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Saturn's F Ring core: Calm in the midst of chaos

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ABSTRACT

The long-term stability of the narrow F Ring core has been hard to understand. Instead of acting as "shepherds", Prometheus and Pandora together stir the vast preponderance of the region into a chaotic state, consistent with the orbits of newly discovered objects like S/2004 S 6. We show how a comb of very narrow radial locations of high stability in semimajor axis is embedded within this otherwise chaotic region. The stability of these semimajor axes relies fundamentally on the unusual combination of rapid apse precession and long synodic period which characterizes the region. This situation allows stable "antiresonances" to fall on or very close to traditional Lindblad resonances which, under more common circumstances, are destabilizing. We present numerical integrations of tens of thousands of test particles over tens of thousands of Prometheus orbits that map out the effect. The stable antiresonance zones are *most* stable in a subset of the region where Prometheus first-order resonances are least cluttered by Pandora resonances. This region of optimum stability is paradoxically closer to Prometheus than a location more representative of "torque balance", helping explain a longstanding paradox. One stable zone corresponds closely to the currently observed semimajor axis of the F Ring core. Corotation resonance may also play a role. While the model helps explain the stability of the narrow F Ring core, it does not explain why the F Ring material all shares a common apse longitude; we speculate that collisional damping at the preferred semimajor axis (not included in the current simulations) may provide that final step. Essentially, we find that the F Ring core is not confined by a combination of Prometheus and Pandora, but a combination of Prometheus and precession.

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1. Introduction

Saturn's "kinky" F Ring has attributes which depend on the observing geometry and wavelength. Imaging observations best reveal its dramatic, spiky longitudinal structure, which depends on both time and longitude relative to Prometheus. The so-called "gap and streamer" structure has been explained by Prometheus perturbations (Murray et al., 2005, 2008; Chavez, 2009; Beurle et al., 2010). Evanescent outlier strands of a spiral nature, usually present and extending to hundreds of km from the core, are thought to result from ongoing collisions with crossing bodies (Charnoz et al., 2005). Images show that much of the F Ring particle area is in particles smaller than 100 μm (Showalter et al., 1992) with globally time-variable abundance (French et al., 2012). However, the spiky structure, "fans", and "mini-jets" (Beurle et al., 2010; Attree et al., 2012) also require some large but countable number of embedded bodies of sizes perhaps up to a km or so. Stellar occultations are, like the images, sensitive to particles larger than about a micron. They show the ring to have a narrow core with width of order 10 km, and reveal sporadic off-core clumpiness (Albers et al., 2012; Meinke et al., 2012). Radio occultations from Cassini and Voyager (sensitive to cm and larger size particles) reveal what must be the true core of the ring to be only about 100 meters wide, and azimuthally broken so that it is only seen on one-third of radio occultations (Marouf et al., 2010).

Application to the F Ring of the original "shepherding" concept (e.g. Goldreich and Tremaine, 1979) has a problem, in that the ring is not in torque balance between the putative shepherds

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(Showalter and Burns, 1982; henceforth SB82). However, when resonances are not overlapping, the ring could in principle find its support from an isolated resonance in some way, without being "in balance" between the two straddling ringmoons (see Section 4); what we will propose is in fact somewhat along these lines. Indeed the F Ring region is filled with a comb of resonances (Fig. 1). Because of the sizeable eccentricities of Prometheus and Pandora, second- (and higher-) order resonances have significant strength, especially close to the moons.

Noting the puzzle of the F Ring location and stability, Cuzzi and Burns (1988, CB88) suggested that the F Ring is not shepherded, but is only one of a series of transitory features arising from collisions between multiple km-size moonlets in a moonlet belt lying between Prometheus and Pandora. Scargle et al. (1993), in a preliminary version of the work presented here, presented a simple toy model for cyclic eccentricity variations, and orbital integrations showing large eccentricity fluctuations of objects throughout the region caused by repeated encounters with Prometheus and Pandora. They noted that the Chirikov criterion (Wisdom, 1980) for the radial width of a chaotic zone (say, surrounding Prometheus or Pandora) was an underestimate. Because of the significant eccentricities of Prometheus and Pandora, higher-*m* resonances with closer spacings than those found for circular perturbers play a role, overlap sooner, and yield chaotic zones which are considerably wider than predicted by the Chirikov criterion. They suggested that the entire region was chaotic. Winter et al. (2007, 2010) and Sfair et al. (2009) demonstrated this convincingly with detailed numerical integrations and analytical modeling.

