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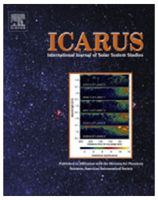

A noon-to-midnight electric field and nightside dynamics in Saturn's inner magnetosphere, using microsignature observations

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ABSTRACT

We have created a new, updated catalog of energetic electron microsignature events caused by the moons Tethys and Dione. We used electron data of the MIMI–LEMMS detector that is onboard the Cassini spacecraft, in the energy range 20–300 keV and for the period from July 2004 to January 2011. The present study looks at how the location of a moon's wake deviates from the nearly circular orbital path of the body. The radial deviation of the wake from the moon's orbit is a very sensitive tracer of plasma motion in the magnetosphere including its small radial components. The positions of the dropouts the spacecraft detects when it flies through the wakes, or microsignatures, cannot be explained in our study by asymmetric magnetic fields in the inner magnetosphere. Instead, we hypothesize a uniform electric field of around 0.11–0.18 mV/m within 4.4–7.0 R_s approximately, oriented roughly from noon to midnight, to explain the persistent radial offsets of the microsignatures from their expected positions. This corresponds to a radial speed that is at most a few percent of rigid corotation and therefore very difficult to measure by direct means. We additionally report a tendency for microsignatures with non-monotonic energy dispersion to have drifted across the post-midnight sector more than those with zero or monotonic energy dispersion.

1. Introduction

Energetic electron microsignatures are localized electron dropouts observed in the particle fluxes. They are mainly created by the icy satellites that absorb the incident charged particles and create a flux-depleted region that maintains its coherence as it moves in longitude and L-shell at the drifting rate of the missing particles (Van Allen et al., 1980; Paranicas and Cheng, 1997). If a spacecraft passes through this wake region it will then record a dropout, which we call a microsignature. The rings and other dust concentrations could also be causing microsignature events (Van Allen, 1982; Roussos et al., 2008). The microsignatures are located very close to the satellites' dipole L-shells, i.e. the equatorial distances of dipole field lines that map to the orbit of a saturnian moon. Their depth depends strongly on the longitudinal distance between the location of the absorbing body and the location that the microsignature is detected by the particle instrument on the spacecraft.

Electron microsignatures at Saturn and Jupiter have been already observed in the pre-Cassini era, using data from the particle detectors on Voyager 1 and 2, Pioneer 11 and Galileo spacecraft (Van Allen et al., 1980; Carbary et al., 1983; Randall, 1998). These findings have been extensively used in studies related to the deduction of the diffusion coefficients for the radial transport of trapped radiation (Simpson et al., 1974; Van Allen et al., 1980). Additionally, using a microsignature from the jovian moon Amalthea, Randall (1998) provided constraints to the models that describe Jupiter's magnetic field configuration. A microsignature model has been developed by Paranicas and Cheng (1997) with the assumption that the charged particles are transported by radial diffusion and longitudinal particle drifts. Determination of the radial diffusion coefficients in Saturn's inner magnetosphere has also been realized using microsignature data detected from the Cassini mission (Paranicas et al., 2005; Roussos et al., 2007).

A very interesting feature of the energetic electron microsignature events, on which this study is mainly focused, is their radial

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displacements from the orbital radius of the absorbing satellite (Paranicas et al., 2005; Roussos et al., 2005, 2007). Specifically, if we consider the dipole field approximation and a symmetric radially outward electric field, our expectation is that microsignatures will be encountered very close to the locations that map magnetically to the orbital path of the moon. Since we are generally considering very low eccentricity moons in this paper, we will simultaneously refer to these as circles of the moon's orbit or the moon's L-shell. In reality, the microsignatures appear to follow slightly different orbits as they can be detected either radially inward or outward with respect to the moon's L-shell. The degree of the displacement may also vary significantly for different electron energies (Roussos et al., 2010). So far, it is not certain what causes these displacements. One possible reason is the fact that the magnetic dipole field may be insufficient to describe the predicted location. If this is the case, then the displacements could be explained by using an appropriate magnetic field model and realizing field line tracing for the high-latitude microsignatures and/or calculating the drift shell splitting for non-equatorially mirroring particles observed at the equatorial plane. Another reason could be the existence of an unidentified electric field pattern that modifies the electrons' drift. A combination of these two reasons could also provide a possible explanation.

Considering typical microsignature displacements and ages in the order of a few hours near the orbits of Tethys and Dione (Roussos et al., 2007), the estimated radial velocities are of the order of 0.1 km/s for Tethys and 1 km/s for Dione. According to Wilson et al. (2009), the sensitivity of calculating radial velocities near 4 Saturn radii (R_s, 1 R_s = 60,268 km) using the data of the Cassini Plasma Spectrometer (CAPS) (Young et al., 2004) is $\sim$1 km/s under optimal conditions. The nominal rigid plasma corotation speed at that distance is about 40 km/s. Consequently, these electron microsignatures are the most sensitive tracers we have of small radial flows in the magnetosphere.

