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The H_2O and O_2 exospheres of Ganymede: The result of a complex interaction between the jovian magnetospheric ions and the icy moon

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ABSTRACT

The H_2O and O_2 exospheres of Jupiter's moon Ganymede are simulated through the application of a 3D Monte Carlo modeling technique that takes into consideration the combined effect on the exosphere generation of the main surface release processes (i.e. sputtering, sublimation and radiolysis) and the surface precipitation of the energetic ions of Jupiter's magnetosphere. In order to model the magnetospheric ion precipitation to Ganymede's surface, we used as an input the electric and magnetic fields from the global MHD model of Ganymede's magnetosphere (Jia, X., Walker, R.J., Kivelson, M.G., Khurana, K.K., Linker, J.A. [2009]. J. Geophys. Res. 114, A09209). The exospheric model described in this paper is based on EGEON, a single-particle Monte Carlo model already applied for a Galilean satellite (Plainaki, C., Milillo, A., Mura, A., Orsini, S., Cassidy, T. [2010]. Icarus 210, 385–395; Plainaki, C., Milillo, A., Mura, A., Orsini, S., Massetti, S., Cassidy, T. [2012]. Icarus 218 (2), 956–966; Plainaki, C., Milillo, A., Mura, A., Orsini, S., Saur [2013]. Planet. Space Sci. 88, 42–52); nevertheless, significant modifications have been implemented in the current work in order to include the effect on the exosphere generation of the ion precipitation geometry determined strongly by Ganymede's intrinsic magnetic field (Kivelson, M.G. et al. [1996]. Nature 384, 537–541). The current simulation refers to a specific configuration between Jupiter, Ganymede and the Sun in which the Galilean moon is located close to the center of Jupiter's Plasma Sheet (JPS) with its leading hemisphere illuminated.

Our results are summarized as follows: (a) at small altitudes above the moon's subsolar point the main contribution to the neutral environment comes from sublimated H_2O; (b) plasma precipitation occurs in a region related to the open-closed magnetic field lines boundary and its extent depends on the assumption used to mimic the plasma mirroring in Jupiter's magnetosphere; (c) the spatial distribution of the directly sputtered-H_2O molecules exhibits a close correspondence with the plasma precipitation region and extends at high altitudes, being, therefore, well differentiated from the sublimated water; (d) the O_2 exosphere comprises two different regions: the first one is an homogeneous, relatively dense, close to the surface thermal-O_2 region (extending to some 100s of km above the surface) whereas the second one is less homogeneous and consists of more energetic O_2 molecules sputtered directly from the surface after water-dissociation by ions has taken place; the spatial distribution of the energetic surface-released O_2 molecules depends both on the impacting plasma properties and the moon's surface temperature distribution (that determine the actual efficiency of the radiolysis process).

1. Introduction

The atmospheres of Europa and Ganymede are expected to be quite similar in composition since in both cases the surface is expected to be composed mostly of water ice and the physical conditions (temperature and moon dimensions) as well as the radiation environments are comparable. Nevertheless, Ganymede's internal magnetic field (Kivelson et al., 1997) makes this body unique in the Solar System. The existence of tenuous exospheres at the Galilean moons has been demonstrated through the Hubble Space Telescope (HST), Goddard High-Resolution Spectrograph (GHRS) and Advanced Camera for Surveys (ACS) observations of the Far-UV Oxygen lines, signature of dissociated molecular oxygen at Europa and Ganymede (Hall et al., 1995, 1998;

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Feldman et al., 2000; Eviatar et al., 2001a; McGrath et al., 2004, 2013), and through the Hydrogen Lyα line at Ganymede observed by the Galileo UV-spectrometer (Barth et al., 1997) and by the HST-Space Telescope Imaging Spectrograph (STIS) (Feldman et al., 2000), signature of neutral hydrogen.

The mechanisms expected to be predominantly responsible for the generation of a neutral environment around Ganymede are the release of surface material via direct ion sputtering and radiolysis (Johnson et al., 2004) and the sublimation of water ice (Marconi, 2007). The latter mechanism is strongly temperature dependent. The Galileo photopolarimeter (PPR) measurements (Orton et al., 1996) showed that Ganymede's surface temperature has a maximum value of ∼150 K near the subsolar point whereas it remains constant (and equal to ∼80 K) on the unilluminated hemisphere. At Europa, the measured surface temperature range is narrower (from ∼86 K up to ∼130 K, according to Spencer et al., 1999) hence the averaged expected contribution of sublimated water–ice to the moon's exospheric density is expected to be negligible. Only locally (for example at small altitudes above the subsolar point) the released fluxes due to sublimation can become comparable to those due to the other release mechanisms (Plainaki et al., 2010). On the contrary, at Ganymede, the estimated surface release rate due to sublimation is expected to have a wider range of variation and a stronger spatial dependence. In particular, the contribution of this mechanism to the generation of the moon's exosphere could be substantial on the whole illuminated side (Marconi, 2007).

