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MODELING THE INTERACTION OF JUPITER'S MAGNETOSPHERIC PLASMA IONS WITH SATELLITE

O.V. Khelemelia[1], A.P. Fomina[2,3], O.P. Novak[1], R.I. Kholodov[1]
[1]Institute of Applied Physics NAS of Ukraine, Sumy, Ukraine;
[2]Bogolyubov Institute for Theoretical Physics NAS of Ukraine, Kyiv, Ukraine;
[3]University Paris-Saclay, CNRS, IAS, Orsay, France
E-mail: oleksiikhel@gmail.com

Jupiter's moons are constantly bombarded by ions produced by the giant planet's plasma magnetosphere. The influence is considered as one of the main sources of the moons' atmosphere and surface modification. This investigation is an attempt to explore the interaction of space ions with Ganymede's magnetosphere. Computer simulations are performed using electromagnetic fields that are close to experimentally observed fields in previous Jupiter space missions.

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INTRODUCTION

The JUpiter ICy moons Explorer (JUICE) is a European Space Agency (ESA) mission that aims to make multiple flybys of Jupiter's satellites Ganymede, Callisto, and Europa and then to go into orbit around Ganymede. The science goals are focused on Jupiter and its system, with particular emphasis on Ganymede as a planetary body and potential habitat. One of the primary science objectives for Ganymede is to study Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere [1].

Jupiter is the first among the planets in terms of size, mass, magnetic field strength, rotation speed and volume of the magnetosphere. It has several planet-like satellites. Jupiter tidally heats Io's interior and in turn stimulates volcanic activity on Io, making it the most volcanically active planetary body in the Solar system. Io volcanos supply heavy ions and electrons to Jupiter magnetosphere, which afterwards are accelerated within the Io flux tube. This leads to complex interaction between Jovian magnetoshpere and particle currents [2 - 6]. Europa is also located in Jupiter's magnetosphere region with intense radiation belts. This satellite does not have a significant internal magnetic field and its surface is strongly affected by direct interaction with Jupiter's magnetosphere [7].

Ganymede is the largest moon in the solar system (R_G = 2.631 km). It is covered with ice and perhaps a subsurface liquid ocean, and also it has a rocky mantle and an iron core. Ganymede stands out among other Jupiter's satellites in that it possesses the intrinsic dynamo magnetic field with the equatiorial induction of ~ 720 nT and the active Ganymede-centered magnetic dipole moment is about $1.3{\cdot}10^{13}$ T·m^3 [8]. For comparison, Jovian magnetic field is ~ 120 nT at Ganymede orbit at 15 Jupiter radii from the Jupiter's center. Ganymede intrinsic magnetic field is strong enough to dominate the local Jovian magnetic field and magnetospheric plasma approximately to the distance of $2R_G$ (Fig. 1). The equatorial part of the Ganymede magnetosphere is a region of closed field lines and this region extends to latitudes approximately 40°. In the polar regions the magnetic field lines are open with one foot point of the field is attached to Ganymede, and the other is attached to Jupiter.

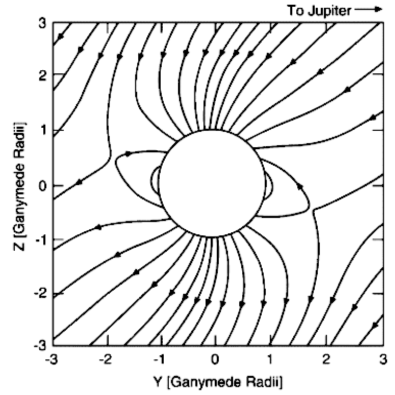


Fig. 1. Ganymede magnetosphere shown in the magnetic meridian plane of Jupiter magnetosphere [3]

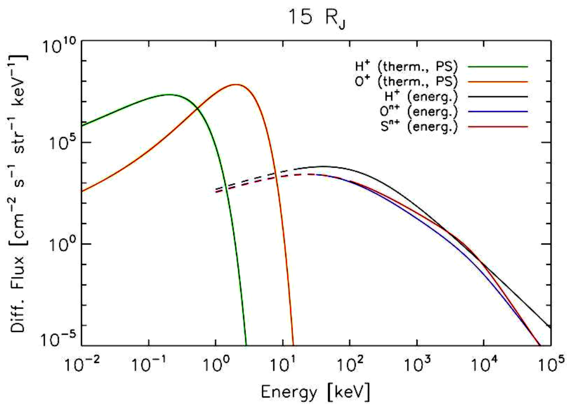


Fig. 2. The distribution of ions in magnetosphere plasma near Ganymede orbit (~15 R_J) as a function of energy for the five ion species [9]

