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On the impact of multiply charged heavy solar wind ions on the surface of Mercury, the Moon and Ceres

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Abstract

We have studied the impact of multiply charged solar wind O^{7+} and Fe^{9+} ions on the surfaces of Mercury, the Moon and on a Ceres-size asteroid using a quasi-neutral hybrid model.

The simulations showed that heavy O^{7+} and Fe^{9+} ions impact on the surface of Mercury non-homogenously, the highest flux being near the magnetic cusps—much as in the case of impacting solar wind protons. However, in contrast to protons, the analyzed heavy ions do not create high ion impact flux regions near the open–closed magnetic field line boundary. Dawn–dusk asymmetry and the total ion impact flux were each found to increase with respect to the increasing mass per charge ratio for ions, suggesting that the Hermean magnetic field acts as a mass spectrometer for solar wind ions. The Moon, in contrast, does not have a global intrinsic magnetic field and, therefore, solar wind ions can freely impact on its surface when this body is in the solar wind. The same is true for a, non-magnetized, Ceres-size asteroid.

The impact of multiply charged ions on a solid surface results in a large variety of physical processes, of often intimately inter-related atomic reactions, e.g. electron exchange between solid and approaching projectile, inelastic scattering of projectile, electronic excitation in the projectile and/or the solid, ejection of electrons, photons, neutral and iodized surface particles, and eventual slowing down and stopping of the projectile in the solid. The electron transfer process between impacting heavy ions and surface constituents can result in soft X-ray ($E<1$ keV) and extreme ultraviolet (EUV) photon emissions. These processes will eventually damage the target surface. Analysis of the hybrid Mercury model (HYB-Mercury) suggests that, at this planet the damaging processes result in non-homogenous ageing of the surface that is controlled by the intrinsic magnetic field of the planet and by the direction of the interplanetary magnetic field. In the corresponding Lunar model (HYB-Moon) and in the non-magnetized asteroid model (HYB-Ceres), surface ageing is demonstrated to take place on that side of the body that faces toward the flow of the solar wind.

Keywords: Mercury; The Moon; Ceres; Multiply charged heavy solar wind ions; Plasma–surface interaction; Numerical simulation

1. Introduction

Mercury is a planet with a relatively weak intrinsic magnetic field, and without an atmosphere. The Moon, instead, has neither an atmosphere nor a global intrinsic magnetic field. Many non-magnetized and non-atmospheric objects with sizes smaller than the Moon are found in the asteroid belt between the orbit of Mars and Jupiter as well as beyond Neptune (the Trans-Neptunian objects). The surfaces of these objects are, therefore, subject to bombardment by impacting solar wind ions: protons (H^+),

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alpha particles (He^{++}) and multiply charged heavy ions (O^{6+}, O^{7+}, Fe^{9+}, C^{4+}, Ne^{8+}, etc.).

Ion impact on the surface of an obstacle is a manifestation of a direct plasma–surface interaction and it has many potential consequences with regard to the surface (e.g. Killen and Ip, 1999; Milillo et al., 2005; Wurz et al., 2007). For example, impacting ions can dislodge neutrals, ions and electrons from the surface, thereby affecting both the surface itself and its plasma and neutral atom environments.

The impact of solar wind protons on the surface of Mercury has already received considerable attention in the literature. In these studies the properties of the impacting solar wind protons were based on global, modified terrestrial magnetospheric models which had been adapted to Hermean conditions (Killen et al., 2001; Delcourt et al., 2002; Wurz and Lammer, 2003; Massetti et al., 2003; Mura et al., 2005; Sarantos et al., 2007) and a self-consistent quasi-neutral hybrid model (Kallio and Janhunen, 2003a, b) was also presented. The interaction of solar wind ions (protons and alpha particles) with the Moon has been investigated recently (Wurz et al., 2007).

