Energetic particle tracking techniques and its application to the magnetosphere of Saturn
Anna Kotova

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Anna KOTOVA

Techniques de calcul du transport de particules chargées de haute énergie et leur application à la magnétosphère de Saturne

JURY
M. MICHEL BLANC Astronome Président du Jury
M. DOMINIQUE Directeur de Recherche - Rapporteur
DELCOURT CNRS
M. GERAINTE JONES Directeur de Recherche - Rapporteur
MSSL/UCL
MME ANNA MILILLO Directeur de Recherche - Examinateur
INAF/IAPS
M. THEODORE SARRIS Professeur - DUTH Examinateur
M. IANNIS Directeur de Recherche - Directeur de thèse
DANDOURAS CNRS
M. NORBERT KRUPP Directeur de Recherche - Co-directeur de thèse
MPI
M. ELIAS ROUSSOS Chargé de Recherche - MPI Co-directeur de thèse

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Unité de Recherche :
Institut de Recherche en Astrophysique et Planétologie (UMR 5277)

Directeur(s) de Thèse :
Iannis DANDOURAS, Norbert KRUPP et Elias ROUSSOS

Rapporteurs :
Dominique DELCOURT et Geraint JONES
Abstract

The MeV proton radiation belts of Saturn are isolated from the middle and outer magnetosphere and the source of these high energy protons should be related to the access of Galactic Cosmic Rays (GCRs) in the system. To validate this hypothesis it is first of all necessary to determine the realistic spectrum of GCRs at Saturn. Previously only theoretical attempts were performed in order to calculate the GCR spectra. In this thesis I provide for the first time the numerical solution for the determination of the GCR access to the upper atmosphere and rings of Saturn. The proposed method is based on the charged particle tracing technique and a code that was developed specifically for this purpose. For the validation of the code, the Cassini MIMI/LEMMS observations during the Rhea and Dione flybys were modeled using the tracer and the obtained results were compared to the observations. It was demonstrated that even a weak perturbation of the magnetic field lines can produce measurable changes in the spatial and energy distribution of fluxes measured by MIMI/LEMMS that can be accurately simulated by particle tracing. These results are important for the correct interpretation of the MIMI/LEMMS data, and offer capabilities for a precise in-flight instruments’ cross-calibration besides the validation of our simulation code. After this validation the particle tracer was applied for simulating the access of the GCRs. The GCRs access to the rings and atmosphere was obtained, the GCRs spectra were reconstructed and were in part also validated using additional Cassini observations. Dependencies of the spectral parameters on the time, incidence direction, etc., were also obtained offering all necessary information for simulating the interaction of GCRs with the Saturnian system during different phases of the Cassini mission. That includes also the Proximal orbits of 2017, during which Cassini will sample for the first time the radiation belts inside the D-ring of the planet, a region which is likely populated only by GCR secondaries.
Résumé

Dans la magnétosphère de Saturne les ceintures de radiation des protons de haute énergie (de l’ordre de quelques MeV) s’avèrent être isolées de la magnétosphère moyenne et externe, et la source de ces protons de haute énergie devrait être liée aux rayons cosmiques galactiques (GCR). Pour valider cette hypothèse il est d’abord nécessaire de déterminer le flux de GCR accédant à Saturne de manière réaliste. Auparavant, seulement des tentatives théoriques ont été effectuées afin de vérifier cette idée. Dans cette thèse, pour la première fois une solution numérique est développée pour la détermination de l’accès des GCR à l’atmosphère et aux anneaux de Saturne. La méthode proposée est basée sur le traçage de particules chargées et un code numérique a été développé spécifiquement pour la magnétosphère de Saturne. Lors de la validation de la méthode les observations de Cassini MIMI / LEMMS, acquises pendant les survols de Rhéa et de Dioné, ont été modélisées à l’aide du traceur et les résultats obtenus ont été comparés aux observations. Il a été découvert que le Âń draping Âż des lignes de champ magnétique autour de ces satellites de glace, même s’il produit des perturbations locales de seulement quelques pour cent du champ magnétique ambien, peut produire des changements mesurables dans la distribution spatiale et en énergie des flux des ions énergétiques mesurés par MIMI / LEMMS. Ces résultats sont importants pour l’interprétation correcte des données MIMI / LEMMS et offrent des fonctionnalités pour l’étalonnage croisé précisé en vol des instruments. Après cette validation du traceur de particules il a été appliqué pour calcul à rebours dans le temps des GCR accédant à Saturne. L’énergie d’accès des GCR a été obtenue, les spectres des GCR ont été reconstruits et le flux intégré des GCR autour de Saturne et de ses anneaux a été calculé. Les résultats obtenus sont essentiels pour la compréhension de la formation des ceintures de radiation de protons, ainsi que pour la future investigation du processus CRAND sur Saturne, pour l’évaluation de l’intensité de la ceinture de radiation intérieure et pour d’autres projets, discutés dans cette thèse.
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Introduction

The inner part of a planetary magnetosphere is a critical region, where multiple populations coexist and interact (Van Allen radiation belts, plasma and neutral gas, icy satellites, ring particles, cosmic rays) and where the underlying physical mechanisms and their relative roles are not well understood. Studying the energetic charged particle distributions and dynamics in the inner magnetosphere is thus fundamental. The Cassini spacecraft is in orbit around Saturn since 2004 and is equipped with a great set of instruments for magnetospheric science. This provides a unique opportunity to study in detail energetic particles in the magnetosphere of Saturn as never before.

The presence of energetic charged particles is observed by Cassini in most of the regions of the Saturnian magnetosphere, but most of them are trapped in the radiation belts. Because of numerous moons and rings, the Saturnian radiation belts have a unique layered structure with a sharp and stable proton flux depletions on the L-shells of the rings and the moons Janus and Epimetheus, Mimas, and Enceladus, isolating the radiation belts from the middle and outer magnetosphere, since these moons and rings effectively absorb the diffusing radially inward particles. Consequently the origin of the MeV protons trapped in the inner part of radiation belts, between the planet and the rings, is unknown today. One of the considered mechanisms is the Cosmic Rays Albedo Neutron Decay (CRAND). In order to verify this hypothesis it is necessary first of all to determine the Galactic Cosmic Rays (GCRs) access to Saturn and its rings. Previous attempts to resolve this task were based on the analytical calculation of the GCRs access energy, providing uncertain results, because the dipole magnetic field model was taken and only vertical access was evaluated, what can be used only as a first approximation. An alternative is a careful numerical calculation on the basis of charged particle tracing of GCRs.

This thesis is devoted to the investigation of the charged particle tracing techniques in order to address this problem, and to the development of a suitable tracer used to evaluate the GCR access to the Saturnian system based on the test-particle approach. With this goal I developed relevant simulation code, which was fully adapted for the magnetosphere of Saturn, adjusted for comparison with data from several Cassini instruments and interconnected with other modeling tools for the planetary environment. The particle tracer can be also applied to address various other questions in the study of planetary magnetospheres, where the trajectories of energetic particles plays an important role.

In order to validate the tracing code it was necessary to apply it first to a straight-
forward problem, where the results of the simulation could be directly compared with the in-situ observations and therefore verified. The simulation of the signal from the Cassini Low Energy Magnetospheric Measurements System (LEMMS) during some of the icy-moons flybys was a perfectly suitable problem. Knowing the configuration of the detector and the electromagnetic environment, from measurements by other Cassini instruments, it was possible to simulate the trajectories of energetic particles backwards from the detector and to determine the path of the particles before they encounter the LEMMS detector. Having the energetic particle depletions in the LEMMS observations, caused by plasma absorption by Rhea and Dione, it was interesting to model these depletions and interpret their shape. This work not only validated the particle tracer but also showed the influence on the dynamics of the system of the heavy energetic ions \( (O^+, OH^+, H_2O^+) \), as well as of the disturbances of the electric and magnetic fields in the immediate vicinity of each moon.

After the successful validation of the particle tracer in reproducing the Rhea and Dione absorption signatures the simulation of the GCRs motion in the magnetosphere of Saturn was performed. For that purpose the particle tracer was adapted to trace a high number of relativistic particles. The new calculation methods were based on the Boris scheme and the Vay method Vay (2008). The code was parallelized and adapted for running on high-performance machines. As a result the minimum GCR access energy was obtained, using different magnetospheric models. The dependence of the access energy on the latitude and longitude of the point and on the direction of arrival on the planet was analyzed. A clear East-West asymmetry in the minimum access energy was confirmed and the dependence of the minimum arriving energy on the Saturnian season and on the composition of the GCRs was obtained. The advantages of the particle tracer approach used here over analytical solutions, e.g. based on the Stoermer’s theory (Störmer, 1955), were demonstrated. Using these simulation results the real GCR flux onto the planet and throughout the magnetosphere was estimated. The final results were in part validated by comparison of the results with indirect LEMMS measurements of the GCRs acquired during the Saturn Orbit Insertion (SOI).

The results, which I present in this thesis, create the foundation for a wide range of studies, which involve the GCR impact on the Saturnian system. These new research opportunities include the evolution of the radiation belts, prediction of the innermost radiation belts intensity, estimation of the Saturnian rings thickness, among others.

This thesis is composed of seven chapters.

In Chapter 1 I introduce the concept of planetary magnetospheres and mention key dynamical processes related to energetic particles.

Chapter 2 is focused on the energetic charged particles in the magnetosphere of Saturn. Here I explain why they are of a special scientific interest and why the test-particle approach is suitable for studying their motion. I introduce the CRAND process and show how it can be studied using the numerical methods.
Chapter 3 is devoted to the description of the numerical methods for particle tracing and the particle tracing code I developed.

In Chapter 4 I describe the Cassini mission to Saturn and give a short overview of the Cassini instruments, whose data were used in this thesis. I also discuss the orbital coverage by Cassini during the past 12 years at Saturn and describe the planned orbits until the end of the mission in 2017.

In Chapter 5 I present the simulation of the MIMI/LEMMS observations during Rhea and Dione flybys used for validation of the particle tracing code and for understanding the moon environment and their interaction region.

Chapter 6 is devoted to the study of the GRC access to the Saturnian system. I describe the particular realization of the GCR tracing in the magnetosphere of Saturn and present the results together with comparison of indirect GCR measurements by Cassini.

In the final Chapter 7 I discuss the research opportunities that arise from my results, presented in previous chapters, and how else the developed particle tracer could be used.
Introduction Générale

La partie interne d’une magnétosphère planétaire est une région critique, où plusieurs populations coexistent et interagissent (ceintures de radiations, plasmas et gaz neutres, rayons cosmiques, et dans certains cas, satellites de glace, particules des anneaux) et où les mécanismes physiques sous-jacents et leurs rôles relatifs sont mal connus. L’étude de la distribution des particules énergétiques chargées et la dynamique de la magnétosphère interne est ainsi d’une grande importance. Dans cette thèse, nous nous intéressons à celle de Saturne. La sonde Cassini est en orbite autour de Saturne depuis 2004 et est équipée d’un ensemble important d’instruments dédiés à la science de la magnétosphère. Ceci fournit une occasion unique pour étudier les particules énergétiques dans la magnétosphère de Saturne avec une précision inégalée.

La présence de particules énergétiques chargées est observée par Cassini dans la plupart des régions de la magnétosphère de Saturne, mais la plupart d’entre elles sont piégées dans les ceintures de radiations. En raison de la présence des nombreuses lunes et anneaux, les ceintures de radiation Kroniennes ont une structure en couches multiples et présentent des fortes décroissances des flux de particules sur les coquilles-L correspondant aux lunes et aux anneaux. Il en résulte un isolement des ceintures de radiation de la magnétosphère moyenne et externe, étant donné que ces lunes et anneaux absorbent efficacement la diffusion radiale des particules vers l’intérieur. Par conséquent, l’origine des protons d’une énergie de l’ordre du MeV, piégés dans la partie intérieure des ceintures de radiations, est aujourd’hui inconnue. L’un des mécanismes considérés est le ”CRAND” (”Cosmic Rays Albedo Neutron Decay”). Afin de vérifier cette hypothèse, il est nécessaire tout d’abord de déterminer le flux des rayons cosmiques galactiques (GCR) arrivant à Saturne et à ses anneaux. Les tentatives précédentes pour résoudre ce problème étaient basées sur le calcul analytique de l’énergie d’accès des GCR, fournissant des résultats incertains. Une alternative est un calcul numérique à rebours dans le temps des GCR.

Cette thèse est consacrée à l’étude des techniques de traçage de particules chargées et au développement d’un traceur approprié afin d’évaluer l’accès des GCR au système saturnien en utilisant l’approche de particules-test. Avec cet objectif, j’ai développé un tout nouveau code de traçage de particules. Il est adapté aux simulations dans la magnétosphère de Saturne et est ajusté pour la comparaison de ses résultats avec les données fournies par plusieurs instruments à bord de Cassini. Il est aussi interconnecté avec d’autres outils de modélisation pour la magnétosphère de Saturne. Le traceur de particules développé peut aussi être appliqué pour étudier diverses questions liées à l’étude des magnétosphères planétaires, où la position exacte des particules...
énergie joue un rôle.

Afin de valider le code de traçage développé avant de procéder à son utilisation pour l’étude des GCR, il était nécessaire de l’appliquer d’abord sur un problème clair et simple, où les résultats de la simulation pourraient être directement comparés avec les observations in-situ et donc vérifiés. La simulation des données de l’instrument LEMMS (Low Energy Magnetospheric Measurements System) à bord de Cassini, acquises lors des survols des lunes de glace, était un problème tout à fait approprié. Connaissant la configuration du détecteur et l’environnement électromagnétique, à partir des mesures d’autres instruments à bord de Cassini, il était possible de simuler les trajectoires des particules énergétiques, à partir du détecteur et vers l’arrière, afin de déterminer les trajectoires de particules avant qu’elles ne rencontrent LEMMS. Les fortes décroissances des flux des ions énergétiques, observées par LEMMS et liées à l’absorption de ces ions par les lunes Rhéa et Dione, offraient l’étalon de comparaison pour le signal issu du code de simulation de trajectoires développé. Ce travail a non seulement permis de valider ce nouveau code de traçage, mais il a aussi mis en évidence le rôle des ions énergétiques lourds ($O^+$, $OH^+$, $H_2O^+$) dans la dynamique du système, ainsi que le rôle des perturbations des champs électriques et magnétiques près de ces lunes.

Après la validation réussie du traceur, avec la reproduction des signatures d’absorption observées près de Rhéa et de Dione, la simulation du mouvement des GCR dans la magnétosphère de Saturne a pu être réalisée. A cette fin, le traceur des particules a été considérablement remodelé et adapté pour tracer un grand nombre de particules relativistes. Les nouvelles méthodes de calcul étaient basées sur le système de Boris et la méthode de Vay (Vay, 2008). Le code a été parallélisé et adapté pour le faire fonctionner sur des machines de calcul hautes performances. Parmi les résultats obtenus, l’énergie minimale d’accès des GCR a été obtenue, en utilisant différents modèles du champ magnétique de la magnétosphère de Saturne. La dépendance de l’énergie d’accès en fonction de la latitude et de la longitude du point, et en fonction de la direction d’arrivée sur la planète, a été ensuite analysée. Une nette asymétrie Est-Ouest dans l’énergie d’accès minimum a été confirmée et la dépendance saisonnière de l’énergie minimale arrivant à Saturne, ainsi que la dépendance de la composition chimique des GCR, ont été obtenues. Les avantages de l’approche du traceur de particules par rapport aux solutions analytiques comme celles basées sur la théorie de Stoermer (Stömer, 1955) ont été démontrées. L’utilisation de ces simulations fournit le flux réel des GCR sur la planète et tout au long de la magnétosphère. Le résultat final a été validé par comparaison avec les mesures de LEMMS des rayons cosmiques de fond réalisées pendant l’insertion en orbite autour de Saturne (”SOI”), lorsque la sonde Cassini a effectué une série de manoeuvres au-dessus des anneaux.

Les résultats que je présente dans cette thèse fournissent un socle et ouvrent la voie pour un large éventail d’études qui impliquent l’impact des GCR sur le système saturnien. Les possibilités de recherche ainsi ouvertes comprennent l’évolution des ceintures de radiation, la prédiction de l’intensité de la ceinture de radiation la plus interne, entre la planète et les anneaux, l’estimation de l’épaisseur des anneaux de
Saturne et bien d’autres.

Cette thèse est composée de sept chapitres.

Le 1er chapitre présente le concept de la magnétosphère planétaire et fournit une brève description de sa structure, ainsi que la liste des principales sources de plasma et des processus dynamiques clés, liées aux particules énergétiques.

Le chapitre 2 se concentre sur les particules chargées énergétiques dans la magnétosphère de Saturne. Leur intérêt scientifique particulier est expliqué et pourquoi l’approche particules-test est adaptée à l’étude de leur mouvement. Ensuite sont données les principales équations décrivant le mouvement des particules chargées dans le champ magnétique et la description des notions telles que : giration, L-shell, invariant adiabatique, miroir magnétique, mouvement de rebond et de dérive. La présence de particules énergétiques dans la magnétosphère de Saturne est développée, ses ceintures de radiation et le rôle des rayons cosmiques galactiques (GCR). Le processus Àń CRAND Àž est enfin présenté et on montre comment il peut être étudié en utilisant les méthodes numériques.

Le chapitre 3 est consacré à la description des méthodes numériques pour le traçage des particules. Les modèles de la magnétosphère de Saturne qui sont utilisés dans cette thèse sont décrits. Ensuite sont expliquées l’approche particules-test et les méthodes numériques qui peuvent être utilisées pour calculer la trajectoire d’une particule individuelle. À la fin de ce chapitre je décris le code de traçage de particules que j’ai développé.

Le chapitre 4 décrit la mission Cassini vers Saturne et donne un bref aperçu des instruments à bord de Cassini, dont les données ont été utilisées dans cette thèse. Les caractéristiques et les performances des instruments LEMMS, CHEMS, INCA et MAG sont décrites, la manière dont les mesures sont obtenues ainsi que la physique se trouvant derrière les observations. À la fin de ce chapitre sont discutées la couverture orbitale, obtenue par Cassini au cours des 12 dernières années à Saturne, et les orbites prévues jusqu’à la fin de la mission en 2017.

Le chapitre 5 décrit la simulation développée pour les observations MIMI / LEMMS pendant les survols de Rhéa et de Dionée, en utilisant la technique de traçage des trajectoires des particules et en analysant la forme du signal d’absorption.

Le chapitre 6 est consacré à l’étude de l’accès des rayons cosmiques galactiques (GCR) au système saturnien. La nature des GCR est décrite ainsi que les gerbes atmosphériques générées. Les bases de l’approche analytique dans l’évaluation de l’accès des GCR à la planète sont expliquées et les inconvénients de cette méthode sont examinés, en comparaison par rapport à une approche numérique. Ensuite sont décrits la réalisation particulière du traçage des GCR dans la magnétosphère de Saturne que j’ai développé et sont présentés les résultats obtenus: l’énergie d’accès des GCR à Saturne et au plan équatorial de sa magnétosphère dans de nombreux aspects différents. à la
fin de ce chapitre est fournie une comparaison du flux des GCR obtenu au-dessus des anneaux de Saturne avec les mesures du bruit de fond de MIMI / LEMMS au cours de l’insertion en orbite autour de Saturne (SOI).

Dans le dernier chapitre 7 les perspectives de recherche qui découlent des résultats obtenus, présentés dans les chapitres précédents, sont discutées ainsi que comment le traceur de particules que j’ai développé pourrait être utilisé (ou déjà en cours d’utilisation).
Chapter 1

Planetary magnetospheres

1.1 Magnetospheres of the Solar System

A magnetosphere is the cavity around a celestial body, where the local magnetic field dominates the ambient magnetic field. It can be filled with plasma, neutral particles, gas and dust grains. The dynamics of a magnetosphere is governed by the pressure balance between an external plasma pressure (caused by the solar wind for planets or by the interstellar wind for stars) and an internal plasma pressure. The magnetopause is the boundary between a surrounding magnetized medium and a magnetosphere. The magnetosheath is the zone, where the flow of ambient plasma changes direction, being deflected around the magnetopause and the bow shock determines the outer boundary of the magnetosheath.

Figure 1.1 demonstrates the shape of the planetary magnetosphere (terrestrial on this picture) with the main regions indicated. Here it is shown how the heated solar wind behind the bowshock flows around the magnetopause. The magnetic field lines are highly asymmetric, been suppressed on the subsolar side and forming a magnetotail in the opposite direction. The magnetotail is coaligned with the solar wind and extends for tens of terrestrial radii behind it. The solar wind particles from the magnetosheath have direct access to the planet through the cusp regions, where the magnetic field lines diverge.

All planets with significant internal magnetic field, like Earth, Jupiter, Saturn, Neptune and Uranus, have an intrinsic magnetosphere, where the internal magnetic field of the planet repels the magnetic field of the solar wind. Mercury also holds such a magnetosphere, but a relatively small one with an averaged subsolar magnetopause distance only $\sim 1.5 \, R_M$. The largest moon of Jupiter, Ganymede, has its own permanent internal magnetic field and therefore also holds a magnetosphere, which is embedded in the magnetosphere of Jupiter. Non-magnetized planets, such as Venus and Mars, also have a magnetosphere but an induced one. This type is formed by the interaction of the planetary ionosphere with the solar wind. They are much smaller in size and have different driven processes compared to the intrinsic one. The martian crust is partly magnetized that influences the solar wind interaction with the planet. In Table 1.1 the main properties of the planetary magnetospheres in the Solar System are shown.
### Table 1.1: Properties of the planetary magnetospheres in Solar System (adopted from Kivelson and Bagenal (2014)).

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [AU$^1$]</td>
<td>0.31 – 0.47</td>
<td>0.723</td>
<td>1</td>
<td>1.524</td>
<td>5.2</td>
<td>9.5</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>Radius [km]</td>
<td>2439</td>
<td>6051</td>
<td>6373</td>
<td>3390</td>
<td>71398</td>
<td>60330</td>
<td>25559</td>
<td>24764</td>
</tr>
<tr>
<td>Observed size of magnetosphere [$R_{planet}$]</td>
<td>$1.5R_M$</td>
<td>$1.1R_V$</td>
<td>$8 - 12R_E$</td>
<td>–</td>
<td>$63 - 93R_J$</td>
<td>$22 - 27R_S$</td>
<td>$18R_U$</td>
<td>$23 - 26R_N$</td>
</tr>
<tr>
<td>Magnetic moment [$M_{Earth}^2$]</td>
<td>$4 \times 10^{-4}$</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>20000</td>
<td>600</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Surface magnetic field at dipole equator [nT]</td>
<td>195</td>
<td>$&lt; 30$</td>
<td>30600</td>
<td>$\sim 40$</td>
<td>430000</td>
<td>21400</td>
<td>22800</td>
<td>14200</td>
</tr>
<tr>
<td>Dipole tilt and sense$^3$</td>
<td>$&lt; 3^\circ S$</td>
<td>–</td>
<td>9.92$^\circ S$</td>
<td>–</td>
<td>9.6$^\circ N$</td>
<td>$&lt; 1^\circ N$</td>
<td>59$^\circ N$</td>
<td>47$^\circ N$</td>
</tr>
<tr>
<td>Obliquity$^4$</td>
<td>0.2$^\circ$</td>
<td>–</td>
<td>23.5$^\circ$</td>
<td>–</td>
<td>3.1$^\circ$</td>
<td>26.7$^\circ$</td>
<td>97.9$^\circ$</td>
<td>29.6$^\circ$</td>
</tr>
<tr>
<td>Maximum plasma density [$cm^{-3}$]</td>
<td>$\sim 1$</td>
<td>–</td>
<td>1 – 4000</td>
<td>–</td>
<td>$&gt; 3000$</td>
<td>$\sim 100$</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Composition</td>
<td>$H^+$</td>
<td>–</td>
<td>$O^+, H^+$</td>
<td>–</td>
<td>$O^{n+}, S^{n+}$</td>
<td>$O^+, OH^+, H_2O^+, H^+$</td>
<td>$H^+$</td>
<td>$N^+, H^+$</td>
</tr>
<tr>
<td>Dominant source</td>
<td>Solar wind</td>
<td>–</td>
<td>Ionosphere</td>
<td>~ 1</td>
<td>~ $10^3$</td>
<td>Io Enceladus</td>
<td>Atmosphere</td>
<td>Triton</td>
</tr>
<tr>
<td>Magnetospheric plasma source [kg/s]</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Average IMF magnitude [nT]</td>
<td>4</td>
<td>1.7</td>
<td>1</td>
<td>0.07</td>
<td>0.015</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Typical Solar wind ram pressure [nPa]</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

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1. $1AU = 1.5 \times 10^8 km$
2. $M_{Earth} = 7.906 \times 10^{15} Tm^3$
3. Angle between the magnetic axis and rotation pole (S or N)
4. The inclination of the equator to the orbit
Not only planets, but comets, stars and astrophysical objects like pulsars hold magnetospheres. A comet will obtain a magnetosphere while approaching to the Sun close enough, that water molecules will sublime and later ionized by UV light from the Sun. These ions form a conduction obstacle, similar to the ionosphere at Mars and Venus, that deflects the solar wind forming the comet’s magnetospheric cavity (Nilsson et al., 2015).

