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Small meteoroids' major contribution to Mercury's exosphere

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Abstract

The contribution of the meteoroid population to the generation of Mercury's exosphere is analyzed to determine which segment contributes most greatly to exospheric refilling via the process of meteoritic impact vaporization. For the meteoroid data, a differential mass distribution based on work by Grün et al. (Grün, E., Zook, H.A., Fechtig, H., Giese, R.H. [1985]. *Icarus* 62(2), 244–272) and a differential velocity distribution based on the work of Zook (Zook, H.A. [1975]. In: 6th Lunar Science Conference, vol. 2. Pergamon Press, Inc., Houston, TX, pp. 1653–1672) is used. These distributions are then evaluated using the method employed by Cintala (Cintala, M.J. [1992]. *J. Geophys. Res.* 97(E1), 947–974) to determine impact rates for selected mass and velocity segments of the meteoroid population.

The amount of vapor created by a single meteor impact is determined by using the framework created by Berezhnoy and Klumov (Berezhnoy, A.A., Klumov, B.A. [2008] *Icarus*, 195(2), 511–522). By combining the impact rate of meteoroids with the amount of vapor a single such impact creates, we derive the total vapor production rate which that meteoroid mass segment contributes to the Herman exosphere. It is shown that meteoroids with a mass of 2.1×10^{-4} g release the largest amount of vapor into Mercury's exosphere. For meteoroids in the mass range of 10^{-18} g to 10 g, 90% of all the vapor produced is due to impacts by meteoroids in the mass range 4.2×10^{-7} g m 8.3×10^{-2} g.

Keywords

Impact processes; Interplanetary dust; Mercury; Atmosphere

1. Introduction

The interplanetary environment is permeated with dust particles, whose sources include asteroids and comets. These dust particles are also referred to as micrometeoroids when their mass is below 10^{-6} g (Srama, 2010). A review of the interplanetary dust environment, including the source and loss processes for these particles and measurement techniques, can be found in the paper by Mann et al. (2004). Here, we focus on the interaction of the

interplanetary dust complex with the surface of Mercury. Mercury is of particular interest to us due to the current MESSENGER mission orbiting Mercury and the upcoming BepiColombo mission which will be launched in 2015. A review of the MESSENGER mission is provided by Gold et al. (2001), while Benkhoff et al. (2010) provide an overview of the BepiColombo mission. Mercury's atmosphere is so tenuous that even at the surface the mean free path of the atmospheric constituents exceeds the scale height, and thus the Hermean atmosphere is classified as a surface-bounded exosphere. Since the Hermean exosphere is so tenuous and extends down to the surface, any meteoroids encountering Mercury have virtually no interaction with the particles that make up the atmosphere. Hence, meteoroids impact onto the surface essentially unchanged by their transit through the exosphere and convey their kinetic energy to the planetary surface upon impact. This energy is partitioned into various processes, such as surface fracturing, shockwave creation, melting of material, and the release of material as a vapor into the exosphere. It is the latter process on which we will focus here. Meteoritic impact vaporization (MIV) is such an energetic process that not only volatiles but also refractory elements are released from the surface into the Hermean exosphere. Therefore, analyzing the evolved gas from MIV provides an opportunity to sample the composition of Mercury's regolith without utilizing a lander to take in situ data. Both the MESSENGER and BepiColombo missions to Mercury seek to analyze the composition of the Hermean exosphere as a method to interpret the surface composition as well as the phenomena that act on and modify the chemical and physical properties of the surface (Milillo et al., 2010; Zook, 1975).

The interplanetary dust or micrometeoroid population alone spans over 12 orders of magnitude of mass, and this does not yet include the larger meteoroid population. Rates of collision vary for different segments of the meteoroid population; here we analyze the meteoroid distribution data to determine which portion of the meteoroid population contributes the most to the release of surface material as a vapor into the exosphere. Larger meteoroids have more kinetic energy to impart in a collision with the surface, but their impact rate is small compared to less massive meteoroids. Comparatively, smaller meteoroids will not produce as much in terms of vaporization products from a single impact, but their frequency of impact is greater than that of larger meteoroids. The vapor produced by a large meteoroid impact can create a localized increase in exospheric densities, as is discussed by Mangano et al. (2007). Given the sparser impact rates of such large meteoroids, this analysis will instead focus on smaller meteoroids, which have more frequent impacts and thus contribute more steadily to Mercury's exosphere. Section 4 will show that we expect a maximum of production for meteoroids in the range of 10^{-4} g. A similar analysis focusing on the release of sodium atoms via MIV acting on the Hermean surface was performed by Cremonese et al. (2005), and updated via a corrigendum (Cremonese et al., 2006). They determined that 99% of the sodium atoms were released due to impacts by meteoroids with radii between 10^{-8} m and 10^{-2} m. This corresponds to a mass range of $\sim 10^{-17}$ g to 10 g. In this analysis we focus on the total vapor production, i.e. including all species of atoms and molecules which are released from Mercury's surface. The meteoroids which are responsible for this production cover a smaller mass range than that which pertained to Cremonese et al.'s analysis.