Since the moon's orbital period of 172 h exceeds Jupiter's rotation period of 10 h, Ganymede represents an obstacle to the drifting plasma that corotates with the planet. The magnetosphere plasma continually impacts the Ganymede's orbital trailing hemisphere as it overtakes the moon at a relative velocity of nearly 140 km·s^{-1}. The plasma density fluctuates between 1 and 10 cm^{-3} as Jupiter's magnetospheric plasma sheet sweeps over the moon [8, 10]. This particle flux affects the weathering of the Ganymede surface, on radiolysis of the surface layers and on production of a sputtered Ganymede exosphere [11 - 13]. The plasma near Ganymede consists of both thermal (with energies $E \leq 10$ keV) and energetic ions and electrons ($E \geq 10$ keV up to 100 MeV). The energetic ion component of the Jovian magnetospheric population mainly consist of H^+, O^{n+}, and S^{n+} ions with energies up to 10…50 MeV (Fig. 2) [14].

The ions in the energy range between 1 keV to several MeV have sufficiently high fluxes and large sputtering amounts and make main contributions to surface processes. The distribution of the energetic ion precipitation is spatially variable [9], depending on the ion properties – type, ionization state, flux intensity, energy.

Computer simulation is used to study the interaction of Jupiter's magnetospheric plasma ions with satellites. There are several types of simulation approaches that are used in studying the interactions of space plasma and satellites, and each of the models has its own advantages and limitations. These are magnetohydrodynamic (MHD) simulation [16 - 18], particle-in-cell [19], hybrid simulation and test particle simulation [15, 20, 21]. There are also complex approaches that complete the modeling of ion emissions from Jupiter, its transportation to the Ganymede magnetosphere, and the subsequent interaction of these ions with the atmosphere and the surface of the moon, for example, SWMF (The Space Weather Modeling Framework) [22]. However, the use of such complex software frameworks requires huge computing capacities.

In our study we use the approach based on the backward tracking of test particles to simulate the interaction of Ganymede with plasma flow in the Jupiter magnetosphere and to find the ion precipitation on the surface of Ganymede.

This approach has already been used to model a Saturn-Titan system [23]. The existence of a shielded equatorial region on Ganymede's trailing hemisphere and small ion precipitation in the low-latitude leading hemisphere is expected.

1. MODEL DESCRIPTION

To simulate energetic ion precipitation, we develop program code based on the integration of the relativistic equation of motion,

$$\frac{d(\gamma m\vec{v})}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right), \quad (1)$$

where $\vec{v}$ is the particle velocity, $\vec{E}$ and $\vec{B}$ are electromagnetic field components, q is the particle charge, m is the particle mass and γ is a relativistic Lorentz factor. We assume that the electromagnetic field in Eq. (1) does not depend on the motion of energetic ion component of the magnetosphere.

The initial coordinates of the tracked ions are generated randomly and are uniformly distributed over the sphere with radius R_G. In each simulation, the ions are considered to be monoenergetic with velocity direction randomly distributed within the inward-looking hemishpere, $\vec{r}\vec{v} < 0$. The ion motion is then tracked backward in time. The tracking is stopped when one of the following conditions is fulfilled: (1) the particle collided with the moon surface, $r<R_G$, or (2) the particle reached the distance of 10 R_G. In the first case the trajectory is considered as impossible, while in the second case the particle is considered as originated outside of the Ganimede mangetoshpere and its trajectory is added to the total irradiation of the surface.

To characterize the accessibility of the Ganimede surface for irradiation by the energetic ions we calculate the percentage of the ions that were able to escape the Ganimede magnetoshpere and reach the outer boundary for each location on the surface,

$$A(\Omega) = (N_e \cdot W_e(\Omega)) / (N_i \cdot W_i(\Omega)), \quad (2)$$

where N_e is the number of ions that have left the magnetosphere, N_i is the total number of ions, Ω denotes the coordinates of the surface point (latitude, longitude), W_e is the probability density function of the initial coordinates of the ions that left the magnetosphere, W_i is the probability density function of the initial coordinates of all ions. Both W_i and W_e have been obtained from the simulation data using Gaussian kernel density estimation on the haversine metrics.

The value $A(\Omega)$ can be interpreted as the access of the satellite surface for precipitation by external cosmic ions.

