Erosion of Volatiles by Micrometeoroid Bombardment on Ceres and Comparison to the Moon and Mercury

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Abstract

Ceres, the largest reservoir of water in the main belt, was recently visited by the Dawn spacecraft, which revealed several areas bearing H2O-ice features. Independent telescopic observations showed a water exosphere of currently unknown origin. We explore the effects of meteoroid impacts on Ceres by considering the topography obtained from the Dawn mission using a widely used micrometeoroid model and ray-tracing techniques. Meteoroid populations with 0.01–2 mm diameters are considered. We analyze the short-term effects Ceres experiences during its current orbit, as well as long-term effects over the entire precession cycle. We find that the entire surface is subject to meteoroid bombardment, leaving no areas in permanent shadow with respect to meteoroid influx. The equatorial parts of Ceres produce 80% more ejecta than the polar regions due to the large impact velocity of long-period comets. Mass flux, energy flux, and ejecta production vary seasonally by a factor of 3–7 due to the inclined eccentric orbit. Compared to Mercury and the Moon, Ceres experiences significantly smaller effects of micrometeoroid bombardment, with a total mass flux of $4.5 \pm 1.2 \times 10^{17}$ kg m$^{-2}$ s$^{-1}$. On average, Mercury is subjected to a $50 \times$ larger mass flux and generates $700 \times$ more ejecta than Ceres, while the lunar mass flux is $10 \times$ larger and the ejecta generation is $30 \times$ larger than on Ceres. For these reasons, we find that meteoroid impacts are an unlikely candidate for the production of a water exosphere or significant excavation of surface features. The surface turnover rate from the micrometeoroid populations considered is estimated to be 1.25 Myr on Ceres.

Unified Astronomy Thesaurus concepts: Zodiacal cloud (1845); Impact phenomena (779); Mercury (planet) (1024); The Moon (1692); Space weather (2037); Meteoroid dust clouds (1039); Micrometeoroids (1048); Meteoroids (1040)

Supporting material: animation

1. Introduction

Ceres is the only dwarf planet with a global high-resolution shape model (Park & Buccino 2018) thanks to the Dawn mission and the Dawn spacecraft’s Framing Camera.4 The dwarf planet itself is surrounded by the zodiacal cloud, a cloud of dust and meteoroids enveloping the entire solar system, that is mainly sourced from main-belt asteroids (MBAs) and short-/long-period comets (Nesvorný et al. 2010). Since the zodiacal cloud is increasingly denser with decreasing heliocentric distance (Leinert et al. 1981), Ceres is expected to experience a smaller meteoroid flux and impact velocities than those seen by the Moon and Mercury.

Two sets of telescopic observations suggest that Ceres has a water exosphere, at least temporarily (A’Heam & Feldman 1992; Küppers et al. 2014). Despite negative results from follow-up observations with different observational facilities (Rousselot et al. 2011, 2019; Roth et al. 2016; McKay et al. 2017; Roth 2018), the production of the water exosphere on Ceres was the subject of many works (Tu et al. 2014; Formisano et al. 2016; Schorghofer et al. 2016; Landis et al. 2017; Schorghofer et al. 2017; Villarreal et al. 2017). Landis et al. (2019) analyzed the surface evolution based on the flux of impactors larger than 100 m in diameter; however, the effects of smaller meteoroids are yet to be assessed. Therefore, it is natural to investigate this gap and address how different meteoroid populations imprint their activity on the surface of Ceres, how they are affected by the complex topography, and how they influence the regions with exposed water ice.

Until recently, the availability of precise shape models and detailed dynamical meteoroid models was scarce, to say nothing of the existence of models to study the effects of meteoroid bombardment using ray-tracing techniques. Pokorný et al. (2020) analyzed the effects of meteoroid bombardment on the lunar surface, specifically on both lunar poles, using detailed topography derived from Lunar Orbiter Laser Altimeter observations (Smith et al. 2010). Advanced solar illumination models (Mazarico et al. 2018) show that the lunar poles harbor many cold traps and permanently shadowed regions (PSRs), consistent with spacecraft data (e.g., Diviner instrument; Paige et al. 2010). On the other hand, Pokorný et al. (2020) showed that meteoroids, due to their broad range of impact directions, reach even the deepest craters on both lunar poles, including those that are permanently shadowed from the Sun. Pokorný et al. (2020) also showed that the crater walls that were more inclined toward the high energetic meteoroid flux concentrated close to the ecliptic experienced a higher rate of impact gardening compared to the crater floors. The floors were
partially shielded from the meteoroid flux and experienced the high energetic impacts at grazing angles.

Compared to the Moon, Ceres is on an inclined, eccentric orbit embedded inside the source region of a significant portion of the zodiacal dust cloud (MBAs; e.g., Nesvorný et al. 2006). The obliquity of Mercury and the Moon is stable in the long term (Goldreich 1966), which allows the existence of long-lived permanently shadowed environments, whereas the obliquity of Ceres oscillates between $\epsilon = 2^\circ$ and $20^\circ$ with a period of 24.5 kyr and complicates the existence of PSRs (Ermakov et al. 2017). However, as shown in Ermakov et al. (2017), PSRs indeed exist on Ceres and can potentially retain water ice. In addition to the ice deposits in the PSRs, Combe et al. (2019) showed nine areas with H$_2$O absorption features detected in Dawn visible and infrared (VIR) spectra (2.0 $\mu$m line). These areas are not currently accessible by direct solar radiation; however, as shown in Pokorný et al. (2020), they might be accessible to meteoroid impacts. These meteoroid impacts bring exogenous energy to PSRs that can remove volatiles from them. It has been suggested that destabilized volatiles might produce a tenuous exosphere at airless bodies such as Mercury and the Moon (Cintala 1992), which motivates us to quantify the effect of meteoroids on these interesting regions at Ceres.

Landis et al. (2019) discussed various explanations for the temporary existence of the water exosphere on Ceres: (a) sublimation from subsurface water-ice tables (Fanale & Salvai 1989; Prettyman et al. 2017); (b) sublimation from transient surface exposures of water ice (Landis et al. 2017); (c) sputtering by solar energetic particle events from surface ice (Villarreal et al. 2017); and (d) seasonal, optically thin water-ice polar deposits (Schorghofer et al. 2017). The telescopic evidence from A'Hearn & Feldman (1992) and Küppers et al. (2014) suggests 3-6 kg s$^{-1}$ of water vapor produced to sustain the observed exosphere. None of these mechanisms or their combination provides such a high rate (Landis et al. 2019). The residence time of the water exosphere was shown to be around 7 hr (Schorghofer et al. 2016); thus, a continuous active source is needed to sustain the long-lasting exosphere observed by Küppers et al. (2014). Since meteoroids provide a quasi-continuous source of energy to the surfaces of airless bodies, we aim to estimate the meteoroid impact-driven production rates and provide a missing piece to this puzzle. Moreover, meteoroids and dust may also erode water-ice deposits.

2. Methods

2.1. Ceres Topography Model

For the representation of Ceres, we use an object (OBJ) file containing 1,579,014 vectors and 3,145,728 faces (triangles) derived from the digital terrain model (DTM) constructed from Framing Camera 2 (FC2) images taken during the Dawn High Altitude Mapping Orbit (HAMO). The HAMO DTM covers approximately 98% of the Cererian surface with a lateral spacing of $\approx$136.7 m pixel$^{-1}$. We converted the original ICQ file to an OBJ file using an example code described at https://sbnarchive.psi.edu/pds3/dawn/fc/DWNCSPC_4_01/DOCUMENT/ICQMODEL.ASC. We also provide the working version of this code at the project’s GitHub page (see Software section).

5 The mission data product can be found at https://sbnarchive.psi.edu/pds3/dawn/fc/DWNCSPC_4_01/DATA/ICQ/CERES_SPC181019_0512.ICQ.