2. Meteoroid data at 1 AU

The dust environment at Mercury's orbit is not well-defined, due to a lack of in situ observations. However, the dust environment near the Earth's orbit has been studied in great detail. Thus, we will focus first on the distributions of the meteoroid population near Earth and then propagate that data into expected distributions at Mercury's orbit. Recently, Cremonese et al. (2012) re-evaluated the data from the Long Duration Exposure Facility (LDEF), which was also used as a basis for the work by Love and Brownlee (1993). Cremonese et al. found during their literature search that it is estimated that over 80% of the meteoroid mass delivered into Earth's atmosphere is due to meteoroids with a mass range of $\sim 10^{-7}$ – 10^{-3} g. Furthermore, Cremonese et al.'s analysis showed that the results of Love and Brownlee overestimated the sizes of the projectiles which had caused the craters on the LDEF. Instead, their results more closely resembled those of Grün et al. (1985).

Grün et al. (1985) developed an interplanetary mass flux model for meteoroids based on data from the HEOS 2, Pioneer 8 and Pioneer 9 spacecraft, as well as a calculation for the β meteoroid flux. β meteoroids have a mass of $\geq 10^{-13}$ g and are small enough to be affected by radiation pressure. Only portions of the data sets which were “far from the Earth” were included, in order to avoid the need for corrections for gravitational shielding and concentration effects. Their equation A3 gives the formula for the interplanetary flux model as:

$$F_2(m, r_0) = (c_4 m^{\gamma_4} + c_5)^{\gamma_5} + c_6(m + c_7 m^{\gamma_6} + c_8 m^{\gamma_7})^{\gamma_8} + c_9(m + c_{10} m^{\gamma_9})^{\gamma_{10}} \quad (1)$$

where r_0 is the radial distance from the Sun which is assumed to be 1 AU, m is the meteoroid mass, and c_m and γ_n are coefficients. Grün et al. (1985) apply this model to a mass range from 10^{-18} g to 10^2 g and obtain the flux $F_2(m, r_0)$, expressed in $\# \text{ m}^{-2} \text{ s}^{-1}$, with the following constants: $c_4 = 2.2 \times 10^3$, $c_5 = 15$, $c_6 = 1.3 \times 10^{-9}$, $c_7 = 10^{11}$, $c_8 = 10^{27}$, $c_9 = 1.3 \times 10^{-16}$, $c_{10} = 10^6$, while the exponents are $\gamma_4 = 0.306$, $\gamma_5 = -4.38$, $\gamma_6 = 2$, $\gamma_7 = 4$, $\gamma_8 = -0.36$, $\gamma_9 = 2$, and $\gamma_{10} = -0.85$. The resulting distribution is shown in Fig. 1.

In Fig. 1, we show the distribution in terms of the meteoroids' mass. If one prefers, one can convert from mass to radius by assuming that each meteoroid is spherical and using the

following equation: $m = \frac{4}{3}\pi r^3 \rho$ where m is the meteoroid mass, r is the meteoroid radius, and ρ is the mass density of the meteoroids. The value of ρ quoted in the literature varies depending on the source, and includes such values as 1 g cm^{-3} (Morgan et al., 1989), 1.8 g cm^{-3} (Cintala, 1992), 2.8 g cm^{-3} (Killen et al., 2001), and 3 g cm^{-3} (Berezhnoy et al., 2003; Mangano et al., 2007). For the case of dust being released by a comet, some literature actually includes different dust densities depending on the mass segment for the dust population. In the vicinity of comet Halley, dust in the mass range of 10^{-15} – 10^{-6} g was calculated to have a density of 3.5 g cm^{-3} , while in the 10^{-2} – 10^5 g range the density dropped to 0.3 g cm^{-3} (Hughes, 1979). In the course of this analysis we assume that the meteoroids have a mass density of 2.5 g cm^{-3} , which is the most recent and more often cited value (Borin et al., 2010; Bruno et al., 2007; Cremonese et al., 2005; Grün et al., 1985; Love and Brownlee, 1993; Mann et al., 2004).