Considering that water ice is the major component of the surface of an icy moon, the generated exosphere is expected to be a mixture of H_2O, O_2 and H_2 and of some other water products, such as OH and O (Smyth and Marconi, 2006; Shematovich et al., 2005; Plainaki et al., 2012). The spatial distribution of the exosphere of Europa is expected to depend mainly on the illumination of the moon, since its surface temperature is responsible for the efficiency of radiolysis (Famà et al., 2008) as well as for the sublimation rate (Smyth and Marconi, 2006); secondarily, the exosphere distribution depends on the ion flux that impacts the trailing hemisphere more intensively (Pospieszalska and Johnson, 1989; Cassidy et al., 2012; Plainaki et al., 2012, 2013). At Ganymede, the situation is expected to be more complex. In fact, the intrinsic magnetic field of Ganymede, reconnecting with the external jovian magnetic field, partially shields the surface from the ion impact, especially at the equatorial latitudes (e.g.: Kivelson et al., 1997). The jovian magnetospheric plasma at Ganymede, confined by Jupiter's magnetic field, slightly subcorotates at 150 km/s (Scudder et al., 1981), while the orbital velocity of Ganymede is 11 km/s (both velocities have anticlockwise direction, if seen from the North). As a result, the bulk plasma flow is constantly overtaking the satellite. The scale height of the plasma sheet at the distance of Ganymede, centered roughly around the jovian magnetic equator, is low (Khurana et al., 2004, 2007); moreover, Jupiter's magnetic axis is tilted by 10 degrees with respect to its rotational axis, hence the plasma sheet oscillates up and down the satellite (McGrath et al., 2013). Above about 10 keV the ion flux falls off with increasing energy (Paranicas et al., 1999); however, these energetic particles have a significant role in the magnetosphere–moons interactions. Mauk et al. (1996) showed that the energy deposited on the icy satellites by magnetospheric particles is carried mainly by the particles at energies above 10 keV. The maximum ion precipitation to the surface, leading to intense sputtering and radiolysis effects, therefore, is expected to take place near the Open-Closed magnetic Field lines Boundary (OCFB) regions (e.g.: Kivelson et al., 1997). Eventually, the release of surface material at Ganymede is expected to depend both on the configuration of Ganymede's magnetospheric field and the illumination of the moon by the Sun. Furthermore, the dynamics of the jovian magnetospheric plasma control the dynamics of plasma entry into and circulation inside Ganymede's magnetosphere primarily through reconnection between Jupiter's and Ganymede's magnetic fields (Jia et al., 2010) and eventually determine the precipitation toward the surface (Johnson, 1997).

Some efforts to model Ganymede's exosphere, considering a completely collisionless neutral environment, have been already made in the past (see for example the works of Yung and McElroy, 1977; Purves and Pilcher, 1980). Recently, Marconi (2007) presented an improved 2D axisymmetric kinetic model where a simplified plasma precipitation geometry and two different cases of constant overall ion velocities (equal to 1 or 10 km/s) were considered. Moreover, these authors evaluated the generation of minor water products as a result of the interaction of the atmospheric gas mainly with photons and electrons. Ganymede's atmosphere in the Marconi (2007) model has been considered quasi-collisional (at altitudes <200 km) or collisionless, while a collisional regime was assumed only in the low-altitude regions close to the subsolar point, where sublimation of water could be non-negligible. The Marconi (2007) model showed that close to the subsolar point (i.e. below the altitude of ∼300 km), the major atmospheric species is water (with a density up to $\sim 7 \cdot 10^{14}\ m^{-3}$); at higher altitudes, the major species is H_2 (with a density of about $10^{12}\ m^{-3}$) while water products like OH, O and H rapidly stick onto the surface and, hence, have a minor role just below the altitude of 200 km. On the contrary, above surface regions where the plasma impact is the major release driver, two distinct atmospheric regions were revealed: at altitudes below 70 km, the O_2 is the densest species ($\sim 3 \cdot 10^{14}\ m^{-3}$) whereas above this altitude H_2 is prevailing. However, in the exosphere generation mechanisms considered in the axisymmetric model of Marconi (2007), inhomogeneous surface phenomena (like temperature dependent H_2O radiolysis rate, or plasma precipitation dependent on the actual intrinsic magnetic field of the moon) were not considered. Turc et al. (2014) confirmed the general picture given by Marconi (2007) results. However, comparing their results to the observations they concluded that the H density could be underestimated while the O_2 density seemed in agreement with the observations. Thus, their sublimation rates could be significantly underestimated, whereas the sputtering rates not. Furthermore, they argued that the sublimated H_2O peak in the subsolar region would disappear within one hour in the shadow of Jupiter.

The inclusion of the plasma effects (geometry and ion energy) is crucial in order to have a reliable model of the neutral environment around Ganymede. The present study is intended to describe the 3D configuration of the major components of the exosphere in a large scale, taking into account the detailed plasma-dependent geometry and accurate simulations of the plasma – surface interactions. For this purpose we use the electric and magnetic fields from the Jia et al. (2009) global Magnetohydrodynamic (MHD) model of Ganymede's magnetosphere in order to perform a single-particle Monte Carlo (MC) simulation of the ions precipitation toward the moon's surface (Section 2); in our model, we consider only the configuration where Ganymede is located close to the center of Jupiter's Plasma Sheet (JPS). In Section 3 we describe the exosphere simulations; we model Ganymede's neutral environment only for the configuration at which the leading hemisphere (longitude 90°) is the illuminated one. In Sections 3.1 and 3.2, we describe the H_2O and O_2 exosphere sources considered in our MC model (i.e. surface sputtering and radiolysis by the energetic H^+, S^+ and O^+, and H_2O sublimation respectively). In Section 3.3, we describe the O_2 and H_2O exosphere loss processes and, in Section 3.4, we present the simulations results for the considered configuration. In Section 4 we discuss our overall results and in Section 5 we give