringlet (and inner gap) edges and OLR-type modes on inner ringlet (and outer gap) edges, representing standing waves between the resonance locations and the ring edges. Modes with larger $|m|$ generally have narrower resonant cavities, and of the dozens of detected normal modes, none has been identified with a resonance radius that falls outside the ring material.

1. Introduction

Saturn's C ring is the innermost and least opaque of the three classical components of the planet's main ring system. It contains

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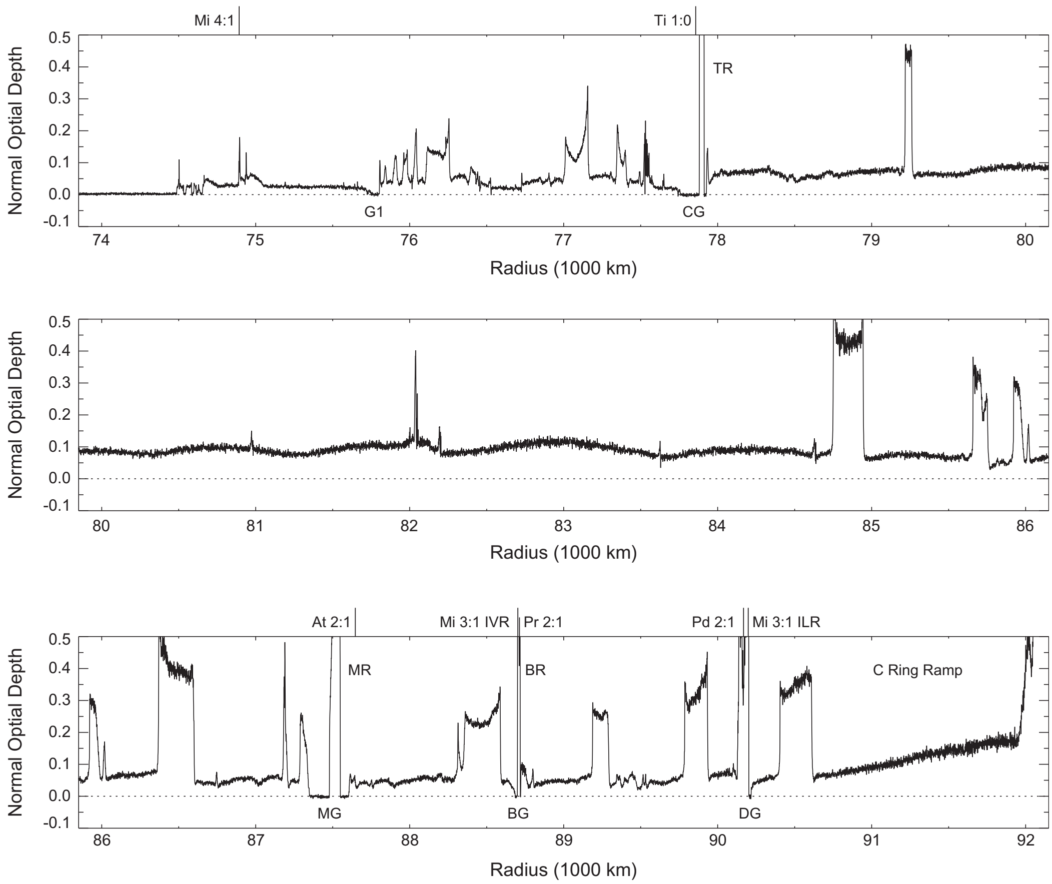

Fig. 1. An optical depth profile of the C ring, derived from the *Cassini* radio occultation on Rev 7. Abbreviations refer to the Titan ringlet (TR) and Colombo gap (CG), the Maxwell gap and ringlet (MG, MR), the Bond gap and ringlet (BG, BR) and Dawes gap (DG). Tick marks across the top of the plot indicate the locations of significant satellite resonances, with Ti = Titan, Mi = Mimas, At = Atlas, Pr = Prometheus and Pd = Pandora.

five significant gaps, four of which contain or are bordered by narrow, optically-thick ringlets (Colwell et al., 2009). Several of the gap edges and all of the associated ringlets are known to be noncircular, as first noted in studies of imaging and occultation data returned by the two *Voyager* spacecraft in 1980 and 1981. In some cases, the observed radial perturbations appear to be driven by resonances with external satellites, while in other instances, notably the Maxwell ringlet, the feature's eccentricity appears to be unforced and likely represents a natural state of dynamical equilibrium. An overall view of the C ring is provided in Fig. 1 (based on Fig. 13.21 in Colwell et al. (2009)) where we have identified the principal gaps and isolated ringlets that are the focus of this study.

Most prominent of the noncircular features are the informally-named Titan ringlet, which inhabits the Colombo gap at 77,880 km, and the Maxwell ringlet located within its eponymous gap at a radius of 87,510 km. Studies of these features by Esposito (1983) and Porco et al. (1984b) demonstrated that they are both well-described by keplerian ellipses, precessing under the influence of Saturn's zonal gravity harmonics. The Titan ringlet, however also happens to be located at a distance where the local apsidal precession rate matches the mean motion of Titan ($22.577^\circ\ d^{-1}$), and Porco et al. (1984b) concluded that its eccentricity is likely forced by this apsidal resonance.[1] This idea was further pursued by Nicholson and Porco (1988), who used the ringlet's eccentricity to place a constraint on Saturn's zonal gravity harmonics, notably J_6. The Maxwell ringlet, on the other hand, appears to be more akin to the narrow, freely-precessing Uranian rings, and is in fact similar in many of its characteristics to that planet's ϵ ring. Particularly notable are the large gradients in eccentricity across both rings, which are thought to approach the maximum sustainable value (Mosqueira, 1996). In both cases it was proposed that the ring's self-gravity acts to counteract the tendency to differential precession, which would quickly destroy such an eccentric ring if the particles' orbits were subject solely to the planet's gravity (Goldreich and Tremaine, 1979; Porco et al., 1984b). However, subsequent observational and theoretical studies have cast some doubt on this hypothesis, at least in its original form (Marouf et al., 1987; Borderies et al., 1988; Chiang and Goldreich, 2000; Mosqueira and Estrada, 2002).

Much less is known about the C ring's other noncircular features, primarily because their deviations from circularity are about an order of magnitude smaller, and near the limit detectable in *Voyager* data. Porco and Nicholson (1987) and Nicholson et al. (1990) studied the gaps and associated ringlets at $88,720$ km ($= 1.470\ R_S$) and at 90,200 km ($= 1.495\ R_S$) – since renamed the Bond and Dawes gaps, respectively. Each is associated with one of the strongest satellite resonances in the C ring: the inner edge of the Bond ringlet coincides with the Mimas 3:1 inner vertical resonance (IVR), while the inner edge of the Dawes gap (or the outer edge of the 1.495 R_S ringlet) coincides with the Mimas 3:1 inner Lindblad resonance (ILR). The situation is further complicated, however, by the presence of two other, only slightly weaker, resonances: the 2:1 ILRs due to the F ring shepherd satellites, Prometheus and Pandora. Porco and Nicholson (1987) found significant departures from circularity for both the Bond ringlet and the inner edge of the Dawes gap, the latter at the several km level, but were unable to demonstrate a clear connection with any of the four possible satellite resonances.

[1] This is in fact a special case of an inner Lindblad resonance (see Appendix A), and it is also referred to as the 1:0 ILR.