This meteoroid mass distribution is in cumulative form, but for the following we reformulate the flux in terms of differential flux. We derived the differential form of the mass distribution directly from the model given by Grün et al. If we take Grün et al.'s inter-planetary meteoroid mass flux model, and differentiate with respect to mass, we get:

$$\begin{aligned} \phi_1(\mu) = & 2948.616\mu^{-0.694} \left(2.2 \times 10^3 \mu^{0.306} + 15 \right)^{-5.38} \\ & - \left(-4.68 \times 10^{-10} - 93.6\mu - 1.872 \times 10^{18} \mu^3 \right) \\ & \times \left(\mu + 1 \times 10^{11} \mu^2 + 1 \times 10^{27} \mu^4 \right)^{-1.36} \\ & - \left(-1.105 \times 10^{-16} - 2.21 \times 10^{-10} \mu \right) \\ & \times \left(\mu + 1 \times 10^6 \mu^2 \right)^{-1.85} \end{aligned} \quad (2)$$

where μ is the meteoroid mass, and the differential flux ϕ_1 is given in units of $\text{g}^{-1} \text{m}^{-2} \text{s}^{-1}$, with the assumption of a radial distance from the Sun of 1 AU. Note that we have already made use of Grün et al.'s definition of “the cumulative meteoroid flux $[F(\mu)]$, which is the number of meteoroids with masses bigger than or equal to mass m which impact one square meter each second”. Their Eq. (9) shows how to transform from the cumulative to the differential form, represented here as $\phi_1(\mu)$, of the distribution (Grün et al., 2001):

$$\phi_1(\mu) = - \frac{dF(\mu)}{d\mu} \quad (3)$$

The resulting differential mass distribution is shown in Fig. 2.

Note that Cintala (1992) provides a table of coefficients for the differential mass distribution. As discussed by Cremonese et al. (2006) the wrong set of coefficients was published in the work by Cintala. Thus, we used the analytical method described above to determine the differential form of Grün et al.'s mass distribution.

In order to determine the amount of kinetic energy an impacting meteoroid delivers during an impact with a planetary body we need not only the meteoroid's mass but also its velocity. Cintala (1992) based his meteoroid velocity distribution on the function by Zook (1975), which in turn is based on a dataset for 2×10^4 meteoroids at Earth at an altitude of 100 km prepared by Southworth and Sekanina (1973). This distribution is given in a form that has already been propagated to represent values at Mercury's orbit.

3. Meteoroid data adjusted to Mercury's orbit

The differential meteoroid velocity distribution is converted to different heliocentric distances via the method used by Morgan et al. (1988) which can be described as:

$$f_t(v_t) = \left(\frac{v_t}{v_o} \right)^3 f_o(v_o) \quad (4)$$

where f are the velocity distributions, v are velocities, subscript t refers to the converted distribution, and subscript o refers to the original distribution, which in this case will be at a distance of 1 AU from the Sun. Furthermore, Morgan et al. employ the following inversely proportional relationship between velocities at different radial distances from the Sun:

$$v_t = r^{-0.5} v_o \quad (5)$$

where r is the radial distance from the Sun in AU.

This usually includes a transformation to a location at 1 AU from the Sun to remove the gravitational “focusing” effects caused by Earth in Southworth and Sekanina's data. When one also takes into account the conservation of energy via translating velocities from one location to another by incorporating the escape velocities of the planetary bodies being considered, the result for the meteoroid differential velocity distribution near Mercury, as formulated by Cintala (1992), becomes:

$$f_M(v_M) = 3.81 r^{0.2} \left[\frac{v_M}{\sqrt{r(v_M^2 - v_{Me}^2) + v_{Ee}^2}} \right]^3 \times e^{-0.247 \sqrt{r(v_M^2 - v_{Me}^2) + v_{Ee}^2}} \quad (6)$$

