Icarus 226 (2013) 1595–1611

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Numerical simulation of energetic electron microsignature drifts at Saturn: Methods and applications

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ARTICLE INFO

Article history:
Received 6 May 2013
Revised 20 August 2013
Accepted 21 August 2013
Available online 30 August 2013

Keywords:
Saturn, magnetosphere
Saturn, satellites
Magnetospheres

ABSTRACT

Many recent studies show that energetic electron microsignatures are a powerful tool for characterizing key aspects of Saturn's magnetospheric configuration and dynamics. In all previous investigations, however, analysis of these features was performed through the use of a series of simplifying assumptions (e.g. dipole field model). Furthermore, typical observable parameters of microsignatures (e.g. energy dependent location) have only been discussed qualitatively and a clear understanding about how microsignatures evolve in the magnetosphere is currently lacking. In this study we present a numerical simulation that we developed in order to describe the apparent motion of microsignatures in Saturn's magnetosphere, under the influence of arbitrary magnetic and electric field models. Our simulations reproduce successfully some typical microsignature properties (energy–time dispersion, high/low lifetime at low/high electron energies). They also indicate how simplifying assumptions used in analytical methods introduce several systematic errors. We demonstrate that, depending on the application and under certain conditions these errors can be neglected, like for instance for small pitch angles and at regions that the dipole approximation is sufficient (inside the orbit of Dione) or for electron energies below few hundred keV. For higher electron energies, systematic errors amplify significantly and existing analytical methods cannot be used. Our model can reconstruct the energy dependent position of microsignatures observed by the MIMI/LEMMS detector with high accuracy, allowing the inference of non-corotational flows (or electric fields) that can be as low as few tens of m s^{-1}. Since, however the calculation of such flows is indirect, the accuracy of such a determination can be reduced by more than an order of magnitude, if some of these free parameters involved in the simulation cannot be sufficiently constrained. One way to provide such constraints is through inputs (e.g. instantaneous plasma moments) from various Cassini instruments and updated magnetospheric field models. In that case, microsignature analysis may prove to be one of the best methods for attempting to measure or to at least constrain the magnitude of the very slow and global plasma outflow in Saturn's magnetosphere that is driven by mass loading at Enceladus.

1. Introduction

Energetic electron microsignatures are well established features that are commonly detected in Saturn's inner magnetosphere and have also been observed in the magnetospheres of all other outer planets (Van Allen et al., 1980; Carbary et al., 1983; Selesnick, 1993; Paranicas and Cheng, 1997; Paranicas et al., 2005; Roussos et al., 2005; Jones et al., 2006; Roussos et al., 2007; Andriopoulou et al., 2012). In essence, a microsignature is a short duration (up to several minutes) count rate or flux dropout recorded from a charged particle detector at a given energy range. The dropout may originate from the absorption of charged particles on moon surfaces or rings and its lifetime is limited by various magnetospheric processes (e.g. diffusion) that will eventually smooth this dropout away.

Observations show that electron microsignatures at energies above several keV in Saturn's magnetosphere are sustained for many hours after their formation. Due to these long lifetimes, microsignatures drift away from the local moon–magnetosphere interaction region, after which their apparent motion (Section 3.1) is determined only by magnetospheric electric and magnetic fields.

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0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.08.023

As a result, the location at which they are detected with respect to the (known) position that they formed are crucial parameters that can be used to define properties relevant to the dynamics, the structure and the state of the magnetosphere.

While many studies highlight the strength of using microsignatures to study planetary magnetospheres, analysis techniques applied so far may be sometimes limited due a series of assumptions or simplifications they include. For instance, Paranicas et al. (2005), Roussos et al. (2007) and Andriopoulou et al. (2012) used analytical expressions from Thomsen and Van Allen (1980) to calculate the ages of the microsignatures and their locations of origin, for the purpose of their analysis. These expressions are constructed for a corotating, dipolar magnetosphere. The actual field starts to deviate from a simple dipole model beyond a dipole L-shell (L) of 5 (Birmingham, 1982). These deviations may be considered insignificant for certain applications, but could be important for models that aim to reconstruct microsignature positions in order to extract information about their drift pattern in the magnetosphere. Such a reconstruction should be done with an accuracy better than 0.05–0.1R_S. Besides that, the equations in that model do not account for the influence of non-corotational electric fields (Andriopoulou et al., 2012). The latter may dominate the motion of electrons at high energies (between few hundred keV and several MeV) where corotation tends to be canceled by the opposing gradient and curvature drift of the electrons (Cooper et al., 1998). The work of Randall (1994) for Jupiter's magnetosphere was also done under the assumption that the location of the microsignature by the moon Amalthea was only determined by the strength of corotation and the structure of the magnetospheric field, neglecting the possibility that additional electric field components may influence the observations (Barbosa and Kivelson, 1983). Finally, several fundamental aspects about microsignature observations, such as the energy dependence in their location (Andriopoulou et al., 2012; Roussos et al., 2010) or their faster apparent refilling rate at high energies (Roussos et al., 2007), have so far been discussed only qualitatively and are not well understood.

