

NUMERICAL MODEL OF FORMATION OF EJECTA FACULAE ON CERES

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ABSTRACT. On the dwarf planet Ceres, there are bright spots known as faculae. Four types of faculae are distinguished: (a) floor faculae, (b) faculae on Ahuna Mons, (c) rim/wall faculae found on craters' rims or walls, and (d) ejecta faculae in the form of bright ejecta blankets. Our investigation on the interaction of the hypothesized subsurface originated jet of gas and the granular material indicated that floor faculae (a) could be a result of separation of fine bright component of regolith. Here, we consider the hypothesis that the ejecta faculae (d) may be the result of separation of grains due to explosive gas expansion during the formation of the impact crater. We consider the axisymmetric gas motion above the surface of Ceres. We transform our system of equations into a dimensionless form. Our numerical model indicates that the separation effect is strong enough to separate the grains (according to size, density, and other aerodynamics properties). In some cases, separation gives a monotonic, systematic effect: smaller particles are ejected farther than heavier particles. Generally, however, the distance over which the particles will be thrown depends in a rather complicated way on the parameters of the particles and the parameters of motion of the gas. This property fits the faculae of type (d). Because we used the dimensionless form of the equations, our results can be also applied to other celestial bodies where the regolith contains volatile substances. This paper is an extension of our investigations on the origin of faculae (a).

Keywords: planetary systems, minor planets, asteroids, geomorphology of minor bodies

1. INTRODUCTION

Ceres is a dwarf planet between the orbits of Mars and Jupiter. It is a dark body with geometric albedo ~ 0.09 (Ciarnello et al., 2017). Ceres' radius is ~ 469 km, density is 2162 kg/m^3 , and surface gravity is 0.284 m/s^2 (Park et al. 2019, Hargitai and Kereszturi, 2015). It is a partially differentiated body. It has a mainly rocky part and the crust. The crust consists of rock, with less than 40% water ice, salts, and clathrates (Scully et al., 2020; Ermakov et al., 2017). Note that the possible liquid water in Ceres interior now or in the past has high importance for astrobiology (e.g., Domagal-Goldman et al., 2016).

There are many bright spots (known as faculae [singular facula]) on the surface of Ceres discovered in 2015. They are built from bright material. Albedo of faculae could be four times higher than the average albedo of Ceres (Hargitai and Kereszturi, 2015). According to Palomba et al. (2019), the faculae are almost randomly distributed on the dwarf planet (Figure 1). The faculae contain mainly NH_4 -chloride, Al-phyllsilicates, and Na-carbonate.



The dark area contains Mg-phyllosilicates, Mg-carbonate, and NH₄-phyllosilicates (Raponi et al., 2019). For the bright matter, the term “salt” is often used here, without specification its chemical composition.

On Ceres, there are four types of faculae: (a) floor faculae (they are on the floor inside of impact craters), (b) faculae on Ahuna Mons, (c) rim/wall faculae found on craters' rims or walls, and (d) ejecta faculae in the form of bright ejecta blankets. With the exception of case (b), faculae are (in some way) associated with impact craters (Stein et al., 2019). We consider here mainly the ejecta faculae type (d) – Figure 2. The thickness of faculae is probably in the range ~2–50 m (Scully et al., 2020).

The aim of the work is to present and discuss a hypothesis explaining the formation of faculae type (d) as a result of grain separation due to the interaction of regolith with gas streams expanding during the formation of impact craters.

2. SEGREGATION OF GRAINS AND ORIGIN OF THE FLOOR FACULAE

There is a hypothesis that floor faculae (type a) were formed by evaporation of water from brine or by sublimation of ice from frozen brine (Nathues et al., 2022; Schröder et al., 2021). According to this hypothesis, the release of H₂O to the surface would be the result of crumbling of the regolith and its heating during the meteorite impact. Floor faculae could be a direct result of this process (Thomas et al., 2018; Ruesch et al., 2016; Ruesch et al., 2019; Castillo et al., 2019).

However, this hypothesis has some drawbacks. It requires the recent (in geological terms) existence of substantial water reservoirs close to the surface on Ceres (e.g., compare the age of Ceres surface) (Neesemann et al., 2019; Bowling et al., 2019) or transferring large impact energy deep into the planet. The energy should melt some volume of brine (if necessary) and give rise to the mechanism (e.g., compressed gases) that transport the brine to the surface several Myr after the impact (e.g., in Occator crater).

Therefore, Czechowski (2023a, b), based on his experiments, proposed another hypothesis. It states that evaporation and/or sublimation of water have occurred on Ceres mainly before the formation of faculae. These processes took place in the regolith. After evaporation (or sublimation), grains of salt had been left dispersed in regolith. The concentration of salt on the surface (in the form of the present floor faculae) was the result of grain segregation occurring later by gas jets. This hypothesis has some advantages: it does not require substantial water reservoirs to exist several Myr after the impact. It only requires jets that can be a result of a fracture extending from the surface to a gas (e.g., CO₂) reservoir.