where the differential velocity distribution f_M has units of ‘fraction of terrestrial flux’ $\text{km}^{-1} \text{s}$, all velocities are in units of km s^{-1} and v_M is the meteoroid impact velocity at Mercury, v_{Me} is the escape velocity at Mercury's surface (4.24 km s^{-1}), v_{Ee} is the escape velocity at Earth at an altitude of 100 km (11.1 km s^{-1}), and r is the distance from the Sun in units of AU. Cintala's table A2 (Cintala, 1992) indicates that the distribution should be used between 4.24 km s^{-1} , i.e. the escape velocity, and 116.4 km s^{-1} , at which point the distribution drops to values in the 10^{-6} range. The resulting distribution, at different locations along Mercury's orbit, is shown in Fig. 3. Note that, in accordance with the cited authors, we make here the implicit assumption that all masses have the same velocity distribution. In depth analysis of this aspect of the problem goes beyond the scope of this paper.

In order to adjust the differential mass distribution to reflect conditions at Mercury, we first find the area under the differential velocity distribution as follows:

$$F_M = \int_{v_{min}}^{v_{max}} f_M(v_M) dv_M \quad (7)$$

where F_M is a dimensionless quantity (3.38 at perihelion, 2.27 at the mean circular orbit, and 1.64 at aphelion), v_{min} is the minimum velocity of 4.24 km s^{-1} , v_{max} is the maximum velocity of 116.4 km s^{-1} , f_M is the meteoroid differential velocity distribution, and v_M is the meteoroid impact velocity. Next, the differential mass distribution from Eq. (2) is divided by F_M to adjust the distribution to reflect conditions at Mercury's orbit:

$$h(\mu) = \frac{\phi_1(\mu)}{F_M} \quad (8)$$

note that $h(\mu)$ is still a differential mass distribution with units of $\text{g}^{-1} \text{m}^{-2} \text{s}^{-1}$. This form of the differential mass distribution is the same as that shown in Fig. 2, except for scaling due to the normalization via the factor F_M .

4. Impact rates and vapor production

The absolute differential meteoroid flux can be determined by multiplying the two fluxes from Eqs. (6) and (8) together:

$$\phi_M(v_M, \mu) = f_M(v_M) h(\mu) \quad (9)$$

so that $\phi_M(v_M, \mu)$ has units of 'fraction of terrestrial flux' $\text{g}^{-1} \text{km}^{-1} \text{m}^{-2}$. In order to get the total flux of meteoroids impacting on Mercury one must integrate the absolute differential meteoroid flux function, over the range of velocities and masses which are of interest, as follows:

$$I = \int_{v_{\min}}^{v_{\max}} \int_{\mu_{\min}}^{\mu_{\max}} f_M(v_M) h(\mu) dv_M d\mu \quad (10)$$

where $v_{\min}$ and $v_{\max}$ are the minimum and maximum impact velocities, respectively, while $\mu_{\min}$ and $\mu_{\max}$ are the minimum and maximum meteoroid masses, respectively, and I is the total flux expressed in # of impacts $\text{m}^{-2} \text{s}^{-1}$.

Thus, by incorporating $h(\mu)$ the meteoroid flux is scaled from being some fraction of terrestrial meteoroid flux to represent an absolute flux at the chosen location, in this case Mercury's orbit. As an example, if we choose to integrate over the mass range from $1.31 \times 10^{-9} \text{ g}$ to $1.05 \times 10^{-5} \text{ g}$, and over velocities from 4.24 km s^{-1} to 116.4 km s^{-1} at Mercury's mean orbital distance, the resulting impact rate is $1.2 \times 10^{-6} \text{ m}^{-2} \text{s}^{-1}$. Since Mercury has a surface area of $7.5 \times 10^{13} \text{ m}^2$, the rate of impacts on Mercury becomes 2.8×10^{15} per year if we assume all of Mercury's surface to have an equal likelihood of being subject to meteoroid impacts.² This impact rate is within a few orders of magnitude to values quoted by Borin et al. (2009) as shown in Table 1. The work by Cintala and this analysis are based on meteoroid distribution models that are based on near-Earth observations. Then, the data is adjusted to create meteoroid mass and velocity distributions at Mercury's orbit. Borin et al. created a model which tracks simulated dust particles and calibrated their resulting particle flux estimations at Mercury's orbit with observational data of dust near-Earth.