Cassini has found a number of objects with plausibly chaotic properties, such as S/2004 S 6 (henceforth 2004S6) and similar objects; it is hard even to get an orbit for these objects (N. Cooper, personal communication, 2012) given observations spaced by months. Where do they come from? Their eccentricities (several times 10^{-3}) are much larger than assumed in the moonlet belt models of CB88, in which the ensemble eccentricities (a few times 10^{-4} at the F Ring) were assumed to be only due to single passage perturbations by Prometheus. Attree et al. (2012) postulated a comparably low eccentricity (about 10^{-4}) for objects *within* the

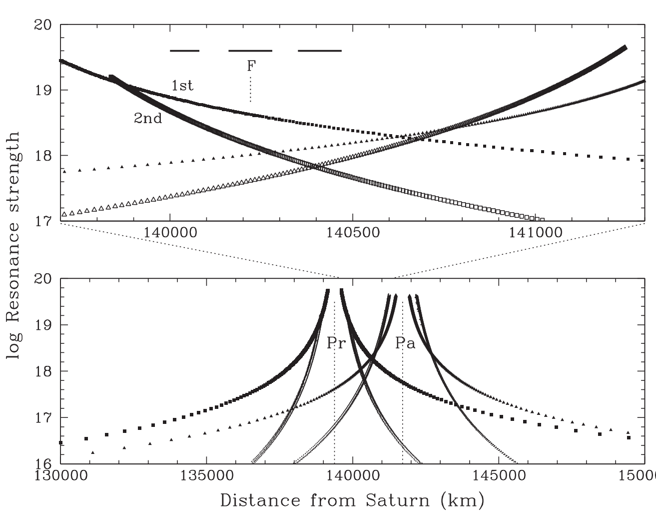

Fig. 1. An overview of the region surrounding Prometheus and Pandora (the broadly-defined "F Ring region"), showing first and second order Lindblad resonances with the two so-called "shepherds" (filled and open symbols respectively). The vertical dotted line at 140,220 km indicates the semimajor axis of the F Ring. The heavy horizontal bars indicate the three radial regions we have studied in detail (Section 3). Resonance location and strength calculations are described in Appendix A.

core, in the absence of strong damping, suggesting that damping between Prometheus encounters maintained their low values. Yet, it is not clear whether the large objects presumably observed by Attree et al. (2012) can be damped so quickly by the small particles making up the bulk of the F Ring, any more than 2004S6 is, which crosses the ring routinely. On the other hand, even a grazing Prometheus passage would only confer an eccentricity of about 5×10^{-4}. How then can we explain the large observed eccentricities for 2004S6 and its kin without cumulative, chaotic effects?

The observed presence of large eccentricities, and the theoretical results of Winter et al. (2007, 2010) suggest that chaotic behavior is pervasive. Indeed 2004S6 does seem to have violent collisional interactions with the F Ring core, which it crosses regularly. In 2008, a substantial segment was torn from the F Ring core, initially covering nearly 200 km in semimajor axis. The material spread in longitude by Keplerian shear and dispersed over a period of several years, with several apparently co-orbital clumps being its last-seen remnants (Murray et al., 2011; French et al., 2012). The very large clumps seen in the 1995–1996 ring plane crossing by McGhee et al. (2001) may be other examples of this rare phenomenon. These substantial bursts of material do not become new F Rings like the long-lived core, but disperse rapidly even while not very far away from the core.

In the presence of large perturbations even *away* from resonances, which lead to the chaotic behavior demonstrated by Winter et al. (2007), it is hard to understand how the narrow F Ring core can be preserved at essentially the *same* semimajor axis as seen during Voyager, precessing uniformly since then (Bosh et al., 2002; Murray et al., 2011; Marouf et al., 2010; Albers et al., 2012; Cooper et al., 2013). A connected puzzle is a strangely undistorted "pencil line" strand observed occasionally by Murray et al. (2008); see also Colwell et al. (2009). How does this strand avoid incurring the ubiquitous spiky structures produced when Prometheus is near apoapse (Murray et al., 2008, 2010; Beurle et al., 2010), and how does the F Ring core remain so calm and unperturbed in the global sense? That is, if large and dispersive perturbations *are* the rule, as suggested by our models and by Winter et al. (2007, 2010), and demonstrated by the 2008 strand, how does the F core itself, which contains numerous sizeable objects in addition to μm-sized dust, maintain its very stable orbit (Bosh et al., 2002; Marouf et al., 2010; Murray et al., 2011) and low relative velocities observed by Attree et al. (2012)?

We present in this paper the first part of an explanation for at least some of these puzzles: a novel "antiresonance" in which an unusual combination of orbital properties in the region causes semimajor axis perturbations from Prometheus on successive encounters to cancel, or nearly so, *at or near traditional Lindblad resonances*. Without this special situation, which provides *prompt cancellation* of successive Prometheus perturbations, the eccentricity of the embedded core moonlet population would inevitably grow to several times 10^{-3}, as seen for 2004S6 and other discrete objects. We believe that the F Ring core lies quietly where it does because its material has found one of a number of very narrow (< 1) km locations, with the roughly 8 km spacing of Prometheus first-order resonances, which are stable to chaotic dispersion because of this prompt cancellation.

In Section 2, we describe a "toy" physical model motivating the effect. In Section 3, we present extensive numerical integrations of tens of thousands of test particles, illustrating the effect. In Section 4, we discuss several implications, including the true nature of the F Ring core and the sporadic production of erratic ringmoons. In Section 5 we present our main conclusions and note future work. In Appendices A and B we give some background on resonances and our numerical code, respectively.