Icarus 258 (2015) 402–417

Contents lists available at ScienceDirect

Icarus

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

Modeling of the energetic ion observations in the vicinity of Rhea and Dione

Anna Kotova [a,b,*], Elias Roussos [a], Norbert Krupp [a], Iannis Dandouras [b,c]

[a] Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, Göttingen 37077, Germany
[b] Université Paul Sabatier Toulouse III, Toulouse, France
[c] Institut de Recherche en Astrophysique et Planétologie (IRAP), CNRS, Toulouse, France

ARTICLE INFO

Article history:
Received 24 October 2014
Revised 21 May 2015
Accepted 20 June 2015
Available online 29 June 2015

Keywords:
Saturn, magnetosphere
Saturn, satellites

ABSTRACT

During several flybys of the Cassini spacecraft by the saturnian moons Rhea and Dione the energetic particle detector MIMI/LEMMS measured a significant reduction of energetic ion fluxes (20–300 keV) in their vicinity, which is caused by the absorption of those ions at the moon surfaces.

In order to simulate the observed depletion profiles we developed an energetic particle tracer, which can be used to simulate the charged particle trajectories considering different models of the saturnian magnetosphere. This particle tracer is using an adaptive fourth order Gauss Runge–Kutta calculation method and its background magnetospheric model can be varied from that of a simple dipole, to a more complex one that includes also non-dipolar perturbations. The electromagnetic environment of each local, moon–magnetosphere interaction region is modeled through a hybrid plasma simulation code. Using this energetic particle tracer we explore which of these magnetospheric characteristics are more important in shaping the MIMI/LEMMS ion profiles. We also examine if MIMI/LEMMS responds primarily to protons (as typically assumed in many studies) or also to heavier ions, using calibration information, observations of the energy flux spectrum by the MIMI/CHEMS instrument (on board of Cassini as well) and different simulation results.

Our results show that MIMI/LEMMS indeed measures heavier ions as well. Also we discovered that wrapping of magnetic field lines, even if it caused local perturbations only about few percent of the background magnetic field, can cause measurable changes in the spatial and energy distribution of fluxes measured by MIMI/LEMMS. These results are important for correct interpretation of MIMI/LEMMS data, and offer capabilities for a precise in-flight instruments' cross-calibration. Besides that, our simulation approach can be employed in similar environments (Titan, Enceladus, jovian moons, etc.) for constraining the magnetic topology of their interaction region and for identifying the composition and charge-states of ions at high energies, where capabilities of the available or future instruments can be limited.

1. Introduction

During several flybys of the saturnian icy moons Rhea and Dione MIMI/LEMMS detected a significant depletion of energetic ion differential fluxes (from now on we refer to as "fluxes"). Previous studies that reviewed MIMI data from those flybys focused mainly on the energetic electron observations by MIMI/LEMMS (Krupp et al., 2009; Roussos et al., 2012). Energetic ion observations were briefly discussed for the Dione flybys by Krupp et al. (2013), where they noted a reduction of ion fluxes with an energy dependent location near that moon. Using simplified calculations they proposed that in principle the depletion can be explained on the basis of proton absorption at Dione's surface, with the energy dependence reflecting the varying proton gyroradius with energy. What those calculations fail to show, however, is whether the details of the background magnetospheric model, the local electric and magnetic field perturbations near a moon, or instrument specific parameters, such as response to heavier ions or charged states and instrument pointing, play a role in shaping such depletion profiles. While Cassini has the necessary instrumentation to describe several of these effects or parameters with direct measurements (e.g. from MIMI/CHEMS), it is important to demonstrate whether the latter can be alternatively constrained by these indirect measurements of energetic ion losses.

The current study is devoted to the analysis of these energetic ion flux depletions and to the identification of processes responsible for them through the simulation of the MIMI/LEMMS signal.

* Corresponding author at: Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, Göttingen 37077, Germany.

http://dx.doi.org/10.1016/j.icarus.2015.06.031
0019-1035/

There are several practical aspects which make such an investigation useful and necessary. For instance analysis of the shape of these "flyby signatures" can reveal information about the topology of the magnetic field near the moon and act as an "in-flight calibration" experiment for instruments. For instance, Selesnick and Cohen (2009) simulate similar MeV ion flux depletions near Jupiter's moon Io as these can reveal information about the charge state of these ions, and properties of the Alfven wing type of perturbation downstream of that moon. Should this technique prove to be sensitive to all these magnetospheric and local environment parameters, it can be used to constrain properties of more complex environments, such as Enceladus and Titan, or Ganymede's mini-magnetosphere which will be visited by the JUICE mission in the future.

In order to study the aforementioned energetic ion flux depletions we developed a charge particle tracer, which simulates the trajectories of energetic charged particles in the vicinity of the moons and reconstruct measurements obtained by the MIMI/LEMMS. The comparison of the simulations with the MIMI/LEMMS observations allows to infer the significance of the different factors that shape the energetic ion flux profiles.