2.2. Ray-tracing Code

We improved our own procedure from Pokorný et al. (2020) in terms of computational speed and combined it with two external libraries written in C++: (1) tinyobjloader for loading up to 10 million polygon models and (2) fastbvh, a bounding volume hierarchy algorithm that uses axis-aligned bounding box (AABB) trees to efficiently calculate line-triangle intersections. Our program loads the OBJ file into memory using tinyobjloader and then constructs using fastbvh, an AABB tree that allows us to quickly evaluate ray–face intersections for the entire triangular mesh. For each combination of longitude, latitude, and velocity in the meteoroid model, our code determines whether each surface triangle is reachable or obstructed/shadowed by any other triangle. We also calculate the incidence angle $\varphi$ for each surface triangle and meteoroid direction/velocity combination independently. Each surface triangle represents a plane for which we calculate a normal vector pointing outside of the object, $\vec{n}_{\text{surf}}$. Then $\cos \varphi = \vec{n}_{\text{surf}} \cdot \vec{e}_{\text{imp}}$, where $\vec{e}_{\text{imp}}$ is the velocity vector of the impacting meteoroid normalized to unity. For impacts perpendicular to the surface, $\cos \varphi = 1$, whereas for meteoroids at grazing angles, $\cos \varphi \to 0$, since $\varphi \to 90^\circ$.

2.3. Model for Meteoroid Environment at Ceres and Its Variations Over Current Ceres Orbit

The meteoroid model in this work uses the same constraints and configuration as the model used in Pokorný et al. (2018, 2019, 2020) for studies of Mercury’s and the Moon’s meteoroid environments. This means we do not change the configuration of the zodiacal cloud/meteoroid model with respect to those previous studies, ensuring they are comparable with each other. Our model combines contributions of four meteoroid populations originating from MBAs, Jupiter-family comets (JFCs), Halley-type comets (HTCs), and Oort Cloud comets (OCCs). These four populations dominate the meteoroid mass and number density flux in the inner solar system (Nesvorný et al. 2010, 2011a), while the outer solar system is mostly dominated by Edgeworth–Kuiper Belt meteoroids (Poppe et al. 2019). The details of the model used here are summarized in Table 1 and references therein. We calculate the distribution of the directions and velocities of impacting meteoroids for one orbit from 2015 January 1 to 2019 August 18 in 10 day intervals, resulting in 169 individual snapshots of the meteoroid environment at Ceres. Each of these snapshots provides the meteoroid mass flux distributed in Sun-centered longitudes $\lambda - \lambda_0$ and latitudes $\beta$ with $2^\circ$ resolution (i.e., directions) and impact velocities with 2 km s$^{-1}$ resolution, thus providing the full three-dimensional map of velocity vectors for meteoroids in each meteoroid population separately. An example of the meteoroid environment map and the impact velocity distribution is shown in Figure 1. The directionality of meteoroids on Ceres is similar to that seen on other airless bodies like Mercury (Pokorný et al. 2018) or the Moon (Pokorný et al. 2019). The mass flux is dominated by meteoroids impacting Ceres from directions close to the orbital plane ($\beta \approx 0^\circ$) and within $90^\circ$ of the ram/apex direction ($-180^\circ < \lambda - \lambda_0 < 0^\circ$), where JFC meteoroids dominate the total influx ($-180^\circ < \lambda - \lambda_0 < -140^\circ$, $-30^\circ < \beta < 30^\circ$ and $-40^\circ < \lambda - \lambda_0 < -0^\circ$, $-30^\circ < \beta < 30^\circ$). The HTC and OCC meteoroids preferentially originate from the apex direction (a circle around $[\lambda - \lambda_0, \beta] = [-90^\circ, 0^\circ]$ with a $45^\circ$ radius). The
MBA meteoroids have the smallest relative impact velocities, \( V_{\text{imp}} < 10 \, \text{km} \, \text{s}^{-1} \), and impact Ceres preferentially from higher Sun-centered latitudes \(|\beta| > 60^\circ\) and/or from the Sun/anti-Sun directions \((\lambda - \lambda_0) \approx -180^\circ\) and \((\lambda - \lambda_0) \approx 0^\circ\). The impact velocity distribution (Figure 1(b)) shows that MBA meteoroids have a median \( V_{\text{imp}} = 5.5 \, \text{km} \, \text{s}^{-1} \), JFC meteoroids are slightly faster with \( V_{\text{imp}} = 9.2 \, \text{km} \, \text{s}^{-1} \), and the long-period comet sources provide much more energetic impactors with \( V_{\text{imp}} = 20.5 \, \text{km} \, \text{s}^{-1} \) for HTC meteoroids and \( V_{\text{imp}} = 25.3 \, \text{km} \, \text{s}^{-1} \) for OCC meteoroids.

Due to the nonzero eccentricity and inclination of Ceres, the meteoroid environment undergoes significant changes during one orbit (Figure 2). During one of its orbital cycles, Ceres crosses the ecliptic twice (gray regions in Figure 2); this is where we record the global and local maxima of the meteoroid mass flux \( M \) for MBA and JFC meteoroids. This is not unexpected because MBA and JFC meteoroid models show that they are concentrated close to the ecliptic (Nesvorný et al. 2010, 2011a). On the other hand, HTC and OCC meteoroids are unaffected by Ceres’s departure from the ecliptic plane due to the broad range of inclinations of their parent bodies (Nesvorný et al. 2011b; Pokorny et al. 2014). Overall, JFC meteoroid mass flux dominates the total mass influx at Ceres throughout the entire orbit due to the dominance of JFC meteoroids in the zodiacal cloud. This stems from the population mixing ratios obtained from Carrillo-Sánchez et al. (2016) and Pokorny et al. (2019), where JFCs dominate the terrestrial flux by a factor of 10 compared to other meteoroid populations. The departure from the ecliptic is not the only factor shaping the meteoroid mass flux at Ceres. From spacecraft observations and modeling, we know that the zodiacal cloud density inside 1 \( \text{au} \) increases with heliocentric distance, \( r \) (e.g., Leinert et al. 1981; Pokorny et al. 2019), while the outer portions of the zodiacal cloud show constant density (Poppe et al. 2019). With Ceres being inside the main belt, we can expect significant differences from what is observed inside 1 \( \text{au} \) for MBA and JFC meteoroids. For the outer solar system sources (HTC and OCC), the meteoroid mass flux scaling should be similar to that observed/modeled inside 1 \( \text{au} \). We calculate the proportional changes of \( M \) for all four sources assuming the single power-law scaling \( M \propto r^p \) and positions close to the ecliptic, \(|z| < 0.01 \, \text{au} \) (labels above arrows in Figure 2). While not directly comparable to the zodiacal cloud density, due to the velocity changes that Ceres experiences
during its orbit, the proportionality of HTC ($\propto r^{-2.65}$) and OCC ($\propto r^{-2.23}$) meteoroids is quite similar to those modeled in Pokorný et al. (2019). On the other hand, JFC ($\propto r^{-3.08}$) and, most significantly, MBA ($\propto r^{-4.71}$) meteoroids show much steeper scaling with heliocentric distance than what was observed inside 1 au. There are two main factors that drive the proportionality of different populations. One is the location of the source region with respect to the target (Ceres), where MBA and JFC meteoroids are ejected on semimajor axes close to that of Ceres while long-period comet meteoroids can be considered distance source regions. This causes larger variations for the close source regions due to the fact that some meteoroids are released at semimajor axes smaller than that of Ceres. Another is the impact velocity of different populations at Ceres, which is modulated by the populations' semimajor axis/eccentricity/inclination distributions. The MBA and JFC meteoroids can acquire very small impact velocities at Ceres due to their orbital similarity, while for the long-period meteoroids, this is insignificant.

