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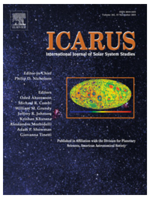

Evidence for dust-driven, radial plasma transport in Saturn's inner radiation belts

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ABSTRACT

A survey of Cassini MIMI/LEMMS data acquired between 2004 and 2015 has led to the identification of 13 energetic electron microsignatures that can be attributed to particle losses on one of the several faint rings of the planet. Most of the signatures were detected near L-shells that map between the orbits of Mimas and Enceladus or near the G-ring. Our analysis indicates that it is very unlikely for these signatures to have originated from absorption on Mimas, Enceladus or unidentified Moons and rings, even though most were not found exactly at the L-shells of the known rings of the saturnian system (G-ring, Methone, Anthe, Pallene). The lack of additional absorbers is apparent in the L-shell distribution of MeV ions which are very sensitive for tracing the location of weakly absorbing material permanently present in Saturn's radiation belts. This sensitivity is demonstrated by the identification, for the first time, of the proton absorption signatures from the asteroid-sized Moons Pallene, Anthe and/or their rings. For this reason, we investigate the possibility that the 13 energetic electron events formed at known saturnian rings and the resulting depletions were later displaced radially by one or more magnetospheric processes. Our calculations indicate that the displacement magnitude for several of those signatures is much larger than the one that can be attributed to radial flows imposed by the recently discovered noon-to-midnight electric field in Saturn's inner magnetosphere. This observation is consistent with a mechanism where radial plasma velocities are enhanced near dusty obstacles. Several possibilities are discussed that may explain this observation, including a dust-driven magnetospheric interchange instability, mass loading by the pick-up of nanometer charged dust grains and global magnetospheric electric fields induced by perturbed orbits of charged dust due to the act of solar radiation pressure. Indirect evidence for a global scale interaction between the magnetosphere and Saturn's faint rings that may drive such radial transport processes may also exist in previously reported measurements of plasma density by Cassini. Alternative explanations that do not involve enhanced plasma transport near the rings require the presence of a transient absorbing medium, such as E-ring clumps. Such clumps may form at the L-shell range where microsignatures have been observed due to resonances between charged dust and corotating magnetospheric structures, but remote imaging observations of the E-ring are not consistent with such a scenario.

1. Introduction

Saturn's radiation belts ($L > 2.2$, where L is the dipole L-shell) coexist with a complex system of Moons and faint rings that act primarily as energetic particle absorbers (sinks). The most common signatures of ring and Moon-magnetosphere interactions in the radiation belts are count-rate/flux dropouts recorded with energetic charged particle detectors at locations that map magnetically at or near these obstacles. Such signatures have been commonly used in order to infer the presence and the physical properties of previously unknown Moons, rings or ring arcs (Cuzzi and Burns, 1988; Hedman et al., 2007; Roussos et al., 2008a; Selesnick, 1993; Van Allen, 1982; 1983; 1987; Van Allen et al., 1980b). The same signatures are also excellent tools for tracing magnetospheric dynamics. For instance, the profile of flux dropout signatures from Saturn's icy Moons has been used to estimate how fast these particle depleted regions refill by magnetospheric diffusion (Carbary et al., 1983; Paranicas et al., 2005; Roussos et al., 2007; Van Allen et al., 1980a). Their observed location with

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respect to the known position of the absorbers is also indicative of non-corotational components in the convection of particles in the magnetosphere, which can be otherwise difficult to directly measure (Andriopoulou et al., 2014; 2012; Paranicas et al., 2010b; Roussos et al., 2010; 2005).

When we focus on the ring interaction signatures alone, we realize that despite the numerous events reported in the literature, there are still many unresolved issues regarding the way these features should be interpreted. One problem is that it is not always obvious whether flux dropout signatures are caused by rings or not. Chenette and Stone (1983) proposed that electron absorption signatures (microsignatures) detected by Voyager 1 at Mimas's distance originated by dust clouds that share a similar orbit with that Moon. Jones et al. (2008) suggested that a series of keV electron depletions close to Saturn's Moon Rhea could form due to absorption by large grains residing on an equatorial disk and a ring system within the Moon's Hill sphere. None of these results or similar ones (Vasundhara et al., 1984) were subsequently verified (Cheng et al., 1985; Roussos et al., 2012; Tiscareno et al., 2010). For instance, we now understand that absorption signatures, which follow the trajectories of the pre-depleted particles, may change L-shell as they drift around the planet (Andriopoulou et al., 2012; Roussos et al., 2007; 2005), something that may potentially be used to explain the Chenette and Stone (1983) observations as having a Mimas origin.