To evaluate the vapor production due to the meteoroid influx represented by the differential mass and velocity distributions from Cintala (1992) and Grün et al. (1985)), we use the framework of Berezhnoy and Klumov (2008). First, an impact velocity for the meteoroids was chosen from the velocity range set by Cintala, where $4.24 \text{ km s}^{-1} \leq v \leq 116.4 \text{ km s}^{-1}$. Next, an impactor mass is chosen to be the midpoint value for a small subset of the mass elements which cover the range $1 \times 10^{-18} \text{ g} \leq m \leq 10 \text{ g}$.

²As the original works on which these calculations are based, i.e. (Cintala, 1992; Grün et al., 1985), do not include error estimates, we are not able to estimate the errors inherent in these results.

The average impactor mass and impact velocity values are then plugged into Berezhnoy and Klumov's Eq. (2) to yield the total mass of the impact-induced vapor cloud for a single such impact, which is given as follows:

$$M_v \approx M_i \left(2 \left[\frac{4 \left(\frac{Q_v}{\nu} \right)^{0.5}}{V_i} \right]^{\nu-2} - 1 \right) \quad (11)$$

where M_i is the mass of the impactor, Q_v is the evaporation heat of the target (assumed to be 1.3 MJ/kg, typical for silicates), ν is a modeling parameter (assumed to be 0.33 for continuous media), and V_i is the impactor's velocity.

Finally, the total vapor mass for a single impact is multiplied by the meteoroid impact rate for the corresponding ranges of masses and velocities, yielding a total vapor production rate which is plotted in Fig. 4.

When examining any horizontal slice, which represents an impactor velocity, one can see that it has a maximum in the 10^{-4} g range. More specifically, the maximum vapor production rate occurs for meteoroids with mass $m = 2.1 \times 10^{-4}$ g. Though only the aphelion case is shown here, the situation is similar for different locations along Mercury's orbit, i.e. different radial distances from the Sun.

Therefore, despite the lower amount of kinetic energy each individual small meteoroid imparts, the higher frequency of their impacts makes them the largest contributor amongst the meteoroid population in the process of refilling the Hermean exosphere via the MIV process. One should keep in mind that if two meteoroids have the same velocity but different masses, they have different amounts of kinetic energy available for release into the impact vaporization process. Consequently, the smaller meteoroids studied in this analysis tend to have low temperature impact-produced vapor clouds. This means that most of the constituents of the vapor clouds will re-impact onto Mercury's surface. However, the Hermean atmosphere is a surface-bounded exosphere, thus any released vapor is already a part of that exosphere. Smaller meteoroids have higher impact frequencies and they impact over the entire surface. Therefore, though the vapor released by a single small meteoroid impact may be transient, the combined activity of all such small meteoroids provides a persistent population of particles for the lower altitudes of the Hermean exosphere.

5. Conclusions

One should keep in mind that the distributions used by Cintala (1992) assume that mass and velocity can be treated separately for meteoroid distributions. This is a common simplification, but does not fully reflect the actual behavior of meteoroids.

Recent work at the European Space Agency (ESA) has resulted in an updated meteoroid model which does incorporate some interdependence between the mass and velocity distributions (Dikarev et al., 2005). Their paper provides an overview of this new meteoroid model, but the details of the mass and velocity interdependence have not yet been published.

We look forward to updating this analysis once the new mass and velocity distributions become available.

The differential mass distribution we used in this paper only extended to masses up to 10 g. Meteoroids with masses between 9 and 10 g and velocities between 4.24 km s^{-1} and 100 km s^{-1} only impact ~44 times a day. We did not consider larger masses as their impact rates are even less frequent. As pointed out by Mangano et al., meteoroids in the range of ~12.6–100.5 g impact on Mercury 140 times a day (Mangano et al., 2007). Meteoroids with masses $\sim 1.6 \times 10^3$ – 4.2×10^4 g collide with the Hermean surface 2.3 times a day. Even larger meteoroids with masses $\sim 1.6 \times 10^6$ – 4.2×10^7 g only impact on Mercury about twice a year. Thus, though individual impacts of larger meteoroids do release larger amounts of surface material in the form of vapor into the Hermean exosphere, the low impact frequency of these larger meteoroids diminishes their contribution to the exospheric refilling process. Note that Mangano et al. categorize meteoroids by size rather than mass, but with their stated density of 3.0 g cm^{-3} and the assumption of spherical impactors we converted these sizes to mass values for consistency (Mangano et al., 2007). By comparison, the impact rate of meteoroids with mass 2.1×10^{-4} g and an impact velocity of 15.8 km s^{-1} even while Mercury is at its aphelion distance of 0.467 AU is 664 impacts per day.