The magnetic field of the Sun forms the heliosphere, which is controlled by the balance between the interstellar medium pressure from outside and the solar wind pressure from inside. Fast spinning magnetic neutron stars (pulsars) also host a magnetosphere, expected to be filled with electron-positron plasma and to produce relativistic plasma jets and other hard radiation emissions. These huge magnetospheres probably are the places, were Galactic Cosmic Rays are accelerated and gained their enormous energies before they escape to the wider Universe.

1.2 Saturn and its environment

Saturn is the second biggest planet in the Solar System. It is a giant gas planet, that consists mainly of hydrogen and helium. Due to the large distance from the Sun Saturn was able to accrete much of the primordial gas, which was not yet trapped by the Sun and now the composition of this system give us an opportunity to look back in time to the early ages of our Solar System (Levison et al., 2015). Saturn is 9.5 times
farther away from the Sun than Earth, that decreases the solar wind pressure by $\sim 80$ times and leads to an increased galactic cosmic ray flux.

Saturn has an impressive ring system, which stretches from 1.1 up to 2.4 Saturn radii away from the centre of the planet. The rings mainly consist of water ice grains with traces of rocky material and dust with sizes of particles from micrometers to meters (Cuzzi et al., 2009). The origin of the Main Rings is still uncertain as well as the precise age and mass of its matter. 62 moons orbit around Saturn, 9 of them have a radius bigger than 100 km: Titan ($R_T = 2575$ km), Rhea ($R_{Rh} = 764.3$ km), Iapetus ($R_{Ia} = 735.6$ km), Tethys ($R_{Th} = 533$ km), Dione ($R_{Di} = 561.7$ km), Enceladus ($R_{En} = 252.1$ km), Mimas ($R_{Mi} = 198.2$ km), Hyperion ($R_{Hy} = 135.0$ km), Phoebe ($R_{Ph} = 106.1$ km). Figure 1.2 illustrates Saturn, its rings and numerous moons.

Titan is the largest moon of Saturn and is the only one known to host an extended dense atmosphere composed primarily of $N_2$ and $CH_4$. It orbits Saturn at a distance of $20 \ R_S$. Having no significant internal magnetic field, it interacts with Saturn’s magnetosphere and the solar wind in a cometary fashion, producing an induced magnetosphere (Blanc et al., 2015).

Saturn is a magnetized planet; its intrinsic magnetic field can be well described as

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Figure 1.2: Saturn, its ring structure and moons to relative scale with Neutral Gas Torus indicated (picture credit: David Seal NASA/JPL/Caltech).
a magnetic dipole perfectly aligned with a rotation axis of the planet. The surface magnetic field at the dipole equator with small contribution from non-dipole moments is $\sim 21400 \text{ nT}$. The magnetosphere of Saturn is the second largest magnetosphere in the Solar System after Jupiter’s one, Figure 1.3 demonstrates its structure and main elements. For convenience the region inside $\sim 5 R_S$ in the equatorial plane is called the inner magnetosphere, between $\sim 5 - 15 R_S$ - the middle magnetosphere and beyond $15 R_S$ - the outer magnetosphere.

Saturn rotates very quickly with a period about only 10 hours 39 minutes, determined by using the Saturn Kilometric Radiation (SKR) periodicity (Carr et al., 1981; Khurana et al., 2009) - strong radio emissions at kilometer wavelengths most probably related to aurora. However, active debates about the exact rotation period of Saturn are still going on (Helled et al., 2015).

The Saturnian magnetosphere combines the properties of the solar wind-driven terrestrial magnetosphere and rotation-driven magnetosphere of Jupiter and can be considered as an interlink between those two extreme cases (Krimigis et al., 1983; Mauk et al., 2009). The study of it is extremely valuable for the understanding of magnetospheric processes at Earth.
1.2. Saturn and its environment

1.2.1 Plasma sources

The main source for Saturnian plasma at low and medium energies is a plume of water-group molecules originating from active geysers at the south pole of the Saturnian moon Enceladus (Dougherty et al., 2006; Jones et al., 2006; Porco et al., 2006). Enceladus continuously supplies the Saturnian magnetosphere with neutral gas, and together with the impressive rings and the numerous moons it creates an environment similar to the Sun’s planetary nebula. With Cassini it is possible to observe particle acceleration processes and transport in this environment. Figure 1.4 illustrates Saturn, Enceladus, its water plume and their magnetic connection.

This moon is orbiting Saturn at 3.95 $R_S$ and produces approximately 60 – 100 kg/s of new plasma (Fleshman et al., 2013). Ejected ice grains and water vapor form cor-

![Figure 1.4: Artist’s concept of the magnetic connection between Saturn and Enceladus. The auroral footprint is shown in Saturn’ northern hemisphere near the main aurora oval. Above Enceladus is shown a cross-section of the magnetic field between the moon and the planet, as it was detected by the Cassini MIMI instrument on August 11, 2008. At the south pole of Enceladus the water gas plume is demonstrated, resulting from the cryovolcanic activity on the moon, which is the main internal source of plasma in the magnetosphere of Saturn, similar to Io on Jupiter. Picture courtesy: NASA/JPL/JHUAPL/University of Colorado/Central Arizona College/SSI.](image-url)
Chapter 1. Planetary magnetospheres

respondingly the relatively compact E-ring and the widely spread Neutral Gas Torus, extending from the orbit of Mimas ($3.1 R_S$) up to the orbit of Titan ($20 R_S$). Photoionization, charge exchange and impact of energetic electrons lead to ionization of these molecules into $H_2O^+$, $O^+$, $OH^+$ with subsequent dissociation into $H^+$. Then various sputtering and acceleration processes facilitate the distribution of mass and energy into the entire magnetosphere (Bagenal and Delamere, 2011).

In their latest study Felici et al. (2016) reported, that Saturn’s ionosphere produces an amount of plasma ($49.7 \pm 13.4$ and $239.8 \pm 64.8$ kg/s) comparable to Enceladus, as deduced from observations of the ionospheric outflow in the magnetotail. However it is still unclear, how much of the ionospheric plasma returns to the magnetosphere.

Titan supplies the magnetosphere through ion outflow and by ionization of neutral particles from Titan’s atmosphere (pickup ions). Cassini observations showed, however, that Titan, the other moons, the rings and the solar wind play a minor role as plasma sources compared to Enceladus.

The energetic particles (electrons and ions of energies above tens of keV) originate from the acceleration of the lower energy plasma by various processes driven by the fast rotation of Saturn. The origin of the highest energy particles (above several MeV) is expected to be related to the solar energetic particle and galactic cosmic rays. This thesis is devoted to the energetic charged particles and in the next Section I list the key dynamical processes related to their transport and acceleration in the magnetosphere of Saturn.

1.2.2 Key dynamical processes

Due to the high conductivity of the plasma in the ionosphere of Saturn the magnetic field is frozen into the ionospheric plasma and magnetic field lines follow the rotation of the planet. The term frozen-in refers to Alfvén’s theorem (Alfvén, 1943), which states that in a perfectly conducting fluid the magnetic field lines move with the fluid and the field lines are “frozen” into the plasma. Despite the fact that in real plasma environments the electrical conductivity is not infinite and the magnetic field lines are not ideally frozen into the fluid, this theorem can still be a good approximation for those environments with a high electric conductivity. Therefore plasma just above the ionosphere is also dragged and so the radially directed corotation electric field is created. The combination of magnetic and electric fields influence newly created plasma in the inner magnetosphere and accelerate plasma to the corotation velocity.

At the same time the centrifugal forces exceed the gravitational forces on newborn water group rich plasma. This plasma flows outwards in the equatorial plane together with the frozen-in magnetic field lines forming the magnetodisk (Arridge et al., 2008). Being strongly compressed on the dayside ($\sim 16.5 R_S$), the Saturnian magnetodisk is extremely stretched-out on the night-side proceeding into the magnetotail, which extends for hundreds of Saturn radii on the antisolar side. In the magnetotail the magnetic field lines are stretched so much, that oppositely directed field lines come very
1.2. Saturn and its environment

Figure 1.5: Schematic view on the reconnection process. Blue and red lines represent open and closed magnetic field lines, arrows point to ionospheric outflow, reconnection outflow and post-reconnection injection. Adopted from Felici et al. (2016).

close to each other. Stable conditions are maintained by a thin current sheet, where magnetic field values are very low. At the same time the magnetic field above and below this current sheet is very strong and points nearly radially outward above the current sheet and radially inward below (Gombosi et al., 2009). Regions of open field lines around the current sheet are called "lobes" and connect the ionosphere of Saturn with the interplanetary magnetic field (IMF). From time to time magnetic reconnection between northern and southern lobes may occur in the magnetotail, leading to the release of plasmoids in the magnetotail, as reported by Jackman et al. (2007) and Hill et al. (2008). The reconnection events are associated with planetward transport and heating of plasma on the night side of the current sheet (Mitchell et al., 2015). During this reconfiguration ions are quickly energized resulting in an injection of accelerated particles into the middle magnetosphere. Figure 1.5 illustrates the reconnection process (adopted from Felici et al. (2016)).

Another type of injection event is caused by flux tube interchange. The term flux tube usually refers to the charged particle flux along certain magnetic field lines, which are often connected to some fixed regions in the magnetosphere. Since the plasma temperature at Saturn decreases closer to the planet, the centrifugally-driven interchange instability occurs, and cold dense plasma is displaced by hot tenuous plasma which moves radially inward, being energized additionally by coming into the stronger magnetic field. This results in interchange injection events, where protons and electrons moving perpendicular to the magnetic field undergo strong acceleration, as described by Mitchell et al. (2015).

As a result of pressure gradient, plasma flow shears and other processes, various electric currents arise in the magnetosphere. At Saturn one should first of all mark out the ring current, resulting from the combination of gradient and curvature drifts (explanation is provided in Section 2.2.4) in a nonuniform magnetic field, which starts at 6 $R_S$, peaking at $\sim 10 R_S$ and continuing up to $12 - 22 R_S$, depending on the position
Figure 1.6: Artist’s interpretation of Saturn’s plasma sheet and ring current, based on data from Cassini’s Magnetospheric Imaging Instrument. The plasma sheet, separating the upper and lower magnetosphere halves, thins gradually toward the nightside of the planet. The magnetopause indicates the inner boundary of the deflected solar wind. Credit: NASA/Jet Propulsion Laboratory / Johns Hopkins University Applied Physics Laboratory

of the magnetopause. The strength of the ring current also depends upon the position of the magnetopause and becomes higher when the magnetosphere is less suppressed by the solar wind pressure. Inside the ring current the strength of the planetary field is locally depressed (Khurana et al., 2009). Figure 1.6 illustrates the plasma sheet and ring current concepts at Saturn, where the plasma sheet is the region of dense hot plasma and low magnetic field near the equatorial plane, between the magnetosphere’s north and south lobes.

The field-aligned currents flow along the magnetic field lines and are associated with the ionosphere coupling to the magnetosphere, forming a large-scale closed-loop current system (Hunt et al., 2015). The magnetopause current flows on Saturn’s magnetopause surface and is characterized by increasing electron density and decreasing electron temperature (Masters et al., 2012). It resists the motion of the magnetosheath plasma across the magnetopause and creates the magnetopause obstacle.

The inward radial diffusion, caused by fluctuations of the electromagnetic field, plays an important role in the distribution of energetic particles in the magnetosphere. As reported by Kollmann et al. (2011), radial diffusion is the dominating plasma transport process at distances of at least $12 \ R_S$ from the planet in the equatorial plane.
However, inside the orbit of Rhea (from $\sim 8 R_S$ inward) other dynamical processes become more important.

Energetic charged particles are among the most important components that hold key information for understanding the dynamics and configuration of any planetary magnetosphere. Their study will be the focus of this thesis with an overall goal of probing fundamental processes in Saturn’s magnetosphere. Chapter 2 introduces key findings and open questions regarding energetic particles in the Saturnian magnetosphere, more specifically about the origin of Saturn’s proton radiation belts. It also includes the mathematical formulation of charged particles’ motion in planetary magnetic fields. The main two methods of studying energetic particles are numerical simulations and in-situ observations and are introduced in Chapters 3 and 4, respectively. The results of my work are reported in the consequent Chapters 5 and 6, while Chapter 7 presents an outlook.
Chapter 2

Energetic charged particles

Electrons and ions of energies above tens of keV are usually named "energetic". There are several internal and external sources for these particles. Origin of such energetic particle can be found both inside the magnetosphere (then these sources are internal) and outside the magnetosphere (external sources). The main internal sources are ionospheric plasma, volcanoes and geysers from the moons and particles sputtered from rings and moons that are subsequently accelerated by magnetospheric processes to high energies. Various acceleration mechanisms also supply energetic particle population by energization of cold plasma. As an external source one can include the solar energetic particles, solar wind, cosmic rays and cascades of secondary particles from their interaction with rings, moons and the atmosphere of a planet. Losses of energetic charged particles happens due to charge exchange with neutral clouds, absorption by dust, rings, moons and scattering by waves so that the particles are precipitated into the upper atmosphere (Krupp, 2005; Kivelson and Bagenal, 2014).

2.1 Why study energetic particles?

Because of very high energy they carry, energetic particles can be used as indicators of different processes. The energetic charged particles’ kinetic scales are comparable to Saturn’s moon sizes and can resolve certain features in the dynamics of plasma; energetic neutrals can travel very large distances transferring the information about the processes that created them. Krupp (2005) provided an exhaustive review about the importance of studying energetic particles, and I would like here to emphasize, that from one hand the observations of energetic particles can provide useful information, for instance:

- Energetic particles can be used to determine the magnetic field configuration of the planet (Selesnick and Cohen, 2009; Kollmann et al., 2011);

- They can indicate dynamical processes in the magnetosphere: plasma sources, sinks and transport mechanisms (Young et al., 2005; Rymer et al., 2007);

- Determination of anisotropies, flux intensity gradients for the estimation of particle drifts. Particularly moon-driven absorption signatures in energetic particles
2.1. Why study energetic particles?

can be used to identify unknown electric fields (Andriopoulou et al., 2012, 2014);

- Spectral and flux intensity changes of energetic particles can be used to study various acceleration mechanisms (Masters et al., 2013);

- They can help to monitor substorm events, particle injections events and to observe the effects of reconnection process (Mitchell et al., 2015);

- Energetic particle observations can help revealing the nature of different kinds of periodicities and oscillations in the magnetosphere (Carbary and Mitchell, 2013).

Energetic particles should be monitored in order to better understand the processes following their interaction with matter, because:

- They can precipitate into the atmosphere of a planet or moon and change its chemistry. They can impact the surfaces of planet, their moons and ring matter, change their albedos, spectral and even surface properties (Müller-Wodarg et al., 2006; Frankland and Plane, 2015).

- Penetration into a planetary ionosphere and into an atmosphere can lead to auroral emissions (Stallard et al., 2008; Badman et al., 2015), heating of upper layers of the atmosphere, can produce showers of secondaries, cause specific lightning effects, such as gamma-rays flashes and even influence the formation of clouds (Fishman et al., 1994).

- Energetic particles interact with existing gas tori along the orbits of moons (Mauk et al., 2009). By studying these interactions one can obtain the characteristics of the interaction with matter itself.

- Energetic particles create a radiation hazard for spacecraft electronics.

All these aspects make energetic particles a fascinating and important subject to study. In the frame of this thesis I would like to demonstrate the value of studying and modeling the motion of energetic particles in planetary magnetosphere, specifically in the magnetosphere of Saturn.

The highest fluxes of energetic charged particles are usually concentrated in the so-called "radiation belts" - stable torus zones around a magnetized planet, where the energetic charged particles are trapped (Van Allen and Frank, 1959). The energies of these particles are much higher than the energy of the thermal plasma. While the thermal plasma expresses the collective behavior, energetic particles’ flux density is much lower and they do not really change the properties of the ambient magnetic field. Consequently kinetic theory and the test-particle approach is more appropriate for the modeling of this zone of the magnetosphere rather than using the magnetohydrodynamic (MHD) approach.
2.2 Motion of charged particles in planetary magnetic fields

Electrically charged particles are sensitive to the electromagnetic forces and their initial motion therefore changes. The equation of motion of a charged particle in the presence of an electromagnetic field can be expressed by the Newton-Lorentz equation:

$$\frac{d(\gamma m\vec{v})}{dt} = q\vec{E}(\vec{r}) + q\vec{v} \times \vec{B}(\vec{r})$$  \hspace{1cm} (2.1)

where a relativistic factor $\gamma$ is:

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$ \hspace{1cm} (2.2)

Here $m$ is the particle’s mass, $q$ is the charge of the particle, $v$ is the particle’s speed, $c$ is the speed of light, $\vec{E}$ is the strength of the electric field and $\vec{B}$ is the strength of the magnetic field at the location $r$.

2.2.1 Gyration

The Lorentz force constantly accelerates the charged particle perpendicular to both the particle’s velocity and the magnetic field. As a result in a uniform magnetic field and in the absence of an electric field or other external forces the charged particle performs constant circular motion in the plane perpendicular to the magnetic field, called gyromotion or sometimes cyclotron motion or gyration. The direction of the circular gyromotion depends on the sign of the charge. Its frequency $\omega_g$ is defined as:

$$\omega_g = \frac{|q|B}{\gamma m}$$ \hspace{1cm} (2.3)

where $B = |\vec{B}|$ is the uniform magnetic field strength. Consequently the period of the gyration can be expressed as:

$$T_g = \frac{2\pi\gamma m}{|q|B}$$ \hspace{1cm} (2.4)

The central point of this circular orbit is called the guiding center and the radius of the circle is named the gyroradius (sometimes it is also called Larmor or cyclotron radius). The gyroradius $r_g$ is defined as:

$$r_g = \frac{\gamma mv_{\perp}}{|q|B}$$ \hspace{1cm} (2.5)

where $v_{\perp} = \left(v_x^2 + v_y^2\right)^{1/2}$ is the component of the particle’s velocity perpendicular to the magnetic field vector $\vec{B}$. Figure 2.1 illustrates the gyration of an ion and an electron.

If the initial velocity of a particle has a component parallel to the magnetic field, this particle follows a helical trajectory about the magnetic field line. The pitch angle $\alpha$ of a helix is defined as:
2.2. Motion of charged particles in planetary magnetic fields

Figure 2.1: Gyration of charged particles around a guiding center. Updated figure from Baumjohann and Treumann (1996).

\[ \alpha = \tan^{-1}\left(\frac{v_\perp}{v_\parallel}\right) \]  

(2.6)

To describe the motion of charged particles in a planetary magnetic field sometimes it is convenient to resolve the kinetic energy \( K \) of the particle into perpendicular and parallel kinetic energies:

\[ K_\perp = \frac{1}{2}mv_\perp^2 \]  

(2.7)

\[ K_\parallel = \frac{1}{2}mv_\parallel^2 \]  

(2.8)

\[ K_{\text{tot}} = K_\perp + K_\parallel \]  

(2.9)

Correspondingly for relativistic energies Equations 2.7 and 2.8 can be rewritten as:

\[ K_\perp = \frac{p_\perp^2}{2\gamma m} \]  

(2.10)

\[ K_\parallel = \frac{p_\parallel^2}{2\gamma m} \]  

(2.11)

where particle momentum is \( \mathbf{p} = \gamma m \mathbf{v} \).

When the magnetic field variations are small compared to the gyroperiod \( T_g \) in time and compared to the gyroradius \( r_g \) in space, then the magnetic moment \( \mu = K_\perp/B \) stays nearly constant whenever the particle moves into stronger or weaker magnetic field as first shown by Alfvén (1940) (the detailed proving can be found in many physics textbooks, for instance in Baumjohann and Treumann (1996)). Therefore the magnetic moment is an invariant of the particle motion associated with the gyration and is named the first adiabatic invariant.
2.2.2 Dipole magnetic field

The magnetic field of many astronomical objects near their surfaces can be described as a dipole, including the magnetic field of Saturn (see Section 1.2), at least for a distance up to $\sim 8 R_S$ away from the planet (Birmingham, 1982). The strength of the azimuthally symmetric dipole magnetic field $\tilde{B}_{\text{dip}}$ in spherical coordinates $(r, \lambda)$, where $r$ is the radial distance from the center of the planet and $\lambda$ is the magnetic latitude, is defined as:

$$\tilde{B}_{\text{dip}}(r, \lambda) = \frac{B_0 R_p^3}{r^3} \sqrt{1 + 3 \sin^2 \lambda} \quad (2.12)$$

where $B_0$ is the equatorial surface magnetic field and $R_p$ is the radius of the planet ($R_p = \sqrt{x^2 + y^2}$). As it was shown in Öztürk (2012) the strength of the dipole magnetic field $\tilde{B}_{\text{dip}}$ at the location $r$ (where $r = \sqrt{x^2 + y^2 + z^2}$) can be rewritten in Cartesian coordinates, and then for Saturn it will be expressed as:

$$\tilde{B}_{\text{dip}} = \frac{B_0 R_p^3}{r^5} \left[ 3 x' \hat{x} + 3 y' \hat{y} + \left( 2 z'^2 - x'^2 - y'^2 \right) \hat{z} \right] \quad (2.13)$$

where $R_S$ is the radius of Saturn and $z' = z - 0.036 \times R_S$, since on Saturn the center of the intrinsic dipole is slightly shifted northward by an offset of 0.036 * $R_S$ (Gombosi et al., 2009). Consequently for Saturn $B_0 = 21160 \ [nT]$ and $R_S = 60.268 \times 10^6 \ [m]$ (Davis and Smith, 1990). It was shown, for instance by Baumjohann and Treumann (1996), that the dipole field line equation in spherical coordinates is:

$$r = r_{eq} \cos^2 \lambda \quad (2.14)$$

where $r_{eq}$ is the radial distance of the magnetic field line in the equatorial plane. In order to simplify the measurements and calculations along the magnetic field lines of a dipole McIlwain (1961) proposed a new coordinate system, introducing the $L$-value or the $L$-shell parameter (first mentioned in Section 1.2.1), which can be derived from Equation 2.14 as:

$$L = \frac{r_{eq}}{R_S} = \frac{r}{R_S \cos^2 \lambda} \quad (2.15)$$

Figure 2.2 illustrates the typical configuration of the magnetic field lines of a magnetic dipole with indicated L-shells.

2.2.3 Bounce motion

As it is seen in Figure 2.2 the magnetic field lines of a planetary dipole come closer to each other around the poles, illustrating stronger magnetic field closer to the poles than on the equator. Consequently, in order to conserve the first adiabatic invariant (see Section 2.2) - magnetic moment $\mu$, with increasing $B$ the perpendicular kinetic energy $K_\perp$ should also grow. And since the total kinetic energy $K_{\text{tot}}$ should stay constant, its parallel component should decrease, as well as the parallel component of the particle’s velocity $v_\parallel$. With a decrease of $v_\parallel$ the pitch angle $\alpha$ will grow and at a certain point it will reach $90^\circ$. At this moment all the particle’s energy will be contained in $K_\perp$, $v_\parallel$. 

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2.2. Motion of charged particles in planetary magnetic fields

![Field lines of a magnetic dipole with indicated dipole L-shells. Here $r$ is the radial distance, $\lambda$ is the magnetic latitude and $r_{eq}$ is the equatorial distance, from which the dipole L-shell is derived.]

will reach zero and the particle will not be able to move further along the magnetic field line towards the poles. Consequently magnetic mirroring occurs and the particle is repelled backwards to the weaker magnetic field region - towards the equator. This reflection was for the first time suggested by Poincaré (1896) in his remarks on work by K. Birkeland on a magnetic monopole.