Adding to that, there are several cases of electron microsignatures that almost certainly originate from absorption by rings but still have unexplained aspects. For instance, the MeV electron absorption from an arc within Saturn's G-ring, observed post-periapsis on day 248/2005 and during a close arc flyby, was displaced outwards by more than 3000 km from its expected location (Hedman et al., 2007) despite its apparent, very recent formation. No signature was observed during the pre-periapsis segment although Cassini was at a location that mapped even closer to the arc's center. A microsignature from a ring arc at the orbit of the asteroid-sized Moon Methone appears also to have been rather rapidly displaced radially by almost 4800 km (Roussos et al., 2008a). Paranicas et al. (2010a) reports also an unexpected asymmetry in the location of the energetic electron depletion by Saturn's main rings. Such offsets appear too large given that the magnitude of non-corotational electric fields required to explain them should be greater than 0.5–1.0 mV m^{-1}), while on average values are well below that range (Andriopoulou et al., 2014; Thomsen et al., 2012; Wilson et al., 2013).

In this paper, we review a series of previously unpublished signatures recorded from Cassini's MIMI/LEMMS detector (Krimigis et al., 2004) that may result from interactions of rings with energetic particles, we put forward an organizing framework for the conflicting observations mentioned above and highlight the importance of such measurements with regards to magnetospheric and geophysical applications for the saturnian system. Unlike most papers mentioned in the introduction that investigated the interaction of dust with energetic particles, we will not treat the dust only as an absorbing or energy degrading medium for energetic charged particles. As dust grains have non-zero electric potentials (Kempf et al., 2006), we will also consider them as current carriers that may affect local electric fields and therefore the motion and the distribution energetic charged particles.

More specifically, after briefly introducing the dataset that we will analyse (Section 2), we provide an overview of how the use of energetic electron and ion observations can help locate planetary rings and trace their properties (Section 3). We argue that MeV ions are better tracers than energetic electrons for locating permanent, faint rings in the Saturnian system and in Section 4 we demonstrate this by identifying for the first time the signature of several of these rings in MeV ion measurements by Cassini. Since the ion signatures were found only at the known ring locations, we then propose that a series of energetic electron dropouts found displaced from these known ring positions were subjected to enhanced radial flows in the magnetosphere (to which energetic ions are not sensitive) (Section 5). In the final Section 6 we discuss a series of scenarios that may explain why such enhanced flows occur near planetary rings and propose alternatives that may explain the energetic electron observations, in case such flows do not exist.

2. Instrumentation

All data presented in this study are from Cassini's MIMI/LEMMS energetic charged particle detector (Krimigis et al., 2004). LEMMS has two telescopes separated by 180°, called the Low Energy and the High Energy Telescope (LET/HET respectively). Since the data we analyze are collected from the inner radiation belts, we use only the "rate" electron and proton channels of HET, and a few proton channels of LET, most of which have good efficiency in rejecting instrument penetrating energetic particles from their counters. A disadvantage of the rate electron channels is their moderate or poor energy resolution at the MeV range ($\Delta E/E > 1$). More specifically, electron rate channels used are E0-E7 (HET: $>$ 95 keV) and proton channels A6, A7 (1.1–2.4 MeV, LET) and P2-P8 (HET, 2.4–60 MeV). The lowest E-channels may also be contaminated to some extent by higher energy electrons, but can still be useful in cases penetrating radiation contamination is low. In addition, channel G1 (HET) is used for the detection MeV electron signatures which are outside the nominal field of view of LEMMS. G1 responds primarily to instrument penetrating MeV electrons and its effective field of view is very wide (Roussos et al., 2011). Data are used at the maximum time resolution (about 5 s) so as to detect short-lived absoprtion signatures in electrons that may come from Saturn's faint rings. Time or spatial averaging of the data is done where deemed necessary and is described in the text. The latest nominal passband information for LEMMS channels can be found in Krupp et al. (2009). Particle pitch angles are calculated using information on the LEMMS pointing and the magnetic field orientation from Cassini's magnetometer (MAG) (Dougherty et al., 2004).

3. Rings as energetic particle sinks

For the purposes of our analysis it is first essential to know at which locations energetic particles may be absorbed. Particle depletions are typically expected to be seen at the L-shells of known Moons or rings. Besides the L-shells of known, large Moons (Janus, Epimetheus and Mimas) there are four additional locations of interest between the distances of the F-ring and Enceladus: Pallene ($L = 3.52$), Anthe (3.28), Methone (3.23) and the G-ring and its arc (arc: 2.78–2.80, G-ring: 2.78–2.88). The first three Moons also have ringlets or ring arcs along their orbit. A 250-m Moon (S/2008 S1-Aegaeon) has also been discovered within the G-ring arc (Hedman et al., 2010). Energetic electron depletions have been observed at all the aforementioned L-shells except at the one of Pallene (see entries 2–4 in Table 1, introduced in Section 5). Most of these bodies reside within Saturn's E-ring and the inner neutral gas cloud that also act as energetic particle sinks. On the other hand, the latter structures are extended in L-shell and the spatial scales of any relevant particle losses will be much broader than those by the more localized sinks mentioned earlier.

A definite confirmation about the existence of a ringlet or a small Moon may only come from direct, remote sensing observations (e.g.. imaging) or in-situ sampling of dust. For the possibility that an absorber has not yet been detected by such observations, we should consider what is the most reliable method to successfully infer its presence using energetic charged particle observations. It is important to be confident that no other permanent