We calculate that, averaged over one of its current orbits around the Sun, the mean meteoroid flux at Ceres is $\dot{M} = 4.49 \pm 1.18 \times 10^{-17}$ kg m$^{-2}$ s$^{-1}$, which is approximately 9.5 times smaller than that at the Moon, $\dot{M}_{\text{Moon}} = 42.17 \times 10^{-17}$ kg m$^{-2}$ s$^{-1}$, and 22 times smaller than the terrestrial meteoroid mass flux, $\dot{M}_{\text{Earth}} = 98.53 \times 10^{-17}$ kg m$^{-2}$ s$^{-1}$. The mean contributions of the four meteoroid populations are the following: $\dot{M}_{\text{MBA}} = 0.52 \pm 0.26 \times 10^{-17}$, $\dot{M}_{\text{HTC}} = 2.85 \pm 0.86 \times 10^{-17}$, $\dot{M}_{\text{JFC}} = 0.60 \pm 0.08 \times 10^{-17}$, and $\dot{M}_{\text{OCC}} = 0.52 \pm 0.06 \times 10^{-17}$ kg m$^{-2}$ s$^{-1}$. The median impact velocities averaged throughout the entire orbit are the following: $\bar{v}_{50\%}(\text{MBA}) = 4.73 \pm 0.69$, $\bar{v}_{50\%}(\text{JFC}) = 9.32 \pm 0.46$, $\bar{v}_{50\%}(\text{HTC}) = 20.47 \pm 0.63$, and $\bar{v}_{50\%}(\text{OCC}) = 25.31 \pm 1.05$ km s$^{-1}$. The overall shape of the population velocity distributions shown in Figure 1 does not significantly change throughout the orbit; only their relative contributions consequently change the overall velocity distribution at Ceres.

2.4.** Quantities Induced by the Meteoroid Bombardment**

In this paper, we discuss four different quantities that result from the bombardment of the Cererean surface by interplanetary meteoroids: (1) the meteoroid mass flux $\dot{M}$, (2) the meteoroid energy flux $\dot{E}$, (3) the ejecta mass produced by impacting meteoroids $\dot{P}^+$, and (4) the area of craters produced by meteoroid bombardment $A$.

In Section 2.2, we describe how we determine whether each surface element is reachable by the flux of meteoroids incoming for a selected direction (i.e., it is not shadowed by any feature on the surface of the dwarf planet). This analysis results in a list of $\cos\varphi$ values (cosines of incident angles) for each triangular element on Ceres and the value $S(\lambda - \lambda_o, \beta)$, which represents the percentage of shadowing of a particular element ($S = 0$ is a completely shadowed element, $S = 1$ is unobstructed). Here $\lambda - \lambda_o$ and $\beta$ are the Sun-centered longitude and latitude, i.e., the angles representing the meteoroid directionality. The meteoroid model we use here gives us the five-dimensional information for each time snapshot we analyze in this manuscript; for each combination of directions $\lambda - \lambda_o$, impact velocity $v_{\text{imp}}$, and
meteoroid diameter $D$, we obtain the meteoroid number flux $N_{\text{met}}$. Assuming that all meteoroids are spheres, we get the meteoroid mass flux $M_{\text{met}}$ and cross-sectional area of impacting meteoroids per unit time $A_{\text{met}}$ as

$$M_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) = \frac{2}{6} \sum \rho_{\text{met}} N_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}, D),$$

$$A_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) = \frac{2}{4} D^2 N_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}, D),$$

where we adopt the meteoroid bulk density $\rho_{\text{met}} = 2000$ kg m$^{-3}$ used in the meteoroid models we show in Table 1.

Equipped with these quantities, we then calculate for each triangular element on Ceres $M, \mathcal{E}, \mathcal{P}^+, \mathcal{P}^-$, and $A$, defined as follows:

$$M = \sum_{\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}} M_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) \times S(\lambda - \lambda_{\odot}, \beta) \cos \varphi(\lambda - \lambda_{\odot}, \beta),$$

$$\mathcal{E} = \sum_{\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}} \frac{1}{2} M_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) v_{\text{imp}}^2 \times (\lambda - \lambda_{\odot}, \beta) S(\lambda - \lambda_{\odot}, \beta) \cos \varphi(\lambda - \lambda_{\odot}, \beta),$$

$$\mathcal{P}^+ = \sum_{\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}} M_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) v_{\text{imp}}^2 \times (\lambda - \lambda_{\odot}, \beta) S(\lambda - \lambda_{\odot}, \beta) \cos^3 \varphi(\lambda - \lambda_{\odot}, \beta),$$

$$\mathcal{A} = F_{\text{cr}} \sum_{\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}} A_{\text{met}}(\lambda - \lambda_{\odot}, \beta, v_{\text{imp}}) \times S(\lambda - \lambda_{\odot}, \beta) \cos \varphi(\lambda - \lambda_{\odot}, \beta),$$

where $C = 7.358$ km$^{-2}$ s$^2$ is a scaling constant determined from the laboratory experiments reported by Koschny & Grün (2001). We assume the impactor-to-crater area ratio $F_{\text{cr}} = 63$, which is based on fitting results from Table 1 in Koschny & Grün (2001).

The precession of the pole is implemented by rotating the Ceres rotational axis around the axis perpendicular to the orbital plane and adopting a pole precession rate of 210 kyr (Ermakov et al. 2017). The default rotational axis pointing in our model is set to R.A. $\alpha = 291^{\circ}42751$ and decl. $\delta = 66^{\circ}76043$, which translates to ecliptic longitude $\lambda_{\odot} = 11^{\circ}18622$ and latitude $\beta_{\odot} = 81^{\circ}55038$, or longitude and latitude with respect to the orbital plane $\lambda_{\odot} = 328^{\circ}24905$ and $\beta_{\odot} = 85^{\circ}96854$. The rotation from ecliptic to orbital coordinates is $R_\odot(-\omega)R_\odot(-I)R_\odot(-\Omega)$, where $R_\odot(y)$ is the rotation matrix with respect to an axis $y$ which represents a clockwise rotation by an angle $y$. In a more specific way,

$$\begin{pmatrix}
\cos \lambda & \cos \beta & \sin \beta \\
\sin \lambda & \cos \beta & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
\cos \Omega & -\sin \Omega & 0 \\
\sin \Omega & \cos \Omega & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
\cos \omega & -\sin \omega & 0 \\
\sin \omega & \cos \omega & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
\cos \lambda_{\odot} & \cos \beta_{\odot} & \sin \beta_{\odot} \\
\sin \lambda_{\odot} & \cos \beta_{\odot} & 0 \\
0 & 0 & 1
\end{pmatrix}.$$

The effects of obliquity/axial tilt are calculated for each obliquity value separately, and then the contribution of each obliquity regime is weighted by the time Ceres spends in that obliquity regime, based on Figure 1 in Ermakov et al. (2017).

3. Results: Precession Cycle Average

First, we look at the results of the meteoroid bombardment of Ceres averaged over the entire precession cycle, i.e., approximately 210 kyr (Ermakov et al. 2017). Here we assume the proper orbital elements of Ceres, with $a = 2.7671$ au, $e = 0.116198$, and $\sin(i) = 0.167585$ ($i = 96^\circ 64744$).

Figure 3(a) shows in detail the entire surface of Ceres color-coded by the value of the meteoroid mass flux $M$. Despite the seemingly significant difference between the equatorial and polar regions, the average $\mathcal{M}$ is almost constant over the entire

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6. We use synthetic values from https://newton.spacedys.com/astdys/index.php?pc=1.1.6&n=Ceres.
Figure 3. (a): global map of the meteoroid mass flux $M$ on Ceres, with nine areas of interest from Combe et al. (2019) highlighted (white areas with white labels). The left side of the figure shows the north/south pole views in Cartesian coordinates, showing areas within 30° of the pole. The meteoroid environment is averaged over the entire precession cycle. (b): same but for the ejecta mass production rate $P^e$ on Ceres. (c): same but for the surface e-folding lifetime on Ceres. All units are in SI except for the surface e-folding lifetime, which we show in years.
surface, where the difference between the maximum and minimum values is 7.8%. The average value over the entire surface is \( \overline{M} = 4.54 \pm 0.04 \times 10^{-13} \text{ kg m}^{-2} \text{ s}^{-1} \), where \( M \) peaks at mid-latitudes, around 60°. The local topography of Ceres plays a negligible role when the meteoroid environment is averaged over a longer timescale. This is also apparent on both Cererean poles (right side in Figure 3(a)), where we see <2% differences between the maximum and minimum values.