Of course, this hypothesis can be considered also as a complement to the hypotheses presented by Nathues et al. (2022), Schröder et al. (2021), Thomas et al. (2018), Ruesch et al. (2016), and Ruesch et al. (2019). It is possible that some floor facula arose as a direct result of evaporation on the surface, while others are the result of the mechanism proposed by Czechowski (2023a, b). Moreover, it is possible that both mechanisms may contribute when forming a given facula.

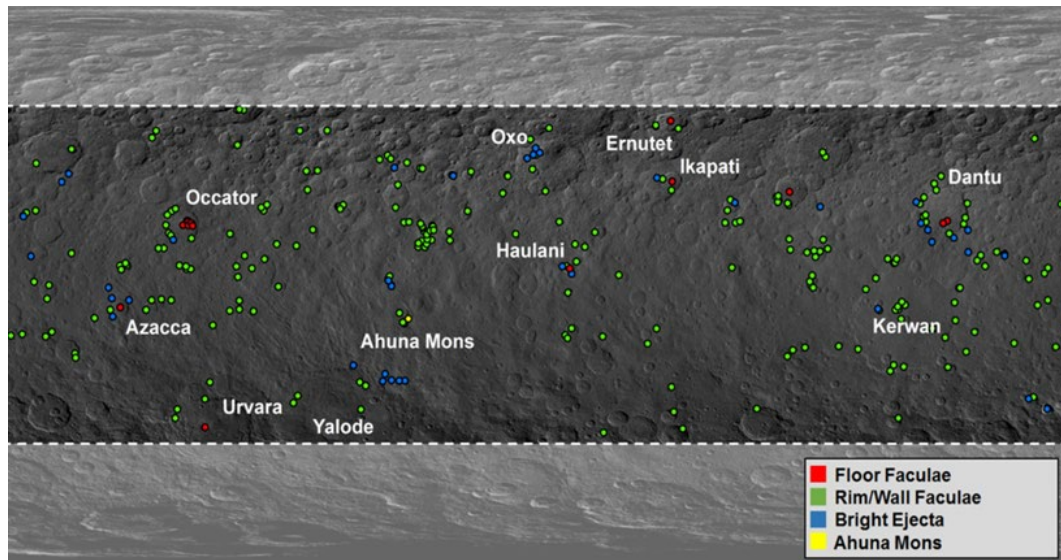


Figure 1. The locations of bright spots (faculae) on the dwarf planet Ceres. There are more than 300 faculae. The bright ejecta are blue in this map. PIA21914.jpg.
Image credit: NASA / JPL-Caltech / UCLA / MPS / DLR / IDA / PSI / Caltech.

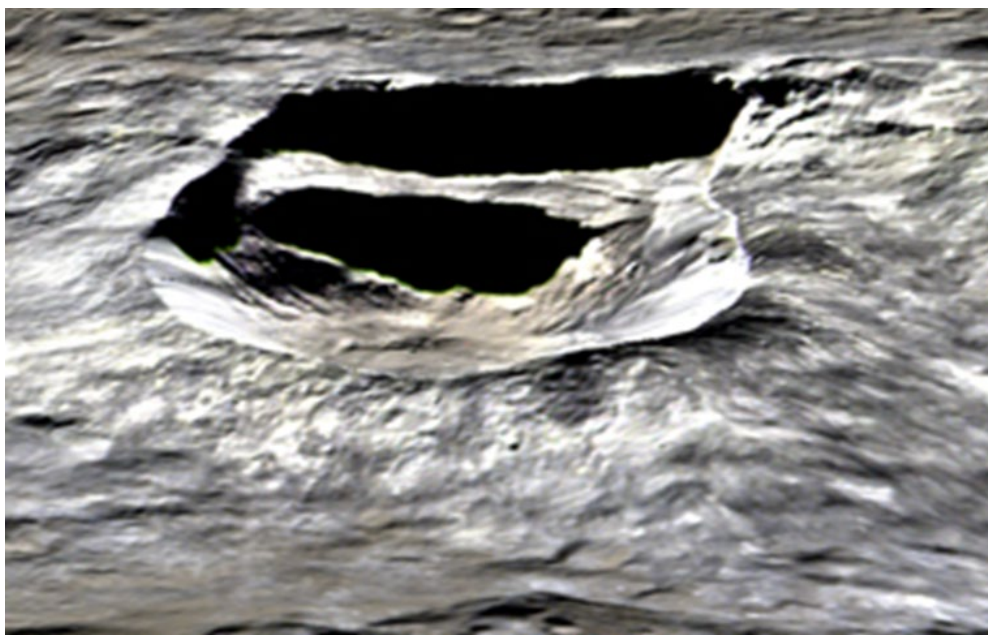


Figure 2. The small (~10 km) bright crater Oxo on Ceres in perspective view. The elevation has been exaggerated by a factor of 2. The resolution is ~35 m/px. Recorded by NASA's Dawn mission. Note the irregular distribution of bright matter on the surface. PIA20916.jpg.
Image credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

3. FORMATION OF EJECTA FACULAE

The origin of ejecta faculae of type (d) is the main subject of the present paper. According to some hypotheses, faculae (d) were formed as a result of meteoroid impacts (e.g., Stein et al., 2019), which exposed previously covered deposits of bright matter and ejected them outside the crater. However, this hypothesis has several drawbacks:

- 1) The initial bright deposits should have been covered before exposure. Ceres does not have typical mechanisms for covering sediments (e.g., covering by material brought by water or wind) known from Earth.