If the magnetic field has a symmetric geometry with converging magnetic field lines on the sides and low density magnetic field region in the middle, like in a magnetic bottle or in a dipole field, then once the relevant particle appears in the region, it will continue to bounce between mirror points and such particles are termed "trapped". This effect has numerous applications, particularly for controlled thermonuclear fusion power.

With regard to the planetary dipole magnetic field the mirroring effect was first suggested by Alfvén (1940) and the existence of the radiation belts around Earth was proven by experiments of James Van Allen onboard the space missions Explorer 1 and Explorer 3 in 1958. The left panel of Figure 2.3 illustrates the particle’s bounce motion between mirror points in a dipole magnetic field.

The second adiabatic invariant - the longitudinal invariant $J$ - is associated with the bounce motion of the particles along the magnetic field. It is defined by:

$$J = \oint mv_\parallel ds$$  \hspace{1cm} (2.16)  

where $ds$ is an element of the guiding center path, while the integral is taken over a full path between two mirror points: starting from the equatorial plane to one mirror point, then all the way to the second mirror point and back to the equatorial plane. Basically it means that in a magnetic bottle configuration the charged particle performs a bounce motion between stable mirror points without changes in its total energy.
However with moving mirror points the particle can gain or lose some energy, depending on whether mirror points move towards the particle or away from it. Particularly, Fermi (1949, 1954) considered this mechanism as one responsible for GCR acceleration.

If the mirror point of a particle is located below the surface / or in the exosphere of the planet, then this particle will enter the region, where it will most probably experience numerous collisions and consequently will be lost. The magnetic latitude of the particle’s mirror point \( \lambda_m \) ultimately depends on the particle’s \textit{equatorial pitch angle} \( \alpha_{eq} \) (which determines an angle between the particle velocity vector and magnetic field line when the particle is crossing the magnetic equator) and is independent of the particle’s mass, speed, charge and the distance from the planet. Particles with smaller \( \alpha_{eq} \) have larger parallel components of the velocity and thus their mirror points will be located closer to the planet.

There exists a concept of a \textit{loss cone}, which defines the region in velocity space in the shape of a double cone, depicted in Figure 2.4. All the particles with equatorial pitch angles smaller than \( \alpha_\ell \) appear inside the solid angle \( d\Omega \) and will be lost. The \( \alpha_\ell \) value depends only on the field line radius, in other words on L-value. This dependence can be expressed as:

\[
\sin^2 \alpha_\ell = \left( 4L^6 - 3L^5 \right)^{1/2}
\]

This equation results from the definition of a L-shell. The full derivation can be found in Baumjohann and Treumann (1996).

### 2.2.4 Drift motion

The presence of an electrical field and an inhomogeneity in the magnetic field lead to a drift superimposed onto a particle’s gyration and bounce motion. In the static homogeneous electric and magnetic fields the guiding center of the particle will drift perpendicularly to both the magnetic field and electric field vectors, since the electric field will charge the particle’s velocity in different phases of one gyromotion. During one half of the gyration orbit the particle velocity has a component parallel to the
2.2. Motion of charged particles in planetary magnetic fields

Figure 2.4: Definition of the loss cone.

electric field and thus is accelerated. During the other half the particle has a velocity component which is antiparallel to the electric field and consequently the particle is decelerated. This drift is usually called the $E \times B$ drift and its velocity is determined as:

$$v_E = \frac{E \times B}{B^2}$$

This drift is independent of the particle’s electric charge and mass, thus electrons, protons and heavier ions are all drifting in the same direction with the same velocity.

If the electric field is varying slowly, then the polarization drift occurs, which shifts the guiding center of ions and electrons in opposite directions along the electric field vector and polarizes the plasma. At the same time the magnetic field usually has a gradient and field lines are often curved, as in the case of the planetary magnetic field. Such inhomogeneity in the magnetic field leads to the magnetic drift of the particle’s guiding center, and moreover the associated inhomogeneous electric field may additionally accelerate charged particles.

The gradient drift occurs as a result of the difference in gyroradii on opposite halves of the gyration orbit, since with increasing magnetic field strength the gyroradius becomes smaller and vice versa. As a result, electrons and ions drift in opposite directions, perpendicular to both magnetic field $B$ and its gradient $\nabla B$. More energetic particles drift faster, since the gyroradius is proportional to the perpendicular velocity of the particle, as can be seen in Equation 2.5.

The curvature drift appears, when the magnetic field lines are curved and particles experience a centrifugal force. Therefore the curvature drift depends on the particle’s parallel energy. It is perpendicular to both the magnetic field and its curvature and it
moves ions and electrons in opposite directions.

The general form for guiding center drift velocity in the presence of a relevant force \( \mathbf{F} \) acting on a particle perpendicular to the magnetic field vector \( \mathbf{B} \) (as long as the drift velocity is much smaller than the gyration velocity), can be expressed as following:

\[
\mathbf{v}_F = \frac{\mathbf{F} \times \mathbf{B}}{qB^2} = \frac{1}{\omega_g} \left( \frac{\mathbf{F} \times \mathbf{B}}{m} \right)
\]  

(2.19)

Consequently the gradient \( \mathbf{F} \nabla \), polarization force \( \mathbf{F}_P \), gravitation force \( \mathbf{F}_G \) and centrifugal force \( \mathbf{F}_R \) can be expressed as:

\[
\mathbf{F}_\nabla = -\mu \nabla B
\]  

(2.20)

\[
\mathbf{F}_P = -m \frac{d\mathbf{E}}{dt}
\]  

(2.21)

\[
\mathbf{F}_G = -mg
\]  

(2.22)

\[
\mathbf{F}_R = m\mathbf{v}_d^2 \frac{R_c}{R_c^2}
\]  

where \( R_c \) is the local radius of curvature.

As long as the considered forces do not depend on the electrical charge of the particles, all these drifts will move ions and electrons in opposite directions creating a transverse current, which is associated with the ring current, mentioned in Section 1.2.1. The total drift motion is the sum of different drifts. Saturn ions drift eastward and electrons westward, opposite to Earth, since the terrestrial South magnetic pole is located in the Northern hemisphere, while on Saturn this is not the case.

In summary, a charged particle motion in a planetary magnetosphere can be resolved into three main components: gyration, bounce motion between mirror points and drift around the planet. Figure 2.5 illustrates a trajectory of an 500 keV ion around Saturn.

The third adiabatic invariant - the drift invariant \( \Phi \) - is associated with the perpendicular drift of particles around the planet and describes the conserved magnetic flux enclosed on the drift shell. It can be expressed by:

\[
\Phi = \oint v_d r d\psi
\]  

(2.24)

where \( v_d \) is the sum of all perpendicular drift velocities, \( \psi \) is the azimuthal angle, and the integration is taken over a full drift orbit of a particle around the planet. If the variations of the electric and magnetic fields are slower than the drift motion, then \( \Phi = \mu(2\pi m/q^2) = \text{const} \), where \( \mu \) is the magnetic moment of the field.
2.3 Energetic particles in the magnetosphere of Saturn

The distribution of energetic particles in the magnetosphere of Saturn is quite inhomogeneous. Figure 2.6 shows spectrograms of energetic ion and electron intensities (top and bottom panels, respectively) inside $12 R_S$, energy as a function of L-shell. This spectrogram (updated from Gombosi et al. (2009)) was taken by the Low Energy Magnetospheric Measurements System (LEMMS), which is a part of the Magnetospheric Imaging Instrument (MIMI) of Cassini during the Saturn Orbit Insertion (SOI) in July 2004, negative L values correspond to the inbound and positive - to outbound pass during SOI. Energetic ions are rather abundant in the middle magnetosphere particularly between 7 and $12 R_S$, but there is a clear depletion between the orbits of Enceladus and Dione (indicated on the plot as "En" and "Di" correspondingly). Most likely the particle loss here happens through charge-exchange processes between these energetic ions and cold neutral gas (Esposito et al., 2005). Energetic electron fluxes are also dropping in this region but far less radically. Inside $3.5 R_S$ the radiation belts of Saturn appear quite sharp, where fluxes of energetic (keV-MeV) ions and electrons are the most intense. On Figure 2.6 in both ion and electron spectrograms also shown several dispersed features, which can be interpreted as injection signatures. Some rep-
Figure 2.6: Energetic ion and electron intensity spectrograms energy versus L-shell, measured by Cassini MIMI/LEMMS instrument during SOI in July 2004. Figure is taken from Gombosi et al. (2009). Injection signatures are marked with thin dotted lines.

representative “injections” are outlined with dotted lines.

2.3.1 Radiation belts of Saturn

The radiation belts of Saturn have a complex structure and the energetic particle population in this region widely differs from other parts of the Saturnian magnetosphere. In this region the high energy charged particles (tens of keV - MeV) are trapped by the magnetic field of the planet.

The presence of stable radiation belts between the outer edge of the A ring (2.3 $R_S$) and Tethys’ orbit (4.8 $R_S$) was confirmed already during the first visits of this planet by Pioneer 11, Voyager 1 and 2 (Fillius et al., 1980; Krimigis and Armstrong, 1982; Simpson et al., 1980; Vogt et al., 1982). Rings and numerous moons of Saturn shape the unique configuration of the Saturnian radiation belts. Bouncing between mirror points the energetic charged particles regularly cross the equatorial plane of the magnetosphere. Owing to the nearly symmetric magnetic field and almost circular and equatorial orbits, the large moons of Saturn effectively sweep out trapped energetic particle along their motion around the planet.

Because of the large number of the moons and the extent of the neutral gas cloud, radial diffusion process cannot supply the radiation belts with a sufficient portion of
new energetic particles from the middle magnetosphere. Sweeping corridors behind the moons barely replenish and particles that follow the magnetic field lines of the moons L-shells will be absorbed. Cassini observations confirmed, that energetic ions along these L-shells are absent in all magnetospheric local times and latitudes, independent from the location of the moons. Similarly absorption of the charged particles happens along the L-shells connected to the Main Rings. As a result energetic particles are completely absent between the L-shells of the inner edge of D ring \((1.1 \, R_S)\) and the outer edge of A ring \((2.3 \, R_S)\).

Stable and azimuthally averaged depletions in the energetic particle radial distribution usually are referred to a “macrosignature”. A temporal decrease in the particle count rate that depends strongly on the longitudinal distance from the absorbing body is called a “microsignature” (Van Allen et al., 1980). Analysis of the macrosignature and the microsignature properties, such as shape, depth, magnetospheric coordinates and longitudinal distance from the absorbing body, can provide essential information about the dynamical processes in the magnetosphere and the absorbing matter itself.

Figure 2.7 shows differential ion fluxes measured by Cassini MIMI/LEMMS P2 ion channel \((2.28 - 4.49 \, \text{MeV/nuc})\) as a function of dipole L-shell for 7 random orbits from 2004 until 2015. Negative L indicates the inbound part of the orbit, positive - outbound, the L-shells of largest moons and main rings are indicated as well. The figure shows that the ion flux intensity steadily increases from the orbit of Tethys \((4.8R_S)\) towards the planet and sharply disappears on the L-shell of the outer edge of the A ring. One can see clear and stable absorption signatures on the L-shells of the moons Janus, Epimetheus, Mimas, Enceladus and Tethys which do not change over the years. The ion flux intensity inside the orbit of Enceladus also looks quite constant from or-
bit to orbit, while outside the orbit of Enceladus some variability can be noticed. For instance during orbit 3 in 2005 the transient Dione belt between the L-shells of Tethys and Dione was discovered and described by Roussos et al. (2008a), the flux intensity from this orbit is indicated in pink. Such intensification was detected several times during the Cassini mission period as a response to interplanetary energetic particles events caused by solar eruptions.

Cassini MIMI/LEMMS observations over several years demonstrated, that outside the Tethys orbit proton fluxes are changing a lot from one orbit to another. However, the particles flux in radiation belts inside the orbit of Tethys remains unchanged during large interplanetary events, such as Coronal Mass Ejections (CMEs) from the Sun arriving at Saturn, which significantly perturb the middle and the outer magnetosphere, indicative of isolation of the radiation belts from the outer magnetosphere, as it was described by Roussos et al. (2008a) and Paranicas et al. (2008). Also a significant increase in the high energy protons intensity is noticeable towards the planet. Together with this Roussos et al. (2011) analyzed Cassini MIMI/LEMMS observations during years 2004-2010 and reported a weak intensification of the high energy protons flux (> 10 MeV) during solar minimum.

All of this suggests the idea that the high energy components of the radiation belts cannot be produced in the middle magnetosphere followed by transport the planet via diffusion. The neutral gas cloud from Enceladus and the moons Tethys and Dione effectively absorb energetic ions and prevent inward radial transport. On the contrary the source for these energetic ions should be local, most likely being connected to the interaction of Galactic Cosmic Rays (GCR) with Saturn and its rings through the CRAND process (Blake et al. (1983), Cooper (1983), Cooper et al. (1985)). This hypothesis is also supported by analysis of the proton energy spectrum in the radiation belts first measured by Voyager and later confirmed by Cassini. A power-law energy dependence of the proton spectrum with a secondary peak around 20 MeV, can be interpreted with two different source populations: the lower energy protons originate in the middle and outer magnetosphere or from the solar wind and the secondary peak most probably originates from CRAND, as it was discussed by Krimigis and Armstrong (1982) and Armstrong et al. (2009).

During SOI the Cassini spacecraft made a passage inside the radiation belts just above the planetary rings and had an opportunity to measure the flux of energetic particles directly next to the Saturnian atmosphere. During this passage the Ion and Neutral Camera (INCA) detected energetic neutral atoms (ENAs) emission extremely close to the planet. Those ENAs may originate from the double charge exchange collision with energetic charged particles indicative of a significant population of high energy charged particles in the region between the Saturnian atmosphere and the D ring. If an additional radiation belt exists in this narrow zone inside the D ring, it can originate also only from CRAND. Figure 2.8, adopted from Roussos et al. (2008a), shows the layered structure of the Saturnian radiation belts with the predicted innermost radiation belt.
2.3. Energetic particles in the magnetosphere of Saturn

Figure 2.8: Differential flux map of the stable belts inside Tethys’ L-shell of the 25 – 60 MeV/nuc ions, based on MIMI/LEMMS data from 36 orbits. The L-shells of the various moons are indicated. The inner radiation belt indicated with red background hatched with light-blue, since its intensity is currently uncertain. Hatched regions above the main rings have particle flux lower or equal to that of the color bar (adopted from Roussos et al. (2008a)).

2.3.2 CRAND

CRAND stands for Cosmic Ray Albedo Neutron Decay and was first named by Singer (1958), who pointed out that cosmic ray albedo particles can be trapped by the terrestrial magnetic field. In a following work Hess et al. (1959) demonstrated how the CRAND injections can be responsible for the observed proton energy distribution and fluxes in the radiation belts of the Earth.

At Saturn this process was described by several authors including Fillius et al. (1980); Cooper and Simpson (1980); Fillius and McIlwain (1980); Van Allen et al. (1980); Cooper (1983); Blake et al. (1983); Cooper et al. (1985); Randall (1994). A proton with a sufficient high energy (Cosmic Ray) enters the magnetosphere, reaches the planet and interacts with its atmosphere, rings or neutral gas cloud and produces cascades of secondary particles, partly at much lower energies, including neutrons, protons and the whole family of lighter particles such as electrons, pions, muons, various antiparticles and photons. Charged secondary particles will be trapped by the magnetic field and most probably will be absorbed during their bounce motion in a short time. Neutrons in contrast are not bound by electromagnetic forces and consequently can freely escape from their production region. Outside a nucleus, a free neutron is unstable and has a mean lifetime of $885.7 \pm 0.8$ sec (Nakamura and Group, 2010). Beta decay of the neutron leads to the production of a proton, an electron and
Figure 2.9: Sketch of the CRAND process in the Saturn system. An incoming GCR comes from above, penetrates planetary rings, and travel away from the system. A nuclear interaction with ring matter creates cascades of secondary particles, including protons (p’), neutrons (n’), pions, muons, etc. The created proton (p’₁) is trapped in the magnetic field of Saturn and is removed within a few bounces by repeated passages through the rings, consequently more neutrons are created. The first neutron (n’) successfully passes L-shells of the rings and decays in flight injecting an energetic proton (p’₂) into the radiation belt outside the rings.

\[ n \rightarrow p^+ + e^- + \bar{\nu}_e \]  

(2.25)

The difference in atomic mass of neutron and proton leads to the release of 782 keV of the kinetic energy, which is shared between the electron and the antineutrino, and all the kinetic energy of a parent neutron goes to the daughter proton (Blake et al., 1983). Due to relatively short lifetime there is a probability that the neutron will decay inside the magnetosphere and thus populate it with a newborn energetic proton and electron. Figure 2.9 schematically illustrates the CRAND process on the Saturnian rings.

In order to estimate the CRAND input on the radiation belts population it is essential first of all to determine the incoming GCR flux onto the Saturnian atmosphere and rings. There exist analytical and numerical solutions for its determination. However most of them were developed for Earth and do not take into account specifics of other planets. Particularly for Saturn only analytical calculations were performed so far (Cooper and Simpson, 1980; Fillius and McIlwain, 1980; Van Allen et al., 1980; Cooper, 1983; Blake et al., 1983; Cooper et al., 1985; Randall, 1994), providing very uncertain results. Therefore the comprehensive study of the CRAND process at Saturn using a numerical method, which considers the complexity of the Saturnian magnetosphere, corresponds to modern scientific requirements and responds to the needs of
the Cassini mission is essential.

In this thesis I attempt to propose such a method, which is based on particle tracing and allows one to determine precisely the incoming GCR flux at the certain location in space. This method can provide a solution for many different questions in the study of magnetospheres where the precise position of particles, especially energetic, plays a role.
Chapter 3

Charged particle tracing techniques

Charge particle tracing refers to the numerical methods for calculation of the particle motion in certain environment. Nowadays those methods are widely in use for the needs of plasma physics, medicine, particle physics, and especially for studies of high energy particle transport. In high-energy astrophysics the particle tracing methods are popular for modeling neutron star evolution and emission, for emission and propagation of GCR, to simulate the supernova explosion and shock propagation.

In the domain of the magnetospheric research those methods are useful for a wide range of problems involving the high energy ions, which motion is mainly governed by the internal magnetic field of the planet and therefore the kinetic approach for the trajectory calculation is overall appropriate, and where the precise trajectory of the particles plays significant role in the result. The application field includes both the small scale local interaction of high energy particles with the planet, rings or moons, and also global influence of energetic particles on the system, especially for the cases, when even access of the particles to certain location is important for correct interpretation of the governing processes. To address these problems the starting point would be to understand which particles will arrive at the place of interest and at which energy and for which direction. Particle tracing methods provide the perfect solution for it.

As far as the magnetosphere of Saturn is concerned the particle tracing is the best method for numerical simulation of such processes as, for instance, the energetic particles interaction with the moons. Since the gyroradius of high energy ions is comparable to the size of the moon, the precise calculation of the trajectory is essential to distinguish fine structures in the data. For the cross-calibration of the space instrumentation and to understand better the scientific data sometimes it is important to simulate precisely how exactly and which particles actually enter the instrument, and particle tracer is a suitable tool for this task. This method also allows the study the evolution and refilling rate of the macrosignatures, and to explain the transport of electron microsignatures through the magnetosphere.

Considering the large scale problems this tool is indispensable for the questions related to the GCR. Because of their extremely high energy, these particles are not influenced by the local electrical currents in the magnetosphere and their motion is
mainly controlled by the interplanetary magnetic field and to some extent by the magnetospheric field of the planet, which can at least deflect their trajectory if not trap the particle completely.

3.1 Magnetospheric models

In general charged particle tracing techniques imply the calculation of trajectories of individual charged particles, which do not directly interact with each other and do not affect significantly the external magnetic field. Such a single particle approach is only valid when the collective behavior of the plasma can be neglected, for instance, for the calculation of the test particle trajectory to resolve the small scale interaction processes, or to model the motion of the high energy particles, which are rather rarified in space and time. These techniques require the direct solving of an equation of motion for every particle and consequently the particular determination of the electric and magnetic forces at specific locations. The dipole magnetic field model, described above in Section 2.2.2, can be used as a first approximation for the magnetic field of Saturn in the inner magnetosphere.

The most realistic model of a global magnetospheric configuration of Saturn was provided by Khurana et al. (2006). Its modeling algorithm is based on the developed magnetospheric model of Jupiter (Khurana, 1997). The Khurana model is based on the observations of Pioneer 11, Voyager 1 and 2 and Cassini spacecraft. It consists of several modules determining the internal spherical harmonic field, the ring current, corotation current and magnetotail current system, shielding field from the magnetopause and the interconnection magnetic field from the solar wind IMF.

More complex and realistic magnetospheric models can contribute to more accurate modeling of the charged particles motion. There exist various methods for planetary magnetic field modeling. For the needs of this thesis besides a dipole model I used the hybrid code A.I.K.E.F. (Müller et al., 2011) to obtain the electric and magnetic field strength in the vicinity of the icy moons Rhea and Dione. This code treats ions as individual particles separately and electrons as a massless fluid in order to simulate the local disturbances in the electric and magnetic field in the close vicinity of an obstacle.

3.2 Test particle approaches

Depending on the problem to be studied different methods to compute charged particles motion are appropriate. The test particle approach is suitable if the energy density of the magnetic field exceeds that of the particles, for instance in the study of the radiation belts or cosmic rays. For more turbulent fields, for example, the study of solar wind particles propagation in IMF, it is more suitable to consider the particle transport as a diffusive process, since particle scattering by field fluctuations plays a significant role there. In this case the equations of motion should be replaced by transport equations. For this thesis I will focus on the test particle approach.
Chapter 3. Charged particle tracing techniques

Figure 3.1: Simulation of a charged particle trajectory using: A. full trajectory calculation method, B. guiding center approximation, C. bounce averaged approximation.

The study of single particle dynamics study usually consists of an explicit calculation of the charged particle trajectory. The most precise way is to calculate the full trajectory of the particle. However for certain cases this method is redundant and for the purpose of computational costs a reduction in the number of approximations is commonly accepted. These approximations can be divided into the guiding center and bounce averaged approximations.

The concept of *guiding center approximation* was actively developed in 1960s (e.g., Northrop (1963)) and then applied so magnetospheric modeling by Roederer (1967). This method averages the gyromotion of the charged particle around the center of gyration and calculates the displacement of this center. This is a good solution to study the particle motion through the smoothed fields, which weakly changes on spatial and temporal scales compared to the particle gyromotion.

The bounce averaged approximation averages the bouncing of particles between mirror points and focuses on the particles’ drift around the planet and across the L-shells. These methods are usually applied to study the particle motion over timescales longer than one bounce period and can be very useful to display the adiabatic drifts, for the estimation of the electric field configuration or the diffusion of certain particle populations across the magnetosphere. Figure 3.1 illustrates the modeling of trapped particle motion using those three approaches.

Nevertheless, if the magnetic field varies significantly during one gyration the aforementioned approximations are not valid and the full trajectory calculation is needed to solve the problem. In this thesis I focus on this latter case. In the next Section 3.3 I explain the numerical implementation of the full trajectory calculation.
3.3 Numerical methods

Fundamentally in the core of the numerical solution of the full trajectory calculation method lies the equation of motion, 2.1. There exist numerous methods to solve this differential equation. These methods can be logically divided into two groups:

1. Newtonian integrators
2. Hamiltonian or symplectic methods

Depending on the mathematical logic in their basement all methods differ by the complexity of implementation and computational efficiency, and on the other hand by their ability to determine trajectory and to conserve energy.

The classical Newtonian integrators are representing the first group and they rely on the integration of particle equation of motion. These integrators calculate the trajectory step by step without an option of general adjustment of the trajectory according to the errors. They can only propose to reduce the step-size and therefore decrease the errors on every step; however the total error is accumulated over a large number of time steps and for the modeling on large scales can become unacceptably large. At the same time these methods are explicit and their important advantages include an easy implementation, rather straightforward algorithm, and sufficiently high accuracy for short time-scale problems together with reasonably low computational time. The 4th-order Runge-Kutta (RK4) method is the most popular example of this group. The Boris integrator and its modification are in high demand by plasma physicist, since the Boris method was initially developed for the plasma simulation by Boris (1970).

The second group unites the so-called symplectic or Hamiltonian methods. They integrate the Hamiltonian equations of motion in phase space, operating particle’s momentum and generalized coordinates with condition, that the total energy of the system, otherwise the Hamiltonian \( H \), is conserved. The electromagnetic field is represented here by the electric potential and the magnetic vector potential. These methods focus on controlling the error in total energy, but usually they are implicit and therefore their computational time is much higher. Feng and Qin (2010) provided a comprehensive description of the Hamiltonian methods.