We also highlight nine areas of interest from Combe et al. (2019) that showed detections of exposed H₂O from VIR (the mapping spectrometer of the Dawn mission) remote-sensing observations (white labeled rectangles in Figure 3). The coordinates of these nine areas are shown in Table 2. Unlike solar irradiation, which is almost a point source at the distance of Ceres, the meteoroid environment is able to influence any surface element on the Cererean surface, and even the most significant features do not provide permanent shadowing from the meteoroid bombardment. Ermakov et al. (2017) identified seven bright crater floor deposits that are correlated with the most persistent PSRs. Since all of these areas have high latitudes (|\( \beta \)| > 69°77), they are all comparable to area C, the Messor Crater from Combe et al. (2019).

The global map of the ejecta mass production rate \( P^+ \) is shown in Figure 3(b). For \( P^+ \), the equatorial areas experience the maximum exposure, while the polar regions experience 43% less exposure (i.e., a factor of 1.76 difference). A similar situation holds for the meteoroid energy flux, where the pole receives ~19% less \( E \) than the equatorial regions. The reason for the difference between the global behavior of \( M \) and \( P^+ \) shown in Figure 3(a) is the different impact velocities of meteoroid populations. As shown in Figure 2, the HTC and OCC meteoroids have the highest velocities, with median velocities 2.1–2.6 times larger than the JFC population that dominates the meteoroid mass flux. High-velocity meteoroids from both the HTC and OCC populations are impacting Ceres preferentially from the invariable plane, which is close to the ecliptic. Due to their high impact velocities, these meteoroids are not sensitive to Ceres’s own orbital velocity variations. This results in a continuous high-energy bombardment of the equatorial regions, while polar regions experience high-energy impacts on grazing angles. The mean values for the meteoroid energy flux and ejecta production rate are \( \bar{E} = 5.16 \pm 0.31 \times 10^{-16} \text{ MJ m}^{-2} \text{ s}^{-1} \) and \( \bar{P}^+ = 1.56 \pm 0.22 \times 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1} \), respectively.

The last quantity we discuss here is the surface e-folding lifetime, \( T_A \) (Figure 3(c)). The shortest e-folding times are in the equatorial area, while \( T_A \) increases toward both poles. However, the difference between the maximum and minimum values of \( T_A \) is small: <6%. Unlike \( P^+ \) and \( E \), the e-folding time is not modulated by the impactor velocity, since we assume a constant impactor-to-crater area ratio \( F_{cr} = 63 \) (see Section 2.4). The mean e-folding time, \( T_A = 1.25 \pm 0.02 \times 10^6 \text{ yr} \), means that in 3.75 Myr, 95% of the surface should be covered by meteoroid-induced craters. This does not include impacts of secondary ejecta (secondaries; see, e.g., Costello et al. 2018, 2020). The typical depth of meteoroid-induced craters is a factor of 2–4 larger than the impactor radius (Koschny & Grün 2001). When we average over the entire size range simulated here, we find a mean crater depth of around 100–300 \( \mu \text{m} \). The mean crater depth depends on the location of Ceres, as well as the meteoroid population causing the impacts. This is due to the different size–frequency distributions (SFDs) that the meteoroid populations simulated here have when impacting Ceres. Note that Koschny & Grün (2001) explored only impact velocities up to 10 km s\(^{-1}\), so the crater depth has a high uncertainty that we cannot quantify at the moment.

A closer look at the areas showing exposed H₂O signatures, the crater morphology, and the general topography have a rather small effect, even for the Juling Crater, which shows the largest ratio between the maximum and minimum values for all four quantities: \( R_A = M_{\text{max}} / M_{\text{min}} = 1.03, R_E = 1.24, R_P = 1.75, \) and \( R_{T_A} = 1.06. \) The only exception is the ejecta mass production rate \( P^+ \), which, for the Juling Crater, shows a 75% difference between the crater rim, \( P^+ = 1856 \times 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1} \), and partially shadowed crater floor, \( P^+ = 1063 \times 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1} \). This is due to its cubic dependence on the cosine of the incident angle and the \( \nu_{\text{imp}} \) velocity scaling, which emphasize the effect of fast meteoroids close to the ecliptic. The surface features facing the ecliptic produce significantly more ejecta than those that are effectively shadowed by the crater rim. This effect is most efficient for mid-latitudes, 30° < |\( \beta \)| < 50°, where it provides an ~70% difference between the exposed and shadowed portions of the crater. This efficiency of shadowing drops toward the equator and both poles, where for the Messor Crater, we see a drop to 49% difference between the exposed/shadowed areas.

### 4. Results: One Orbit of Ceres

The image of the meteoroid environment imprint on the Cererean surface averaged over one precession cycle of Ceres greatly simplifies the picture. The averaged picture is important for understanding the long-term surface evolution, but Ceres experiences significant meteoroid flux changes during the Cererean year (Figure 2). In this section, we analyze variations of several quantities over one orbit of Ceres, 4.61 yr. Such a
time segment is longer than the duration of the scientific stay of the Dawn spacecraft at Ceres (the RC3 orbit phase started on 2015 April 23, and on 2018 October 31, the spacecraft ran out of its propellant).

In Figure 2, we show that the meteoroid mass flux $\mathcal{M}$ impacting Ceres is most significantly modulated by the asteroid’s distance from the ecliptic. To put this in a different perspective, we show the orbit of Ceres in Cartesian coordinates in Figure 4. This figure shows 12 different time records of $\mathcal{M}$ on the Cererean surface averaged over one rotation period (9.1 hr) in SI units from 2015 January 1 to 2019 March 21. In Figure 4, we see the effects of the orbital motion of Ceres on the global shape of the meteoroid mass flux. On 2015 January 1, Ceres has just passed the descending node, and its negative $z$-axis velocity is close to its maximum, $v_z = -3.32\text{ km s}^{-1}$ (note that the median impact velocity of JFC meteoroids is $V_{95\%}(\text{JFC}) = 9.32 \pm 0.46\text{ km s}^{-1}$). This increases the number of impacts to the southern hemisphere, since Ceres is plunging downward and the relative velocity of meteoroids impacting the southern hemisphere is increased, while the northern hemisphere experiences attenuated meteoroid mass flux. The opposite effect can be seen on 2017 April 20, when Ceres is close to the ascending node and its positive $z$-axis velocity is close to its maximum, $v_z = 3.40\text{ km s}^{-1}$. When the $z$-axis velocity is close to zero, i.e., the sum of the argument of perihelion and true anomaly is $\sin(\omega + f) = 0$, the meteoroid mass flux is symmetric around the Cererean equator, as seen on 2016 July 14 and 2018 June 14.

