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Release of neutral sodium atoms from the surface of Mercury induced by meteoroid impacts

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Abstract

Meteoroid impact has been shown to be a source of sodium, and most likely of other elements, on the Moon. The same process could be also relevant for Mercury. In this work we calculate the vapor and neutral Na production rates on Mercury due to the impacts of meteoroids in the radius range of 10^{-8}–10^{-1} m. We limit our calculations to this size range, because meteoroids with radius larger than 10^{-1} m have not to be found important for the daily production of the exosphere. This work is based on a new dynamical model of the meteoroid flux at the heliocentric distance of Mercury, regarding objects in the size range 10^{-2}–10^{-1} m. This size range, never investigated before, is not affected by nongravitational forces, such as the Poynting–Robertson effect, which is dominant for particles smaller than 10^{-2} m. In order to evaluate the release of neutral sodium atoms also for smaller meteoroids we have used the distribution reported by M.J. Cintala [1992. Impact-induced thermal effects in the lunar and mercurian regoliths. J. Geophys. Res. 97, 947–973] calculated for particle size range 10^{-8}–10^{-3} m. We have extrapolated this distribution up to 10^{-2} m and we have based the impact calculations on a new surface composition assuming 90% plagioclase and 10% pyroxene. The results of our model are that (i) the total mass of vapor produced by the impact of meteoroids in the size range 10^{-8}–10^{-1} m is 4.752×10^8 g per year, and (ii) the production rate of neutral sodium atoms is 1.5×10^{22} s^{-1}.

Keywords: Mercury, surface; Impact processes; Abundances, atmospheric

1. Introduction

Mercury has an extended and tenuous exosphere containing H, He, O, Na, K, and Ca (Bida et al., 2000; Killen and Ip, 1999; Killen et al., 2005; Potter and Morgan,1985, 1986).

The Hermean exosphere is the result of a dynamical balance between different source and sink mechanisms acting on the planetary surface. A good comprehension of the exosphere as a complex system needs to include the different processes involved both in its formation and in its depletion. Among these processes, there is meteoroid impact vaporization, i.e., the vapor production derived from the infall of small and medium-sized objects present in the Solar System. On the basis of existing models (Killen et al., 2001; Leblanc and Johnson, 2003; Morgan et al., 1988), the fraction of sodium atoms released by this mechanism is estimated to be in the range from about 10% to 100% (in the case of no release of regolith erosion products). According to a different hypothesis, the composition of the Hermean exosphere reflects the chemical composition of meteorites impacting Mercury, possibly mixed with solar wind products. Killen et al. (2001) found that impact vaporization consistently produces only about a quarter of the source flux of sodium to the exosphere, so that photon-stimulated desorption is consistently the dominant source process for their data set. In any case, meteoroid vaporization is likely the

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most important process for the nightside, unless significant ion sputtering occurs.

It is clear that the contribution of meteoroid impacts to the exosphere still need to be debated. Some estimates of sodium production due to micrometeoroid impact have been obtained by extrapolating the micrometeoroid flux on Earth: Hunten et al. (1988) suggested a production rate of 10^{22} $\mathrm{Na\,s^{-1}}$, while Morgan et al. (1988) estimated an orbital average vaporization rate of sodium atoms of about $0.15–14 \times 10^{23}\ \mathrm{s^{-1}}$; and Leblanc and Johnson (2003) in their model assumed a value of about $5 \times 10^{23}\ \mathrm{s^{-1}}$ at perihelion.

The dynamical evolution of meteoroids in the size range 10^{-8}–10^{-3} m and the vapor production due to their impact on Mercury's surface have been determined by Cintala (1992). Starting from Cintala's work, we have developed a model that provides an estimate of the vapor and sodium production rates due to impacts of meteoroids in a wider size range, 10^{-8}–10^{-1} m. We have confined our study to meteoroids with radius up to 10^{-1} m, because, as explained in the following, meteoroids with a radius larger than 10^{-1} m have an impact probability on Mercury's surface that cannot influence the daily observations of the exosphere.

In particular, the distribution of the objects in the size range 10^{-8}–10^{-2} m (small meteoroids) has been taken from Cintala (1992). We have assumed that Cintala's model also works for meteoroids in the size range 10^{-3}–10^{-2} m, where 10^{-2} m is the limit over which the Poynting–Robertson effect is negligible and Cintala's model does not apply. Meteoroids with radius greater than 10^{-2} m (large meteoroids) have been taken into account according to the distribution estimated by Marchi et al. (2005). We have assumed a meteoroid density (ρ_p) of 2.5 $\mathrm{g\,cm^{-3}}$, consistent with measurements of the density of stratospheric cosmic dust particles (Rietmeijer, 1998) and with density data of S-type igneous asteroids (Krasinsky et al., 2002), which are the main constituents of the inner part of the Main Belt.

In the following we will describe the impact model, based on new dynamical results on the meteoroid flux, along with recent surface composition assumptions.