Explicitness and computational cost were the crucial parameters in my choice of numerical methods for the developed particle tracer. Together with an adaptive time stepping and suitable modifications of classical methods, the Newtonian integrators can perform even better than the Hamiltonian methods not only in the sense of computational effectiveness, but also in terms of energy conservation, as shown, for instance, in the work by Mao and Wirz (2011), who compared 5 different numerical techniques for the charged particle tracing problem.

In my particle tracer I implemented three numerical methods: the classical RK4, the Boris method and the Vay method - modification of the Boris method for relativistic particles.
3.3.1 Fourth-order Runge-Kutta method

One of the most widely used numerical method to solve ordinary differential equations like Eq. 2.1 is the 4th-order Runge-Kutta method (RK4). This is an explicit method and its computational principle consists of calculating the error term 4 times per one step before final movement to the next particle’s position to rise the accuracy in the calculation of the entire step.

The RK4 method can be formalized as:

\[ y_{n+1} = y_n + \frac{1}{6} \left( k_0 + 2k_1 + 2k_2 + k_3 \right) \] (3.1)

where the error terms determined as follows:

\[ k_0 = hf(x_n, y_n) \] (3.2)
\[ k_1 = hf(x_n + \frac{1}{2}h, y_n + \frac{1}{2}k_0) \] (3.3)
\[ k_2 = hf(x_n + \frac{1}{2}h, y_n + \frac{1}{2}k_1) \] (3.4)
\[ k_3 = hf(x_n + h, y_n + k_2) \] (3.5)

Figure 3.2 illustrates the principle of the RK4 method. The detailed description and full derivation of it could be found in Press et al. (1992).

For the needs of the model I implemented an adaptive step-size algorithm, depending on the current particle gyroradius, which significantly reduced the calculation time. For the needs of the research devoted to energetic particle trajectory modeling in the close vicinity of icy moons, described in Chapter 5, on the scale of few gyroradii, this method perfectly fits to the project’s needs with sufficiently high accuracy and reasonable run time. However for the large scale project, with particles of energies around tens of GeV and traced through the distance of 25 Saturn radii, this method is not appropriate and a more advanced numerical solution was needed, suitable for relativistic particles with significantly smaller error per step.
3.3.2 Leapfrog and Boris methods

Boris (1970) developed the new numerical method specifically for the plasma simulation needs. It is widely used, especially in so-called "Particle-in-Cell" algorithms.

The Particle-in-Cell (PIC) concept, first proposed by Harlow (1955) and his colleagues, usually describes the modeling approach, where "macro-particles" are used to represent the real ions, electrons and neutrals in a grid of predefined electromagnetic field. The main parts of computational algorithm include the "field solver", which solves Maxwell’s equations for positions between the grid nodes, and the "particle pusher", which solves the Newton-Lorentz equation and determines the next particle’s position. I am interested in the realization of a second part.

The simplest variation of a particle pusher is the so-called leapfrog method. It is fast and numerically stable. It consists of two steps: velocity integration through the time step and update of a particle’s position:

\[
\frac{x_{k+1} - x_k}{\Delta t} = v_{k+1/2}
\]

\[
\frac{v_{k+1/2} - v_{k-1/2}}{\Delta t} = \frac{q}{m} \left( E_k + \frac{v_{k+1/2} + v_{k-1/2}}{2} \times B_k \right)
\]

The times at which velocity and positions are calculated are offset from each other by a half of a time step, and from here comes the name of this method. Figure 3.3 illustrates this idea.

The Boris method is a second-order leapfrog integrator of the equations of motion. It is more complex and enables the transient values of electric and magnetic impulses acting on the particle. The Boris scheme is realized in the following set of equations:

\[
x_{k+1} = x_k + \Delta t v_{k+1/2}
\]

where

\[
v_{k+1/2} = u' + q'E_k
\]

\[
q' = \Delta t \left( \frac{q}{2m} \right)
\]

\[
u' = (u + (u \times h)) \times s
\]

\[
u = v_{k-1/2} + q'E_k
\]

\[
h = q'B_k
\]

\[
s = \frac{2h}{1 + h^2}
\]

For the tracing of GCR through the magnetosphere of Saturn in the distance range of several Saturn radii, described in Chapters 6 and 7, the Boris method provided much better accuracy than RK4, at the same time being significantly more expensive in terms of computational time. However, with the increase of the particle’s energy up to
several GeV the relativistic effects should be taken into account. In the Boris algorithm the discretization of electric and magnetic field may lead to the wrong evaluation of a relativistic factor $\gamma$, as shown by Vay (2008). In order to overcome this ambiguity Vay (2008) proposed an alternative formulation of the second-order leapfrog solver, and I implemented this method for the problem under study.

Figure 3.3: Computational principle of the Leapfrog method.
3.3. Numerical methods

3.3.3 Vay method for relativistic particles

To trace GeV particles the method provided by Vay (2008) was chosen, which conserves the strict Lorentz invariance even for relativistic energies. The specificity of this method consists in the determination of the relativistic factor $\gamma$ at the point $k - 1/2$ along with setting the corresponding $u$ variable, which is determined as $u = \gamma v$. Then knowing the position at the point $k$ to calculate the velocity at the point $k + 1/2$ it is first needed to get the value of $u_k$ from $u_{k-1/2}$ using 3.15:

$$u_k = u_{k-1/2} + \frac{q\Delta t}{2m} \left( E_k + v_{k-1/2} \times B_k \right)$$

$$= u_{k+1/2} - \frac{q\Delta t}{2m} \left( E_k + v_{k+1/2} \times B_k \right)$$  \hspace{1cm} (3.15)$$

and then to get $u_{k+1/2}$ from $u_k$ using the series of auxiliary equations 3.16, 3.17 and 3.18. Finally this leads to $v_{k+1/2}$.

$$u' = u_k + (q\Delta t/2m) E_k$$  \hspace{1cm} (3.16)$$

$$\gamma_{k+1/2} = \sqrt{\frac{\sigma + \sqrt{\sigma^2 + 4(\tau^2 + u^2)}}{2}}$$  \hspace{1cm} (3.17)$$

$$u_{k+1/2} = s \left[ u' + (u' \cdot t) t + u' \times t \right]$$  \hspace{1cm} (3.18)$$

where

$$\tau = (q\Delta t/2m) B_k$$  \hspace{1cm} (3.19)$$

$$u^* = u' \cdot \tau/c$$  \hspace{1cm} (3.20)$$

$$\sigma = \gamma^2 - \tau^2$$  \hspace{1cm} (3.21)$$

$$\gamma' = \sqrt{1 + u^2/c^2}$$  \hspace{1cm} (3.22)$$

$$t = \tau/\gamma_{k+1/2}$$  \hspace{1cm} (3.23)$$

$$s = 1/ \left( 1 + t^2 \right)$$  \hspace{1cm} (3.24)$$

Numerous tests of GeV particles tracing using the above described methods confirmed the fidelity of the Vay method in contrast to the Boris scheme. Both, RK4 and Boris algorithms did not pass the control tests, which includes the energy conservation control and the convergence of trajectories modeled first forward and then backwards.
3.4 Particular features of developed particle tracer

In order to answer the main question of my research about the GCR access to Saturn, it was necessary to develop the appropriate tool allowing the calculation of energetic particles trajectories in planetary magnetospheres. For this purpose I developed the new particle tracing code from scratch. The code is written in the programming language C++ and has an interface to the Khurana model, written in Fortran, and to output of the A.I.K.E.F. code (see Section 3.1 for description of magnetospheric models). IDL routines were developed for visualization of the results.

The particle tracer can work in three modes, calculating either the full trajectory of the particle, or the guiding center trajectory, or the bounce averaged trajectory. There are three calculation methods available as integration algorithms: RK4 method, Boris method and Vay method for relativistic energies.

3.4.1 Adaptive step-size

An adaptive step-size was implemented in order to increase accuracy and reduce time consumption. The integration steps are less than 0.1% of the gyroradius and are adjusted according to its changes, relevant for GCR tracing, since an incoming GCR changes its gyroradius drastically during its approach to the planet.

3.4.2 Backwards tracing

In order to estimate the GCR access to the planet it is more appropriate to calculate trajectories of GCR backward in time: starting from the planet until the boundaries of the magnetosphere. If the particle leaves the magnetosphere successfully, it means, that the particle with the same parameters could actually enter the magnetosphere and impact the planet with the same energy and pitch angle, as stated at the beginning of the experiment. Therefore it significantly reduces the number of simulated trajectories.

In this code backward tracing of the charged particles is performed through the use of negative time steps $-dt$ during integration. The validity of the backwards tracing was verified by comparison of results with forward-modeled trajectories.

3.4.3 Parallel calculations

Calculation of high energy GCR trajectories through the entire magnetosphere requires a lot of computational facilities. However the particle tracing code is quite easy to parallelize since the energetic particles do not influence each other on their trajectories. Consequently, the code was parallelized and run on the cluster of High-Performance-Computers, provided by the Max Planck Institute for Solar System Research.
3.4. Particular features of developed particle tracer
Chapter 4

The Cassini mission to Saturn and its magnetospheric science instrumentation

The Cassini-Huygens mission to Saturn is one of the biggest and most successful planetary missions to the outer Solar System so far. It unites the Cassini orbiter of Saturn and the Huygens lander to Titan, largest moon of Saturn and the only moon in the Solar System with a dense atmosphere and confirmed liquid surface elements, such as rivers and seas. The spacecraft started its journey from Earth in October 1997 and after almost 7 years it arrived to Saturnian system in the beginning of July 2004. The Huygens probe landing happens half year later, on January 15, 2005, and the orbiter Cassini operates well for already almost twelve years. The mission, initially planned for four years, was extended twice and currently it is close to its final stage: later in 2016 it will start the so-called ”proximal” orbits extremely close to the F ring first and later to the planet itself inside the inner edge of the D ring. Finally in September 2017 the orbiter will point its main antenna towards Earth and will plump into Saturn’s atmosphere continuously sending unique data before it stops operating.

Before Cassini Saturn was visited three times: the space missions Pioneer 11, Voyager 1 and Voyager 2 performed close flybys of this giant planet in September 1979, in November 1980 and in August 1981 respectively. These flyby missions provided spectacular data and demonstrated the deep complexity of the Saturnian system, raising such a large number of questions exceeded the number of answers provided. That is why an orbiting mission, providing global coverage of all regions of the Saturn’s environment and during different seasons, was essential for a deeper exploration of the system.

The main goal of the Cassini mission is to study planet Saturn, its rings, magnetosphere, numerous icy satellites and Titan. This spacecraft carries onboard 12 instruments, a list of which can be found in Table 4.1. Initial magnetospheric and plasma science objectives are to determine the magnetic field configuration and its relation to the Saturn Kilometric Radiation (SKR), to define current systems, composition, sources, and sinks of charged particles, to investigate wave-particle interactions and the dynamics of the dayside magnetosphere and the magnetotail of Saturn and their interactions with the solar wind, the satellites, and the rings, to study Titan’s
### 4.1 Magnetospheric IMaging Instrument

The Magnetospheric IMaging Instrument (MIMI) is a neutral and charged particle detection system designed to carry out both remote global imaging and in-situ measurements to study the overall configuration and dynamics of Saturn’s magnetosphere and its interactions with the solar wind, Saturn’s atmosphere, Titan, and the icy satellites. MIMI consists of three sensors: the low energy magnetospheric measurements system (LEMMS), the charge-energy-mass-spectrometer (CHEMS) and the ion and neutral camera (INCA). Synergistic remote sensing and in-situ measurements of the magnetosphere provide numerous benefits. For instance, by in-situ measurements one can validate inferences from imaging observations or deconvolve structures along the line-of-sight. On the other hand the imaging observations provide the global context for the local measurements.

Figure 4.1 depicts the position of the three MIMI sensors and two magnetometers.
Chapter 4. The Cassini mission to Saturn and its magnetospheric science instrumentation

4.1.1 LEMMS

The LEMMS instrument is a double-ended telescope designed to measure distribution of energetic ion and electron fluxes. The Low-Energy (LE) End detects 27 keV - 18 MeV ions and 15 keV - 0.884 MeV electrons, it has a conical field of view through a collimator with an aperture angle 15°, which is divided into 7 hexagonal entrance channels. The High-Energy (HE) End is measuring high-energy ions (1.6 – 160 MeV) and electrons (> 100 keV) and it has a conical field of view of 30° with a collimator divided into 19 hexagonal entrance channels. The instrument is heavily shielded by a platinum cover in order to avoid penetrating particles with energies less than 30 MeV through the sides of the instrument. However, very energetic particle, like Cosmic Rays for instance, are still able to penetrate and cause cosmic rays background in the data. Weight of the instrument is 6.72 kg.

LEMMS is mounted on a platform rotating about the -y-axis of the spacecraft (co-aligned with the remote sensing and optical instruments) and measures angular distributions of ions and electrons within a scan plane. Unfortunately the rotating plate stopped working 6 months after arriving at Saturn. Initially, during the rotation the field of view of telescopes was partly obscured by the spacecraft itself (by the cover of one of the radioactive thermal generators, by one of the thrusters and the antenna), but when LEMMS’s turning platform finally stopped on 2nd of February 2005, LEMMS was placed in a way that neither of LEMMS telescopes is obscured. A picture of LEMMS is shown on Figure 4.2.
4.1. Magnetospheric IMaging Instrument

The measuring principle of LEMMS is based on energy loss of incident particles in solid state detectors (SSD). Figure 4.3 shows the overall configuration of LEMMS and positions of its 11 SSDs.

The LE telescope is equipped with an internal permanent magnet, which produces an inhomogeneous magnetic field. It separates incoming ions and electrons and consequently they hit different detectors, as shown on Figure 4.4. Electrons are deflected by the magnet and directed to the electron detectors E (E1 and E2) and F (F1 and F2) depending on their incident energy. Ions have much bigger gyroradii and their trajectory remains almost straight. They hit the detector A and, if not absorbed, the detector B (shown on Figure 4.3). Behind detector B a golden absorber is placed (with a thickness of 1 mm), which separates LE and HE telescopes and it stops all ions of energy below 40 MeV and all electrons of energy below $\sim 7 \text{ MeV}$.
The HE telescope consists of a stack of five detectors D1, D2, D3a, D3b, and D4. An aluminum foil is inserted in front of the entrance to HE end in order to prevent incoming light and the flux of low-energy ions and electrons to enter it. Depending on their energy, ions will penetrate certain number of detectors and will be absorbed in one of them. Coincidence of these detectors provides measurements for co-called “rate channels” of LEMMS. Similarly the coincidence logic is realized in LE telescope for detectors E and F, and for detectors A and B. This measuring principle take into account only particles entering from the collimator and also filters the secondary particles from the data. In this technique the data are obtained from the amplified voltage, which results from the electron/hole production in the semiconductor and is exceeding certain threshold values. Sacrificing the resolution, this allows to cover a wider energy range with limited energy channels. However this method does not provide very good energy resolution.

An alternative measuring principle is provided by detectors A, E1 and F1, which are also processed through a pulse height analyzer (PHA) that produces 64-channel energy spectra for ions and 128 energy steps for electrons in the so-called ”PHA channels”. Here the initial energy of particle is extracted from the amplified voltage with much better accuracy. Nevertheless these detectors have quite small thicknesses and if the particle energy is too high it can penetrate detector, and will not be detected at all.

With the stopping of LEMMS’s turning mechanism the time resolution of its measurements increased by a factor of 16 to about ∼ 5 seconds. The 3-D observations may be compiled when the spacecraft itself is rolling or using the data from several passages through the same area but with different looking directions.

4.1.1.2 Calibration of LEMMS

Several calibration campaigns have been performed in order to determine the instrument’s responses. Numerous beam facilities were used to calibrate the instrument with electrons and ions in various energy ranges. Moreover several radioactive sources
Figure 4.5: Determination of energy channel limits for protons for LEMMS channels A0 – A4 of the low energy end (from Krimigis et al. (2004)). Color lines represent the normalized count rates for every channel.

Later, when Cassini Mission was already started, its measurements during the Earth flybys were used for additional calibration of some instruments including LEMMS. Improved modeling facilities and additional tests provided better understanding of LEMMS sensitivity. Armstrong et al. (2009) provided the updated values for LEMMS energy passbands and determined the response of LEMMS to ions heavier than protons. In Table 4.2 I list energy ranges for channels A0-A4 for different species, and the difference in response occurs since the energy loss of ions on semiconductors depends on the ion mass. These values were used for data interpretation in Chapter 5.

Table 4.2: LEMMS calibration results for channels A0 – A4 for $H^+$, $He^+$ and $O^+$ (based on work by Armstrong et al. (2009)).

<table>
<thead>
<tr>
<th>Channel</th>
<th>$H^+$</th>
<th>$He^+$</th>
<th>$O^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>27-35 keV</td>
<td>32-40 keV</td>
<td>58-70 keV</td>
</tr>
<tr>
<td>A1</td>
<td>35-56 keV</td>
<td>40-64 keV</td>
<td>64-96 keV</td>
</tr>
<tr>
<td>A2</td>
<td>56-106 keV</td>
<td>63-116 keV</td>
<td>96-160 keV</td>
</tr>
<tr>
<td>A3</td>
<td>106-255 keV</td>
<td>117-272 keV</td>
<td>160-336 keV</td>
</tr>
<tr>
<td>A4</td>
<td>255-506 keV</td>
<td>270-520 keV</td>
<td>336-608 keV</td>
</tr>
</tbody>
</table>
Figure 4.6: Cassini MIMI/CHEMS mechanical configuration (from Krimigis et al. (2004)).

4.1.2 CHEMS

CHEMS uses electrostatic deflection, energy per charge analysis and the time-of-flight (TOF) versus energy measuring technique to determine the mass per charge and separately mass of ions. CHEMS observes the 3-D distribution function of elemental and molecular ions from ∼ 3 to 220 keV/e from protons up to iron in the magnetosphere of Saturn and in interplanetary space by measuring the flux spectrum, charge state and composition. When the spacecraft is rolling it can also measure the 3-D distribution of particles. CHEMS provides much more detailed analysis of energetic ions compared to LEMMS, but with significantly lower time resolution. Figure 4.6 demonstrates the configuration of this detector.

The operation principle is as follows. Ions with a certain kinetic energy, mass and charge state enter the detector. The electrostatic deflector filters UV photons and ions with inappropriate energy, therefore only ions of a certain energy range, determined by the stepped deflection voltage, can enter the TOF system. Ions penetrate the thin (∼ 2.5µg/cm²) carbon foil (start detector) at the entrance of the TOF telescope, producing secondary electrons, which are detected by one of the three microchannel plates (MPCs) and therefore the start signal for TOF analysis is generated. In 10 cm from the entrance the three silicon SSDs (stop detectors) are located. Ions strike one of the SSDs, again producing secondary electrons, which are deflected onto one of three stop MCPs, creating the stop signal. The TOF analysis together with measurements of residual energy in SSDs allows to identify the parameters of incident particles. Along with three types of counting rate data, CHEMS provides also the PHA events, which give the complete information about individual ions.
4.1. Magnetospheric IMaging Instrument

4.1.3 INCA

INCA is a large time-of-flight (TOF) detector of energetic neutral atoms (ENAs) and ions, which is able to measure the composition and directions of motion of incident particles. ENAs are produced during the charge-exchange collisions between energetic ions and a cold neutral gas population. Capturing electron from ambient neutral gas but keeping its energy, the former ion becomes an energetic neutral particle, its trajectory becomes a nearly straight line and is not affected anymore by the electromagnetic forces. ENAs can travel far away from the location of charge-exchange collisions, but their trajectory will point directly to it and they can be used similarly to photons to form "ENA-images" of the emitting regions. Hence every INCA pixel provides a counting rate, which is proportional to the energetic ions intensity along the line-of-sight, cold neutral densities and the corresponding charge-exchange rate. INCA can distinguish ENA hydrogen and ENA oxygen and these two species can be analyzed separately.

INCA remotely sense magnetospheric ions with energy $> 7\text{keV/nuc}$ and $< 3\text{MeV/nuc}$ by taking images of the global distribution of the energetic neutral emission of hot plasmas and by determinate the directional distribution, energy spectra, and crude composition of charge-exchange neutrals and ions for each pixel in the image. Figure 4.7 shows the configuration of this sensor.

The measuring principle of INCA is also based on TOF technique. Neutral particles penetrate a thin foil at the entrance of the detector, producing secondary electrons which then are deflected to the start microchannel plate (MCP), generating a start signal. The original particle later strikes the second foil, correspondingly producing secondary electrons, which are deflected to the stop MCP and 2-D imaging anode, mapping the position of impact and registering the stop time for the TOF measurement. The back-scattered electrons are also counted by the side coincidence MCPs in order to filter the uncorrelated background from the target measurements. Since
oxygen particles are producing several times more secondary electrons, than hydrogen, the PHA of the MCP signal is enough to determine the atomic number of the incident particle. In other words the arrival direction is detected by back-foil penetration location, TOF measurements give the particle’s velocity and PHA determines particle atomic number and energy. Charged particles that are directed towards INCA are excluded through an electric field applied on the collimator blades. When the electric field of these blades is switched off, INCA acts as a very sensitive energetic ion detector.

4.2 Magnetometer

Cassini Magnetometer (MAG) is an instrument devoted to determine the internal magnetic field of Saturn and develop the 3-D model of its magnetosphere by measuring the absolute magnitude of the magnetic field with an accuracy of 1 nT. This instrument consists of a flux-gate magnetometer (FGM) and a helium magnetometer (VHM), and its operational principle is based on the dual technique and it can operate either in vector or in scalar mode (V/SHM). The latest mode allows to calibrate FGM measurements with the absolute scalar measurements of VHM and to detect wave fields with high accuracy. Measurements of two magnetometers perfectly complement each other, since the FGM is more sensitive at high frequencies and the VHM better performing below 1 Hz, and together they cover the whole range of frequencies from below 1 Hz and up to 20 Hz.

Sensors are mounted on the 11 m spacecraft boom, the FGM in the middle of it and the V/SHM at the end, indicated on the left panel of Figure 4.1. This helps to reduce the influence from the spacecraft generated field fluctuations on the scientific data. The difference in the distance from the main spacecraft is also contributing to a better determination of the spacecraft originating noise in the data.

The FGM configuration based on three orthogonal ring core fluxgate sensors, each of them is wound around by a drive coil and a sense coil. The operation principle is based on the asymmetry of the saturation of the core. It happens, when along with the magnetic field generated by the drive coil, the ambient magnetic field has a component parallel to the axis of the sense coil. The operation of the V/SHM sensor is based on the Zeeman effect (field dependent light absorption) and optical pumping to sense the magnetic field. Unfortunately the V/SHM stopped working in 2005. The detailed description of MAG instrument and its operation methods can be found in Dougherty et al. (2004).

MAG data provides the orientation of the magnetic field used to determine the particle’s pitch angles measured by LEMMS. Also, in the frame of this thesis the MAG measurements are used indirectly as a base for global magnetosphere modeling (for instance Khurana model, described in Section 3.1) and also to calibrate local models of magnetospheric processes, such as, for instance, the plasma interaction with icy moons, as it is described in Section 5.4.3.
4.3 Cassini orbital coverage

Arrival of Cassini at Saturn was on July 1, 2004 with a very close approach to the planet accompanied by a set of maneuvers for the "Saturn Orbit Insertion" (SOI). So far it was the only passage of the spacecraft so close to Saturn and rings and the single opportunity to look at the magnetosphere inside of the radiation belts. Cassini MIMI/INCA observations during this passage brought unique data, which are discussed in Section 6.4 together with the details of this orbit.

After arriving at Saturn Cassini has performed 234 orbits so far (as of April 2016). The nominal mission was accomplished during the first 4 years from July 2004 to July 2008 and included the delivery of the Huygens probe to Titan. In total 75 orbits around Saturn, 44 Titan targeted flybys, 4 Enceladus targeted flybys and numerous icy moons flybys were completed. The main scientific observations were focused on the planet itself, its icy satellites, the ring system, Titan and the Saturnian magnetosphere. Cassini’s trajectory during Nominal Mission is demonstrated on Figure 4.8 with SOI highlighted.