In the present study we will use a numerical model for microsignatures that bypasses many of the aforementioned simplifying assumptions. The aim is to describe the apparent motion of microsignatures under the influence of arbitrary electric and magnetic field models, explain some of their typical observable parameters (e.g. energy dependent location),understand under which conditions several assumptions of the previous studies are acceptable or not and demonstrate how the numerical approach can help us acquire electric field measurements with very high accuracy. Results and predictions of our model will be compared with microsignature observations by Cassini.

2. Data

All microsignature data presented here are from Cassini's MIMI/LEMMS sensor. MIMI stands for Magnetospheric Imaging Instrument and LEMMS for Low Energy Magnetospheric Measurement System. LEMMS is the energetic charged particle detector of the MIMI suite and can measure the energy, flux and pitch angle of incoming electrons and ions through two oppositely pointing telescopes, the Low and the High Energy Telescope (LET and HET respectively) (Krimigis et al., 2004). The latest calibration information for LEMMS is available in Krupp et al. (2009).

In this study we use data mostly from LEMMS's Pulse Height Analysis (PHA) electron channels that belong to the LET. They achieve an energy resolution ($\Delta E/E$) between 0.06 and 0.07 for the energy range of 25 keV and 1.6 MeV. This high energy resolution allows to assume with a good certainty that the response function of each channel is uniform within its energy range. A microsignature from the PHA channels is shown in the top panel of Fig. 1.

PHA electron channels are only responding up to 1.6 MeV and their geometric factor is one order of magnitude lower from that of the rate channels of the HET (e.g. E3–E7) at high energies. The rate channels of LEMMS are low-energy resolution channels. Rate channels monitoring electrons close to 1 MeV or higher have $\Delta E/E$ comparable to or greater than unity. Because of their high geometry factor they are better equipped than the PHA channels for resolving microsignatures at those energies (Roussos et al., 2007) (Fig. 1, bottom), where fluxes are typically low. On the other hand, their broad and complex energy response makes interpretation of that signal difficult. Simulating microsignatures for those channels will be briefly discussed here.

The PHA channels have lower time resolution than the rate channels, but both can achieve a sampling every few seconds, which is sufficient to resolve a microsignature. Particle pitch angles are calculated using information from Cassini's magnetometer (MAG) (Dougherty et al., 2004).

3. Microsignatures and the numerical simulation code

In this section we will describe the model that we developed to analyze energetic electron microsignatures. Before doing so, we believe it is essential for the completeness of this study to list a few basic introductory facts about microsignatures. Many more details can be found in the papers cited in Section 1.

3.1. Microsignature basics

As mentioned in Section 1, electron microsignatures at Saturn typically form due to the loss of those particles on an icy moon that orbits the planet. Since the ambient electrons of a given energy and pitch angle that surround the microsignature continue to drift with zero relative velocity, the enclosed depleted region appears to move in the sense of these ambient electrons. For that reason, the location of a microsignature at a given pitch angle and energy can be used to track the drift trajectories of electrons with similar properties in the magnetosphere.

Saturn's large moons that cause the majority of the reported microsignatures are from the Janus/Epimetheus pair ($L \sim 2.5$), Mimas ($L \sim 3.1$), Enceladus ($L \sim 3.95$), Tethys ($L \sim 4.89$), Dione ($L \sim 6.28$) and Rhea ($L \sim 8.74$). Excluding the three innermost moons, all others have nearly circular and equatorial orbits. Due to the almost perfect alignment of the magnetic and the rotational axes at Saturn these moons can be assigned to a unique value of a dipole L-shell.

For the approximation where only a dipole field and azimuthal corotation are considered (Thomsen and Van Allen, 1980), the bounce-averaged drift trajectory of microsignatures forms a circle, nearly identical to a moon's orbit. Due to the rapid bounce motion of energetic electrons, the absorption effects of a microsignature can be observed at very high latitudes, not just in the equatorial magnetosphere.

Deviations from the assumptions of this simplified dipole/corotation model are the sources of the so-called "microsignature displacements": these are offsets of the observed microsignature L-shell with respect to a moon's L-shell (δL). As Andriopoulou et al. (2012) explains, non-corotational electric fields and/or non-dipolar magnetic field configurations can explain why such displacements exist, but so far these two possibilities were never considered simultaneously in order to explain the observations, as discussed earlier.

In the Thomsen and Van Allen (1980) model the drift speed of electrons depends on energy, pitch angle and the strength of