- 2) Therefore, another meteorite impact was proposed as a mechanism of covering. In some meteoroid impact, the ejecta may actually cover deposits of bright matter. However, the impact would also scatter bright matter. It is, therefore, difficult to accept the impacts as the typical mechanism responsible for the two opposing effects.
- 3) The existence of "covered deposits of bright matter" is only an unconfirmed hypothesis. Due to the large number of faults, some of these deposits should be visible on outcrops. Regolith layering would also be visible on the inside walls of impact craters.
- 4) If there are really concentrated deposits of bright matter in the regolith, the existence of ejecta faculae should correlate with the depth of the crater. The deeper the crater is, the greater the likelihood that a deposit of bright material was exposed. Therefore, the number of faculae (c) and (d) should increase with the depth of the host crater. However, Stein et al. (2019) indicate that the observed relationship is different: the existence of faculae is correlated not only with depth, but also with the ratio of depth to radius (crater).

Points (1–4) indicate that it is worth to discuss further hypothesis. We propose our mechanism subsequently. We suggest that initially, grains of salt had been dispersed in regolith (Section 2). However, during meteorite impact, volatiles from regolith evaporate and form intensive jets. These jets lead to segregation of grains and formation of deposits of bright matter.

Of course, contribution from the mechanism given in points 1–4 and from our mechanism is possible. In this sense, we propose an additional possible mechanism that may be responsible for the formation of some faculae of type (d) (on bodies with regolith containing significant amounts of volatile substances).

4. SEGREGATION DURING IMPACT

Our investigations mentioned in Section 2 concerning formation of floor faculae (type a) indicate intensive segregation of granular matter by means of a gas stream. However, they do not take into account the process during formation of impact craters. During the meteoroid impact, the gas stream is much more intense than during formation of faculae of type (a). Moreover, the geometry of impact gas streams is different. Therefore, we developed the numerical model here.

The formation of impact craters is developing in several phases. Melosh (2011) indicated the following phases: (1) contact and compression of the impactor and the surface of celestial body, (2) excavation (i.e., excavation flow), (3) early modification of the transient crater, and (4) later modification by erosion and accumulation in the long term. Vaporization of some matter may also take place. Even silicate might be vaporized, but the mass of such vapor is small due to the properties of the silicates (Gustavo et al., 2017; Bu et al., 2019).

The above scheme is based mainly on the study of impact craters on bodies with a low content of volatile substances. There are substantial differences for impact processes with a large amount of volatile substances (e.g., Hörz, 1982; Schenk et al., 2020; Sturm et al., 2013).

During impact on regolith containing significant amount of volatiles, the mass of the vaporized volatiles may be large (see also, e.g., Vickery, 1986; Silber et al., 2018). This gas expands in the space above the surface of the planet as well as in the fractured regolith. These gas streams may be agents of grain separation according to size, density, or shape.

The above considerations are confirmed by field studies. Three major facies are found in Ries Crater ejecta, indicating intensive processes of segregation (Hörz, 1982). Formation of facies (1) (of moldavite tektites) required drag forces in a rapidly ascending cloud of vaporized materials. The gravitational field alone does not give separation in the case of free motion of grains.

In the present work, we consider the model of interaction of gas with granular matter during the formation of an impact crater. We consider here only radially moving gas and grains' motion above the surface of the celestial body because this is the process that may be mainly responsible for forming ejecta blankets and faculae of type (d).

During this interaction, the grains could have been segregated according to weight, density, size, and shape. Because grains of bright matter are composed of a different substance than the rest of the regolith, they may be separated and may form faculae of type (d) (in the form of bright ejecta blankets).

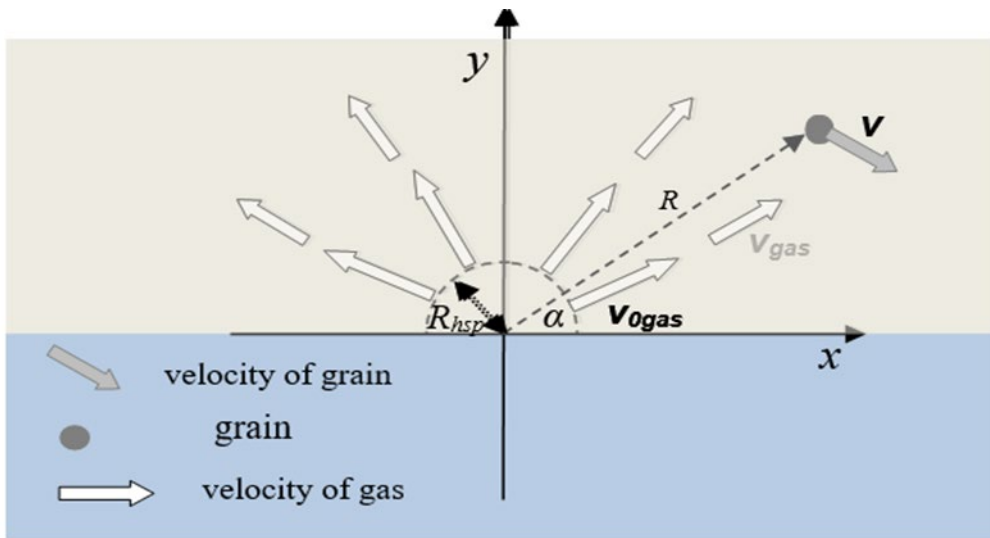


Figure 3. The sketch of the situation considered. Gas flows radially from point (0, 0). The y-axis is the axis of symmetry. At the hemisphere of radius R_{hsp} we assume the radial velocity of the gas to be v_{0gas} . The gas velocity decreases in proportion to $(R_{hsp}/R)^2$, where R is the distance from (0, 0). The gas interacts with the grain (dark dot). The acceleration of gravity is $\mathbf{g} = (0, -g)$.

