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Asymmetries in the dust flux at Mercury

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ABSTRACT

The planet Mercury has an extended and tenuous exosphere made up of atoms that are ejected from the surface by energetic processes, including hypervelocity micrometeoritic impacts, photon-stimulated desorption by UV radiation, and ion sputtering. Meteoroid impacts of particles smaller than 1 cm, which are important for replenishing the exosphere daily, are not well-studied. We present a systematic investigation of spatial asymmetries in the impactor rate of micrometeoroids over Mercury's surface as a function of planetary true anomaly (TAA). Since the orbit of Mercury is quite eccentric a seasonal variation of the impact rate is to be expected. We find that the source peaks near the planetary equator for most TAA. Contrary to previous assumptions, we find the source to be non-uniform in local time. Only certain regions of Mercury are exposed to dust as a result of the orbital elements of Mercury and of the Main Belt particles (inclination less than 20°). Our results offer important constraints on transport models used for interpreting measurements of this exosphere, but also inform studies of space weathering of Mercury's surface.

1. Introduction

Meteoroid impacts play an important role in the continuing evolution of Mercury's surface. The meteoroid impacts influence the regolith of the surface of the planet because parts of the meteoroid and the regolith are vaporized during impact and the molecules are released to Mercury's exosphere while on the surface there is the formation of a new crater (Cremonese et al., 2005; Berezhnoy and Klumov, 2008). After the impact process the ejecta that fall back to the surface, cover again the material which was cropped out. So impacts act as a gardening process in which material present on the surface of the planet is constantly mixed.

It is known that Mercury's exosphere contains H, He and O, discovered by Mariner 10, and Na, K and Ca seen by ground-based telescopes (Bida et al., 2000; Killen et al., 2001, 2005; Potter and Morgan, 1985, 1986; Morgan and Killen, 1997).

Mg was first observed by the UltraViolet and Visible Spectrometer (UVVS) onboard the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft during its second and third Mercury flybys (McClintock et al., 2009; Vervack et al., 2010). Observations of exospheric species such as Na, Ca, and Mg have continued on a daily basis since MESSENGER was inserted into orbit around Mercury in 2011, thus providing an important long sequence of observations that require interpretation.

Together with ion sputtering, the meteoroid impacts are considered the main sources of refractory gases in the exosphere such as Ca (Killen et al., 2005) and Mg (Killen et al., 2010; Sarantos et al., 2011). For instance, Sarantos et al. (2011) found the Mg production rates and exospheric temperatures, derived from MESSENGER 2nd flyby measurements, to be consistent with impacts with smaller contributions by sputtering. For relatively volatile species such as Na impacts could be a less important source process because other processes such as photon-stimulated and thermal desorption could promote these species to the exosphere. For instance, Killen et al. (2001) inferred that impact vaporization is responsible for only about a quarter of the flux of the Na forming the exosphere. More recent studies estimate that impact vaporization of micrometeoroids could provide up to 15% of the total sodium source rate (Burger et al., 2010) with un upper limit in the impact vaporization rate of $2.1 \cdot 10^6$ cm^{-2} s^{-1} (Mouawad et al., 2011). Whereas the access of solar wind ions is concentrated near the day side cusps (e.g., Sarantos et al., 2007; Winslow et al., 2012) and near the equatorial night side (Benna et al., 2010), the access of micrometeoroids onto the surface is frequently assumed in these exospheric models to be uniform.

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MESSENGER measurements suggest significant asymmetries in the distribution of exospheric refractories, Ca and Mg. Burger et al. (2012) analyzed Ca measurements obtained during three MESSENGER flybys and during its first week in Mercury orbit. Using a Monte Carlo model of Ca generation and transport, they found that all Ca could be attributed to an originating site centered around the dawn equatorial region. Sarantos et al. (2012) modeled Mg observations obtained since orbital insertion and found that this species too exhibits a dawn–dusk asymmetry in its production rate (Sarantos et al., 2012). Can such a relatively localized and asymmetric source be consistent with impacts?

The goal of the work presented in this paper is to use a dynamical model of dust transport near Mercury to investigate if micrometeoroid impacts occur asymmetrically at Mercury. With this method we also obtain the variation of total micrometeoroid mass influx along Mercury's orbit, a quantity that helps constrain the exospheric production rates that can be attributed to impacts.