In this work we have analyzed microsignatures using electron data from the MIMI/LEMMS instrument (Krimigis et al., 2004) onboard the Cassini spacecraft. A large number of electron microsignature events caused by the Kronian icy satellites Tethys (L = 4.89) and Dione (L = 6.28) have been detected and cataloged. We have detected events in the energy range from 20 to 300 keV, during 144 orbits in the time period July 2004–January 2011.

A statistical analysis of the displacements of these microsignature events has been conducted, revealing some interesting microsignature properties, such as the presence of a noon-to-midnight electric field in Saturn's inner magnetosphere that seems to be necessary in order to explain observed radial shifts of the charged-particle orbits.

2. Energetic-particle drift motion

For the analysis of the microsignature events we assume that the drift motion of the energetic electrons follows the formulation described in Thomsen and Van Allen (1980). Minor modifications have been made to some constants, such as Saturn's radius (60,268 km instead of 60,000 km) and the equatorial dipole magnetic field (0.21 G instead of 0.20 G). This approach is a fairly good approximation for the part of the magnetosphere that has been studied here, $\sim$4.4–7.0 R_s. That is confirmed by the results of Birmingham (1982), (Fig. 3b of that paper), who calculated the particles' drift motion by using a dipole and a ring-current model.

According to the Thomsen and Van Allen (1980) approach, the energetic-particle drift is determined from the corotational angular velocity in the inner magnetosphere and from the magnetic gradient and curvature drifts that depend on the species, the energy, and the particle's pitch angle. For particles that have the same electric charge, the gradient and curvature drift have always the same direction. The corotational angular drift, on the other hand, has the same direction as the gradient and curvature drift for ions, but it has the opposite direction for electrons. Therefore, a transitional energy can be found for electrons, called the resonant energy, where the gradient and curvature drift cancel the corotational and the Keplerian moon motion. Electrons that move relative to a moon in a circular prograde orbit in the equatorial plane and at the same radial distance and have energies below the resonant energy will form a wake ahead of the moon in its orbital motion. Electrons with energies higher than the resonant energy will form a wake, trailing the moon in its orbital motion.

According to the results of Wilson et al. (2009) for the calculated azimuthal velocities in the magnetospheric region of our interest, the particles seem to be sub-corotating with 77–84% of the rigid rate. Taking these percentages into account, the resonant energy for electrons lies in the range 0.31–1.10 MeV near Tethys and 0.22–0.92 MeV near Dione. The first values correspond to 90° equatorial pitch angle, while the second values to particles with nearly field-aligned velocities. Due to light contamination we do not have many microsignature data for equatorial pitch angles. It is then reasonable to conclude that all the electron energy range of the current microsignature analysis (20–300 keV) is lower than the calculated resonant energies. Therefore, the angular separation of the moon from the microsignature is measured in the prograde sense.

We also note from Birmingham (1982) that non-dipolar drifts are less significant for non-equatorially mirroring particles. This further justifies the use of the simplified formulas of Thomsen and Van Allen (1980).

3. Description of the method and instrumentation

The MIMI instrument is onboard the Cassini spacecraft and consists of three main sensors that measure charged particles above the keV energy range (Krimigis et al., 2004). In this study we have used data only from one of these sensors, LEMMS. The Low-Energy Magnetospheric Measurement System (LEMMS) uses semiconductor detectors to measure ions in the energy range from approximately 20 keV to several tens of MeV and electrons from 20 keV to several MeVs.

LEMMS is mounted on a platform that rotated with an 86-s period for all the orbits before 2 February 2005, separating the data into 16 different pitch-angle sectors. For all the orbits after 2 February 2005 the instrument has not been rotating and it can only monitor pitch angles in a very narrow range but with a high-time resolution. Greater pitch-angle coverage can only be achieved in the non-rotating case when the spacecraft changes attitude.

In this analysis, the data of the MIMI/LEMMS detector from July 2004 to January 2011 have been used, from 144 orbits in total. We have detected and cataloged a number of microsignature events from the saturnian icy satellites Tethys and Dione.

This work is a continuation of the Roussos et al. (2007) study, using a larger number of microsignature events. In particular, we detected 149 events from Tethys, in comparison to 25 events and 59 events from Dione, in comparison to 13 events in previous works. For the present study, the energy range used is 20–300 keV and it is divided into 41 electron energy channels with the help of a pulse height analyzer (PHA), while Roussos et al. (2007) used the energy range 20–100 keV, divided into only five rate channels, but they also included observations in the MeV range. Since each microsignature can be split to its different energy components, statistical results may differ when these different energy elements are treated as separate events (more statistics) or when they are treated as part of a single event (less statistics).