The variations of $\mathcal{M}$, $\mathcal{P}^+$, and $T_A$ for the Combe et al. (2019) areas (Table 2) are shown in Figure 5. The mass flux during one orbit of Ceres shows a double-peaked structure where, depending on the latitude of the feature, the global maximum occurs at a true anomaly angle $\text{TAA} = 106^\circ$ (for southern hemisphere features D (Juling) and I (Baltay)) or $\text{TAA} = 286^\circ$ (for northern hemisphere features), coinciding with the ecliptic crossing (Figure 5(A)). These mass flux spikes are correlated with the density of the zodiacal cloud that is densest close to the ecliptic and gets more tenuous further from the ecliptic. The northern/southern hemisphere seasonality is caused by the orbital velocity in the $z$-axis described in Figure 4. As shown in Figure 2, the $\text{TAA} = 286^\circ$ peak is stronger than the $\text{TAA} = 106^\circ$ peak due to Ceres’s smaller heliocentric distance; the zodiacal cloud gets denser with decreasing heliocentric distance. The north/south asymmetry is changing as Ceres undergoes nodal precession, and, when averaged over the entire precession cycle, the difference between the areas in the south and north is negligible (see Table 2).

The ejecta mass production rate $\mathcal{P}^+$ true anomaly profile differs from that of $\mathcal{M}$ mainly due to two factors. First, $\mathcal{P}^+$ is strongly dependent on the impact velocity of individual meteoroids ($v_{imp}^2$, see Equation (5)). The highest-impact velocities come from OCC and HTC meteoroids (see median velocities for each population in Section 2.3), which shifts the dominance over $\mathcal{P}^+$ from JFCs and MBAs to long-period comet particles. As we show in Figure 2, the long-period comets are not very sensitive to the distance from the ecliptic that attenuates the variations of $\mathcal{P}^+$ during its orbit to a factor of 2–3 (compared to a factor of 4–7 variations of $\mathcal{M}$). Second, the 5th–95th percentile (gray shaded area in Figure 5) is wider than that for $\mathcal{M}$ due to the $\cos^3$ of incidence angle dependence. This accentuates the effect of surface features, where surface patches experiencing almost perpendicular impacts produce significantly more ejecta than those subjected to grazing impacts.
The surface e-folding timescales $T_A$ show a similar trend in the north/south asymmetry as the two previous values, but their maxima are inverse with respect to the true anomaly angle (Figure 5(c)). This is understandable, since the higher impactor flux produces shorter e-folding timescales. The $T_A$ is not sensitive to the impact velocity; thus, it is similar to the mass flux variations with slightly smaller minimum/maximum ratios of 3–4.

Analysis of the Combe et al. (2019) areas showed significant variations of all quantities analyzed here during one Ceres orbit. From Figure 5, we can infer that areas on similar latitudes are undergoing very similar variations within one orbit. Since the Combe et al. (2019) areas are preferentially closer to the Cererean poles, many potentially interesting areas are left out. Furthermore, due to the short rotation period of Ceres that longitudinally averages meteoroid bombardment effects at a given latitude, we can simply divide Ceres into latitudinal strips and analyze the entire dwarf planet as a whole. In Figure 6, we show variations of $M$, $P^+$, and $T_A$ with a true anomaly angle for $20^\circ$ wide latitudinal strips, revealing the variations experienced by the entire surface. Lines in Figure 6 can be used to determine $M$, $P^+$, and $T_A$ for any point on the surface. The uncertainty of this approximation is quite small, because for each latitudinal strip, the difference between the median value (color-coded lines in Figure 6) and the 5th or 95th percentile is <35%.

Figure 6 shows that the equatorial latitudes experience smaller variations in all quantities analyzed here, where the ratio between the maximum and minimum values during one orbit increases with latitudes closer to the Cererean poles. For example, the $M$ max–min ratio for $-10^\circ < \beta < 10^\circ$ is 2.43,
while the same quantity for the north pole areas, \(70^\circ < \beta < 90^\circ\), is 6.88. As mentioned before, the north pole peak values are smaller than those on the south pole because Ceres passes through the ascending node closer to the Sun and hence through the denser portion of the zodiacal cloud.

Telescopic observations of the water exosphere on Ceres by A’Hearn & Feldman (1992) and Küppers et al. (2014) suggest production rates of 3–6 kg s\(^{-1}\). Let us assume an extreme case where all ejecta produced by meteoroids convert to the detectable water exosphere. We can obtain the water exosphere production rate via multiplying \(\mathcal{P}^+\) by the surface area covered with surface water ice. Using our values of \(\mathcal{P}^+ = 0.5–2.5 \times 10^{-13}\) kg m\(^{-2}\) s\(^{-1}\), this would require a surface water-ice area of \(1.2–12 \times 10^{13}\) m\(^2\) to obtain production rates of 3–6 kg s\(^{-1}\), which is equivalent to a sphere with a radius of 1000–3000 km. This would mean that even if the entire surface of Ceres was covered by water ice, the meteoroid impacts would not be able to produce the ejecta required to sustain the water exosphere observed by A’Hearn & Feldman (1992) and Küppers et al. (2014). Suppose that the entire Occator crater with diameter of 92 km is covered in water ice and continuously bombarded by meteoroids. The Occator crater area is about \(6.65 \times 10^9\) m\(^2\), and the ejecta mass produced per second is then \(0.3–1.7 \times 10^{-3}\) kg s\(^{-1}\). Such a hypothetical value is much smaller than the sublimation from known water-ice patches (0.16 kg s\(^{-1}\); Landis et al. 2019).

In the next section, we will compare these values with the identical quantities on Mercury and the Moon and draw conclusions for the meteoroid bombardment effects on these three bodies.

**Figure 6.** Top: variations of the meteoroid mass flux \(\mathcal{M}\) with Ceres’s true anomaly angle for nine latitudinal strips with 20° width. The two peaks in \(\mathcal{M}\) correspond to the ecliptic crossings and the maximum flux from MBA and JFC meteoroid populations. Middle: same as the top panel but for the ejecta mass production rate \(\mathcal{P}^+\). Bottom: same as the top panel but for the surface exposure e-folding time \(T_e\).
5. Comparison of Ceres to Mercury and the Moon

Similarly to Section 3, we calculate the effects of meteoroid bombardment using our meteoroid model on the surfaces of Mercury and the Moon (Pokorný et al. 2018, 2019, 2020). For Mercury, we use the following orbital elements and escape velocity: $a = 0.3871$ au, $e = 0.2056$, $i = 7^\circ0056$, and $V_{esc} = 4.25$ km s$^{-1}$, whereas for the Moon, we use $a = 1.0000$ au, $e = 0.0167$, $i = 0^\circ0005$, and $V_{esc} = 2.38$ km s$^{-1}$. The remaining orbital elements are assumed to be randomly distributed between $0^\circ$ and $360^\circ$. In order to simplify our calculation, we use the shape model of Ceres as a substitute for the shape models of Mercury and Mars. Since in this section, we aim to analyze the global models of three airless bodies, we assume that simplification is acceptable. To further check our assumptions, we compare our results to those calculated on a smooth sphere representing Mercury and the Moon. The values shown in this section agree within 1%. Note that all three objects rotate much faster than their nodal precession periods, they are not in 1:1 spin–orbital resonance with the Sun, and we can approximate that the meteoroid bombardment is longitudinally uniform. This ensures that the surface of each of these three bodies is uniformly affected with respect to the surface longitude. The 3:2 spin–orbit resonance of Mercury with respect to the Sun can possibly introduce some secondary nonuniform variations in the effects of meteoroid bombardment. Mercury is still rotating with respect to the meteoroid environment; thus, we expect that the effects of the meteoroid bombardment average out. We reserve the quantification of the 3:2 spin–orbit resonance for future work due to the necessity of simulating the entire Hermean 2 yr cycle in fine detail.