Figure 4.8: Cassini Nominal Mission orbits.
Cassini’s Equinox Mission went on for another two years until October 2010, included 60 revolutions around Saturn, 26 Titan flybys and many new icy moon flybys along with 7 Enceladus targeted flybys. The goal of this mission was the observation of seasonal changes in the Saturnian system related to the Saturn vernal equinox: the Sun passed the equatorial plane on 11 August 2009 and the Saturnian Southern Summer changed to Saturnian Northern Summer.

Cassini Solstice Mission is continuing from 2010 until now and includes 155 orbits around Saturn, 54 flybys of Titan and 11 of Enceladus. The Sun will reach its highest elevation on the northern hemisphere in May 2017 and therefore Cassini will spend exactly half of the Saturnian year in its neighborhood. Orbits of Cassini during Equinox and Solstice Missions are shown on Figure 4.9.

Figure 4.9: Cassini Equinox and Solstice Missions orbits.
4.3. Cassini orbital coverage

The final part of Cassini Mission was named "Proximal orbits”, it will start in the end of November 2016 and will include 20 highly inclined F-ring orbits and 22.5 D-ring orbits passing directly through the tiny gap between the rings and Saturn’s atmosphere. During these orbits Cassini will finally revisit the mystery region inside the D-ring, which was scanned once during SOI (Krimigis et al., 2005). The last targeted Titan flyby will happen in April 2017 and will lead to the "Grand Finale” orbits, last of them is planned for 15th of September 2017 and will lead to the final descend into Saturn. Cassini’s trajectory during this part of the mission is depicted on Figure 4.10 with Grand Finale orbits highlighted.

Figure 4.10: Cassini Proximal orbits.
Chapter 5

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

In order to validate the developed particle tracer it was essential to apply it to some clear and straightforward problem, where the results of particle tracing can be directly compared with in-situ observations and therefore verified, before proceeding to the tracing of GCR.

Modeling of Cassini MIMI/LEMMS observations is an appropriate task for a particle tracer. Knowing the configuration of the detector and the electromagnetic environment from measurements by other Cassini instruments, it is possible to simulate trajectories of energetic particles backwards from the detector and determine the path of the particles before they encounter LEMMS. This approach allows one to reproduce the particle flux, measured by LEMMS, during certain events or on specific parts of the Cassini orbit.

One of the interesting questions which can be answered by such a technique is the interpretation of the LEMMS measurements of energetic ion differential fluxes in the close vicinity of the Saturnian icy moons. During some of these flybys LEMMS measured a significant reduction of energetic ion fluxes (20 keV - 300 keV), caused by the absorption of those ions onto the moon surfaces. Using the charged particle tracer it is possible to determine which of the magnetospheric characteristics are more important in shaping the LEMMS ion profiles. At the same time the performance of the LEMMS detector itself can be examined and the hypothesis about the LEMMS effective response to heavier ions can be verified, in contrast to the previously assumed reaction solely to protons.

The results of this study show that the LEMMS detector indeed responds to heavier ions. Also it was discovered that the bending of magnetic field lines around the moons, even if it caused local perturbations of only about a few percent of the background magnetic field, can cause measurable changes in the spatial and energy distribution of fluxes measured by LEMMS. These results are important to correctly interpret the
LEMMS data, and offer capabilities for precise in-flight instruments' cross-calibration. It was demonstrated, that the particle tracing approach can be applied in various environments (Titan, Enceladus, Jovian moons etc.) to constrain the magnetic topology of their interaction region and to identify the composition and charge-states of ions at high energies, as well as to support future limited instruments capabilities.

The results presented in this chapter were published in Kotova et al. (2015). This study was performed in the years 2012-2014 and does not include the last two Dione flybys in 2015.

5.1 Introduction

During several flybys in the close vicinity to the Saturnian icy moons Rhea and Dione Cassini the MIMI/LEMMS instrument detected a significant depletion of energetic ion differential fluxes (below referred to as "fluxes"). Previous studies that reviewed MIMI data from those flybys focused mainly on the energetic electron observations by 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 close to the 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. 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 charge states and instrument pointing, play a role in shaping such depletion profiles and are not included in those studies. 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 LEMMS signal. There are several practical aspects which make such an investigation useful and necessary. For instance the 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. Selesnick and Cohen (2009) simulate similar MeV ion flux depletions near Jupiter’s moon Io which can reveal information about the charge states of these ions, and properties of the Alfvén wing type of perturbation downstream of that moon. If this technique is 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, target of the JUICE mission in the future.

In order to study the aforementioned energetic ion flux depletions the developed charge particle tracer was used, simulating the trajectories of energetic charged parti-
Chapter 5. Modeling of the energetic ion observations in the vicinity of Rhea and Dione

icles in the vicinity of the moons to reconstruct measurements obtained by LEMMS. The comparison of the simulations with the LEMMS observations allows one to infer the significance of the different factors that shape the energetic ion flux profiles.

5.2 Cassini observations during Rhea and Dione flybys

During the first 10 years of the Cassini mission at Saturn the spacecraft performed numerous flybys by icy moons Rhea and Dione. Between 2004 and 2014 five (four targeted) Rhea flybys and three Dione flybys occurred. Two more Dione flybys were performed in 2015 and not included in this research. Table 5.1 contains the general information about these flybys and Figure 5.1 (adopted from Roussos et al. (2012)) shows the Cassini spacecraft trajectory during the Rhea and Dione flybys. Detailed descriptions of Rhea flybys can be found in Roussos et al. (2012), Krupp et al. (2013) provided comprehensive information about the first three Dione flybys and Teolis and Waite (2016) among others described the last two Dione flybys.

Table 5.1: Rhea and Dione flybys orbital information. Flybys D4 and D5 are not included in this study.

<table>
<thead>
<tr>
<th>Number</th>
<th>Date</th>
<th>Orbit NN</th>
<th>DOY</th>
<th>CA time</th>
<th>CA distance</th>
</tr>
</thead>
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<tr>
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<td>183</td>
<td>68</td>
<td>10:17</td>
<td>997 km</td>
</tr>
<tr>
<td>R3</td>
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<td>143</td>
<td>11</td>
<td>04:53</td>
<td>75.9 km</td>
</tr>
<tr>
<td>R2</td>
<td>2 Mar 2010</td>
<td>127</td>
<td>61</td>
<td>17:42</td>
<td>100.9 km</td>
</tr>
<tr>
<td>R1.5</td>
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<td>49</td>
<td>242</td>
<td>01:22</td>
<td>5737 km</td>
</tr>
<tr>
<td>R1</td>
<td>26 Nov 2005</td>
<td>18</td>
<td>330</td>
<td>22:37</td>
<td>500 km</td>
</tr>
<tr>
<td>D5*</td>
<td>17 Aug 2015</td>
<td>220</td>
<td>229</td>
<td>18:33</td>
<td>474 km</td>
</tr>
<tr>
<td>D4*</td>
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<td>217</td>
<td>167</td>
<td>20:11</td>
<td>517 km</td>
</tr>
<tr>
<td>D3</td>
<td>12 Dec 2011</td>
<td>158</td>
<td>346</td>
<td>09:48</td>
<td>99 km</td>
</tr>
<tr>
<td>D2</td>
<td>7 Apr 2010</td>
<td>129</td>
<td>97</td>
<td>05:16</td>
<td>503 km</td>
</tr>
<tr>
<td>D1</td>
<td>11 Oct 2005</td>
<td>16</td>
<td>284</td>
<td>17:52</td>
<td>498.5 km</td>
</tr>
</tbody>
</table>

During two of the Rhea flybys (namely R2 and R3) and during the first Dione’s flyby (D1) the LEMMS detector (described in Section 4.1.1) detected significant reductions in energetic ion fluxes. Figure 5.2 demonstrates the LEMMS data during these three flybys. Different line colors represent different channels: A0 - A4 for energetic ions and C0 for energetic electrons 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). Closest approach (CA) of the spacecraft to the moon is marked by the vertical dashed line. It can also be effectively recognized by the center of the electron flux depletion. The electron gyroradius is small relative to the size of the moon, meaning that the

69
5.2. Cassini observations during Rhea and Dione flybys

Figure 5.1: 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 at the origin of the coordinates, 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 multiplies of every moon’s radius are shown with dotted circles. The dashed lines show the expected location of the corotational wake (adopted from Roussos et al. (2012)).

depth marks the width of the moon’s flux tube.

All three plots demonstrate that ion depletions have a complex shape. They are asymmetric with respect to the closest approach, the width of the depletion is increasing with energy and the depletion profile has several steps, and even two local minima occur in the case of the A4 channel during the D1 flyby. All of this leads to the idea that these dropouts are most likely caused by energetic ion absorption onto the moons. The radius of Rhea $R_{Rh}$ is about 764 km and the radius of Dione $R_{Di}$ is almost 562 km, which is comparable to the gyroradius of the energetic ions with energies of about tens or hundreds of keV. Therefore the use of the guiding-center approximation or similar methods, mentioned in Chapter 3, is unapplicable for studying this question and the precise calculation of the full energetic ion trajectories is needed for a correct interpretation of the LEMMS observations: ion trajectories and absorption signatures are dominated by finite ion gyroradii effects, similar to Titan (Garnier et al., 2010). Consequently the full trajectory tracing is an essential technique for studying the energetic ions interaction with icy moons on such a scale.

Assuming that the depletion in energetic ion fluxes is caused by ion absorption onto the moon, then the shape of the depletion is mostly determined by the ion gyroradius. The radius of gyration is given by Equation 2.5 and depends on particle’s mass $m$, the
Chapter 5. Modeling of the energetic ion observations in the vicinity of Rhea and Dione

Figure 5.2: The LEMMS data for selected Rhea and Dione flybys: R2, R3, D1 in particle flux units. In the flyby R3 plot, light contaminated data of A0 and C0 have been removed. In the plot of D1 the signal of A0 and A1 is not shown as it is very weak and noisy (ions at that energy range are completely removed due to charge exchange at Saturn’s dense neutral cloud in Dione’s orbit). Vertical dashed line represents the closest approach to the moon.
5.2. Cassini observations during Rhea and Dione flybys

Figure 5.3: Sketch of particle trajectories in a dipole magnetic field tracing backwards in time from the LEMMS instrument with different energies. Due to the different gyroradius, protons starting from the same location will impact the moon (500 keV proton - red line) or not (1 keV proton - blue line, and 50 keV proton - yellow line).

The obtained LEMMS signal depends significantly also on various instrument parameters, such as pointing, channel energy range, geometrical aspects of the detector (conic shape etc.) and species response. The CHEMS detector (described in Section 4.1.2) data show that at the distance of Rhea protons and oxygen ions are equally abundant in the $20 - 200$ keV range (Dialynas et al., 2009). But LEMMS cannot discriminate between ion species. Measurements of different ion species are reported as a total count rate. However this separation is important for the LEMMS signal interpretation. The study of particle transport in the magnetosphere requires the transformation of fluxes to phase space densities (PSD). A comprehensive model of ions lost by encountering the neutral cloud of Saturn is also essential. Both the conversion of fluxes to PSD and the calculation of loss rates are species dependent. Below in Section 5.4.2 it is demonstrated how the CHEMS data can help.

As the gyroradius depends also on $B$, ion depletions are sensitive to the various magnetospheric parameters (magnetospheric field model, corotation velocity, distor-
Chapter 5. Modeling of the energetic ion observations in the vicinity of Rhea and Dione

ions in local interaction region with the moon etc.). Rhea orbits Saturn at a distance of $527.108 \times 10^6$ m ($\approx 8.75R_S$, where $R_S = 60268$ km is a radius of Saturn) (Orton et al., 2009), at the inner edge of Saturn’s ring current region (Roussos et al., 2008b). The magnetic field strength at this distance from the planet is already significantly diminished to a value of $19 - 21$ nT, compared to an expected 31 nT from Saturn’s dipole field alone. This reduction, caused by the ring current, leads to the plasma beta approaching unity (Sergis et al., 2013). As a consequence currents resulting from the interaction of Rhea with Saturn’s magnetosphere will also cause relatively strong, localized distortions in the magnetic and electric field downstream of the moon. In contrast, Dione orbits Saturn at a distance of $377.420 \times 10^6$ m ($\approx 6.3R_S$) (Matson et al., 2009), where Saturn’s internal magnetic field still is the dominant one and thus the local perturbances in the magnetic and electric fields are not so strong.

By tracing energetic ions in the vicinity of Rhea and Dione the LEMMS signal is simulated based on the local parameters during the different flybys and features in the LEMMS observation profile are investigated.

5.3 Particle tracing for LEMMS signal modeling

Using the developed particle tracer one can investigate how the particle trajectory will change after altering certain parameters of the background environment.

Since it is assumed that the depletion in the energetic particle flux was caused by absorption at the moon, the backward tracing of the particles from the position of the LEMMS detector toward the direction of the particle’s origin can be performed. Hereby it is possible to determine if this particle hits an obstacle (the moon) along its trajectory or not. If the particle does hit the moon it will be assumed that this particle was absorbed by the moon and therefore was not able to reach the LEMMS detector. If the particle passed by the moon freely, it is accepted that particles with the same characteristics coming from this given direction can be counted by LEMMS.

The drift motion of energetic ions around Saturn is very fast because they experience gradient/curvature drift plus the influence of a corotation electric field, which is along the gradient/curvature drift direction on Saturn (see Section 2.2.4 for theoretical explanation of a drift motion). For instance, the half bounce period (time they need to return to the equatorial plane) of 100 keV protons is about 130 sec while they drift with a velocity of 45 km/sec. This means that during half a bounce they drift a distance of 6000 km, much larger than the $\sim 1500$ km diameter of Rhea or the $\sim 1200$ km diameter of Dione, and much faster than the moon’s motion along its orbit. Figure 5.4 illustrates this idea. That means that ions have only a single chance to impact the moon during their bounce motion and this allows us to significantly reduce the calculation time. After the particle bounces back to the equatorial plane from its mirror point, it is already far from the moon due to the action of the corotation. Consequently, it is appropriate to include in the simulation only one passage of every particle next to the moon and then stop the simulation for this particle after it
5.4. **Flyby simulation**

Figure 5.4: This figure illustrates how corotation electric field accelerates the drift of a charged particle. The drift motion of energetic ions around Saturn is very fast because they experience corotation plus the gradient/curvature drift which is along the corotation direction. For comparison, blue line represents the trajectory of an energetic ion if the corotation electric field is neglected and red line - if it is taken into account. Here the x-axis is a longitude angle of the particle \( \varphi = \arctan(y/x) \) - illustrated longitude displacement of the particle and the y-axis is the z-position of the particle. An apparent size of Rhea is given for reference as a bold black line on the right side of the plot.

successfully leaves the zone of the moon’s neighborhood.

The general approach is to calculate the particle trajectories for different parameters to verify which of the properties are more influencing the final simulated LEMMS signal. For this reason on top of the basic calculation of the particle’s trajectory three groups of “features” are sequentially added and results are compared with the observations. These three groups include: 1) general properties of the magnetosphere in the region of the moon’s orbit, 2) the LEMMS characteristics, 3) local properties of the plasma behavior in the vicinity of the moon. For this project the backwards-tracing was performed using the 4\(^{th}\)-order Runge-Kutta numerical method, described above in section 3.3.1. The next section is devoted to a detailed description of all these modeling components. And to illustrate how these features influence the simulation of the LEMMS signal, the cross-comparison of the results for A1 energy channel for all three flybys \( R2, R3 \) and \( D1 \) is provided in Section 5.5.

### 5.4 Flyby simulation

The basic calculation of the particle trajectory was done assuming the dipole magnetic field model for Saturn with an offset towards the North pole, as described in Section 2.2.2.
Chapter 5. Modeling of the energetic ion observations in the vicinity of Rhea and Dione

5.4.1 General properties of the Saturn’s magnetosphere in the region of the flybys

The general properties included were the corotation electric field, the convection electric field and a ring current.

To simulate the effect of the ring current on the reduction of the field strength at the equatorial plane, 10 nT are added to the (negative) $B_z$ component. The choice of this value is based on the MAG data (description of this instrument is provided in Section 4.2).

5.4.1.1 Corotational electric field

At Saturn, where the field is southward, gradient curvature drifts occur in the same direction as corotation, allowing the ions to drift large distances during one bounce period, as shown in Figure 5.4 in the previous section.

The corotation electric field $\tilde{E}_{\text{corot}}$ can be calculated as:

$$\tilde{E}_{\text{corot}} = -C_s \cdot (\tilde{\nu}_{\text{corot}} \times \tilde{B}_{\text{dip}})$$

where $C_s$ is the subcorotation coefficient (depends on the distance from the planet, for Rhea it is about 0.74 (Wilson et al. (2010), Thomsen et al. (2010)) and for Dione is about 0.84) and

$$\tilde{\nu}_{\text{corot}} = \tilde{\Omega} \times \tilde{r}$$

where $\tilde{\Omega}$ is the angular velocity of the planetary rotation and $\tilde{r}$ is the distance at which the field is being calculated in the equatorial plane. However it should be noted that the tracing results did not seem to be sensitive (on a scale of the considered problem) to the choice of the precise $C_s$ value, which may vary. Deviation of the $C_s$ value by $\pm 0.1$ does not bias much the trajectory of ions on scales comparable to the size of Rhea or Dione, and brings significant effect only on the simulation of trajectories on the scale of the planet.

5.4.1.2 Convection electric field

Andriopoulou et al. (2012) suggested the presence of the noon-to-midnight electric field in the magnetosphere of Saturn. To verify the influence of this additional electric field component on the LEMMS signal, the extreme case was simulated. In Andriopoulou et al. (2012) this electric field component was measured with an intensity in the range of 0.1 and 0.4 mV/m in most cases. The maximum possible value was used, however as it will be discussed below in Section 5.5, even the unrealistically high values cannot lead to significant changes in the LEMMS signal: for the flyby geometries studied here the flight time of a particle from the moon to the Cassini spacecraft during a flyby is on the order of a few seconds, which makes it insensitive to this electric field component on such a scale. Adding an extra electric field component effectively covers the case of the weak, radially outward flow component in Rhea’s wake, reported by Wilson et al. (2010).
5.4. **Flyby simulation**

Figure 5.5: Sketch of the charged particles beam entering LEMMS inside its opening cone (opening angle of counter is 15 degrees). The LEMMS pointing strictly determines the range of pitch-angles for particles which can theoretically enter the detector and therefore specifies possible trajectories of the particles. In this figure the black line shows the Cassini trajectory, red point is the Cassini position, red arrow indicates the LEMMS pointing and blue lines represent the variety of energetic particles trajectories valuable for LEMMS.

### 5.4.2 LEMMS aspects

The overall description of the LEMMS detector is provided in Section 4.1.1. There are several features of the LEMMS instrument itself, which can influence its observations, particularly the pointing of the detector, its opening angle and the response to different ion species.

The current study is focused on the ion fluxes observed by the Low Energy End of the LEMMS. The entrance aperture for the particles has a conic shape with an opening angle of 15 degrees and only particles inside this volume are traced backwards to the magnetosphere. Inside this volume angle the uniform distribution of particles is assumed. The direction of the entrance pointing plays a key role in choosing the fraction of particle flux, that can be detected, thus in this model the data about the position of the spacecraft and the LEMMS pointing are taken every 2 – 3 seconds during the flyby. Figure 5.5 shows a beam of particles of the same energy traced backwards from the LEMMS entrance inside its opening cone. The red arrow indicates the pointing of the detector.

As already mentioned in Chapter 4, the MIMI instrument includes also the CHEMS detector, which measures the composition of the ambient suprathermal ions and among other things provides the energy distribution of the protons, water group and helium ions, and also from double charged oxygen and double charged helium particles. A full energy sweep of the CHEMS sensor takes about 3 minutes to complete, and it
Figure 5.6: Ion flux intensity during the $R2$ flyby measured by the CHEMS instrument onboard the Cassini spacecraft. Upper panel represents the energetic ($E > 3$ keV) $H^+$ intensity spectrogram, lower panel - energetic ($E > 9$ keV) $O^+$ intensity spectrogram from the CHEMS (in particle flux units).

is typically required to average the CHEMS measurements in longer time blocks to increase the signal to noise ratio. It is therefore difficult to resolve the energetic ion interaction structures during moon flybys using only the CHEMS data. Figure 5.6 shows the CHEMS measurements of protons (upper panel) and of the water group ions (lower panel) during the $R2$ flyby. Even if in the proton data it is possible to see hints of the moon’s presence, water group ion data are featureless due to the averaging done to improve the signal to noise ratio.

In contrast to the CHEMS sensor the typical time resolution of LEMMS is about 5 sec, but LEMMS cannot distinguish different species. In this particle tracing model the combination of data from the two instruments is realized. The CHEMS data are
used to determine the average flux spectra of different ions species in the ambient plasma as input data for the simulation of the LEMMS signal. The real LEMMS data are used later for comparison with a simulated signal.

Protons always represent a significant fraction of the total flux (50 percent or usually much more) for all energies above 20 – 30 keV and in all regions in the Saturnian magnetosphere. In many previous studies it was reasonable to assume that the total ion counts in several LEMMS channels were due to protons, since separation of the different species was not adding much to the interpretation of the data. However, ground calibration and theory show that LEMMS should also respond to heavier ions with various charge states (Armstrong et al., 2009). For solving the particle transport in the Saturnian magnetosphere, the correct interpretation of the LEMMS signal is essential for obtaining correct conclusions.

The CHEMS data show that at Rhea’s orbit fluxes of energetic water group ions are of the same order as those of energetic protons up to about 100 – 200 keV (Dialynas et al. (2009), DiFabio et al. (2011)). Spectra of other ions and/or charge states are also detectable by CHEMS, but their fluxes are at least an order of magnitude lower that the main ion components (water group and protons). Nevertheless, their contribution to the total LEMMS signal may become important at the regions where Rhea removes most of the protons and/or the water group ions. Therefore in this simulation the trajectories of these components were modeled as well. The CHEMS measurements of the averaged spectra are considered for each of these species during each flyby. The final output combines the fluxes of all these energetic particles: $H^+$, $O^+$, $He^+$, $O^{++}$, $He^{++}$.

Armstrong et al. (2009) published estimations of the LEMMS A-channel responses to protons and heavier ions, which are in good agreement with ground calibration measurements in Krimigis et al. (2004). According to these measurements, the LEMMS responds differently to the various types of ions of the same energies. Thus the same channel in the LEMMS detector will respond to the protons of energy 27 keV - 35 keV and to the oxygen ions of the energy 58 keV - 70 keV. The calibration results for channels of interest ($A0 - A4$) can be seen in Table 4.1.1.2.

5.4.3 Local features of the moon environment

Rhea is located in a region of the magnetosphere of Saturn where magnetic fields generated from the ring current region and from the interaction between Rhea and the magnetosphere itself may distort the background dipole magnetic field significantly.

5.4.3.1 Hybrid code simulation

While the disturbances in magnetic field strength caused by the ring current might be approximated in a very simple way (Section 5.4.1), localized features of the moon-magnetosphere interaction need to be extracted from a self-consistent model of the interaction. Simon et al. (2012) described the application of the hybrid code A.I.K.E.F., mentioned already in 3.1, to Rhea. For the present study the hybrid code output was
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Figure 5.7: Magnetic field strength simulated by hybrid code (blue line) in comparison with real observations by the Cassini Magnetometer (red line) for $R_2$ flyby.

used for modeling the trajectories of energetic particles under the influence of local disturbances in the electric and magnetic field. The output of a hybrid code is available in a cubic box sized about $15R_{Rh}$ in each direction, which include the regions where the energetic ion dropouts have been observed. The separate specific hybrid code outputs were used for every flyby studied: $R_2$, $R_3$ and $D_1$.

The hybrid code actually can reproduce the local disturbances in the moon-magnetosphere interaction region quite accurately. Figures 5.7 and 5.8 show the comparison of simulated magnetic field strength using the hybrid code with real observations from the Cassini Magnetometer for $R_2$ and $R_3$ flybys, respectively.

When particles escape the simulation box, their tracing was stopped since the long bounce period prevents them from returning in the interaction region, as described in Section 5.3.

5.4.3.2 Charge exchange in the exosphere of the moon

Teolis et al. (2010) identified the existence of a weak exosphere around Rhea composed mainly of $O_2$ and with a small fraction of $CO_2$. The presence of an exosphere could possibly broaden even more the ion depletion region. To estimate the maximum possible influence of Rhea’s exosphere on the LEMMS signal, a Monte Carlo Collisions
method was used for the evaluation of the possible charge exchange rate in Rhea’s exosphere. The calculations were made using the following formalism.

