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3D-modeling of Mercury's solar wind sputtered surface-exosphere environment

M. Pfleger[a], H.I.M. Lichtenegger[a,*], P. Wurz[b], H. Lammer[a], E. Kallio[c], M. Alho[c], A. Mura[e], S. McKenna-Lawlor[f], J.A. Martín-Fernández[d]

[a] *Space Research Institute, Austrian Academy of Sciences, Schmiedlstraße 6, A-8042 Graz, Austria*
[b] *Physikalisches Institut, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland*
[c] *Aalto University, School of Electrical Engineering, Helsinki, Finland*
[d] *Department for Computer Science and Applied Mathematics, University of Girona, Edifici P-IV, Campus Montilivi, E-17071 Girona, Spain*
[e] *Istituto Nazionale Di Astrofisica, Viale del Parco Mellini n°84, 00136 Roma, Italy*
[f] *National University of Ireland, Maynooth, Ireland*

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ABSTRACT

The efficiency of sputtered refractory elements by H^+ and He^{++} solar wind ions from Mercury's surface and their contribution to the exosphere are studied for various solar wind conditions. A 3D solar wind–planetary interaction hybrid model is used for the evaluation of precipitation maps of the sputter agents on Mercury's surface. By assuming a global mineralogical surface composition, the related sputter yields are calculated by means of the 2013 SRIM code and are coupled with a 3D exosphere model. Because of Mercury's magnetic field, for quiet and nominal solar wind conditions the plasma can only precipitate around the polar areas, while for extreme solar events (fast solar wind, coronal mass ejections, interplanetary magnetic clouds) the solar wind plasma has access to the entire dayside. In that case the release of particles form the planet's surface can result in an exosphere density increase of more than one order of magnitude. The corresponding escape rates are also about an order of magnitude higher. Moreover, the amount of He^{++} ions in the precipitating solar plasma flow enhances also the release of sputtered elements from the surface in the exosphere. A comparison of our model results with MESSENGER observations of sputtered Mg and Ca elements in the exosphere shows a reasonable quantitative agreement.

1. Introduction

In the tenuous exosphere of Mercury a number of different species have been detected up to now: H, He, O, Na, Ca, K (e.g. Killen et al., 2007) and – more recently – Mg (McClintock et al., 2009). The total surface pressure of these species is $\sim 10^{-12}$ mbar and is about two orders of magnitude lower than the derived upper limit of the exospheric pressure of $\sim 10^{-10}$ mbar (Fjeldbo et al., 1976; Hunten et al., 1988). Hence some additional yet unobserved volatile material may populate the Hermean exosphere.

There is good reason to consider the solar wind and magnetospheric plasma precipitation onto the surface of Mercury to contribute to the population of the exosphere by ion implantation and sputtering processes. Numerical modeling of Mercury's magnetosphere has shown that the weak intrinsic magnetic field of the planet is sufficient to prevent the equatorial regions from being impacted by solar wind ions during moderate solar wind conditions (Kallio and Janhunen, 2004). However, intense fluxes of protons are expected to hit the surface at high northern and southern latitudes, the auroral regions, giving rise to the release of surface elements at high latitudes by ion sputtering. During extremely high solar wind dynamic pressure conditions, the solar wind ions will have access to the entire dayside surface of Mercury (Slavin et al., 2014), which may result in a considerable increase in the particle population of the exosphere by sputtered material from Mercury's surface.

Ground-based observations of Mercury's surface can only provide averages of its mineralogical composition over a large area on the surface due to the limited spatial resolution because of atmospheric disturbances (Sprague et al., 2007). Recent measurements of the x-ray and gamma-ray spectrometers aboard the MErcury Surface, Space Environment, GEochemistry, and Ranging (MESSENGER) spacecraft acquired at different localized areas

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[*] Corresponding author.
E-mail address: herbert.lichtenegger@oeaw.ac.at (H.I.M. Lichtenegger).

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allowed to estimate the abundances of some elements like Si, Mg, S, Fe, Ti, and Al. Relatively high Mg/Si and S/Si ratios have been found, while Al/Si, Ca/Si, Fe/Si and Ti/Si ratios appear to be low (Nittler et al., 2011; Rhodes et al., 2011; Evans et al., 2012; Starr et al., 2012). Moreover, comparison of the x- and gamma-ray observations indicate that Mercury's regolith is on average vertically homogenous to a depth of tens of centimeters (Evans et al., 2012).

In this paper we consider only refractory elements that are ejected into the exosphere via solar wind sputtering. Therefore, the contribution of volatile elements like sodium or potassium to the exospheric composition is not considered in the present study. For refractory elements, release processes like electron and photon stimulating desorption are expected to be of minor importance. Also thermal desorption may contribute to the exosphere density at most close to the surface of Mercury. Micro-meteorite impact vaporization may result in a surface density comparable to that of sputtering, depending on the assumed impact flux. The initial ejecta can be described by a high-temperature vapor (~4000 K) allowing only a small fraction of non-volatile material to reach higher altitudes and to escape (Killen et al., 2007).

The Hermean environment is a complex system immersed in the solar wind, consisting of a surface-bounded exosphere containing volatile and refractory species from the regolith and interplanetary dust. We are not attempting to describe this dynamic system in detail, rather we are aiming to establish a global model of Mercury's exosphere. For this purpose we start with a plausible mineralogical model of the surface consistent with recent observations and consider the precipitation of solar wind ions onto the surface of Mercury for different solar wind conditions. By means of the corresponding sputter rates the 3-dimensional exosphere density of the sputtered species can be estimated and a self-consistent model of the expected average neutral particle environment of Mercury is obtained.