However, a fraction of the impacting solar wind plasma contains also multiply charged solar wind ions, such as O^{6+}, O^{7+}, Fe^{9+} to Fe^{14+}, C^{4+}, C^{5+}, Ne^{8+}, etc. (see, for example, von Steiger et al., 2000, and references therein). From sputter experiments in the laboratory it is known that the potential energy which is stored in multiply charged ions is liberated when the ions recombine during impacts on solid surfaces (Aumayr and Winter, 2003). In addition to their kinetic energy, the potential energy carried by multiply charged ions can lead to a kind of ion-induced sputtering which is called potential sputtering. Furthermore, the interaction between multiply charged ions and neutral species originating from a solar system object can result in a charge exchange (CX) process where an ion captures an electron from a neutral atom or molecule. In case of a significant atmosphere the CX processes cause the soft X-ray emission, as was observed from comets (Cravens, 1997, 2002). Soft X-ray and extreme ultraviolet (EUV) photon emission is also anticipated to take place in planetary exospheres, such as at the Earth (Robertson and Cravens, 2003), Mars (Holmström et al., 2001) and Venus (Gunell et al., 2007). For the objects considered in this paper, which have no atmosphere and only a thin exosphere, the multiply charged ions will interact with the material of the surface.

There is a considerably large body of laboratory research on the interaction of multiply charged ions with solid surfaces, which has been reviewed recently for multiply charged ions (Arnau et al., 1997; Aumayr and Winter, 2003), and for highly charged ions (Schenkel et al., 1999). However, possible effects of impacting multiply charged solar wind ions on the surface of solar system objects has received little attention hitherto. One reason for this is the lack of laboratory experiments and numerical simulations that could describe the complicated processes associated with different projectiles and targets. Recently, it was suggested (Shemansky, 2003) that impacting, multiply charged, solar wind ions results in soft-X-ray emission that produces ionization and dissociation of the molecular structure of relevant surfaces, resulting in even more effective ion sputtering than is caused by impacting solar wind protons. On the other hand, it was also recently concluded, based on available laboratory data, that a significant increase in the sputter yield due to impacting multiply charged ions cannot be expected at planetary surfaces (Wurz et al., 2007).

For this paper, we calculated the flux of impacting solar wind O^{7+} ions on three solar system objects using a self-consistent, quasi-neutral, hybrid model. The three objects are (1) Mercury which has a magnetosphere due to its relatively weak intrinsic magnetic field, (2) the non-magnetized Moon when it is in the solar wind and (3) a Ceres-size asteroid, assuming that this has a negligible intrinsic magnetic field and is without an atmosphere. The role of the mass per charge ratio of the heavy impacting ions at Mercury is also studied through calculating the impacting flux of solar wind Fe^{9+} ions.

The paper is organized as follows. First, we describe the numerical model adopted and give an overview of the solar wind interaction with three objects of different sizes at different distances from the Sun. Then we present the fluxes of impacting H^{+}, O^{7+} and Fe^{9+} ions on the surface of Mercury and compare these with ion impacts on the Moon and on an asteroid. Finally, we address issues involving effects resulting from CX processes near the surfaces of the three objects.

2. Description of the HYB models

The ion impact flux was calculated using a self-consistent, three-dimensional (3D), quasi-neutral hybrid model. In a quasi-neutral hybrid model, or briefly in a hybrid model, ions are modelled as particles while electrons form a massless charge neutralizing fluid. An important feature in the hybrid model simulation is that ions can impact to the surface of the object, making it possible to study the flux of impacting ions at a given position on the surface of the object considered. Our Mercury hybrid model (which is called HYB-Mercury), and the hybrid Moon model (which is called HYB-Moon) are described in detail elsewhere (Kallio and Janhunen, 2003a, b; Kallio, 2005) and we describe here only those features that are of special importance for the present study.

In all three runs of the model, the coordinate system was such that the solar wind flowed in the $-x$-direction, $+z$-axis was perpendicular to the orbital plane of the object and $+y$-axis completed the right-hand system. The centre of the object was at the origin at $(x,y,z) = (0,0,0)$.

In the HYB-Mercury model, the Hermean intrinsic magnetic field was modelled as a magnetic dipole located at the centre of the planet. The magnetic moment was on the z-axis and the magnetic field on the surface of Mercury at