The particle number density \( n_n \) in the exosphere of the moon is given by (Saur and Strobel, 2005):

\[
n_n = n_0 \left( \frac{R_m}{r} \right)^2 \exp \left( \frac{R_m - r}{H} \right)
\]

where \( n_0 \) is the density at the surface of the moon \( (n_0 = 3.5 \times 10^{11} m^{-3}) \), \( R_m \) is the radius of the moon, \( r \) is the location relative to the center of the moon and \( H \) is the scale height \( (H = 100 km) \) (Teolis et al., 2010).

The charge exchange collision probability is:

\[
P = 1 - \exp \left( -n_n \sigma \nu \Delta t \right)
\]

where \( \sigma \) is the collision cross-section (dependent on the type of colliding particles), \( \nu \) is the relative velocity between two particles and \( \Delta t \) is the time that a particle spends in the exosphere where the average density is \( n_n \).

The composition of the exosphere was simplified to just \( O_2 \) and the cross-section values for \( H^+ - O_2 \) were taken from Basu et al. (1987) and for \( O^+ - O_2 \) from Luna
Table 5.2: Collision probability in the exosphere of Rhea.

<table>
<thead>
<tr>
<th>Altitude [m]</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>2.56 \times 10^{-2}</td>
</tr>
<tr>
<td>20000</td>
<td>2.26 \times 10^{-2}</td>
</tr>
<tr>
<td>30000</td>
<td>1.9 \times 10^{-2}</td>
</tr>
<tr>
<td>40000</td>
<td>1.76 \times 10^{-2}</td>
</tr>
<tr>
<td>50000</td>
<td>1.56 \times 10^{-2}</td>
</tr>
<tr>
<td>100000</td>
<td>8.4 \times 10^{-3}</td>
</tr>
<tr>
<td>500000</td>
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</tr>
<tr>
<td>764000</td>
<td>3.5 \times 10^{-6}</td>
</tr>
<tr>
<td>1000000</td>
<td>3 \times 10^{-7}</td>
</tr>
<tr>
<td>1528000</td>
<td>0</td>
</tr>
</tbody>
</table>

et al. (2005). As it is seen in Table 5.2, even very close to the surface of the moon, the collision probability is quite low. The maximum possible values for all variables in Equation 5.4 were used in order to estimate the highest probability in these circumstances, e.g. relative velocity \( \nu \) was calculated between the ion and the neutral, assuming that the neutral is at rest and the ion has its velocity corresponding to the highest energy of the given LEMMS channel. It is clear that the presence of an exosphere on Rhea cannot change significantly the energetic particle flux near this moon. This was also confirmed by applying such probability values to particle tracing, where the depletion profiles were not affected at all.

### 5.5 Discussion of the results

To judge whether each of the model components described in the previous section has an influence on the simulated LEMMS signal, the simulations were performed separately for every case and the resulting signals were compared. In Figure 5.9 the simulation results for all three analyzed flybys are demonstrated, but only for one channel: \( A1 \) for flybys \( R2 \) and \( R3 \), and \( A3 \) for \( D1 \), since channel \( A1 \) during the \( D1 \) flyby was too noisy for unambiguous analysis. Accordingly, every column in Figure 5.9 corresponds to one flyby. And every line demonstrates the simulation results dedicated to the analysis of the input of one set of features:

- In the first line of Figure 5.9 (plots \( R2.a \), \( R3.a \) and \( D1.a \)) the depletions in a LEMMS profile were simulated, taking into account only the general magnetospheric properties, and the LEMMS pointing. The shape of the depletion is quite different from the one seen in the LEMMS data.

- In the second line (plots \( R2.b \), \( R3.b \) and \( D1.b \)) it is evident, that when the other species are included, the simulated signal becomes much closer to the LEMMS observations. The fact that LEMMS responds to heavier ions, in addition to protons, should be taken into account for the correct interpretation of its measurements. The characteristic feature of the flux depletion, which reflects
5.5. Discussion of the results

the LEMMS sensitivity to the different species, is the clear "step" in the flux depletions, which resembles the profile of the energetic water group ions. This step is clearly seen especially in the case of R2 flyby (chart R2.b).

- The third line (plots R2.c, R3.c and D1.c) demonstrates the simulation results, when the hybrid code output was used for calculation of the electric and magnetic field strength. The agreement of the simulated with the observed signals actually improves when the fields from the hybrid code output are taken into account. As it is seen, especially in the R2 simulation, when local disturbances are ignored (second line), the simulated dropout starts about 50 seconds later than the real one. This offset disappears when the interaction region field perturbations are "switched on".

The comparison of the simulation results, including all the effects discussed above, and the LEMMS observations for flybys R2, R3 and D1 for all simulated channels are shown in Figure 5.10 respectively. The background fluxes of particles for the energy channels A0 - A3 were calculated directly from onboard measurements by the CHEMS instrument. But for the A4 energy channel the background fluxes were extrapolated from the lower energies, since CHEMS does not cover the energy range corresponding to A4.

For the R2 and R3 flybys the complete model reproduces the depletion in the LEMMS signal with high accuracy repeating the complex shape of the flyby signature. However, unlike the simulations for the R2 and R3 flybys, modeling of D1 flyby does not result in such a good comparison with the LEMMS measurements. The difference can result from the fact that the CHEMS data for the oxygen fluxes are upper limits. The comparison shows that oxygen fluxes are definitely below the upper limit (which is the CHEMS background), because in the wake, where all protons are predicted to go away and oxygen is predicted to be present, there is no flux seen at all. Another cause can be that the signal of the A-channels is also affected by penetrating electrons, which are removed around closest approach, giving the false impression of a very narrow, deep ion wake. Therefore the reasons for the offset may be a combination of oxygen values lower than those defined from the CHEMS background, and the presence of penetrating electrons in the LEMMS ion channels. The simulated proton signal has otherwise good resemblance to the actual data. Our model also helps to explain the "double valley" in the shape of the A4 signal of D1 flyby. It appears because the gyroradius of energetic ions of such energies significantly exceeds the size of Dione. Consequently the depletion starts well before the closest approach, but at a certain point very close to the moon, the spacecraft enters the region, where it receives the flux of particles, which just made it around the moon without hitting it. Later Cassini comes to the closest point and the flux of particles diminished again, because Dione obscures a large fraction of the LEMMS field of view.

Analysis of the different features that may potentially influence the LEMMS signal shows that the LEMMS responses to different ion species (especially protons and water group ions) play an important role, while the shape of the ion depletion region
can have measurable sensitivity to the local magnetic perturbations of a moon’s interaction region, even if these perturbations are only a few percent of their background values. Figure 5.11 shows this analysis for the A1 channel during the R2 flyby, where the region of depletion is highlighted in yellow. The red line shows minimum deviation compared to other cases.

To illustrate why local perturbations give such a significant difference in the simulation of the LEMMS signal Figure 5.12 shows the comparison between trajectories, simulated assuming a simple dipole magnetic field model plus ring current (yellow trajectories) and by using the hybrid code (light blue trajectories). As it is seen in this Figure, the local disturbances affect not only the size of the ion gyroradii but also
5.5. Discussion of the results

Figure 5.10: Comparison between simulation results and the LEMMS data for three flybys. Different colors represent five energy channels $A0 - A4$, thin noisy lines show the LEMMS observations and corresponding solid lines are the simulation results. For $R3$ simulation light contaminated part of the LEMMS data for $A0$ channel was removed. For $D1$ simulation data from $A0$ and $A1$ channel were removed because of the noise.
Chapter 5. Modeling of the energetic ion observations in the vicinity of Rhea and Dione

Figure 5.11: Deviation of the simulation results from the LEMMS data (R2 flyby A1 channel). X-axis represents the time of flyby and y-axis shows the deviation between the differential flux simulated with our model and observed by the LEMMS. The highlighted zone indicates the period of Cassini approach to the moon, different colors represent deviation of the simulation results from real data for three simulation modes. **Blue line** - simulation was done taking into account only general properties of the magnetosphere and internal structure of the LEMMS (such parameters as pointing and opening angle), but assuming the LEMMS measures only protons. **Green line** - the same simulation mode as for blue line, but assuming the LEMMS counts other species as well. The average fluxes of $H^+$, $O^+$, $He^+$, $O^{++}$ and $He^{++}$ were taken from the CHEMS measurements during these flybys. **Red line** - the local perturbations in the electric and magnetic field, calculated using A.I.K.E.F. code, were added. This figure demonstrates, that inclusion into the simulation model of the local perturbations in the magnetic field brings the simulated signal much closer to the initial data and makes the deviation of the simulation from observation close to the zero.

The orientation of the spiral trajectories, allowing ions to access the moon from different locations in each case. One reason why the gyroradius is slightly greater in the "hybrid code" case, is because regions of weak magnetic field magnitude dropout on the side of Rhea’s wake (called "expansion fans" by Khurana et al. (2008)) are included.

It is also important that the ion species studied here have energies much higher than the characteristic ion corotation energy ($< 1$ keV). This means that ions gyrate much faster than the time they need to pass through the moon’s interaction region. In this way they can "sample" the local disturbances and affect the particle trajectory. In that sense, lower energy ions would be less sensitive to these disturbances, at least for the type of trajectories studied here, where the ion’s time-of-flight from the moon to Cassini is very short.
5.6. Conclusions

Figure 5.12: Beams of particles’ trajectories: assuming dipole magnetic field model (yellowish beam) and including local perturbations in the magnetic field (bluish beam). It can be seen here that local perturbations in the magnetic field lead to significant deviation of the particles’ trajectories, which caused changes in the absorption profile.

For the other extreme (very high energies, greater than few hundred keV) the depletion’s profile is probably insensitive to local perturbations, as the gyration scales are larger than those of Rhea’s or Dione’s interaction region. Still, for more complex environments and where field perturbations can be much stronger (e.g. Ganymede, Europa, Titan), the energy regime where ion trajectories are considerably affected may also extend beyond the few hundred keV range. In that respect, our methodology is very important for studying the magnetic topology near planetary moons.

Overall the ability of the particle tracing code to reproduce successfully the depletion signatures detected by LEMMS also confirms the hypothesis that those signatures are caused by plasma absorption of the moons, and any additional physical processes, such as charge exchange, are secondary at best. This also explains why such depletions cannot be seen during flybys when the LEMMS points nearly field aligned, as was the case during the R1 flyby.

5.6 Conclusions

In this chapter I presented the results of a charged particle tracing project using a tracing tool that has been adjusted to work in the environment of a planetary magnetosphere or a moon-magnetosphere interaction region. The developed particle tracer was applied to the simulation of the energetic ion flux profiles in the vicinity of the moons Rhea and Dione. The resulting simulated flux was compared with the LEMMS data during flybys R2, R3 and D1. As a base for these calculation the dipole magnetic field with a corotation electric field were taken and backward tracing of the energetic ions was performed, taking into account the LEMMS pointing and finite field of view, its response to heavier ions, as well as a series of configurations of the local magnetospheric and moon environments. A comparison of the simulation results and the LEMMS observations is shown in Figure 5.10.
During this study it was discovered that for the correct interpretation of the LEMMS signal the composition of the energetic ions is very important since the LEMMS detector responds more efficiently to heavier ions, in contrast to protons, which is opposed to the previously commonly used assumption, that LEMMS responds only to protons. Therefore the developed model can also be used for cross-calibration of the MIMI detectors that measure energetic ions with different methods and efficiencies, such as LEMMS, CHEMS and INCA. Also it was found that local perturbations in the magnetic field near a moon may modify the access of ions to a moon’s surface, even though these perturbations are only about $1 - 2$ nT (or few percent of the background magnetic field). Other effects, such as the exact magnitude of the corotation velocity, the presence of additional electric fields or charge exchange in the moon’s exosphere proved to be negligible.

Hence, the developed model offers a method to validate and/or constrain the ion composition and charge state where instrumentation may not be available, for instance at Titan or other Saturnian moons with Cassini (and for energies beyond the CHEMS’s upper energy bound at $300\text{keV}$) and Ganymede. Similarly, it can be used to evaluate the electromagnetic field perturbations near such moons predicted by MHD or hybrid simulation codes. That offers an additional validation tool, besides the comparison with the magnetic field, as is typically done.

The successful reconstruction of the LEMMS signal through the rather straightforward, geometrical problem of ion absorption, serves also as a validation of the tracing code, which can be gradually extended for application to more complex problems. This can be the reconstruction of ion or electron depletion regions at Titan and Enceladus, where the absorption of particles at the surface (or dense atmosphere) is not the only loss process, or the access of GCR to Saturn’s atmosphere and rings, the collisional products of which form Saturn’s proton belts, including an as yet unvisited belt inside the D-ring that Cassini will sample in 2017.

The application of the particle tracing for the GCR study is presented in the next Chapter 6.
Chapter 6

Galactic Cosmic Rays access to Saturn and its rings

As discussed already in Section 2.3.1, the highest energy component of the Saturnian radiation belt population cannot originate from the middle magnetosphere and by radial transport, but rather should be created locally, most probably from the CRAND process (introduced in Section 2.3.2). To verify this theoretical idea first of all it is necessary to determine the minimum energy which incoming GCR should have in order to reach and interact with the planetary atmosphere or the rings of the planet, and then to calculate the expected incident GCR spectrum. Several theoretical attempts were performed with this goal by Cooper and Simpson (1980); Blake et al. (1983); Randall (1994) among others, however leaving the final answer with a significant degree of uncertainty.

In addition the Cassini MIMI/INCA sensor detected during SOI a significant ENA flux between the atmosphere of Saturn and its rings as reported by Krimigis et al. (2005). This ENA flux reveals the presence of one more inner radiation belt inside the D-ring. If this belt exists, the high-energy particles trapped in this belt should also originate from CRAND.

This chapter is devoted to the study of the GCR access energies to Saturn and its rings, that is essential for the estimation of the CRAND production rate. Using particle tracing the access of GCR was evaluated in many different scenarios and the expected GCR spectrum in the Saturnian system was calculated. The advantages of the numerical technique compared to the analytical approach are discussed and the validation of the resulting GCR flux through the Cassini MIMI/LEMMS background measurements during SOI is provided.

6.1 Galactic Cosmic Rays

Cosmic rays are charged particles with energy much higher than the average energy of the background plasma particles and originating from an external source. Usually there are distinguished extragalactic, galactic, anomalous and solar cosmic rays, de-
6.1. Galactic Cosmic Rays

Figure 6.1: The flux of cosmic rays, detected by different experiments. Figure is taken from Hanlon (2008).

Depending on their origin. Extragalactic cosmic rays are coming from outside our galaxy, galactic cosmic rays from outside the solar system, anomalous cosmic rays from interstellar space at the edge of the heliopause and Solar Energetic Particles are associated with solar flares and other energetic solar events.

The motion of cosmic rays in planetary magnetospheres is governed primarily by the magnetospheric field of the planet, since the \( (v \times B) \)-term in the Lorentz force dominates due to the large value of \( v \). The magnetospheric magnetic field is in turn affected by global scale interactions and various processes within the magnetosphere, but also is affected by variable magnetospheric currents caused by drifts of energetic particles in radiation belts and plasma processes related to the solar wind as well as magnetosphere interactions in combination with interplanetary shock waves and by magnetosphere interactions during magnetic storms and substorms. At the same time, the main sources of radiation belts originate from the interactions of galactic, anomalous, solar, and interplanetary cosmic rays with the upper atmosphere of the planet.
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and are influenced by various processes inside the magnetosphere. The interaction of cosmic rays, solar wind, and interplanetary shock waves with planetary magnetospheres are indeed very complicated nonlinear processes (Dorman, 2009).

The term Galactic Cosmic Ray (GCR) usually indicates the cosmic rays originating outside the Solar System, but generally from within our Milky Way galaxy. The discovery of the cosmic radiation is attributed to F. Hess (1912), who performed several balloon flights up to 5200 meters height in 1912 (and one of them during the solar eclipse) in order to prove, that the source for radioactivity on the Earth is located not fully in the soil, but partially also arrived to the planet from above and not only from the Sun, but also from elsewhere. For his discovery he received a Nobel Prize in 1936.

GCRs have tremendous energies. Figure 6.1 taken from Hanlon (2008) shows the cosmic ray spectrum (all types of particles together) as measured by various experiments. The GCR flux of relatively low energy up to $\sim 10$ GeV demonstrates strong anticorrelation with the solar activity modulation. During periods of high solar activity the solar wind decelerates and partially excludes the lower energy GCR from the inner Solar System (Olive et al., 2014), however, for energies above $\sim 30$ GeV the GCR flux does not show dependence on the solar magnetic activity (Potgieter, 2013).

From the compositional point of view GCRs are the atomic nuclei of different elements. The elemental distribution of these charged particles is similar to those found on the Earth and in our Solar System: $\sim 89\%$ are protons, $\sim 10\%$ are charged helium particles and $\sim 1\%$ are heavier nuclei up to uranium. However, the abundance of some rare elements in the cosmic rays flux is higher than in the Solar System - evidence, that cosmic rays originate from the explosion of the supermassive stars, in the core of which these heavy elements are born, as described, for instance, for $^{60}$Fe by Binns et al. (2016). Figure 6.2, taken from Israel et al. (2005), demonstrates a comparison of the isotopic composition of GCRs with the composition of the Sun.

The origin of the GCRs is hard to determine since their trajectories are affected by the interstellar magnetic field. The most plausible explanation for their origin is the acceleration of particles in supernova remnants (Malkov and Drury, 2001). A supernova explosion expels stellar debris into the tenuous interstellar medium, producing a shock wave. Charged particles traveling back and forth across the shock front, gain tremendous energies before escaping as GCR. This mechanism is known as diffusive shock acceleration or Fermi acceleration (Fermi, 1949). Recent works by Ackermann et al. (2013) and Nikolić et al. (2013) finally provided a direct evidence of proton acceleration in supernova remnants. However, this theory cannot explain all the observed features of GCRs arriving at Earth. For instance, Adriani et al. (2011) pointed out the differences in the energy spectral shapes of protons and helium particles inconsistent with supernova origin theory. That is why the origin of GCRs and the acceleration mechanisms responsible for their gigantic energies are still open questions for today. As other possible source regions of GCRs the massive black holes in the centers of active galaxies (HESS Collaboration, 2016) and the gamma-ray bursts (Eichler and Pohl, 2011; Mészáros, 2014; Baerwald et al., 2015) are also candidates.
GCRs propagate through the galaxy in all possible directions. Some of them enter the Solar System and eventually hit the magnetospheres of the planets. During the approach to the planet the GCR is influenced by the planetary magnetic field and its trajectory is modified. However, if the GCR has enough energy, it still can get into the atmosphere (or onto planetary rings), where it can undergo collisions with atmospheric particles and produce a cascade of secondaries, also known as cosmic ray showers. These secondaries include protons, neutrons, electrons, neutrinos, muons, pions, photons and various antiparticles. For the convenience in this thesis I will refer to the cosmic rays arriving to the planet from outer space as primary cosmic rays and the particles created from the interaction of primary cosmic rays with planetary atmosphere and rings as secondaries. Figure 6.3 illustrates particle production during a cosmic ray shower. It should be noted, that the flux of GCRs above $10^{21}$ eV is so low, that existing instrumentation can only detect them through the air showers they cause, not directly.

Observation of the cosmic rays penetrating the terrestrial atmosphere helps us to investigate the new elements, such as muons and pions. Systematic surveillance of the cosmic rays arriving at Earth is already maintained for a century and is performed using the various ground-based facilities, balloon experiments and satellites.

The production of neutrons during a cosmic ray shower determines the beginning of the CRAND process (Section 2.3.2) and the decay of newly produced neutrons can contribute to the radiation belt population. The CRAND is an energy dependent

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**Figure 6.2:** Normalized abundances of elements observed in the cosmic rays and the Solar System abundances. Picture credits: Israel et al. (2005).
process and therefore in order to estimate the CRAND production rate first of all it is necessary to determine how a planetary magnetic field modulates the access of GCRs towards the planet. For any given location and arrival direction it is necessary to determine an energy, which can overcome the deflection by the planetary magnetic field and reach the atmosphere (or rings). I will name this energy "access energy". Assuming a dipole magnetic field model it is possible to determine the trajectories of an incoming GCR quite accurately. Taking the constancy of the kinetic energy in a static magnetic field one can evaluate the first integral of the equation of motion of a charged particle and derive the analytical solution for the access energies. Such an analytical solution was first proposed by Störmer (1955).

### 6.1.1 Analytical solution based on Störmer theory

The Störmer theory for the calculation of the particle’s energy needed to access the planetary surface (or atmosphere) is based on the concept of magnetic rigidity, which describes the resistance of a particle to change its direction of motion under the influence of a magnetic force (Kallenrode, 2004). Similarly the GCR cutoff rigidity is a quantitative measure of planetary magnetic field shielding (Smart and Shea, 2005) and is proportional to the momentum needed for a cosmic ray to reach the planet at a specific location as a function of arrival direction.
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For the dipole magnetic field model the GCR cutoff rigidity $R_C$ is expressed as follows:

$$R_c = \frac{M_C}{R_S^2} \frac{\cos^4 \lambda}{\left(1 + \sqrt{1 - \cos \omega \cos^3 \lambda}\right)^2} \tag{6.1}$$

where $M_C$ is magnetic moment, $R_S$ is radius of Saturn, $\lambda$ is latitude and $\omega$ is an angle between a particle’s vector of motion and a tangent to the plane of the surface in an eastward direction.

The particle’s momentum can be expressed through the cutoff rigidity as:

$$p = \frac{R_c q}{c} \tag{6.2}$$

where $q$ is the particle’s charge and $c$ is the speed of light. From the momentum the kinetic energy $E_{kin}$ can be derived, following the formula:

$$E_{kin} = \sqrt{p^2c^2 - m^2c^4} - mc^2 \tag{6.3}$$

where $m$ is the particle’s mass.

In many studies a vertical cutoff rigidity $R_{c_{vert}}$ is used, which determines the access to the current latitude at an angle $\omega = 90^\circ$ in order to reduce the amount of calculations:

$$R_{c_{vert}} = \frac{M_C}{4R_S^2} \cos^4 \lambda \tag{6.4}$$

6.1.2 Disadvantages of an analytical approach

The analytical approach is a relatively fast method for the derivation of the GCR cutoff energy and can be sufficient as a first approximation for some problems, but cannot sustain the accurate and precise solution. Analytically derived values for GCR access energies do not fit the observed ones at Earth, because the real planetary magnetic field is not a static dipole magnetic field and because the planetary magnetosphere is deformed by a series of processes changing the shape with solar wind conditions. Figure 6.4 shows the magnetic field lines of a dipole magnetic field and of a real magnetosphere for illustration of the differences.

Figure 6.4: Magnetic field lines of a pure dipole (left panel) versus magnetic field lines of the Saturn magnetosphere (right panel).
Satellite observations show a marked variation of the detected GCR flux with changes of the magnetic activity and suggest that the GCR access energy decreases as the magnetic activity increases (Reid and Sauer, 1967). The dipole model lacks the higher order moments (quadrupole, octopole, etc.) of the magnetic field, which makes a significant difference for the GCR access energies at lower latitudes and at higher energies (Weygand and Raeder (2005), Beer et al. (2012)). Since the contributions of higher order moments of the magnetic field vary as a function of space and time, the GCR cutoff energy varies correspondingly.

Various currents in the magnetosphere, especially the ring current plays an important role in the formation of the tail, are important contributors to decrease the cutoff energies, compared to analytically calculated values (Reid and Sauer (1967), Dorman (2009)). The complex shape of the magnetosphere influences the GCR access and in particular the existence of the tail, since certain particles with lower energy still can access the planet through the tail.

Compression of the magnetosphere under the changing solar wind conditions and during extreme coronal mass ejections (Adriani et al., 2016), solar modulation of the GCR flux in the Solar system, related to the solar cycle, seasonal changes in the magnetosphere along the motion of the planet around the Sun and other periodical changes of the conditions in the magnetosphere and in the ambient GCR flux are all reflected in the final dose of GCR reaching the planet.

Moreover, particularly at Saturn, the presence of rings plays an important role: the rings may obscure the fluxes of particles, GCRs can penetrate rings and produce large number of secondaries multiple times. All these factors cannot be taken into account in an analytical formula. An alternative way is a numerical approach in determination of the access energy (Smart and Shea, 2005).