Throughout this analysis, we assume that impacts occur at an angle of 90° relative to the planet's surface. Schultz (1996) pointed out that as the impact angle decreases with respect to the horizontal surface, more vapor is released. Conversely, as the impact angle decreases the temperature of the vapor cloud drops. In his equation (10), Schultz gives an estimate for the vapor production dependence as m_v/m_p interdependence $v^2 \cos^4 \theta$, where m_v is the mass of the vapor, m_p is the mass of the projectile or impactor, v is the impact velocity, and θ is the angle between the impact vector and the surface. Thus, our vapor mass estimates given here represent a baseline, as oblique impact angles should increase the amount of vapor released via MIV.

Meteoroids of mass 2.1×10^{-4} g are not the only small impactors contributing to vapor production at Mercury. If we apply a simple full-width-half-maximum (FWHM) approach, we find that the distribution shown in Fig. 4 for velocity 15.8 km s^{-1} has a FWHM which stretches from 2.1×10^{-6} g to 1.4×10^{-2} g. The FWHM here is not calculated by graphical means, but rather by finding the maximum point of the vapor production data. Subsequently, the nearest points at lower and higher mass that exhibit half the maximum's vapor production rate are found. This range accounts for 77.2% of the total impact vapor produced by meteoroids in the mass range of 10^{-18} g to 10 g. If we extend this further to determine which masses are responsible for 90% of the impact vapor production at Mercury, the range of interest becomes 4.2×10^{-7} g to 8.3×10^{-2} g. Impactors with $m < 4.2 \times 10^{-7}$ g only contribute 6.6% to the total vapor production, and those with $m > 8.3 \times 10^{-2}$ g account for only 3.4% of the released vapor due to MIV. Thus, future work focusing on the contribution of MIV to the Hermean exosphere should include a heavy focus on the range of 4.2×10^{-7} g to 8.3×10^{-2} g, which even includes micrometeoroids.

Borin et al. (2009) pointed out that for meteoroids with radii smaller than $1 \text{ }\mu\text{m}$ the Poynting–Robertson effect and Solar gravity are overpowered. These miniscule particles are

pushed out of the Solar System by Solar radiation pressure and are also referred to as β meteoroids. According to Borin et al., this corresponds to meteoroids with masses below 1.31×10^{-9} g, whereas Grün et al. (1985) place the cut-off at 10^{-13} g. No matter which of the 2 limits is applied, the range of masses we identified here as the major contributor to the Hermean exosphere falls well outside that limit. Thus, the particles in the range of 4.2×10^{-7} g m 8.3×10^{-2} g are dominated by the Poynting–Robertson effect and Solar gravity, thereby placing them in orbits which do intersect the orbit of Mercury. In this analysis we included meteoroids of smaller sizes as they can be formed by collisions between larger meteoroids. Given that the density of meteoroids increases the closer one gets to the Sun, we assumed that β meteoroids are created by collisions inside Mercury's orbit and then pushed into an intersecting orbit by Solar radiation pressure. For future analyses at other heliocentric distances or where the emphasis lies on a different portion of the meteoroid mass range, care must be taken to properly account for the effects of solar radiation pressure and Poynting–Robertson drag when transforming meteoroid data from 1 AU to other heliocentric distances.

Cremonese et al.'s corrigendum (Cremonese et al., 2006), determined that 99% of the sodium atoms released via MIV at Mercury were due to impacts by meteoroids with radii between 10^{-8} m and 10^{-2} m. This corresponds to a mass range of $\sim 10^{-17}$ g to 10 g, which is larger than the mass range we determined to be of interest for overall vapor production. However, this range given by Cremonese et al. is comparable to the total mass range of meteoroids we studied in this work, namely from 10^{-18} g to 10 g. The difference may be due to the different vapor production equations used, namely those of Cintala (1992) by Cremonese et al., whereas here we utilized Berezhnoy and Klumov (2008). However, there is also the possibility that different sizes of impactors, or rather the differences in amounts of kinetic energy delivered by the impactors, may preferentially release different species during the vaporization process.