5. MODEL OF SEGREGATION IN 2D FLOW GAS CASE

According to our hypothesis, the formation of ejecta faculae type (d) is the result of grains' separation during formation of the impact crater. Separation is the result of the interaction of gas streams on grains with different size, shape, density, etc. To describe this process, we use the numerical model described below.

Let us consider the process of interaction of grains and a 2D flow of gas. Axial symmetry of flow is assumed (y-axis is the axis of symmetry); therefore, the process could be considered only for $(x > 0)$ and $(y > 0)$ and $(x^2 + y^2 > R_{hsp}^2)$. We assume radial motion of the gas above the flat surface (in the upper half-space) (Figure 3).

We use the following formula for the drag force vector for a grain of characteristic size r moving with velocity $\mathbf{v}$ in a gas of density ρ_{gas} and velocity $\mathbf{v}_{gas}$:

$$\mathbf{F}_{drag} = -\frac{1}{2}C_D\rho_{gas}A|\mathbf{v} - \mathbf{v}_{gas}|(\mathbf{v} - \mathbf{v}_{gas}), \quad (1)$$

where cross-section area of the grain is $A = \pi r^2$ and drag coefficient is C_D . Its value depends mainly on the shape; for a perfect sphere, $C_D = 0.47$ and for a cube, it is larger. $|\mathbf{v} - \mathbf{v}_{gas}|$ denotes the absolute value of a vector $\mathbf{v} - \mathbf{v}_{gas}$. Eq. (1) is a 2D form of typical formula of drag force for large Reynolds number Re (e.g., for $Re > 10^2$) (e.g., Czechowski, 2014). Note that

$$Re = \rho_{gas} v s / \eta, \quad (2)$$

where η is dynamical viscosity [Pa s] and s is a size of grains [m] (e.g., Czechowski et al., 2023). For simplicity, we use the same formulas for mass m and cross section A of grains, as for spherical bodies. Of course, it is just an approximation. The equation of motion for a given grain (a test particle) is

$$m d\mathbf{v}/dt = \mathbf{F}_{drag} + m\mathbf{g}, \quad (3)$$

where the mass of grain $m = (4/3)\pi r^3 \rho_{grain}$ and $m\mathbf{g}$ is the gravity force. After substituting (1) into (3) and dividing by mass m , we obtain

$$d\mathbf{v}/dt = -D|\mathbf{v} - \mathbf{v}_{gas}|(\mathbf{v} - \mathbf{v}_{gas}) + \mathbf{g}, \quad (4)$$

where the coefficient D is

$$D = 3C_D \rho_{gas} / (8r \rho_{grain}). \quad (5)$$

We assume that gas flows radially from a hemisphere of radius R_{hsp} located on the surface of the planet (Figure 3). This is a simple model of gas outflow from the region of impact.

On this hemisphere, we assume the velocity of gas $\mathbf{v}_{0gas}$. Only the radial component of $\mathbf{v}_{0gas}$ is nonzero. Assuming the law of mass conservation, $\mathbf{v}_{gas}$ decreases proportionally to $(R_{hsp}/R)^2$, where R is the distance from the origin of coordinate system (0, 0).

Initial position and velocity of grain are given by $R_0, \alpha_0, \mathbf{v}_0$. The initial position is $x_0 = R_0 \cos \alpha_0, y_0 = R_0 \sin \alpha_0$. For initial velocity $\mathbf{v}_0$, we assume that $v_{0x} = v_{0y}$.

In equation (4), most of the parameters are included in coefficient D . The number of independent parameters is therefore smaller. The system contains the following parameters: $D, R_0, \alpha_0, \mathbf{v}_0, \mathbf{g}, R_{hsp}, \mathbf{v}_{0gas}$. Note that $\mathbf{v}_{0gas}$ and $\mathbf{v}_0$ give only two scalar parameters because only the radial component of $\mathbf{v}_{gas}$ is nonzero and we assume that $v_{0x} = v_{0y}$.

There are several independent parameters in our problem. Grain parameters are r [m], ρ_{grain} [kg/m³], drag coefficient C_D (Ciarnello et al., 2017), initial position of the grain (a test particle) R_0, α_0 and its velocity $\mathbf{v}_0$. The gas parameters are $\rho_{gas}, R_{hsp}, \mathbf{v}_{0gas}$. The planet parameter is gravity: $\mathbf{g} = (0, -g)$ [m/s²].