However, previously published studies are limited to the analytical derivation of proton energy cutoff at Saturn (see for example Sauer (1980), Cooper and Simpson (1980), Blake et al. (1983), Kollmann et al. (2013)). Subsequent research of secondary radiation from cosmic rays and the CRAND process on Saturn conducted by Cooper (1983), Cooper et al. (1985), Randall (1994) and Kollmann et al. (2013) was based on these analytical calculations. In contrast, the trajectory tracing method can overcome the aforementioned restrictions and provide a more accurate and comprehensive base for CRAND study on Saturn.

### 6.1.3 GCR tracing through the magnetosphere

GCR trajectory tracing is an extensively used method for the determination of the geomagnetic cutoff energies (Smart and Shea (1994), Kress et al. (2004), Smart and Shea (2005), Weygand and Raeder (2005), Chu and Qin (2016), Adriani et al. (2016)). In order to determine the GCR cutoff energies it is most efficient to calculate the reverse trajectories of particles starting from the point of interest (top of the planetary atmosphere or the surface of rings, for instance) and to trace them until they reach the
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Figure 6.5: Simulated backwards in time from trajectories of five protons of different energies: 1 GeV, 21 GeV, 41 GeV, 61 GeV and 81 GeV. Only the 81-GeV proton has an allowed trajectory and will escape the magnetosphere, while other particles hit the planet these trajectories are forbidden.

magnetopause (Smart and Shea, 1994). Determining the cutoff energy from the magnetospheric borders to the atmosphere would be far more time consuming because the trajectories would need to be calculated from many positions on the magnetopause, and for a large number of pitch and phase angles, but most of these particles would be reflected and would never reach the planet (Smart and Shea, 1994). Therefore the common approach is to launch particles from a given latitude and longitude sequentially at pitch angles from $0^\circ$ to $180^\circ$ and at corresponding phase angles in order to cover the whole range of possible arrival directions, to trace these particles backwards in time and determine, if they escape the magnetosphere or not.

Figure 6.5 shows trajectories of five GCRs launched backwards in time from the top of Saturn’s atmosphere. All five particles were launched from the same location and at the same pitch and phase angle, the only difference is the energy: 1 GeV (black), 21 GeV (red), 41 (magenta), 61 GeV (blue), 81 GeV (green). On this figure it is seen, that only the 81-GeV particle can escape the magnetosphere and other particles are trapped or hit the planet on their way, in other words, the trajectory of the 81-GeV particle is allowed and others are forbidden. This means, for that given location only particles with energy of 81 GeV and above can reach the planet in that particular arrival direction and the minimum access energy still can be smaller than 81 GeV, but definitely bigger than 61 GeV.

In Section 3.3 I described several numerical methods, which were implemented in the developed particle tracing code. For tracing of GCRs I used the Vay method, (described in Section 3.3.3) as the most accurate and efficient one for such energies and distances. As the border of the magnetosphere I took the distance of 25 Saturn radii.

To increase the efficiency of the calculations, I used an adaptive time-step, which was updated along with changing curvature of GCR path, and I parallelized the code, since the GCRs trajectories can be calculated independently.

As a magnetospheric model I used the Dipole model and the Khurana model,
described in Section 3.1. The Khurana model also allows simulations for different seasons (Pre-equinox, Equinox and Post-Equinox). Also, I studied separately motion of protons and charged helium particles.

6.2 GCR access to Saturn

By numerical calculation of the GCRs trajectories the GCR access energy to Saturn was evaluated for each location and arrival direction and studied in different aspects.

6.2.1 Access energy mapped on Saturn

Figure 6.6 reports the GCR access energy mapped on Saturn. Here the left column shows the simulation results based on the Dipole model and the right column - the simulation based on the Khurana model for Equinox (August 23, 2009). On the maps the blue color corresponds to the lowest access energy and the red color - to the highest access energy (up to 350 GeV). The five rows demonstrate access energy for different portions of arrival directions. The first row shows the absolute minimum access energy for every point of the map. The second row shows mapping of access energy, sufficient for 25% of arrival directions to a given location. Accordingly, the third row shows access energy sufficient for 50% of arrival directions, the fourth - for 75% of arrival directions and the bottom row - for 100% of arrival directions, in other words the ultimate access energy, which ensures, that every GCR with such energy can access this location from any direction.

The calculations were made assuming an isotropic distribution of 85 random arrival directions on every point on a grid of latitudes and longitudes.

Figure 6.6 demonstrates distinguishable difference in access energies, calculated using the Dipole model and the Khurana model, but on the color scale of the map it can look insignificant. But let us look more closely at the difference in minimum (at least one arrival direction is allowed) and maximum (100% of arrival directions are allowed) access energies, obtained on the basis of different models. Figure 6.7 contains maximum and minimum access energies calculated using particle tracer on the basis of the Dipole model and averaged across every latitude values for maximum and minimum on the basis of the Khurana model. For comparison on this figure I add also cutoff energy, obtained analytically using the Störmer theory, and also the vertical cutoff energy.

The difference is significant. For convenience, Figure 6.8 shows the schematic view of the dipole L-shells, highlighting L-shells of the Main Rings and the radiation belts. In the equatorial region, where L-shells of the predicted innermost radiation belt connect to the atmosphere of Saturn (blue zone), the minimum access energy calculated by the particle tracer is by one third smaller that the commonly used vertical access energy, consequently, the real flux of the GCR particles in that region can be higher, than previously predicted. This means, that the CRAND process in the equatorial region of the atmosphere can supply the innermost radiation belt with a higher number of particles.

At the same time for the middle latitudes, where the L-shells of the Saturnian Main Rings (from ~ 17° till ~ 50°) are connected (orange zone), the particle tracer
6.2. GCR access to Saturn

Figure 6.6: GCR access energy mapped on Saturn. The simulation results based on the Dipole model are shown on the left side and based on the Khurana model for Equinox (day - August 23, 2009) - on the right side. The five rows demonstrate access energy for different portions of arrival directions.
modeling results in maximum access energy are several times higher, than predicted analytically. Also it can be noticed that the particle tracing on the base of the Dipole model results in similar values to those analytically obtained. For the latitudes of the radiation belts’ L-shells (green zone), the tracing with Khurana model results in the maximum access energy almost 10 times higher, than the analytically derived cutoff energy. All of this suggests that for an adequate estimation of the CRAND production rate it is crucial to calculate the incoming GCR flux using the particle tracing on the base of the realistic semiempirical magnetospheric models.

In order to verify if the higher order moments of the Saturnian magnetosphere influence the access energy I performed also calculations using the Khurana model with zero higher order components. Figure 6.9 reports a comparison of the obtained

Figure 6.7: Access energy obtained by particle tracing using the Dipole model, Khurana model and the Störmer approach. Color zones indicate latitudes connected to the L-shells of the predicted innermost radiation belts and to the Main Rings of Saturn.

Figure 6.8: Schematic view of the L-shells of the Main Rings (red L-shells, connected to the latitudes between \( \sim 17^\circ \) and \( \sim 50^\circ \)) and the L-shells of the radiation belts (orange L-shells, connected to the latitudes between \( \sim 50^\circ \) and \( \sim 60^\circ \)).
6.2. GCR access to Saturn

Figure 6.9: Comparison of the access energies, obtained using the Khurana model and the Khurana model with zero higher order components of the magnetic field. Different colors correspond to access energies for certain portion of arrival directions: red line - minimum access energy, valid at least for one arrival direction, green - access energy for 25\% of arrival directions, violet - for 50\% of arrival directions, blue - for 75\% and magenta - for all arrival directions.

access energy across all latitudes from North to South poles along 40° E longitude. Here the different colors correspond to the access energies for certain portions of the arrival directions: red line - minimum access energy, valid at least for one arrival direction, green - access energy for 25\% of arrival directions, violet - for 50\% of arrival directions, blue - for 75\% and magenta - for all arrival directions. The largest difference in access energies is observed along latitudes from \(\sim 20°\) till \(\sim 50°\) and around \(\sim 70°\) in both hemispheres, but it is always within 3 GeV maximum.

6.2.2 Minimum access energy analysis as a function of longitude

Using the semiempirical magnetospheric models like the Khurana model, it is possible to resolve the diurnal variations in the magnetosphere. In Figure 6.10 I show the deviation of the minimum access energy from the mean value along every latitude. Here 0 corresponds to the subsolar point and 180 is at local midnight. In the legend next to the number of latitude in brackets I put the smallest and the biggest values obtained, correspondingly.

The deviation of the minimum access energies for latitudes below \(\sim 55°\) are within \(\sim 3\%\). For the very high latitudes above \(\sim 80°\) there are already almost no variations since the minimum access energy tends to zero and basically almost all GCRs can access these latitudes. But for upper middle latitudes approximately between 55° and 80° the significant diurnal variation in access energies is observed, not visible on the scale of Figure 6.10.
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Figure 6.10: The minimum access energy along latitudes. X axis shows longitudes: 0 corresponds to subsolar point and 180 is a local midnight. In the legend in brackets next to the number of latitude are presenting corresponding the smallest and the biggest values obtained.

Figure 6.11: The minimum access energy along 70° and 75° latitudes. Figure 6.11 shows the results for 70° and 75° latitudes in both hemispheres in more details. The obtained minimum access energy at local midnight is 10 times (for 75° latitude) and 5 times (for 70° latitude) lower than at local prenoon and afternoon regions.
6.2.3 Dependence on arrival direction of the access energy

The predicted so-called "East-West effect" by Rossi (1930) should also occur at Saturn, but in reversed direction compared to the Earth, because of the opposite orientation of the magnetic moment of the planet dipole. The access energy depends on the arrival direction. To reach the point at the top of the atmosphere from the west the GCR should have much more energy, than from the east. Figure 6.12 illustrates this effect: here two particles reach the equator. The 65 GeV GCR managed to arrive from the east, while from the west the allowed trajectories started only from 350 GeV, since the planet shadows the lower energy trajectories.

Figure 6.13 demonstrates the dependence of the access energy on arrival direction for different latitudes. Here the x-axis is the cosine and the y-axis is the sine of 85 arrival directions. More reddish points indicate higher access energy for this particular arrival direction for the current latitude. On Figure 6.13 a clear east-west asymmetry can be seen, and the separation is bigger at lower latitudes.

Figure 6.12: East-West effect. To reach equator from the East the GCR particle should have at least 65 GeV (red trajectory), while for arriving from the West the GCR particle should have at least 350 GeV (blue trajectory).
Figure 6.13: Minimum access energy per analyzed arrival direction for different latitudes. X-axis is the cosine and y-axis is the sine of the arrival direction. West is on the left and East on the right.
6.2.4 Ring crossing analysis

Another important aspect in the evaluation of the GCR interaction with Saturn is the rings crossing rate. Every time the GCR particle crosses the rings it might lose some portion of its energy, changing its trajectory. Moreover, every passage through the rings will produce a cascade of secondaries, triggering the CRAND process.

Below I analyzed the trajectories of particles with minimum access energy for all considered latitudes, longitudes and arrival directions. Of course, if the actual energy of a particular GCR is higher than the minimum access energy, its trajectory will be more straight and consequently such a particle will cross the rings less often. But since the GCR energy spectra falls off approximately as a power law, the particles more closely to the minimum access energy contribute the most to the actual flux at the considered location and thus these minimum access energy trajectories are of greatest interest.

Figure 6.14 demonstrates the percentage of particles per number of ring crossings averaged across longitudes for different latitudes. It can be noticed, that at latitudes below $\sim 35^\circ$ in both hemispheres most of the allowed trajectories cross the rings at least 3 times on their way. The assumption for this case study is that I do not consider changes in particle energy in the trajectory calculation when rings are crossed, but in reality depending on the thickness of rings, particles lose a few percent of its energy per crossing.

In addition Figure 6.15 reports the percentage of the particles per number of ring crossings as a function of energy. Here it is seen, that most of the particles of energy from $\sim 50$ GeV up to $\sim 150$ GeV cross the rings before they reach Saturn’s atmosphere: up to 48.8% cross the rings three times, up to 20% of particles cross the rings twice on their way and only 20% of particles of this energy range reach the planet directly. GCRs with energies below 7 GeV can reach the planet only at high latitudes and

![Figure 6.14](image_url)

Figure 6.14: GCR ring crossing rate per latitude averaged across longitudes.
they do not enter the equatorial region on their way and do not cross the rings. At
the same time trajectories of GCRs of energies above 400 GeV are not that affected by
the planetary magnetic field and they also approach the planet at nearly all latitudes
with slightly inclined trajectories without crossing the rings.

The ring crossing rate should be taken into account in the estimation of the GCR
flux at lower latitudes of Saturn and for the evaluation of the CRAND production rate.

6.2.5 GCR spectra on Saturn

Using the particle tracing results the fraction of GCR flux reaching Saturn as a func-
tion of energy and latitude was evaluated for different seasons and different models.
Figure 6.16 demonstrates results of the Khurana model simulation for the day when
Cassini arrived at Saturn - 1 July 2004 (referred to below as Preequinox). Here differ-
ent contours represent the fractions of allowed arrival directions to the point on the
grid as a function of access energy and latitude.

The fractional distribution allows to reconstruct the GCR spectra at Saturn as
a function of latitude. Due to lack of detailed GCR measurements on Saturn as an
input it is possible only to make a reasonable estimate of a general GCR flux on that
distance from the Sun. For that the CREME data for general GCR spectra in the
vicinity of the Earth (Tylka et al., 1997; Weller et al., 2010; Mendenhall and Weller,
2012) should be multiplied by a factor of 1.425 in order to take into account the ra-
dial gradient of 5% per AU (McDonald et al., 1997) that is used as the initial GCR
spectra in the vicinity of Saturn. By applying the GCR fraction distribution, one can
model the GCR spectra to the particular location on the planet. Figure 6.17 shows
the obtained initial GCR spectra and modeled spectra averaged along every latitude
(for Preequinox).

Figure 6.15: GCR ring crossings as a function of energy.

Figure 6.16: Fractional distribution of allowed arrival directions to Saturn grid as a function of access energy and latitude.

Figure 6.17: GCR spectra at Saturn as a function of latitude.
6.2. GCR access to Saturn

Figure 6.16: GCR access energy in fractions of arrival directions as a function of energy and latitude for the Khurana model (Preequinox). A dark zone indicates no access of particles with such energy to the corresponding latitude and a white zone indicates the full access from all arrival directions.

Figure 6.17: The estimated GCR spectra in the vicinity of Saturn and modeled spectra for different latitudes (on the basis of Khurana model, Preequinox).
Using the modeled GCR spectra it might be interesting to calculate the GCR integrated flux per latitude. The integrated flux can be obtained by the integration of the GCR spectra, corresponding to each latitude, and is shown on Figure 6.18. Here I plotted results based on simulation using the Khurana model for Preequinox and Equinox (23 August, 2009). The decrease in the integrated flux towards an equatorial zone is a direct consequence of an increase in the access energy at the corresponding latitudes, demonstrated in Figures 6.6 and 6.16. The difference in the two fluxes arise from differences in initial GCR fluxes for these particular days due to difference in solar activity during solar minimum and solar maximum and from variations in the GCR access energies caused by changing conditions in the magnetosphere.

6.3 GCR access to the magnetosphere

A similar approach can be applied for the evaluation of GCR access to other regions of the magnetosphere of Saturn. The most interesting is to evaluate the GCR access to the equatorial plane of the magnetosphere, which can uncover the intensity of the GCR interaction with the Saturnian rings and moons.

6.3.1 GCR access energy to the equatorial plane through the magnetosphere

Like in Section 6.2 I used the backwards tracing of GCRs from different locations and from various arrival directions in order to evaluate the access energy for every case. The trajectory tracing was performed from points located at distances from $1.1R_S$ (Saturn radii) up to $20R_S$ from Saturn towards the Sun in the equatorial plane. For every point
Figure 6.19: GCR proton access energy in fractions of arrival directions as a function of energy and distance from the planet (Rs - is the Saturn radii) in the equatorial plane: comparison between the Dipole model (upper panel) and Khurana model for Preequinox (lower panel). The location of the Main Rings is indicated in the pink zone. Different contours represent fractions of arrival directions as a function of access energy, a dark zone indicates no access of particles with such energy to the corresponding point and a white zone indicated the full access to the point from all arrival directions.

211 arrival directions were evaluated. Figure 6.19 reports the modeling results on the basis of the Dipole model (upper panel) and the Khurana model for Preequinox. The different contours represent the fractions of allowed arrival directions to the point as a function of energy and distance from the planet. The pink zone
indicates the location of the main rings. It should be noted, that some of the arrival directions produce extremely high access energy values in the close vicinity to the planet, since I evaluated them isotropically distributed in a whole volume of incidence angles and about the half of arrival directions very close to the planet are simply forbidden because of the presence of the planet.

The biggest difference in the two plots of Figure 6.19 can be observed at distances outside 7 $R_S$, since the dipole model can approximately describe the magnetic field close to Saturn, but it is not applicable for the description of the middle and outer magnetosphere.

Simulation results for the access energy based on the Khurana model for Postequinox (prediction for 15 September 2017), for charged helium particle and for protons, but on the basis of the Khurana model with zero higher order components can be found in Appendix B.

### 6.3.2 GCR spectra in the Saturnian magnetosphere

Following the same approach as in Section 6.2.5, I used CREME spectra (Tylka et al., 1997; Weller et al., 2010; Mendenhall and Weller, 2012) of GCRs updated for Saturn to obtain the modeled GCR spectra for different distances from Saturn. Simulation results from Figure 6.19 were used to account for GCR access energies depending on arrival directions. Figure 6.20 shows the modeled GCR spectra for distances up to 20 $R_S$ from the planet. For the evaluation of the CRAND production rate from the

![Figure 6.20: The modeled GCR spectra on the base of the CREME data and the Khurana model (Preequinox). The spectra at the distances of the D-ring (the innermost ring) and the F-ring (the outermost ring) are indicated correspondingly.](image-url)
6.4. MIMI/LEMMS background measurements during SOI

The Cassini spacecraft does not have an instrument specifically designed to detect GeV particles. However, during the Saturn Orbit Insertion (SOI) passage above the main rings the LEMMS instrument got an unique opportunity to measure the GCR flux indirectly: since all the trapped charged particles on the L-shells which cross the rings would be absorbed after a few passages by the matter of the rings, there should be no...
trapped radiation on the L-shells of the rings. Consequently, all the particles, which enter the LEMMS telescope during this passage are the very new particles on these L-shells and most probably are related to the GCR secondaries from the interaction with the rings. At the same time the GeV particles cannot be resolved directly by LEMMS, but they can penetrate the instrument through the telescopes and/or from the sides of the instrument causing the permanent background signal in the data. In the absence of the signal from the trapped radiation the background measurements can be studied.

6.4.1 Parameters of SOI

Cassini arrived at Saturn on 1\textsuperscript{st} of July 2004 and its first approach to Saturn was continued by the sequence of maneuvers in order to lead the spacecraft to the stable orbit around Saturn. During this Saturn Orbit Insertion (SOI) the spacecraft collected unique data due to the very specific trajectory of this passage. Here I list some facts about SOI:

- The closest approach was 19980 km from the cloud tops (0.3 Saturn Radii).
- Ring plane crossing in the F-G gap (distance 158500 km) twice (before and after closest approach).
- It was the only orbit above the rings and fully inside of the main radiation belts of Saturn so far.

Figure 6.22 illustrates the trajectory of the Cassini spacecraft during SOI.

6.4.2 LEMMS measurements and modeled flux

During SOI Cassini has crossed regions magnetically connected to Saturn’s main rings. No trapped radiation belt particles were expected to be found there since they are expected to be rapidly absorbed. In fact, MIMI/LEMMS channels measured very low count rates above the ring plane, as expected. Earlier studies using the Pioneer 11 observations, however, claim detection of energetic particles at that location, in particular MeV electron fluxes increasing towards the edge of the main rings (Chenette et al., 1980). A suggested origin is the secondary electrons, just injected as a result of the impact of GCRs on the rings or atmosphere.

Considering the CRAND process (introduced in Section 2.3.2), the newly created neutrons decay into protons and electrons after \( \sim 885.7 \) seconds and negative pions decay in to negative muons within a few nanoseconds, so very near the rings. Those muons decay within microseconds to electrons. And all these electrons Cassini may measure.

MIMI/LEMMS has many electron and ion channels and their instrumental background is controlled by penetrating galactic cosmic rays (e.g. E, P, H, Z channels).
Almost all cosmic ray affected channels show a decrease in their GCR background inside L=7, where Saturn’s volume and magnetic field start to obscure cosmic ray access. This decrease should also develop above the main rings if GCRs contribute to the signal there.

Figure 6.23 contains LEMMS data from the channels $P_7$ and $E_7$ of the SOI passage above the Main Rings without removing the background noise. These two channels of the LEMMS instrument perform measurements of the highest possible energy: $P_7$ channel measures protons of energies from 12.1 to 58.9 MeV and $E_7$ channel detects electrons from 7 to 20 MeV. As discussed by Roussos et al. (2011) in these data it is clearly seen that the intensity of the background noise significantly decreases during the close approach to the planet. That supports the idea of GCR origin of this background signal.

Figure 6.24 shows the modeled integrated GCR flux for the day of SOI from Figure 6.21, but on a logarithmic scale. Comparing the penetrating background and modeled integral flux makes sense because GCR penetration in LEMMS occurs from all directions and for all energies above $\sim 300$ MeV for protons. From Figures 6.23 and 6.24 it is obvious, that the decrease in the LEMMS background noise is proportional to the modeled integrated GCR flux dropout in the close vicinity of Saturn.
Chapter 6. Galactic Cosmic Rays access to Saturn and its rings

Figure 6.23: Data from two LEMMS channels (E7 and P7) during SOI. Counts as a function of distance from the planet in Saturn radii $[R_S]$. 

Figure 6.24: The modeled GCR integrated fluxes as a function of distance from Saturn $[R_S]$. 
6.5 Conclusions

Various observations suggest that a significant flux of GCRs enters the magnetosphere of Saturn and interacts with the planet and rings. Through the CRAND process the highest energy component of the radiation belts of Saturn is populated. So far only an analytical approach was used for the evaluation of the GCR access to the Saturnian system, while there are existing significant disadvantages of this method.

The alternative numerical method based on particle tracing is proposed for the calculation of the GCR access energies to Saturn. In this method the GCRs are traced backwards in time from different locations on the planet and from the equatorial plane of the magnetosphere in order to determine the minimum access energy as a function of arrival direction and location. Different magnetospheric models can be used for such a tracing, particular models used were the dipole model, the semiempirical Khurana model and the Khurana model with zero higher order moments of the magnetic field of Saturn.

The modeled GCR access energies to the Saturnian atmosphere differ significantly from the analytically derived values. For some latitudes the difference is dramatic, up to a factor of 10. At the same time, the Dipole model and the Khurana model also have large disagreements. This suggests that for the correct estimation of the GCR access to Saturn the numerical backwards-tracing of particles on the basis of a realistic magnetospheric model should be used instead of analytical calculations on the basis of Störmer theory.

It was demonstrated, that the numerical approach also provides comprehensive information about the passages of GCR on their way to Saturn. Specifically, the particle tracing provides rings crossing rate and longitudinal variations, that can be useful for the correct estimation of the CRAND production rate and evaluation of the atmospheric chemistry changes due the cosmic ray showers.

On the basis of obtained access energies the GCR spectra reaching Saturn were composed and the integrated flux as a function of latitude calculated. Similarly the GCR access energies to the equatorial plane of the magnetosphere as a function of distance from the planet were obtained and the GCR spectra to different distances were calculated.

On the basis of the calculated spectra was composed the GCR integrated flux as a function of distance from the planet. Comparison with the Cassini MIMI/LEMMS background signal during SOI passage above the Main Rings of Saturn shows that the LEMMS background signal decreases with approach to the planet proportionally to the decrease of the modeled integrated flux. The decrease is comparable, which validates our model calculations. Above the rings our model predicts 1 – 1.5 orders of magnitude lower penetrating radiation signal, which means that the signal above the rings, measured with LEMMS is from GCR secondaries.
Chapter 7

Future applications

Determination of the GCR spectra reaching the atmosphere and the rings of Saturn opens a wide range of opportunities for further studies. In this short chapter I would like to highlight applications of my results described in Chapter 6. I also discuss some other interesting applications for the developed energetic particle tracer, particularly in the magnetosphere of Saturn using the Cassini measurements. Some of these applications have been already realized, while others are currently in progress.

7.1 CRAND secondaries production rate

The reconstructed GCR flux on Saturn and its rings shown on Figures 6.18 and 6.21 provides the necessary input information for the evaluation of the secondaries production through the CRAND process (introduced in Section 2.3.2).