For each of the three airless bodies, we analyze 60 segments that are uniformly distributed in surface latitude $\beta$ (i.e., $3^\circ$ wide segments). The results for Ceres are in Figure 7, where we show variations of $M$, $E$, $P^+$, and $A$ with respect to surface latitude. To make our results more readable and transferable, we fit simple four-parameter functions to each quantity. For $M$, $E$, and $P^+$, we achieve a best fit using the Gaussian function $G(\beta)$,

$$G(\beta) = a_0 \exp \left[ -0.5 \left( \frac{\beta - \mu_0}{\sigma_0} \right)^2 \right] + b_0, \quad (8)$$

where $a_0$ is the maximum amplitude of the function occurring at $\beta = \mu_0$, $b_0$ is the offset of the function in the $y$-direction, $\mu_0$ is the offset from the center in the $x$-axis (i.e., in the latitude), and $\sigma_0$ is the standard deviation. From Figure 7, it is evident that $M$ is not a Gaussian distribution but rather resembles the sum of two symmetric Gaussians. For fitting such a profile, we use a four-parameter function, $G_{sym}(\beta)$,

$$G_{sym}(\beta) = a_0 \exp \left[ -0.5 \left( \frac{\beta - \mu_0}{\sigma_0} \right)^2 \right] + a_0 \exp \left[ -0.5 \left( \frac{\beta + \mu_0}{\sigma_0} \right)^2 \right] + b_0, \quad (9)$$

where the only difference between the two Gaussians is the sign at $\mu_0$. Furthermore, $A$ on Mercury responds best to fitting

Figure 7. Variations of the meteoroid mass flux $M$ (top left), meteoroid energy flux $E$ (top right), ejecta mass production rate $P^+$ (bottom left), and area of craters produced by meteoroid impacts $A$ (bottom right) with the latitude on Ceres for 60 latitudinal strips. Functions of $M$, $E$, and $P^+$ are fitted using Equation (8), while $A$ is fitted using Equation (10). Fits for all quantities are represented by solid black lines.
a cosine function $C(\beta)$,

$$C(\beta) = a_0 \cos\left(\frac{\beta - \mu_0}{\sigma_0}\right) + b_0,$$

(10)

where $a_0$ is the amplitude, $b_0$ is the offset of the function in the $y$-direction, $\mu_0$ is the offset from the center in the $x$-axis (i.e., in the latitude), and $\sigma_0$ describes the period of the cosine. These three functions are chosen for their simplicity and ease of interpretation. We tested more than 80 other probability density distributions available in the SciPy framework, but we find no distribution that would provide significantly better fits than our three functions.

Table 3 shows the results of our function fitting to the latitudinal distributions of $M$, $E$, $P^+$, and $A$ for Mercury, the Moon, and Ceres. For each planetary body, we show the four fit parameters, the difference between the maximum and the minimum value, and the ratios, $R$, between the three objects for the average values of quantities $M$, $E$, $P^+$, and $A$. Mercury and the Moon both have $\mu_0 = 0.0$, except for cases when we fit $G_{\text{sym}}$. This is because we enforce the latitudinal symmetry in our fits, since both bodies have negligible flatness (i.e., an almost perfectly spherical shape).

Mercury experiences the highest values of all quantities analyzed here, which are an order of magnitude higher than those at the Moon and 2–3 orders of magnitude higher than those at Ceres. The meteoroid energy flux $E$ and ejecta mass production rate $P^+$ at Mercury are amplified with respect to those at Ceres due to a combination of higher impact velocities and meteoroid fluxes closer to the Sun. Mercury, assuming that both Mercury and Ceres have the same surface material, produces $\sim$700 times more ejecta than Ceres via meteoroid impacts. Similarly, $E$ is $\sim$400 times higher on Mercury with respect to Ceres. These quantities have shown to have a strong correlation with the existence of a tenuous dust cloud around the Moon (Horányi et al. 2015; Szalay & Horányi 2015; Pokorný et al. 2019), sustaining an exosphere of several metals around Mercury (Killen & Hahn 2015; Merkel et al. 2017; Pokorný et al. 2018), and the potential stability of water ice in PSRs at Mercury and the Moon (Hayne et al. 2015; Deutsch et al. 2019; Pokorný et al. 2020).

The lunar surface water-ice stability was shown to suffer similar erosion rates from meteoroid bombardment (about $10^{-3}$ m yr$^{-1}$; Pokorný et al. 2020) as those from H Ly$\alpha$ radiation (about $7 \times 10^{-11}$ m yr$^{-1}$; Morgan & Shemansky 1991). This means that the surface water ice on Ceres should be primarily excavated by extrasolar radiation because the meteoroid energy flux is $\sim$25 times smaller on Ceres as compared to that on the Moon. Meanwhile, the meteoroid bombardment should dominate the shadowed surface water-ice excavation on Mercury due to an order-of-magnitude higher value of $E$ as compared to the effects of H Ly$\alpha$. The quantification of the surface water-ice loss through meteoroid impacts on Ceres is a complex process that involves the combination of impact vaporization (e.g., Equation (10) in Cintala 1992) and loss of ejecta produced in impacts. Since both of these effects depend linearly on the meteoroid mass flux, scale with some power of impact velocity, and depend on material characteristics, it is beyond the scope of this paper to obtain more concrete values. We can only conclude that the loss of surface water ice through meteoroid impacts on Ceres is an order of magnitude smaller compared to that on the Moon and 2–3 orders of magnitude smaller with respect to that on Mercury.

The area of craters produced by meteoroid bombardment $A$ shows that fresh deposits on the Hermean surface are covered by meteoroid-induced craters 74$\times$ faster than those on Ceres, whereas the lunar surface shows 12$\times$ faster rates. This means that while at Ceres, the mean surface e-folding time is $\bar{t}_A = 1.25$ Myr, the mean value for the Moon is 107 kyr and that for Mercury is 17.1 kyr. These values ignore the effect of secondary impactors, which might enhance the gardening rates on the surface (for the effect on the Moon, see Costello et al. 2018). As such, 95% of Mercury’s surface is covered by meteoroid-induced craters within three e-folding lifetimes, i.e.,

### Table 3 Comparison of Four Different Quantities

|   | $Q$ | $a_0$ | $b_0$ | $\sigma_0$ | $\mu_0$ | Max/Min | $R_{\text{Mercury}}$ | $R_{\text{Moon}}$ | $R_{\text{Ceres}}$ | $\mathcal{F}$ |
|---|-----|-------|-------|-------------|---------|---------|----------------------|------------------|------------------|---------------|
| Mercury | $M$ | $-9.70 \times 10^{-17}$ | $2.34 \times 10^{-15}$ | $21.94$ | $0$ | $4.1\%$ | $1$ | $5.45$ | $51.7$ | $G$ |
|   | $E$ | $8.39 \times 10^{-13}$ | $1.68 \times 10^{-12}$ | $40.05$ | $0$ | $41.7\%$ | $1$ | $17.9$ | $432$ | $G$ |
|   | $P^+$ | $9.32 \times 10^{-11}$ | $5.77 \times 10^{-11}$ | $33.23$ | $0$ | $154.2\%$ | $1$ | $23.4$ | $707$ | $G$ |
|   | $A$ | $-1.30 \times 10^{-15}$ | $2.91 \times 10^{-14}$ | $23.75$ | $0$ | $10.1\%$ | $1$ | $6.26$ | $74$ | $C$ |
| Moon | $M$ | $1.66 \times 10^{-16}$ | $2.84 \times 10^{-16}$ | $99.34$ | $0$ | $12.2\%$ | $0.184$ | $1$ | $9.48$ | $G$ |
|   | $E$ | $4.35 \times 10^{-14}$ | $9.43 \times 10^{-14}$ | $42.77$ | $0$ | $37.6\%$ | $0.0558$ | $1$ | $24.1$ | $G$ |
|   | $P^+$ | $3.18 \times 10^{-12}$ | $2.86 \times 10^{-12}$ | $32.6$ | $0$ | $107.5\%$ | $0.0428$ | $1$ | $30.2$ | $G$ |
|   | $A$ | $2.34 \times 10^{-16}$ | $4.52 \times 10^{-15}$ | $25.44$ | $34.64$ | $4.8\%$ | $0.16$ | $1$ | $11.8$ | $G_{\text{sym}}$ |
| Ceres | $M$ | $9.87 \times 10^{-10}$ | $4.42 \times 10^{-17}$ | $22.8$ | $37.41$ | $2.1\%$ | $0.0194$ | $1.015$ | $1$ | $G_{\text{sym}}$ |
|   | $E$ | $1.19 \times 10^{-15}$ | $4.36 \times 10^{-15}$ | $35.94$ | $1.765$ | $25.4\%$ | $0.00231$ | $0.0415$ | $1$ | $G$ |
|   | $P^+$ | $8.70 \times 10^{-14}$ | $9.87 \times 10^{-14}$ | $36.3$ | $1.781$ | $80.3\%$ | $0.00141$ | $0.0331$ | $1$ | $G$ |
|   | $A$ | $3.21 \times 10^{-17}$ | $3.80 \times 10^{-16}$ | $35.15$ | $1.781$ | $7.9\%$ | $0.0135$ | $0.0845$ | $1$ | $G$ |