A similar analysis of meteoroid impacts onto Mercury was performed by Bruno et al. (2007), though the focus there was on the sodium released via MIV. Our analysis focuses on the total amount of vapor released, including all the species which were included in the work of Berezhnoy and Klumov (2008). Bruno et al. determined that of the sodium released due to MIV, only 7% results from impacts by meteoroids with a radius larger than 10^{-3} m, which is equivalent to $\sim 10^{-2}$ g. Their analysis covered a meteoroid range with masses from $\sim 1 \times 10^{-17}$ g to 1×10^4 g and determined that meteoroid impact vaporization released $\sim 2.3 \times 10^{10}$ Na atoms $m^{-2} s^{-1}$. Though we focused on total vapor production, the advantage of combining the approaches of Cintala (1992) and Berezhnoy and Klumov (2008) is that the latter provides the abundances of constituents of the released vapor with respect to the vapor's temperature. For meteoroids in the mass range from 1×10^{-7} g to 1×10^{-4} g, the MIV-induced vapor clouds have an average temperature of ~ 2400 K. At a temperature of 2400 K, the mixing ratio of atomic sodium is fairly high, representing 52.48% of the number of particles contained in the vapor clouds. Applying this to our vapor production curve, our work predicts a release of 2.1×10^{10} Na atoms $m^{-2} s^{-1}$. Burger et al. created a Monte Carlo model to estimate the release rate of neutral sodium atoms into Mercury's exosphere (Burger et al., 2010). In their model, data from the MASCS instrument on the MESSENGER

mission is used to constrain the results. To estimate the amount of sodium released by MIV they utilized the work by Killen et al. (2004) which stated that most of the meteoroid population which impacts on Mercury is concentrated in the range of masses from 1×10^{-7} g to 1×10^{-4} g. Burger et al. determined that MIV contributes 3.5×10^9 Na atoms $\text{m}^{-2} \text{s}^{-1}$ to the Hermean exosphere. The work by Mouawad et al. (2011), on which Burger is the second author, uses a similar Monte Carlo model approach, but adds a further constraint via observational data from the McMath–Pierce telescope. They estimate that MIV contributes sodium to the Hermean exosphere at a rate of 2.1×10^{10} – Na atoms $\text{m}^{-2} \text{s}^{-1}$. The sodium release rate calculated in our analysis agrees well with the aforementioned results by other authors. This validates the approach of combining the works by Cintala (1992) and Berezhnoy and Klumov (2008), where the former is used to determine impact rates and the latter for the amount of vapor produced by the impacts as well as the abundances of various constituents of the MIV-induced vapor cloud. As a result, we are utilizing this combined approach as part of the inputs for a model to predict the amount of oxygen in the Hermean exosphere. The results of this ongoing work will be presented in a separate paper.

We hope that this analysis stimulates a renewed interest in smaller meteoroids and their contribution to the atmospheres of planetary bodies via impact vaporization. In the future this analysis will be extended to other bodies in our Solar System with relatively tenuous atmospheres, such as the Galilean moons Ganymede, Europa, and Callisto, which will be studied by the JUICE mission. For a quick summary of the JUICE mission, one may consult the presentation abstract by Dougherty et al. (2012). There is still room for refinement of our understanding of the chemical and physical processes involved when the smaller members of the interplanetary dust complex interact with planetary and satellite surfaces in our Solar System.

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Fig. 1.

The cumulative meteoroid mass flux distribution created as an interplanetary model by Grün et al. (1985) at a heliocentric distance of 1 AU.

Fig. 2.

The cumulative meteoroid mass flux shown in Fig. 1 has now been differentiated with respect to mass. This form lends itself, when combined with a differential velocity distribution, to be used to calculate impact rates for the meteoroid population. This data corresponds to a heliocentric distance of 1 AU.

Fig. 3.

The differential meteoroid velocity flux from Cintala (1992) is dependent upon Mercury's position along its orbit around the Sun.

Fig. 4.

The impact of a single meteoroid of a given mass and velocity is multiplied by the impact rate of meteoroids with similar mass and velocity to yield a total vapor production rate. A maximum of production occurs at mass $m = 2.1 \times 10^{-4}$ g.

Table 1

Comparison of impact rates of different models.

Model	Impacts per year
Our model	2.843×10^{15}
Cintala's model	4.073×10^{16}
Borin et al.'s model	3.104×10^{18}

Adapted from Borin et al.'s Table 1 (Borin et al., 2009).

These impact rates cover particles with sizes from 5 to 100 μm .

This corresponds to masses from 1.31×10^{-9} to 1.05×10^{-5} g.

The velocities considered here range from 4.24 km s^{-1} to 116.4 km s^{-1} .