7.1.1 Simulation of the cascades of secondaries

In Chapter 6 the various parameters of the incident GCR flux, reaching Saturn’s atmosphere and rings were determined. Taking them as input parameters, the GEANT4 code (Agostinelli et al., 2003) can be used in order to simulate GCR penetration through the rings of Saturn or the atmosphere.

The GEANT4 toolkit was developed specifically for the simulation of the particle’s passage through matter. It is widespread for use in space science, medicine, high energy, nuclear and accelerator physics.

Figure 7.1 demonstrates the preliminary GEANT4 simulation of a 60 GeV proton beam of 30000 particles penetrating the Saturnian rings perpendicular to the surface of the ring. The rings are composed mainly of pure water ice grains with some traces of dust and rocky material (Cuzzi et al., 2009). The size of the grains vary from 1 cm particles up to 100 m moonlets. For this very first simulation as a material layer of 80 cm thick water ice was taken.

On Figure 7.1 it is seen, that a large number of secondaries is created, which propagate then to all possible directions. Most primary protons went from the penetrated
Figure 7.1: GEANT4 simulation of a 60 GeV proton beam of 30000 particles penetrating the layer of water. Initial beam comes from the left, green lines represent neutrons scattered in various directions.

layer without significant loss of energy and without change of their direction.

Figure 7.2 shows the energy distribution of the outgoing particles from the penetrated material. Here I compare preliminary results, based on three GEANT4 methods of treating the medium energy hadron-nucleon interaction, which are most relevant for our study: QGSP_BERT_HP, QGSP_BERT and FTFP_BERT.

From the output of this very first simple simulation it can be already concluded that approximately two thirds of the particles are penetrating the rings almost without any losses of energy. However, the cascades of secondaries can be quite heavy.

Therefore by a more detailed careful simulation of the penetration process together with varying free parameters listed above it is possible to reveal the secondaries production rate and spectra for different ambient conditions.

7.1.2 Tracing of secondaries

Obtained secondaries spectra can be used for further analysis. For instance, one can use the particle tracer and evaluate the trajectories of newly created protons. How fast
Chapter 7. Future applications

Figure 7.2: Energy distribution of secondary protons, resulting from the interaction of the proton beam with a water layer (number of protons per energy bin). The different GEANT4 models for simulation of the collision process are represented by different colors.

will they be absorbed by the atmosphere or rings and how much new cascades they can create before? It is planned to trace neutrons in order to estimate the fraction of particles, that decay on the L-shells of radiation belts.

Neutron mean lifetime is about $885.7 \pm 0.8 \text{ sec}$ (Nakamura and Group, 2010) and the half-life is about 620 sec, the energies and direction of motion are obtained from the GEANT4 simulation. For instance, Figure 7.3 depicts the preliminary results of the number of produced neutrons as a function of energy during the described above experiment of 30000 protons of 60 GeV energy beam penetrating the layer of ice.

Taking the spectra from Figure 7.3, we can estimate the probability of neutron decay as a function of distance from the incident location using the exponential distribution of the surviving probability:

$$P_{\text{decay}}(t) = 1 - e^{-t/(\gamma \tau)}$$  \hspace{1cm} (7.1)

where $\gamma$ is a Lorentz factor (Equation 2.2) and $\tau$ is the mean lifetime of the particle at the rest.

Figure 7.4 schematically illustrates the distances from the location of the neutron creation and the probabilities, that 1 MeV neutron will decay in that distance, with Saturnian L-shells indicated.
7.1. CRAND secondaries production rate

The ultimate goal of this project is to estimate the contribution of the CRAND secondaries to the radiation belts population, and it includes the following steps: tracing of protons and evaluation of how fast they will be lost in the rings or atmosphere and how much new particles will be produced during their interaction with the planet or

Figure 7.3: Energy distribution of secondary neutrons (number of neutrons per energy bin), resulting from the interaction of the proton beam with a water layer.

Figure 7.4: Schematic view of L-shells of Saturn with indicated distances from the incident location (red star) and probabilities of 1 MeV neutron decay in-flight by reaching that distance. The L-shells of the main rings are in red color and the L-shells of the radiation belts are in orange color.
its rings; evaluation of the probability of the neutron decay within the L-shells of the radiation belts and calculation of the possible protons supply rate into the radiation belts by such a mechanism.

7.2 Intensity of the innermost radiation belt of Saturn

Among other observations during SOI the INCA camera measured Energetic Neutron Atoms (ENA) from the region close to Saturn, that lead to the suggestion of the existence of the ”innermost” radiation belt between the planet and D-ring (Krimigis et al., 2005).

Figure 7.5 demonstrates the INCA measurements of ENAs (upper panel) and the possible origin of these ENAs from the new radiation belts. This observation proves the existence of a trapping region, which may also hold higher energy CRAND ions and electrons.

Figure 7.5: INCA observations during SOI (image credits: Krimigis et al. (2005)).
This study is of the highest priority now, since in 2017 the Cassini spacecraft is going to pass directly through the gap between the atmosphere and the D-ring of Saturn, and the forecast of the possible radiation hazard during these passages is essential. Also, it is exciting to make an estimation of the future LEMMS measurements during those incredible orbits.

There was already an attempt to evaluate the intensity of the innermost radiation belt by Kollmann et al. (2015), using analytical methods. Thus the comparison with a numerical approach will be appreciated. The main principle of this study is to calculate first the supply rate of particles, which can be trapped in this belt, and afterwards to derive its structure taking into account losses to Saturn’s extended atmosphere and dust.

7.2.1 Sources

If this innermost radiation belt exists, then it is even more isolated from the magnetosphere due to the presence of the main rings. All the particles, which diffuse to the L-shells of the rings, will be ultimately absorbed during their first several bounces. That is why in the LEMMS observations during SOI shown on Figure 6.23 the particle flux is dropping sharply in the location of the rings. Therefore the MeV-GeV particles population of this innermost radiation belt should originate from the GCR interactions with the rings and the atmosphere and the CRAND process.

Reionized ENAs can be the source of keV particles. The particle tracer can be used to evaluate the possible fraction of the ENAs, which can undergo reionization through Monte-Carlo simulations. Therefore it is a great opportunity for studies of multiple charge exchange with subsequent validation by Cassini observation during the final Proximal orbits.

Though the combining of different source mechanisms we will be able to calculate the total supply rate of the innermost radiation belt.

7.3 Ring thickness study

The rings of Saturn have been studied extensively since the first visits of Pioneer and Voyager spacecraft. The observation of the ring system, explanation of their origin and composition, is one of the main goals of the Cassini mission. The ring thickness and mass, however, are the crucial parameters, which are poorly constrained (Kempf et al. (2015), Hedman and Nicholson (2016) and Cuk et al. (2016)).

We would like to propose an alternative method of determination of the rings thickness, which can support relevant studies.

In Section 6.4 I described the Cassini passage above the rings of Saturn and the LEMMS background signal during this passage. LEMMS data show that there appears
to be a small excess of signal above the rings, compared to the expected profile of the
penetrating background by GCRs. This may be direct detection of GCR secondaries,
as described also with Pioneer 11 observations by Simpson et al. (1980). Simulating
the excess signal can constrain properties for the ring column density, thickness and
mass.

7.4 Other applications

GCR drive photochemical reactions in the atmosphere of Saturn. The obtained GCR
spectra and flux on the atmosphere of Saturn is essential for the study of the GCR in-
fluence on atmospheric chemistry. The results, described in Chapter 6, can contribute
to the study of the heavy isotope production in the atmosphere and others.

The tracing capabilities of my code can also be used for various other projects, not
just for GCR studies. For instance, trapping lifetimes in the confined space between
the D-ring and the atmosphere of Saturn can be estimated. Moon-magnetosphere
interaction studies similar to what has been shown in Chapter 5 has been already
realized by Regoli et al. (2015), where the particle tracer was used to study the effect
of magnetic field disturbances in the vicinity of Titan in access of energetic ions to the
exobase.

Similarly this method can be extended to other moons, like Enceladus or the
Galilean moons of Jupiter. For instance Krupp et al. (2012) shows a variety of electron
depletion features near Enceladus, which is still uncertain if they derive from losses
at the plume material of the moon, from deflection of electrons due to magnetic per-
turbations near Enceladus or a combination of both. Particle tracing combined with
the output of a global simulation of Enceladus with the magnetosphere of Saturn (as
done in Chapter 5) is the only method to evaluate the processes described above.
7.4. Other applications
Conclusion

The energetic charged particles play a special role in the magnetosphere of Saturn. They create the radiation belts; interact with the rings, moons and atmosphere of the planet. They indicate the topology of the magnetosphere and at the same time influence it. Particle tracing is the instrument for numerical calculation of the energetic particle trajectories, which allows us to simulate the motion of the particles and by comparison with in-situ observations prove various theoretical assumptions.

The Cassini mission provides extensive data about the energetic particles population in the magnetosphere of Saturn. However, many questions still remain open for today. In this thesis I describe, how the numerical methods can help to answer some of them.

The MeV proton radiation belts of Saturn are proved to be isolated from the outer magnetosphere, and the source of these high energy protons should be related to the Galactic Cosmic Rays. To validate this hypothesis first of all it is necessary to determine the realistic flux of GCR to Saturn. Previously only theoretical attempts were performed in order to verify this idea. In this thesis for the first time I provide the numerical solution for determination of the GCR access to the atmosphere and rings of Saturn.

I developed an energetic particle tracing code, which allows simulation of the charged particle’s trajectories in planetary magnetospheres. To validate the performance of the code I applied it first for the modeling of the energetic ions motion in the vicinity of the moons Rhea and Dione and compared the simulation results with in-situ observations. On one hand this helps to validate the code and verify, whether it works correctly. And on the other hand, it provides the unique opportunity to study in great detail the LEMMS measurements. Indeed, using the particle tracer, I simulated the LEMMS signal for different magnetospheric processes and determined, which features shape the LEMMS signal during the moon’s flybys.

Particularly, the developed particle tracer was applied to the simulation of the energetic ion flux profiles in the vicinity of the moons Rhea and Dione. The resulting simulated flux was compared with the LEMMS data during flybys $R_2$, $R_3$ and $D_1$. As a basis for these calculation the dipole magnetic field with a corotation electric field was taken and backward tracing of the energetic ions was performed, taking into account the LEMMS pointing and finite field of view, its response to heavier ions, as well as a series of configurations of the local magnetospheric and moon environments.
7.4. Other applications

During this study it was discovered that for the correct interpretation of the LEMMS signal the composition of the energetic ions is very important since the LEMMS detector responds more efficiently to heavier ions, in contrast to protons, is opposite to previously commonly used assumption, that LEMMS responds only to protons. Therefore the developed model can also be used for cross-calibration of the MIMI detectors that measure energetic ions with different methods and efficiencies, such as LEMMS, CHEMS and INCA. Also it was found that local perturbations in the magnetic field near a moon may modify the access of ions to a moon’s surface, even though these perturbations are only about \(1 - 2\) nT (or few percent of the background magnetic field). Other effects, such as the exact magnitude of the corotation velocity, the presence of additional electric fields or charge exchange in the moon’s exosphere proved to be insignificant.

Hence, the developed model offers a method to validate and/or constrain the ion composition and charge state where instrumentation may not be available, for instance at Titan or other Saturnian moons with Cassini (and for energies beyond the CHEMS’s upper energy bound at 300\(keV\)) and Ganymede. Similarly, it can be used to evaluate the electromagnetic field perturbations near such moons predicted by MHD or hybrid simulation codes. That offers an additional validation tool, besides the comparison with the magnetic field, as it is typically done.

Using backwards-tracing techniques I also simulated the motion of GCR in the magnetosphere of Saturn. As a result I obtained the minimum GCR access energy to the atmosphere of the planet and its rings, using different magnetospheric models: a Dipole model, the Khurana model and the Khurana model with higher order moments (above a dipole) put to zero. I analyzed the variations of the access energy in many different aspects, which is impossible to do with an analytical approach and provide rich material for future applications. As a main output I calculated the GCR spectra and GCR integrated flux to the atmosphere of Saturn as a function of latitude and to the equatorial distance of the Saturnian magnetosphere as a function of distance from the planet.

The obtained results are very important for the future research and for the Cassini mission itself. The obtained GCR flux will be used for calculating the CRAND input to the ion populations of the radiation belts, and for estimating the production of secondaries from GCR impact on the planetary atmosphere and rings. This will be compared with LEMMS measurements during the ”proximal” orbits at the end of the Cassini mission in 2017. Having determined the incoming GCR flux, it is possible now to perform a GEANT4 simulation of the cascade of particles resulting from GCR penetration through the rings, and to estimate their contribution to the radiation belts population. The highest priority study is the estimation of the CRAND production rate from the rings and separately from the atmosphere and the determination of the intensity of the innermost radiation belt, its stability and possible spectra. The existence of the innermost radiation belts will be definitely settled during the final orbits of Cassini. One more study is devoted to the determination of the rings’ thickness,
which can be calculated knowing how much energy GCR lose during their passage through the rings. Among other projects, which are using intensively the developed particle tracing code, are the microsignatures "age" study and the energetic particles interaction with Enceladus study.
7.4. Other applications
Conclusion Générale

Les particules chargées énergétiques jouent un rôle particulier dans la magnétosphère de Saturne. Elles créent les ceintures de radiation; interagissent avec les anneaux, les lunes et la haute atmosphère de la planète. Elles indiquent la topologie de la magnétosphère et en même temps l’influencent. Le traçage des particules est un outil privilégié pour étudier la trajectoire de particules énergétiques, ce qui permet de simuler le mouvement de ces particules et ensuite, par comparaison avec les observations in-situ, d’examiner la validité de certaines hypothèses théoriques.

La mission Cassini fournit depuis 2004 des une riche moisson de données sur la population de particules énergétiques dans la magnétosphère de Saturne. Cependant, de nombreuses questions sont encore ouvertes aujourd’hui. Dans cette thèse je décris comment les méthodes numériques peuvent aider à répondre à certaines d’entre elles.

Les ceintures de radiation de protons de haute énergie (de l’ordre de quelques MeV) de Saturne s’avèrent être isolées de la magnétosphère moyenne et externe, et la source de ces protons de haute énergie devraient être liée aux rayons cosmiques galactiques. Pour valider cette hypothèse il est d’abord nécessaire de déterminer le flux réaliste des GCR (rayons cosmiques galactiques) arrivant à Saturne. Auparavant, seules les tentatives théoriques ont été effectuées afin de vérifier cette idée. Dans cette thèse je fournis pour la première fois une solution numérique pour la détermination de l’accès des GCR à l’atmosphère et aux anneaux de Saturne.

Pour adresser ce problème j’ai développé un code de traçage des particules énergétiques, ce qui permet de simuler les trajectoires des particules chargées dans les magnétosphères planétaires. Pour valider la performance du code je l’ai d’abord appliqué pour la modélisation du mouvement des ions énergétiques dans le voisinage des lunes Rhéa et Dionée, et j’ai comparé les résultats de la simulation avec des observations in situ, fournies par l’instrument LEMMS à bord de Cassini. D’une part cela a permis de valider le code et de vérifier son fonctionnement correct. D’autre part il a offert une occasion unique pour étudier en détail les mesures de LEMMS et pour analyser les mécanismes physiques dominant dans le voisinage de ces lunes. En effet, en utilisant le traceur de particules, j’ai simulé le signal de LEMMS pour différents processus magnétosphériques et j’ai déterminé quels sont ceux qui déterminent la forme du signal acquis par LEMMS lors des survols de ces lunes.

En particulier, le code de traçage particulaire mis au point a été appliqué à la simulation des profils énergétiques du flux d’ions au voisinage des lunes Rhéa et Dionée.
Le flux simulé résultant a été comparé avec les données de LEMMS pendant les survols R2, R3 et D1. Comme base pour ces calculs a été utilisé le champ magnétique dipolaire avec un champ électrique de corotation et le tracage vers l’arrière des ions énergétiques a été réalisé en tenant compte du pointage du champ de vue de LEMMS, de sa réponse aux ions lourds, ainsi que d’une série des configurations des environnements de la magnétosphère et des lunes.

Au cours de cette étude il a été découvert que, pour l’interprétation correcte du signal de LEMMS, la composition des ions énergétiques est très importante puisque le détecteur LEMMS répond plus efficacement aux ions lourds qu’aux protons, ce qui est à l’opposé de l’hypothèse couramment utilisée que LEMMS répond essentiellement aux protons. Par conséquent, le modèle développé peut également être utilisé pour l’étalonnage croisé des détecteurs qui mesurent les populations des ions énergétiques avec différentes méthodes et différentes efficacités, tels que LEMMS, CHEMS et INCA. En outre, il a été constaté que des perturbations locales du champ magnétique près d’une lune peuvent modifier l’accès des ions à la surface de la lune, même si ces perturbations ne sont que d’environ $1 - 2$ nT (ou quelques pour cent du champ magnétique de fond). D’autres effets, tels que l’ampleur exacte de la vitesse de corotation, la présence de champs électriques supplémentaires ou d’interactions d’échange de charge dans l’exosphère de la lune se sont avérés être négligeables.

Par conséquent, le modèle développé offre une méthode pour valider et / ou contraindre la composition ionique et l’état de charge dans d’autres environnements, par exemple autour de Titan ou d’autres lunes de Saturne (et pour les énergies au-delà de l’énergie supérieure de CHEMS : $\sim 300$ keV), ou autour de Ganymède. De même, il peut être utilisé pour évaluer les perturbations du champ électromagnétique à proximité de ces lunes prévues par les codes MHD ou par les simulations hybrides. Cela offre un outil de validation supplémentaire, en plus de la comparaison avec le champ magnétique, comme cela se fait habituellement.

En utilisant des techniques de traçage en arrière j’ai ensuite simulé le mouvement des GCR dans la magnétosphère de Saturne. J’ai ainsi obtenu l’énergie minimale d’accès des GCR à l’atmosphère de la planète et de ses anneaux, en utilisant différents modèles de la magnétosphère: un modèle de dipôle, le modèle de Khurana et le modèle de Khurana avec les moments d’ordre supérieur (au-dessus d’un dipôle) mis à zéro. J’ai pu analyser les variations de l’énergie d’accès en fonction de paramètres différents, ce qui est impossible à faire avec l’approche analytique, et j’ai fourni des nombreux éléments pour des applications futures. Comme résultat principal, j’ai calculé les spectres des GCR et le flux intégré des GCR à l’atmosphère de Saturne en fonction de la latitude, et sur le plan équatorial de la magnétosphère de Saturne en fonction de la distance à la planète.

Les résultats obtenus sont très importants pour la recherche future et pour la mission Cassini elle-même. Le flux des GCR obtenu sera utilisé pour le calcul de l’entrée CRAND aux populations d’ions des ceintures de radiation, et pour l’estimation de la production de particules secondaires provenant des GCR dans l’atmosphère et les an-
neaux planétaires. Ceci sera comparé avec les mesures qui seront acquises par LEMMS au cours des orbites "proximal", à la fin de la mission Cassini, en 2017. Après avoir déterminé le flux entrant des GCR, il est maintenant possible d’effectuer une simulation par GEANT-4 de la cascade de particules résultant de la pénétration des GCR à travers les anneaux, et d’estimer leur contribution à la population des ceintures de radiations. L’étude la plus prioritaire est l’estimation du taux de production CRAND dans les anneaux, et séparément dans l’atmosphère, et la détermination de l’intensité de la ceinture de radiations la plus intérieure, située entre Saturne et les anneaux, sa stabilité et les spectres en énergie possibles. L’existence de la ceinture de radiations la plus interne devrait être confirmée ou non au cours des dernières orbites de Cassini. Une étude supplémentaire sera consacrée à la détermination de l’épaisseur des anneaux, qui peut être calculée à partir de la perte d’énergie des GCR lors de leur passage à travers les anneaux. Parmi les autres projets, qui utiliseront intensivement le code développé de traçage de particules, sont l’étude de l’âge des microsignatures et l’étude de l’interaction des particules énergétiques avec Encelade.
7.4. Other applications
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J. M. Casandjian, C. Cecchi, Ö. Çelik, E. Charles, S. Chaty, R. C. G. Chaves, 
A. Chekhtman, C. C. Cheung, J. Chiang, G. Chiaro, A. N. Cillis, S. Ciprini, 
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Appendices
Appendix A

Simulation results for Rhea and Dione flybys for A0-A4 channel separately

Figure A.1: Simulation results for R2 A0: noisy line represents the LEMMS data, solid bold line - total simulation results.
Figure A.2: Simulation results for R2 A1: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.3: Simulation results for R2 A2: noisy line represents the LEMMS data, solid bold line - total simulation results.
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Figure A.4: Simulation results for R2 A3: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.5: Simulation results for R2 A4: noisy line represents the LEMMS data, solid bold line - total simulation results.
Figure A.6: Simulation results for R3 A0: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.7: Simulation results for R3 A1: noisy line represents the LEMMS data, solid bold line - total simulation results.
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Figure A.8: Simulation results for R3 A2: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.9: Simulation results for R3 A3: noisy line represents the LEMMS data, solid bold line - total simulation results.
Figure A.10: Simulation results for R3 A4: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.11: Simulation results for D1 A2: noisy line represents the LEMMS data, solid bold line - total simulation results.
Appendix A. Simulation results for Rhea and Dione flybys for A0-A4 channel separately

Figure A.12: Simulation results for D1 A3: noisy line represents the LEMMS data, solid bold line - total simulation results.

Figure A.13: Simulation results for D1 A4: noisy line represents the LEMMS data, solid bold line - total simulation results.
Appendix B

GCR access to Saturn

Figure B.1: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model (Equinox) for $H^+$. 

Khurana model Equinox (August 23 (235), 2009)
Figure B.2: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model (Postequinox) for $H^+$. 

Figure B.3: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model (Preequinox) for $He^+$. 
Figure B.4: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model (Equinox) for $He^+$. 

Figure B.5: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model with zero higher order components (Preequinox) for $H^+$. 

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Figure B.6: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model with zero higher order components (Equinox) for $H^+$. 

Figure B.7: GCR access energy to equatorial plane through the magnetosphere of Saturn as a function of distance from the planet: Khurana model with zero higher order components (Postequinox) for $H^+$. 
Publications and communications

Publications:

- "Modeling of the energetic ion observations in the vicinity of Rhea and Dione”, A. Kotova, E. Roussos, N. Krupp, I. Dandouras; Icarus, Volume 258, 15 September 2015, Pages 402-417


- "Modeling the satellite particle population in the planetary exospheres: application to Earth, Titan and Mars”, A. Beth; P. Garnier; D. Toublanc; I. Dandouras; C. Mazelle; A. Kotova, Icarus, Volume 227, 1 January 2014, Pages 21-36
Communications:


• "Energetic ion observations on Rhea", **A. Kotova**, E.Roussos, N. Krupp, I. Dandouras, Rocks-n-Stars Conference, Göttingen, Germany, 8-11.10.2012 (Poster)

• "Tracing of energetic ions in vicinity of Rhea", **A. Kotova**, E.Roussos, N. Krupp, I. Dandouras, MIMI Team Meeting, APL JHU, USA, 28.10.2012 (Oral)


• "Modeling of the MIMI/LEMMS energetic ion observations in the vicinity of Rhea and Dione", **A. Kotova**, E.Roussos, N. Krupp, I. Dandouras, MAPS 2013, San Antonio, USA, 20.03.2013 (Oral)

• "Modelling of the energetic ion observations in the vicinity of Rhea and Dione”, **A. Kotova**, E.Roussos, N. Krupp, I. Dandouras, EGU 2013, Vienna, Austria, 09.04.2013 (Oral)


• "Modeling of the energetic ion observations in the vicinity of Rhea and Dione: final results”, **A. Kotova**, E.Roussos, N. Krupp, I. Dandouras, MIMI Team Meeting, Athens, Greece, 06.07.2013 (Oral)


• "Energetic charged particle populations of the magnetospheres of the outer planets”, **A. Kotova**, ISSI workshop Bern, Switzerland, 23.09.2013 (Oral)
Appendix B. GCR access to Saturn


- "Energetic particle tracing in the magnetosphere of Saturn”, A. Kotova, E. Roussos, N. Krupp, I. Dandouras, MIMI Team Meeting, Göttingen, Germany, 17.06.2014 (Oral)


- "Galactic Cosmic Rays tracing in the inner magnetosphere of Saturn”, A. Kotova, E. Roussos, N. Krupp, I. Dandouras, MOP 2015, Atlanta, USA, 04.06.2015 (Poster)
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