2. SIMULATION AND RESULTS

Simulations are performed in the Ganymede centered inertial phi-Omega coordinate system (GphiO). It has +Z parallel to Jupiter's spin axis (pointing toward north), +Y pointing toward Jupiter and +X completing the right-handed set along the orbital motion of Ganymede and plasma flow direction.

The magnetic field is chosen according to the data representing the measurements of the specific magnetospheric configuration of Galileo G1 flyby near Jupiter and Ganymede [24]. The background magnetic field of Jupiter $\vec{B}_0$ near Ganymede's location for the G1 encounter was dominated by the radial and southward, so that $\vec{B}_0$ =(0, -79, -79) nT (B_0=112 nT) [2, 12, 18].

The second component of the magnetic field is the dipole field of Ganimede given by

$$\vec{B} = \frac{\vec{r}\left(\vec{r}\vec{M}\right)}{r^5} - \frac{\vec{M}}{r^3}. \quad (3)$$

The permanent dipole magnetic field of Ganymede has an equatorial magnitude 722 nT. Its magnetic moment is tilted by 176° from the spin axis with the pole in the southern hemisphere rotated by 24° from the Jupiter-facing meridian plane towards the trailing hemisphere. It means that it is directed almost against Jupiter's magnetic moment. The components of the vector of the magnetic dipole moment magnetic was taken according to the G1 encounter, M = (-24.7, 82.5, -716.8) $nT \cdot R_G^3$. This vector includes both the permanent dipole moment and the induced field of Ganymede in the GphiO coordinate system [12, 18].

The calculations are carried out for ions H^+, O^+, and S^{+++} with energies 1, 10, 30 keV. $N_i = 50000$ ions are tracked in every simulation run.

The percentages of ions $A(\Omega)$ that have left the surface of the satellite and escaped beyond the magnetosphere of Ganymede are presented on Figs. 3-6. In these plots, the longitude is measured from the Jupiter-facing meridian, and latidude is measured from the equator. Thus, coordinates (0,0) correspond to the direction of +Y in the GphiO system.

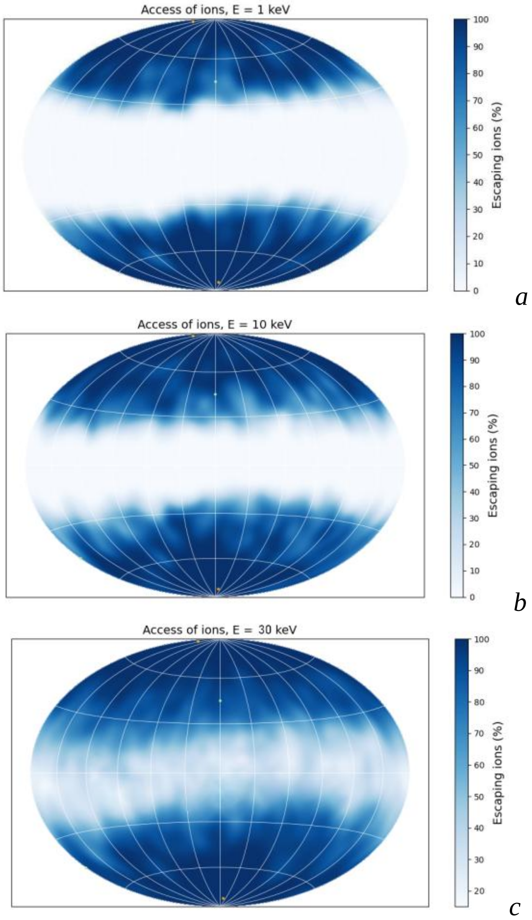
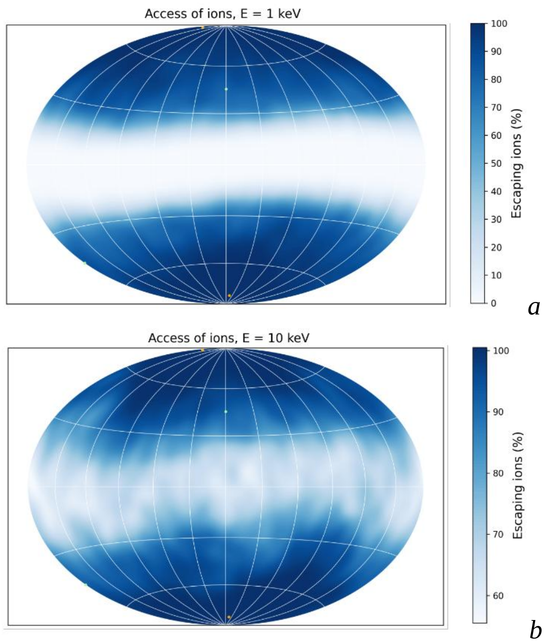