2. Cassini's flybys by the moons Rhea and Dione

Cassini arrived to Saturn in 2004 and during the last ten years has been continuously exploring this planet, its magnetosphere and numerous moons. Among other instruments on board of Cassini there is the Magnetospheric Imaging Instrument (MIMI), which is designed to measure the composition, charge state and energy distribution of energetic ions and electrons, detect fast neutral particles and conduct remote imaging of Saturn's magnetosphere. This instrument has three sensors that perform various measurements, two of which are used in our study:

- Low-Energy Magnetospheric Measurement System (LEMMS), which measures the distribution of energetic ion and electron fluxes by a double-ended telescope: the Low Energy End for detection of 27 keV–18 MeV ions and 15 keV–0.884 MeV electrons and the High Energy End for measurements of high-energy ions (1.6–160 MeV) and electrons (>100 keV), with a high time resolution (typically about 5 s).
- CHarge-Energy-Mass Spectrometer (CHEMS), which measures the flux spectrum, charge state and composition of ions from ~3 to 220 keV/e, but with much lower time resolution in comparison to the LEMMS.

Detailed description of these instruments and their operating principles can be found in Krimigis et al. (2004).

In total Cassini performed five (four targeted) flybys by Saturn's icy moon Rhea and three flybys by moon Dione. Table 1 summarizes the general information about these flybys and in Fig. 1 (adopted from Roussos et al. (2012)) the trajectories of the Cassini spacecraft during Rhea and Dione flybys can be seen. Detailed description of these flybys can be found respectively in Roussos et al. (2012) and Krupp et al. (2013).

During two of the Rhea flybys (R2 and R3) and one Dione's flyby (D1) the LEMMS detected significant reductions in energetic ion fluxes. In Fig. 2 the LEMMS data during these three flybys are shown. Different line colors represent different channels: A0–A4 for energetic ions and C0 for energetic electrons, which is included in these plots for comparison between depletions in electron flux and ion flux. The energy ranges for these channels are indicated on the plot legends (for the A0–A4 channels the energy ranges are those for the proton response). The higher energy A-channels were on background, so they are not shown. Closest approach (CA) of the spacecraft to the moon is marked by the vertical dashed line (as can be verified in Table 1 as well), and it can also be effectively recognized by the center of the electron flux depletion. The

Table 1
Rhea and Dione flybys orbital information.

Number	Date	Orbit NN	DOY	CA time	CA distance (km)
Rhea					
R4	9 March 2013	183	68	10:17	997
R3	11 January 2011	143	11	04:53	75.9
R2	2 March 2010	127	61	17:32	100.9
R1.5	30 August 2007	49	242	01:22	5737
R1	26 November 2005	18	330	22:37	500
Dione					
D3	12 December 2011	158	346	09:48	99
D2	7 April 2010	129	107	05:16	503
D1	11 October 2005	16	284	17:52	1000

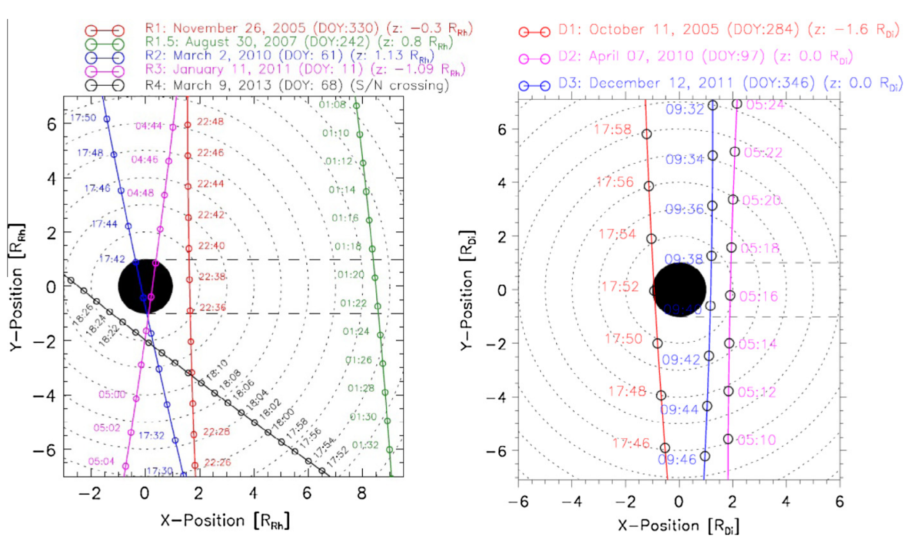

Fig. 1. Equatorial projections of Cassini's trajectories during Rhea (on the left panel) and Dione (on the right panel) flybys. On the both plots the corresponding moon is located in center, the positive y-axis points towards Saturn and the positive x-axis shows the plasma nominal corotation direction. Every two minutes there are tick marks and every moon's radius is shown with dotted circles. The dashed lines show the expected location of the corotational wake (adopted from Roussos et al. (2012)).