2. Dynamical evolution model

To estimate the meteoritic flux at the heliocentric distance of Mercury we use the dynamical evolution model of dust particles of Marzari and Vanzani (1994). It numerically integrates a $(N+1)+M$ body problem (Sun + N planets + M bodies with negligible mass) with the high-precision integrator RA15 version of the RADAU integrator by Everhart (1974). The initial orbital elements of all planets are taken from the JPL Horizon site. Radiation, solar wind pressure and Poynting–Robertson drag are included as perturbative forces together with the gravitational attractions of all the planets in the Solar System.

The gravitational term is given by:

$$\mathbf{F}_{gra} = \mathbf{F}^{k} + \mathbf{F}^{d} + \mathbf{F}^{ind}, \tag{1}$$

where $\mathbf{F}^{k}$ is the keplerian force, $\mathbf{F}^{d}$ is the direct force and $\mathbf{F}^{ind}$ is the indirect force. Eq. (1) can be written as

$$\mathbf{F}_{gra} = \frac{Gm(M_{\mathrm{Sun}}+m)\mathbf{r}_{\mathrm{Sun}}}{r^3_{\mathrm{Sun}}} + \frac{Gm\sum_{j=1}^{N} m_j \mathbf{r}_j}{r_j^3} + \frac{Gm\sum_{j=1}^{N} m_j \mathbf{r}_{\mathrm{Sun},j}}{r^3_{\mathrm{Sun},j}}, \tag{2}$$

where r_{Sun} is the distance between the Sun and dust particles, r_j is the distance between planets and dust particles, m is the mass of each dust particles and N is the number of planets.

The non-gravitational term is made up of two terms: the radiation force, $\mathbf{F}_{rad}$ and the force given by the solar wind, $\mathbf{F}_{wnd}$,

$$\mathbf{F}_{ngra} = \mathbf{F}_{rad} + \mathbf{F}_{wnd}, \tag{3}$$

where

$$\mathbf{F}_{rad} = \frac{S}{c}\left(1-\frac{\dot{r}}{c}\right)AQ_{pr}\hat{\mathbf{p}} = f_r\hat{\mathbf{p}}, \tag{4}$$

and

$$\mathbf{F}_{wnd} = \sum_j \frac{\eta_j u^2}{2} AC_{D,j}\hat{\mathbf{u}} = f_w\hat{\mathbf{u}}. \tag{5}$$

In the previous equations $\hat{\mathbf{p}} = \frac{\mathbf{c}-\mathbf{v}}{c}$ where $\mathbf{c}$ is the velocity of the light (anti-solar direction) and $\mathbf{v}$ is the orbital velocity of the dust particle; $\hat{\mathbf{u}} = \frac{\mathbf{u}}{u}$ with $\mathbf{u} = \mathbf{w} - \mathbf{v}$, where $\mathbf{w}$ is the solar wind flow bulk velocity in the average phase (Marzari and Vanzani, 1994; Mukai and Yamamoto, 1982). $\eta_j = n_j m_j$ is the spatial mass density of the component j of the solar wind flow, having mass m_j and number density $n_j; A$ is the geometrical cross section of the grain; Q_{pr} is the dimensionless radiation-pressure coefficient averaged over the solar spectrum and, $C_{D,j}$ is the dimensionless drag coefficient due to the j-component of the wind flow. S is the solar radiation flux density at heliocentric distance r, and we can write $S = S_0\left(\frac{r_0}{r}\right)^2; w_0 \simeq 4\cdot 10^7$ cm/s for w at 1 AU and $\eta_{p,0}+\eta_{\alpha,0} \simeq 1.2\eta_{p,0}$. f_r and f_w are the magnitude of the radiation force and solar wind force, respectively (Marzari and Vanzani, 1994).