Note. Rows 1, 5, and 9: meteoroid mass flux $M$; rows 2, 6, and 10: meteoroid energy flux $E$; rows 3, 7, and 11: ejecta mass production $P^+$; and rows 4, 8, and 12: meteoroid-induced crater cross section $A$ at Mercury, the Moon, and Ceres. Column (2) represents the selected quantity $Q$, columns (3)–(6) show the function fit parameters, column (7) shows the percent difference between the maximum and minimum values, and columns (8)–(10) show the ratios $R$ for all quantities in this table with respect to other airless bodies analyzed here. For instance, $R_{\text{Moon}} = 5.45$ in the first row indicates $M_{\text{Mercury}} / M_{\text{Moon}}$, the ratio between the average meteoroid mass flux on Mercury with respect to that on the Moon. Column (11) shows the function $\mathcal{F}$ used to fit the quantity. Quantities $M$, $E$, and $P^+$ are fitted using Gaussian distributions described in Equation (8), whereas $A$ is fitted using the cosine function described in Equation (10). Parameters $a_0$ and $b_0$ are in SI units, while $\sigma_0$ and $\mu_0$ are in degrees.
in 50 kyr. However, the crater depth resulting from meteoroid bombardment in the size range in our model is <1 mm according to laboratory experiments in Koschny & Grün (2001). One caveat of such an experiment is the absence of \( V_{\text{imp}} > 10 \text{ km s}^{-1} \) impacts that are dominating the impacts on the lunar and Hermean surfaces; thus, the penetration depths could significantly change with new laboratory experiments.

6. Discussion

6.1. Meteoroid Model

There are several uncertainties that stem from the meteoroid model. First, the meteoroid mass flux at Earth has an intrinsic uncertainty of about 50%–60% based on the latest estimates (Carrillo-Sánchez et al. 2016, 2020). This uncertainty linearly scales all quantities in this paper for all three airless bodies discussed here. Second, the collisional lifetimes used in our meteoroid model are also subject to uncertainty as discussed, for example, in Pokorný et al. (2018, 2019) for Mercury and the Moon, respectively. We analyze different values of the collisional lifetime multiplier \( F_{\text{coll}} \in [10, 50] \) to test the model sensitivity and compare it to the settings used in Pokorný et al. (2018, 2019). Due to Ceres’s proximity to the MBA and JFC source populations, the variations of the collisional lifetime have a negligible effect on the model results. The effect on the long-period comet meteoroids (HTCs and OCCs) is similar for Mercury, the Moon, and Ceres and does not significantly alter the results. Third, the SFDs of our model meteoroid populations are poorly constrained due to the fact that JFC meteoroids dominate the inner solar system budget, and the direct measurements of different components of the meteoroid complex are extremely rare (see, e.g., Section 2.4 in Pokorný et al. 2019). We ran our meteoroid model calculation using a range of mass indices \([3.4, 4.6]\) for each meteoroid population separately to test their sensitivity to different SFDs. Since our model is constrained by the meteoroid mass flux at Earth, the changes in the SFD produce <10% changes in the meteoroid mass flux \( M_t \), meteoroid energy flux \( E_t \), and ejecta production rate \( P^+ \) at Mercury and the Moon, similar to Pokorný et al. (2018, 2019). However, the SFD has a higher impact on Ceres, where we record an up to 46% higher mass flux for a shallower SFD, \( \alpha = -3.4 \), compared to our nominal model, \( \alpha = -4.0 \). On the other hand, steeper SFDs result in a smaller mass flux by up to 25% for \( \alpha = -4.6 \). The highest sensitivity to SFD stems from the main-belt meteoroids due to their extreme proximity to Ceres and their high intrinsic collision probability with Ceres without the need for any dynamical evolution.

Unlike \( M_t, E_t, \) and \( P^+ \), the area produced by meteoroid bombardment \( A \) and, consequently, the e-folding lifetime \( T_A \) do not scale linearly with the meteoroid mass; they scale as \( M^2/\delta^3 \). The meteoroid model we use here is scaled such that the mass flux at Earth is held constant (see Table 1). For this reason, \( A \) and \( T_A \) are more sensitive to the SFD setting than our other variables, which we see for all three airless bodies studied here. The values of \( A \) are approximately twice as large for \( \alpha = -4.6 \) compared to our nominal SFD \( \alpha = -4.0 \), while for the shallow SFD \( \alpha = -3.4 \), the values are twice as small compared to \( \alpha = -4.0 \). This means that for steeper SFDs, the smaller particles dominate the total impactor cross-section area, while this value is attenuated for shallower SFDs. This also impacts the e-folding lifetime \( T_A \), which is ~2\( \times \) shorter for a steeper SFD \( \alpha = -4.6 \) and ~2\( \times \) longer for a shallower SFD \( \alpha = -3.4 \) as compared to values for \( \alpha = -4.0 \). The intermediate values of the SFD indices fall between the two extremes presented here.

Our meteoroid model represents a range of meteoroids with diameters between 10 and 2000 \( \mu \text{m} \). Particles smaller than \( D = 10 \mu \text{m} \) exist in the solar system and add mostly to the number flux experienced by various bodies in the solar system. Their mass flux is small compared to our modeled sample due to their shallower SFD driven by the Poynting–Robertson drag (for the SFD at Earth, see Love & Brownlee 1993). Meteoroids with \( D < 1 \mu \text{m} \) are effectively blown out of the solar system via radiation pressure (Burns et al. 1979) and do not significantly contribute to the quantities analyzed here. By expanding our model to smaller sizes, the results in this paper would not change significantly, because our meteoroid model is scaled to provide a certain mass flux at Earth (Carrillo-Sánchez et al. 2016). The influence of meteoroids larger than those in our population, \( D > 2000 \mu \text{m} \), is more difficult to estimate. We expect meteoroids of \( D = 2000 \mu \text{m} \) to dynamically resemble larger meteoroids because the Poynting–Robertson drag magnitude decreases with increasing particle diameter. Consequently, increases the dynamical timescales of larger meteoroids, making their dynamical evolution similar to their parent bodies. Asteroidal impacts at Ceres are a focus of Marchi et al. (2016). We are not aware of any study that deals with impacts of comets at Ceres.

6.2. Scaling of Impact Processes

In Section 2.4, we establish that the crater-to-projectile cross-section ratio is \( F_{\text{cr}} = 63 \) using the Koschny & Grün (2001) experimental results. This experiment showed that the crater diameters were not correlated with impactor velocity; thus, the velocity part is missing in Equation (6). On the other hand, a literature overview of impact processes at larger sizes and impact velocities \(<8 \text{ km s}^{-1} \) shows that there is a strong correlation between the impactor velocity and crater size (Holsapple 1993).