Fig. 3. H^+ ion precipitation map on the satellite surface, corresponding to initial energies equal to 1 (a); 10 (b), and 30 keV (c)

Fig. 3 shows H^+ ion precipitation map on the surface, corresponding to initial energies equal to 1, 10, and 30 keV. Fig. 4 shows O^+ ion precipitation map on the surface, corresponding to initial energies equal to 1, 10, and 30 keV. Fig. 5 shows S^{+++} ion precipitation map onthe surface, corresponding to initial energies equal to 1, 10, and 30 keV.



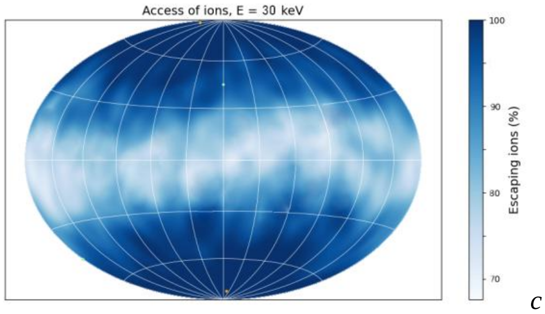


Fig. 4. O^+ ion precipitation map on the surface, corresponding to initial energies equal to 1 (a); 10 (b), and 30 keV (c)

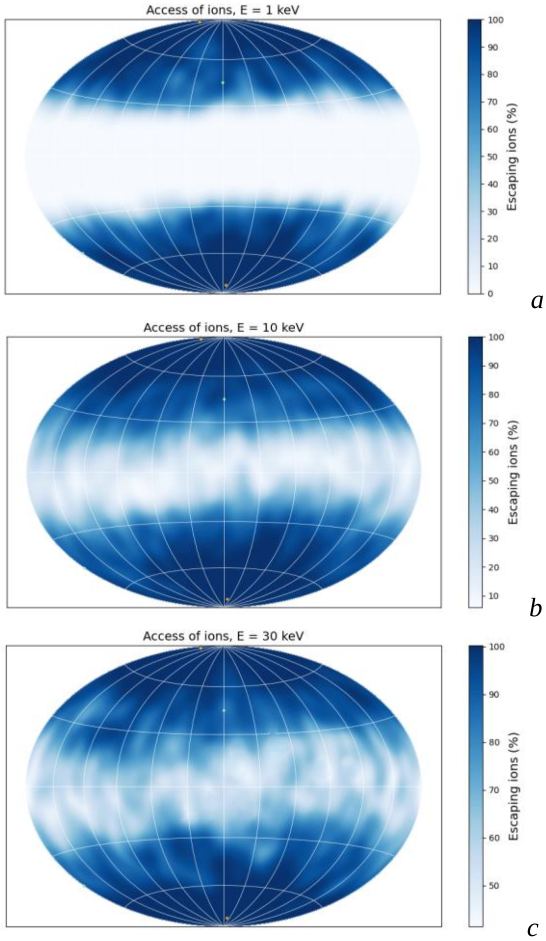


Fig. 5. S^{+++} ion precipitation map on the surface, corresponding to initial energies equal to 1 (a); 10 (b), and 30 keV (c)

The results of the simulation show that with increasing ion energy the number of particles that can precipitate on the surface of Ganymede increases.

At lower energies the magnetosphere of Ganymede can partially shield the impacting ions. Therefore less particles can reach the surface at equator and so they are deflected towards the poles. We get an obvious dichotomy between the precipitation of particles at the equator and at the poles. In general, the polar regions are more accessible for the impact of particles, because there are open magnetic field lines at the poles of the satellite. These results agree with observational data and simulations of other authors.

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МОДЕЛЮВАННЯ ВЗАЄМОДІЇ ІОНІВ МАГНІТОСФЕРНОЇ ПЛАЗМИ ЮПІТЕРА ІЗ СУПУТНИКОМ

О.В. Хелемеля, А.П. Фоміна, О.П. Новак, Р.І. Холодов

Супутники Юпітера постійно бомбардуються іонами плазми гігантської магнітосфери планети. Цей вплив вважається одним з основних джерел модифікації атмосфери і поверхні супутників. Дане дослідження є спробою вивчити взаємодію іонів плазми з магнітосферою Ганімеда за допомогою комп'ютерного моделювання, при цьому використовуються значення електромагнітних полів з даних попередніх космічних місій до Юпітера.