6. DIMENSIONLESS FORM OF EQUATIONS

The number of parameters can be further reduced by introducing the dimensionless form of equation (4) and dimensionless form of initial/boundary conditions. For this purpose, let us

introduce the following natural units (n.u.): of length $L = R_{hsp}$ and time $\tau = (L/g)^{1/2}$. The n.u. of velocity is $\varepsilon = (Lg)^{1/2}$. Using these units, equation (4) takes the form

$$d\mathbf{v}'/dt' = -C|\mathbf{v}' - \mathbf{v}'_{gas}|(\mathbf{v}' - \mathbf{v}'_{gas}) + \mathbf{1}, \quad (6)$$

where dimensionless parameter $C = DL$ and primes denote dimensionless quantities (time t' and velocity $\mathbf{v}'$). Dimensionless forms of parameters are

$$C = DL, \quad R'_0 = (R_0/R_{hsp}), \quad \alpha_0 = \alpha'_0, \quad \mathbf{v}'_0 = \mathbf{v}_0/\varepsilon, \\ g' = 1, \quad R'_{hsp} = 1, \quad \mathbf{v}'_{0gas} = \mathbf{v}_{0gas}/\varepsilon. \quad (7)$$

Note that now $g' = 1$ and $R'_{hsp} = 1$. We stay with only five parameters: $C, R'_0, \alpha_0, \mathbf{v}'_0$, and $\mathbf{v}'_{0gas}$. Let us remember that for the initial grain velocity $\mathbf{v}'_0$, we assume that $\mathbf{v}'_{0x} = \mathbf{v}'_{0y}$. Reducing the number of independent parameters makes it easier to consider a wide range of cases.

As one can see, the introduction of a dimensionless system of equations reduced the number of parameters. In our case, this is mainly the result of the appearance of parameter C , which includes several dimensional parameters. When transforming equations into dimensionless form, such parameters often appear (e.g., Qing-Ming, 2011). Some of them have their own names (e.g., Reynolds number, Rayleigh number, etc.). In hydrodynamics alone, one can find over 70 such dimensionless numbers, but there are actually many more in the literature. For example, a few additional Rayleigh numbers for thermal convection need to be defined (depending on the method of heating or the type of rheology) (Czechowski and Kossacki, 2012). Generally, the number and form of the resulting dimensionless numbers depend on the problem and the choice of n.u. by the scientist (see also, e.g., Czechowski and Kossacki, 2012; Gritsevich, 2009; Moilanen et al., 2021). For a given problem, one can generally select several sets of n.u. and obtain several forms of the system of dimensionless equations. This often depends on the needs of the individual researcher.

6.1. Ranges of dimensionless parameters

There are several independent parameters of our problem. We assume the following ranges of values for independent parameters (Table 1). The chosen values correspond generally to conditions on Ceres. Note, however, that their dimensional values are not critical to the issue. For example, the range of C_D values is chosen in Table 1 from 0.47 to 2. However, these values enter the equations only through the dimensionless number C . Therefore, by appropriately selecting the other parameters entering C (i.e., $\rho_{gas}, r, \rho_{grain}, R_{hsp}$), our results can be scaled (in many cases) to correspond to C_D values also outside the range given in Table 1. The place of landing is here denoted as x_{end} (if x is dimensional) or x'_{end} (for dimensionless x'). Note also that the grain velocity should be less than the orbital velocity on Ceres (365 m/s).

Table 1. Considered ranges of dimensional parameters of the system

	R_{hsp} [m]	v_{0gas} [m/s]	ρ_{gas} [kg/m ³]	C_D [1]	ρ_{grain} [kg/m ³]	r [m]	α_0 [deg]	v_{0grain} [m/s]	R_{init} [m]	g [m/s ²]
min	1000	100	0.01	0.47	500	0.0001	0	0	1000	0.284
max	10,000	1000	0.1	2	2000	0.01	90	1000	5000	0.284

Let us now estimate the possible values of the dimensionless parameters of our equations and the corresponding parameters of the boundary and initial conditions (see Tables 2 and 3).

Table 2. The ranges of values of natural units (n.u.) of length, time, and velocity expressed in SI units

	$L = R_{hsp}$ n.u. of length [m]	$\tau = (L/g)^{1/2}$ n.u. of time [s]	$\varepsilon = (Lg)^{1/2}$ n.u. of velocity [m/s]
min	1000	54.42	17.11
max	10,000	184.74	54.12

Table 3. The considered ranges of values of dimensionless parameters, corresponding to ranges presented in Table 1 expressed in n.u.

	C	R'_{hsp}	R'_{init}	v'_{0gas} Radial component	v'_0 $v'_{0x} = v'_{0y}$	$\alpha'_0 = \alpha_0$	g'
min	0.0881	1	1	1.84	0	0	1
max	15,000	1	5	58.4	58.4	90	1

Note that for homogeneously dispersed grains, the mass in the range $[\alpha, \alpha + d\alpha]dr$ depends on the angle α , since we are considering an axial symmetric case. So, the mass of grains in this range is proportional to $2\pi r \cos \alpha d\alpha dr$. This means that the total mass of particles ejected at large angles is much smaller than for particles ejected at smaller angles. However, for small α_0 (and for small initial grain velocities v_0), the grains fall close to the crater. Eventually, materials with intermediate angles α_0 (we choose here: 20° – 70°) are the most important for creating blankets of ejecta.