The efficiency of the radiation and corpuscolar resistive forces can be expressed by defining their ratio to the solar gravity like

$$\beta_r = \frac{f_r}{f_g}\left[\frac{c}{c-\dot{r}}\right] = \left(\frac{SAQ_{pr}}{c}\right)\cdot\left(\frac{GM_\odot m}{r^2}\right)^{-1}, \tag{6}$$

and

$$\beta_w = \frac{f_w}{f_g}\left[\frac{w}{|\mathbf{w}-\mathbf{v}|}\right] = \left(\frac{f_{w0}\psi}{\kappa}\right)\cdot\left(\frac{GM_\odot m}{r^2}\right)^{-1}, \tag{7}$$

with $\kappa = \frac{u}{w}$ and $\psi = \frac{f_w}{f_{w0}}$, where f_{w0} is obtained from f_w in the limit of neglecting the velocity dispersion of wind particles and taking no notice of the contribution of momentum carried away by the sputtered molecules to $\mathbf{F}_{wnd}$. f_g is the magnitude of the gravitational force.

Assuming the reference-distance r_0 equal to 1 AU and the dust particle with spherical shape of radius s, we obtain

$$\beta_r = \frac{3S_0 r_0^2}{4GM_\odot c}\frac{Q_{pr}}{\varrho s} = 5.74\cdot 10^{-5}\frac{Q_{pr}}{\varrho s}, \tag{8}$$

and

$$\beta_w = \frac{3(\eta_{p,0}+\eta_{\alpha,0})r_0^2 w_0^2}{4GM_\odot}\frac{\psi\kappa}{\varrho s} \simeq 3.27\cdot 10^{-8}\frac{\psi\kappa}{\varrho s}, \tag{9}$$

where ϱ is the mass density of the dust particle measured, like s, in cgs units. S is the solar radiation flux density at heliocentric distance r, and we can write $S = S_0\left(\frac{r_0}{r}\right)^2; w_0 \simeq 4\cdot 10^7$ cm/s for w at 1 AU and $\eta_{p,0}+\eta_{\alpha,0} \simeq 1.2\eta_{p,0}$ (Marzari and Vanzani, 1994).

Finally, the relative importance of the radiation and corpuscolar forces can be estimated by the parameter

$$\gamma = \frac{\beta_w}{\beta_r} \simeq 5.7\cdot 10^{-4}\frac{\psi\kappa}{Q_{pr}}. \tag{10}$$

In terms of the parameters β_r and γ the sum of the radiation and solar resistive forces takes the form

$$\begin{aligned}\mathbf{F}_{ngra} &= \beta_r f_g[(1+\gamma\cos\varphi)\hat{\mathbf{r}} \mp \gamma(\sin\varphi)\hat{\boldsymbol{\vartheta}}] \\ &\quad - \beta_r f_g\left[\left(2+\gamma\frac{c}{w}\right)\frac{\dot{r}}{c}\hat{\mathbf{r}} + \left(1+\gamma\frac{c}{w}\right)\frac{r\dot{\vartheta}}{c}\hat{\boldsymbol{\vartheta}}\right],\end{aligned} \tag{11}$$

where the terms dependent and independent on dust grain's velocity appear separated. Here $\hat{\boldsymbol{\vartheta}}$ is the unit vector normal to $\hat{\mathbf{r}}$ in the orbital plane (positive in the direction of the grain's motion), $\varphi = \arccos(\mathbf{w}\cdot\hat{\mathbf{r}})/w$ is the angle that average solar wind flow direction forms with the grain's velocity. The first part of Eq. (11) is the sum of radiation pressure force $\beta_r f_g\hat{\mathbf{r}}$ with the corpuscolar pressure force $\beta_w f_g\hat{\mathbf{w}} = f_w\mathbf{w}/u$ splitted into its radial and transverse component. The latter part in Eq. (11) is the sum of the classical PR drag with the solar wind drag (Marzari and Vanzani, 1994).

We consider a ring of 1000 asteroidal dust particles in prograde orbit with radius between 5 and 100 μm (mass range $1.31\cdot 10^{-9}$–$1.05\cdot 10^{-5}$ g). The initial semi-major axis is randomly selected in between 2.1 and 3.3 AU, the initial eccentricity varies in the range 0.0–0.4 and the inclination in the range 0–20°. This choice reflects the typical orbital elements of the asteroid belt (Gradie et al., 1989; Zappala' and Cellino, 1993; Zappala' et al., 1994; Milani and Knezevic, 1994). For the grains we assume a density of 2.5 g cm^{-3}, a reasonable value for dust particles coming from the Main Belt (Grun et al., 1985). Spherical particles are