In order to quantify the differences between our estimates for the crater area production rate and the scaling laws shown for larger and slower impactors than those we analyze in this paper, we use the cratering volume \( V_{\text{cr}} \) estimates from Table 1 in Holsapple (1993). We use the strength regime for our impact estimates because our impactors are smaller than 1 mm in radius. Assuming that all meteoroid-induced craters are spherical caps, we get for the volume of the crater

\[
V_{\text{cr}} = \frac{\pi}{6} h (3a^2 + h^2),
\]

where \( a \) is the crater radius, and \( h \) is the crater depth. Assuming a crater radius-to-depth ratio of \( \delta = a/h = 2.55 \), \( V_{\text{cr}} \), we get a simple form that allows us to estimate the crater radius \( a \):

\[
V_{\text{cr}} = \frac{\pi a}{6 \delta} \left[ 3a^2 + \frac{a^2}{\delta^2} \right] = a^3 \left[ \frac{\pi}{6 \delta^3} (3\delta^2 + 1) \right] = a^3 \mathcal{K} \rightarrow a = \left( \frac{V_{\text{cr}}}{\mathcal{K}} \right)^{1/3}, \mathcal{K}
\]

\[
= \left[ \frac{\pi}{6 \delta^3} (3\delta^2 + 1) \right].
\]

(12)
Holsapple (1993) provided a general relation for the crater volume and impactor characteristics,

\[ V_{cr} = C_1 m_{\text{met}} V_{\text{imp}}^3 = C_1 \frac{\pi}{6} d_{\text{met}}^3 \rho_{\text{met}} V_{\text{imp}}^3, \]

where \( C_1 \) is a material constant, \( m_{\text{met}} \) is the impactor/meteoroid mass, \( d_{\text{met}} \) is the impactor/meteoroid diameter, \( \rho_{\text{met}} \) is the impactor/meteoroid bulk density, and \( \epsilon \) is the velocity power index. Finally, the crater cross section \( A \) is

\[ A = \pi a^2 = \left( \frac{V_{cr}}{K} \right)^{2/3} = \frac{\pi d_{\text{met}}^2}{4} \left[ \frac{4\pi C_1}{3K \rho_{\text{met}}} \right]^{2/3} V_{\text{imp}}^{2/3}, \]

\[ = \frac{\pi d_{\text{met}}^2}{4} F_{\text{cr}}. \]  

For simplicity, we assume \( \rho_{\text{met}} = 2000 \, \text{kg m}^{-3} \), the value we use in all meteoroid models in this paper. From Equation (14), we see that \( F_{\text{cr}} \), the crater-to-impactor cross-section ratio, is a function of impact velocity. We recalculate the values of the meteoroid-induced crater cross section \( A \) for Mercury, the Moon, and Ceres that we show in Section 5 for two different surface compositions, dry soil and soft rock (Table 1 in Holsapple 1993), and summarize our results in Table 4.

The influence of the impact velocity is most important for Mercury, where the meteoroids that follow the Holsapple (1993) formulae are expected to produce, on average, a 23.49 times larger area of craters on soft rock and 10.35 times larger area on dry soil. Then, for the soft rock surface, we would expect that the mean surface e-folding time on Mercury is \( T_\Lambda = 730 \, \text{yr} \). Note that the formulae from Holsapple (1993) are not supported by experiments for the size and velocity regimes that we analyze in this paper. All three airless bodies that we analyze here are commonly bombarded by meteoroids with much higher impact velocities and smaller sizes than those used in laboratory experiments. Our original decision to use Koschny & Grün (2001) is based on the fact that this experiment is the closest in impactor size and speed to the meteoroids that we model.

Kato et al. (1995) presented the results of an experiment with \( 15 \times 10 \, \text{mm} \) cylinder impactors made of water ice, polycarbonate, aluminum, and basalt. They tested two types of targets, ice block and ground snow powder, with a maximum impact velocity of \( 1 \, \text{km s}^{-1} \). This experiment used an order-of-magnitude larger impactors than the largest meteoroid we model and velocities much lower than those we record in our model.

The Shrine et al. (2002) experiments showed that impact cratering of polycrystalline ice by \( 1 \, \text{mm} \) aluminum spheres depends heavily on impactor velocity/kinetic energy. Their maximum impact velocity was \( 7.34 \, \text{km s}^{-1} \). The entire sample consisted of 16 shots with velocities between 1.07 and \( 7.34 \, \text{km s}^{-1} \).

Sommer et al. (2013) showed a summary of previous laboratory experiments and added the impacts of iron meteorite and steel projectiles with velocities between 2.5 and \( 5.3 \, \text{km s}^{-1} \) onto dry and wet sandstone. None of the lab experiments except for Koschny & Grün (2001) recorded impact velocities larger than \( 7 \, \text{km s}^{-1} \) and particle diameters below 800 \( \mu \text{m} \). These three works show that the impact cratering regime that the meteoroids we model in this paper experience is very poorly constrained by laboratory experiments.

A possible solution to the lack of experimental records is extensive numerical modeling using state-of-the-art hydrocodes (Elbeshhauser et al. 2009; Kraus et al. 2011; Stickle et al. 2020). However, in this case, we are not aware of any work that analyzes the impacts and cratering of micron-sized meteoroids onto regolith or water ice.

### 6.3. Axial Tilt of Ceres

The effects of the axial tilt are negligible when assumed over time frames longer than one orbit. This is because the meteoroids impacting the surface of Ceres come from a broad range of ecliptic longitudes and latitudes, as opposed to the Sun, which is represented by a singular point on the celestial sphere. We test the effects of the axial tilt for the range of [0°, 20°], similar to the range of axial tilts shown in Ermakov et al. (2017), and record >5% differences between the extreme values of all quantities analyzed in this work.

### 7. Conclusions

We present the first model for micrometeoroid bombardment effects on the dwarf planet Ceres. Using a detailed shape model, an efficient ray-tracing code, and a widely accepted meteoroid population model for the diameter range of 0.01–2 mm, we estimate the effects of the meteoroid bombardment on the entire Cerean surface analyzed over one precession cycle (Section 3) and one current orbital period (Section 4). Finally, the effects of meteoroid bombardment experienced by Ceres are compared to those on Mercury and the Moon (Section 5).

We summarize the most important findings as follows.

1. There are no PSRs with respect to meteoroid bombardment. The local topography creates up to an 80% difference between occluded and exposed regions (floor versus rim).
2. The equatorial regions are producing, on average, 80% more ejecta than the polar regions, whereas the mass flux is more concentrated at the Cerean poles. However, the mass flux is almost uniform over the entire surface, with only 2% variations. The surface e-folding lifetimes are \( \sim 8\% \) shorter at the Cerean poles as compared to the equator.
3. All areas showing detections of exposed H\(_2\)O from Combe et al. (2019) and all areas of interest from Ermakov et al. (2017) experience similar rates of
4. Ceres currently experiences a factor of 3–7 seasonal variations in mass flux, energy flux, and ejecta production along its current orbit. This is due to its inclined orbit that takes the dwarf planet far from the invariable plane, i.e., away from the densest parts of the zodiacal cloud.

5. Ceres experiences an $\sim 10\times$ and $\sim 50\times$ smaller mass flux than the Moon and Mercury, respectively. The meteoroid energy flux and ejecta production rate differences are significantly enhanced by higher impact velocities on the Moon and Mercury resulting in $\sim 30\times$ and $\sim 600\times$ larger effects on the Moon and Mercury, respectively (Table 3). The same area on Mercury is covered by primarily meteoroid-induced craters 74 times faster than the equivalent area on Ceres, while the lunar surface is covered on timescales 12 times shorter than on Ceres.

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Software: GitHub repository (https://github.com/McFly007/AstroWorks/tree/master/Pokornyetal_2020_Ceres), gnuplot (http://www.gnuplot.info), tinyobjloader (https://github.com/tinyobjloader/tinyobjloader), fastbvh (https://github.com/brandonpelfrey/Fast-BVH), swift (Levison & Duncan 2013), SciPy (Virtanen et al. 2020).

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