2. Surface composition

In this work, we assume that the surface mineralogical composition of Mercury is spatially homogeneous and made up of regolith with anorthositic composition (90% plagioclase and 10% pyroxene in volume). Mafic rocks and SiO_2-undersaturated rocks have also been assumed to make up Mecury's crust (e.g., Emery et al., 1998; Sprague and Roush, 1998; Sprague et al., 2000), but the lack of further data prevents unambiguous conclusions about Mercury's surface. Therefore, we consider, as a first approximation, that the surface of Mercury is made up only of anorthosite, which seems to be a rock extensively distributed on the surface (e.g., Blewett et al., 2002; Sprague et al., 2000, 2002; Warell, 2003). We consider the plagioclase as a solid solution of the end-members albite (Ab), $NaAlSi_3O_8$, anorthite (An), $CaAl_2Si_2O_8$, and orthoclase (Or), $KAlSi_3O_8$,

$$(\mathrm{Ca}_x\mathrm{Na}_y\mathrm{K}_{1-x-y})(\mathrm{Al}_{1+x}\mathrm{Si}_{1-x})\ \mathrm{Si}_2\mathrm{O}_8, \tag{1}$$

where x and y are the molar proportions of anorthite and albite, respectively.

Pyroxene is considered a solid solution of diopside (Di), $CaMgSi_2O_6$, enstatite (En), $Mg_2Si_2O_6$, and ferrosilite (Fs), $Fe_2Si_2O_6$,

$$(\mathrm{Ca}_w\mathrm{Mg}_z\mathrm{Fe}_{1-w-z})(\mathrm{Mg}_{w+z}\mathrm{Fe}_{1-w-z})\mathrm{Si}_2\mathrm{O}_6, \tag{2}$$

where w and z are the molar proportions of diopside and enstatite, respectively.

Following Ahrens and O'Keefe (1972) we assume that vaporization of the silicates (plagioclase and pyroxene), caused by meteoroid impacts, is congruent, and that the vaporization products are

$$\begin{aligned}(\mathrm{Ca}_x\mathrm{Na}_y\mathrm{K}_{1-x-y})&(\mathrm{Al}_{1+x}\mathrm{Si}_{1-x})\mathrm{Si}_2\,\mathrm{O}_8\\ &\Leftrightarrow x\mathrm{Ca} + y\mathrm{Na} + (1-x-y)\mathrm{K} + (1+x)\mathrm{Al}\\ &\qquad + (3-x)\mathrm{Si} + 4\mathrm{O}_2,\end{aligned} \tag{3}$$

$$\begin{aligned}(\mathrm{Ca}_w\mathrm{Mg}_z\mathrm{Fe}_{1-w-z})&(\mathrm{Mg}_{w+z}\mathrm{Fe}_{1-w-z})\mathrm{Si}_2\mathrm{O}_6\\ &\Leftrightarrow w\mathrm{Ca} + (w+2z)\mathrm{Mg} + (2-2w-2z)\mathrm{Fe} + 2\mathrm{Si}\\ &\qquad + 3\mathrm{O}_2.\end{aligned} \tag{4}$$

Assuming, as usual, that the vapor composition is exclusively determined by the target phases composition and phases abundance, the volumes of plagioclase, V_{Pl}, and pyroxene, V_{Px}, vaporized are given (for a rock made up of 90% plagioclase and 10% pyroxene) by

$$V_{\mathrm{Pl}} = 0.9V_{\mathrm{vap}}, \tag{5}$$

$$V_{\mathrm{Px}} = 0.1V_{\mathrm{vap}} = V_{\mathrm{vap}} - V_{\mathrm{Pl}}, \tag{6}$$

where V_{vap} (see the following section) is the volume of material vaporized by a spherical projectile impacting the surface.

The moles of elements in the vapor are

$$m_{\mathrm{Ca}} = xm_{\mathrm{Pl}} + wm_{\mathrm{Px}}, \tag{7}$$

$$m_{\mathrm{Na}} = ym_{\mathrm{Pl}}, \tag{8}$$

$$m_{\mathrm{K}} = (1-x-y)m_{\mathrm{Pl}}, \tag{9}$$

$$m_{\mathrm{Mg}} = (w+2z)m_{\mathrm{Px}}, \tag{10}$$

$$m_{\mathrm{Fe}} = (2-2w-2z)m_{\mathrm{Px}}, \tag{11}$$

$$m_{\mathrm{Si}} = (3-x)m_{\mathrm{Pl}} + 2m_{\mathrm{Px}}, \tag{12}$$

$$m_{\mathrm{Al}} = (1+x)m_{\mathrm{Pl}}, \tag{13}$$

where m_{Pl} and m_{Px} are the moles of plagioclase and pyroxene, respectively:

$$m_{\mathrm{Pl}} = \frac{V_{\mathrm{Pl}}\rho}{\mathrm{MW}_{\mathrm{Pl}}}, \tag{14}$$