The paper is structured as follows: Section 2 describes the numerical models used, including the solar wind precipitation (Section 2.1), Mercury's elemental surface composition model (Section 2.2), the resulting sputter flux (Section 2.3), and the exosphere model (Section 2.4). Section 3 discusses the simulation results, while the conclusions are outlined in Section 4.

2. Model description

The sputter contribution to Mercury's exosphere is considered as the result of three major physical processes: (a) precipitation of solar wind ions, i.e., mainly H^+ and He^{++} ions, (b) sputtering of surface elements, and (c) spreading of the sputtered particles around the planet.

2.1. Solar wind precipitation

The precipitating solar wind particles (H^+ and He^{++} ions) are collected at the surface of Mercury, i.e., when absorbed by the obstacle, after the initial transients in the simulation have disappeared. The simulated particles are binned to a 30×30 rectangular latitude–longitude grid by species, from which the corresponding fluxes are obtained from a three dimensional self-consistent Mercury hybrid model simulation (HYB-Mercury). In the hybrid model ions are treated as particles while electrons form a massless charge neutralizing fluid (Kallio and Janhunen, 2003a). Earlier HYB-Mercury runs made before MESSENGER observations modeled the Hermean magnetic field by using a magnetic dipole at the center of the planet, which gave a 300 nT magnetic field at the equator at the surface (Kallio and Janhunen, 2003a,b, 2004). However, the MESSENGER magnetic field observations indicated a 195 ± 10 nT dipole field, which has an offset of 484 ± 11 km northward of the geographic equator (Anderson et al., 2011). Some later studies suggested a 190 nT dipole field (Johnson et al., 2012). In this study the magnetic field of Mercury is modeled in the HYB-Mercury simulation as a dipole, with the dipole source translated 450 km northwards from the center of the planet, with a strength of 190 nT at the magnetic equator at Mercury's surface.

Table 1

Vectors components $\vec{B}_{\mathrm{IMF}} = (B_x, B_y, B_z)$ of the IMF (x parallel to solar wind flow direction, z parallel to magnetic dipole moment and y completes the right handed coordinate system), solar wind bulk velocity v_{bulk}, solar wind density n_{sw}, solar wind dynamic pressure P_{sw}, and fraction x_{He} of He^{++} ions in the solar wind for four considered cases.

	$\vec{B}_{\mathrm{IMF}}$ (nT)	v_{bulk} (km s^{-1})	n_{sw} (cm^{-3})	P_{sw} (nPa)	x_{He} (%)
Case 1	(12.9, 4.7, 10.3)	400	60	15.9	5
Case 2	(0, 0, 15)	400	60	15.9	5
Case 3	(26,9,20)	350	90	18.3	8
Case 4	(26,9,20)	1200	90	215.2	8

In Table 1 the interplanetary magnetic field (IMF) and solar wind conditions for four different cases used in the present simulations are summarized. Case 1 is intended to simulate ‘mean’ near-Mercury conditions similar to those measured during the first Mercury flyby (M1) of MESSENGER (Baker et al., 2009, 2011; Slavin et al., 2010), case 2 considers a northward directed IMF, and cases 3 and 4 represent solar wind conditions with a stronger IMF and higher solar wind density. Additionally, case 4 corresponds to a very high bulk speed. MESSENGER observations of Mercury's dayside magnetosphere under extreme solar wind conditions have been reported by Slavin et al. (2014). Of the three events analyzed, two were the result of coronal mass ejections and one was from a high speed stream, with inferred ram pressures of ~45 to 65 nPa. Case 4 can thus be considered as an example of even more extreme conditions than those observed by Slavin et al. (2014). The calculated solar wind flux onto Mercury's surface for all four cases is illustrated in Fig. 1.

2.2. Mercury's surface composition

As outlined in Wurz et al. (2010) – besides disk-averaged spectra from the first MESSENGER flyby and spatially resolved observations from the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) instrument (McClintock et al., 2008) – the main knowledge of Mercury's global average surface composition is mainly inferred from ground-based observations in the visible and IR spectral ranges, as well as from experiments with analogue materials in laboratories (Warell et al., 2006; Sprague et al., 2007, 2009; Wurz et al., 2010). However, ground-based measurements of Mercury's surface mineralogy are hampered by various circumstances like the absorption features of the terrestrial atmosphere in the infrared wavelength range or the planet's closeness to the Sun. Furthermore, Mercury's surface has experienced space weathering for more than 4 billion years (Hapke, 2001) resulting in a substantial regolith layer, which makes the spectroscopic identification of minerals on the surface difficult.

Based on this available spectroscopic observations regarding the mineralogical information of Mercury's surface, Wurz et al. (2010) designed a global mineralogical model of the planet's elemental surface composition. This surface composition model consists of a selected group of end-member mineral compositions (~27 mol% feldspar, ~32 mol% pyroxene, ~39 mol% olivine, ~0.07 mol% metallic iron and nickel, ~1.03 mol% sulfides, ~0.07 mol% ilmenite, ~1.45 mol% apatite), which are weighted to be consistent with the available observational constraints and yields an average surface density of ~3.11 g cm^{-3}. From this