7. RESULTS AND CONCLUSIONS

7.1. Results and discussion

For the correct interpretation of the results, it should be remembered that large values of the dimensionless parameter C mean small, light grains, with a shape (e.g., a cube) that causes a high gas drag force and a dense gas, that is, for a large C , there is a strong interaction of gas flow and motion of the grains. Large C means also a small role of gravity. A small value of C corresponds to a weak gas interaction, that is, the gravitational force may be more important (or even dominant).

For the same grain density and similar shape, a large C means a small radius r of the grains. Note, however, that gas velocity decreases with distance; so, even for a large C , over long distances, the force of gravity can dominate.

The fast-moving gas can accelerate the grains (where velocity of the gas is high, e.g., close to $(0, 0)$), but the gas can also slow the grains down (where the velocity of gas is lower than the speed of grains, e.g., far from $(0, 0)$). Of course, we only consider cases where the grains fall back on the surface of the considered celestial body (here Ceres).

The distribution of grain parameters described above is often significantly different from each other, but in each case, it is possible to distinguish the dependence of the parameter C on the distance. This parameter is related to further parameters C_D , r , and ρ_{grain} . Determining them

from the orbit is difficult, but some correlations with thermal inertia could allow for some estimates.

Differences between the grain parameters and the gas movement parameters cause differences in the interaction between the gas and the grains, which ultimately leads to the separation of grains depending on the values of these parameters.

The effect of grain separation processes is the difference between the landing site (x'_{end}) of particles with different parameters. The simplest measure of separation is the difference between x'_{end} for different grains. We especially focus on the difference x'_{end} for particles with the same starting place and the same initial velocity (i.e., R'_0 , α_0 , v'_0), but differing in the value of the C parameter, which includes ρ_{gas} , r , ρ_{grain} , and R_{hsp} . In Figures 4–10, the trajectories of particles with the same R'_0 , α_0 , and v'_0 , but different C values start at the same points. We use a color code. According to the legend, increasing C values correspond to the following colors: red, magenta, green, black, cyan, and blue.

Figure 4 gives good examples of the separation. Let us note several features of the test particles' trajectories on this figure:

- 1) Dependence $x'_{end}(\alpha_0)$: For particles with small C (lines: red, magenta, green), $x'_{end}(\alpha_0)$ is a decreasing function, that is, for increasing angles, α_0 , x'_{end} decreases. However, for particles with large C (lines: black, cyan, blue), the function $x'_{end}(\alpha_0)$ is an increasing function (of course, in the examined angle range of $20^\circ < \alpha_0 < 70^\circ$).
- 2) The $x'_{end}(C)$ relationship is quite complicated. Particles with an intermediate C (green, $C = 1.024$) land the close ($11 < x'_{end} < 12$), and particles with a slightly higher C (i.e., black, $C = 8.192$) land a little further ($13 < x'_{end} < 16$). In the next range, we have an interesting situation because particles with $C = 0.128$ and particles with $C = 65.536$ land there (lines: magenta and cyan). This common range ends at $x'_{end} = 22$, while the range of particles with $C = 65.536$ extends up to $x'_{end} = 27$. In a wide range of $27 < x'_{end} < 49$, particles with the largest $C = 524.280$ (blue) fall. However, within this range, in the narrow range $42 < x'_{end} < 43$, the largest particles with $C = 0.016$ also fall, indicating complicated processes of separation.

The results shown in Figure 10 are significantly different from those shown in Figure 4. In this case, we can see that $x'_{end}(C)$ increases monotonically with C . That is, the heaviest particles (with the smallest C) land closest. In this way, moving away from the impact zone, we successively find zones covered with grains with increasingly larger C . In this case, the initial differences in the position of the test particle are less important than the C value. This is a situation where the decisive factors are the gas speed (it is moderate here) and the negligible initial grain speed (just 0). A similar situation is shown in Figures 8 and 9, but due to the higher gas velocity, the grain segregation is not as simple as in Figure 10.

Figures 5 and 6 clearly show the fate of the grains with the lowest C . These are the particles for which the interaction with the gas is relatively the weakest. Because they have a significant initial velocity and are only slightly slowed down, they ultimately fall much further than other particles.

Figure 7 shows the movement for a slightly different range of the C number. The new fraction with $C = 5482.88$ was introduced, that is, the fraction for which the interaction with the gas is the most important. Grains of this fraction are dispersed on a wide range for $x'_{end} > 31$.

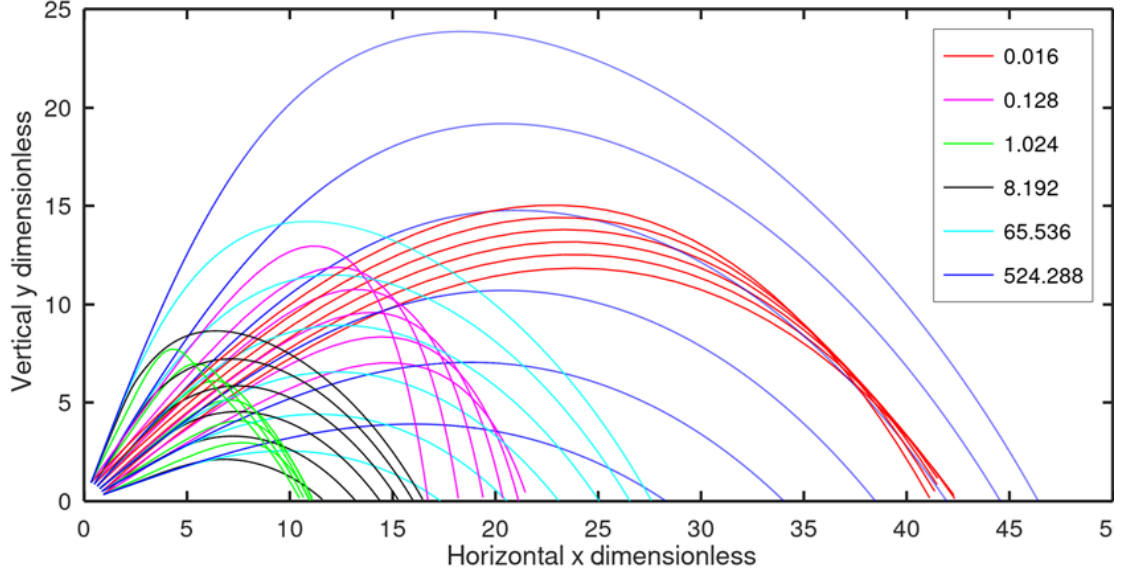


Figure 4. Trajectories of test particles (in n.u.) for C in the range 0.016–524 (see the line colors in the legend), $v'_{0gas} = 50$ (only the radial component), $\mathbf{v}'_0 = (5, 5)$, and $R'_0 = 1$. Parameters are in n.u.

The initial positions of the test particle are $x'_0 = \cos \alpha_0$ and $y'_0 = \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ$. Farthest from the point $(0, 0)$, in a wide range from $x' = \sim 30$ to ~ 50 , the particles with the largest C land (blue lines). This is the result of the strong influence of gas motion on this group of particles. Inside this region, a concentrated group of particles with the smallest $C = 0.016$ lands. In this group of particles, the effect of drag of gas is less important and the trajectories are mainly determined by the force of gravity. Particles from the other groups ($C = 0.128$ – 65.536) land in the region of $x' = \sim 10$ – 30 , creating rather complicated relationship between the x' of landing and the particle parameters.

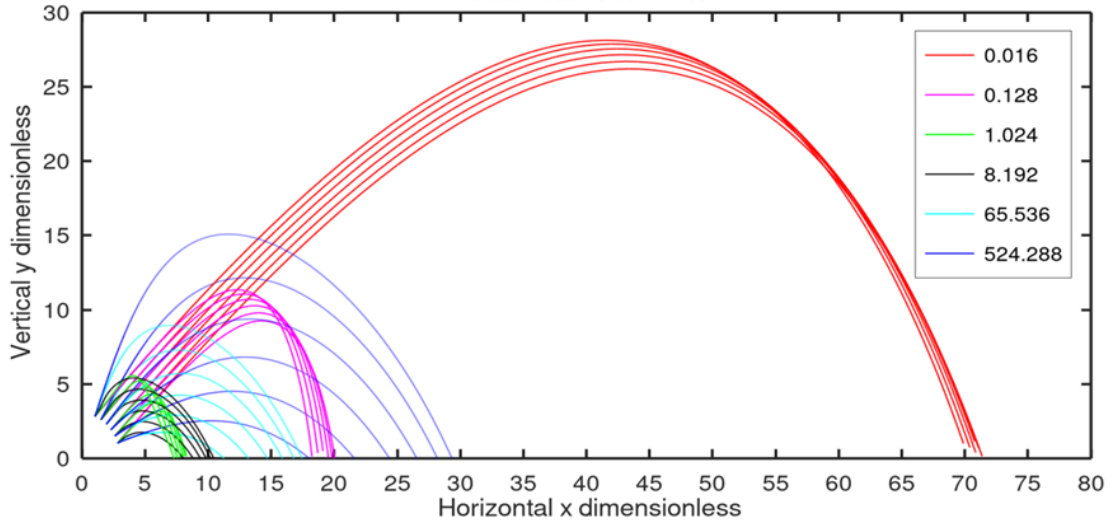


Figure 5. Trajectories of test particles for C in the range 0.016–524 (see the line colors in the legend), $v'_{0gas} = 20$ (only the radial component), $\mathbf{v}'_0 = (10, 10)$, and $R'_0 = 3$. The initial positions of the test particle are $x'_0 = 3 \cos \alpha_0$, $y'_0 = 3 \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, and 70° . Here, we observe a far ejection of particles for small $C = 0.016$ (red lines, $x'_{end} = \sim 70$). It is a result of high initial velocity $\mathbf{v}'_0$. The remaining groups fall near $x'_{end} = 7$ – 30 , creating a relatively complicated dependence on particle parameters, similar but not identical to Figure 4.

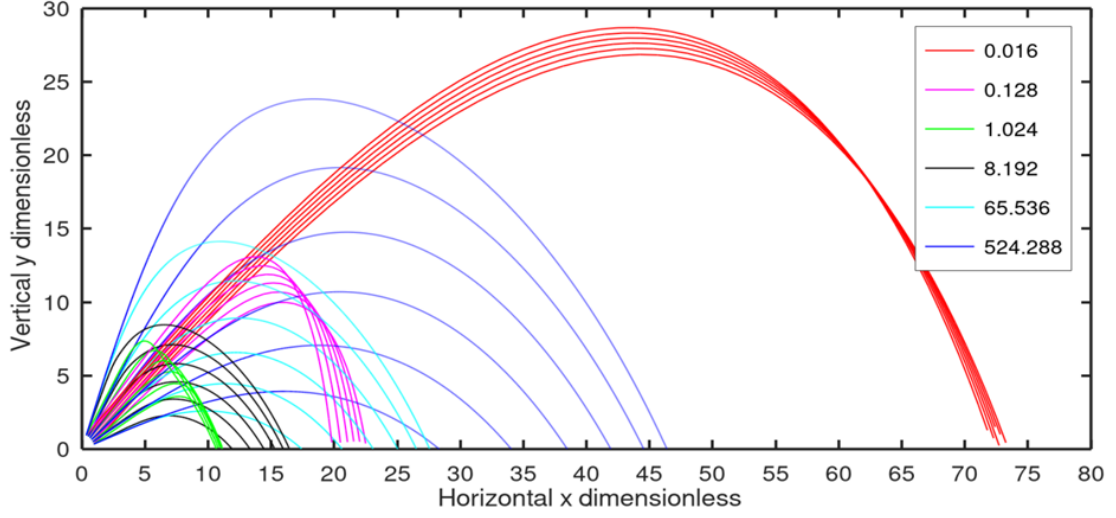


Figure 6. Trajectories of test particles for C in the range 0.016–524 (see the legend), $v'_{0gas} = 50$ (only the radial component), $\mathbf{v}'_0 = (10, 10)$, and $R'_0 = 1$. The initial positions of the test particle are $x'_0 = \cos \alpha_0$, $y'_0 = \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, and 70° . Here, we observe a far ejection of particles for small $C = 0.016$ (red lines, $x'_{end} = \sim 70$). These trajectories are almost identical to red trajectories in Figure 5. The remaining groups fall near $x'_{end} = \sim 10$ –40, creating a relatively complicated dependence on particle parameters, similar but not identical to Figures 4 and 5. The difference is a result of initial positions of the test particles.

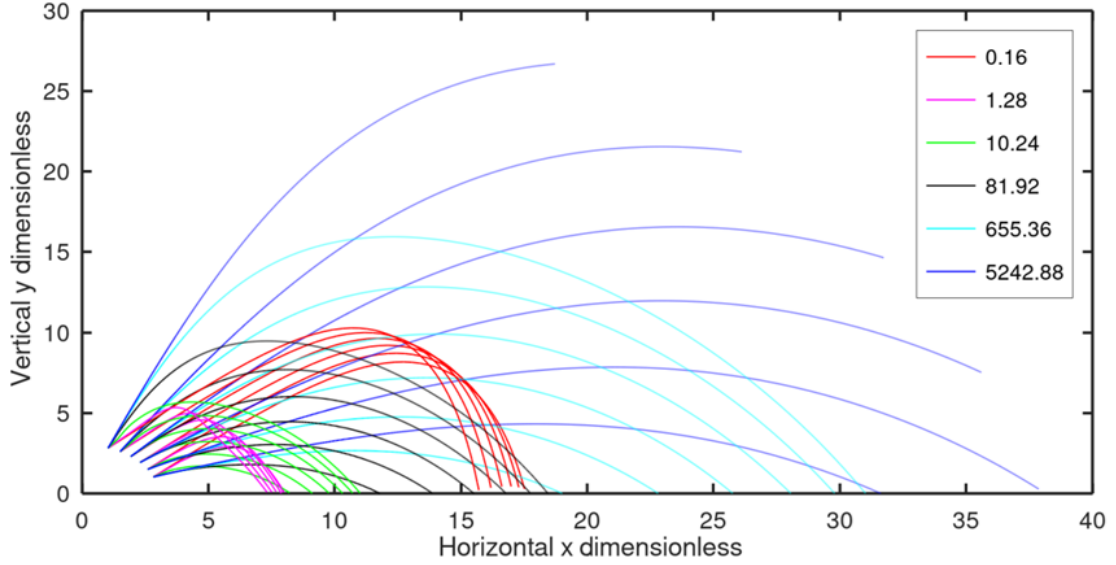


Figure 7. The parameters are similar to Figure 5, but the largest particles are excluded (with $C = 0.016$) and the smallest are added ($C = 5242$) – see the legend. The rest of the parameters are the same as in Figure 5: $v'_{0gas} = 20$, $\mathbf{v}'_0 = (10, 10)$, and $R'_0 = 3$. The initial positions of the test particle are $x'_0 = 3 \cos \alpha_0$, $y'_0 = 3 \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, and 70° .

The smallest particles (i.e. added particles with $C = 5242$) land at $x'_{end} > 30$.

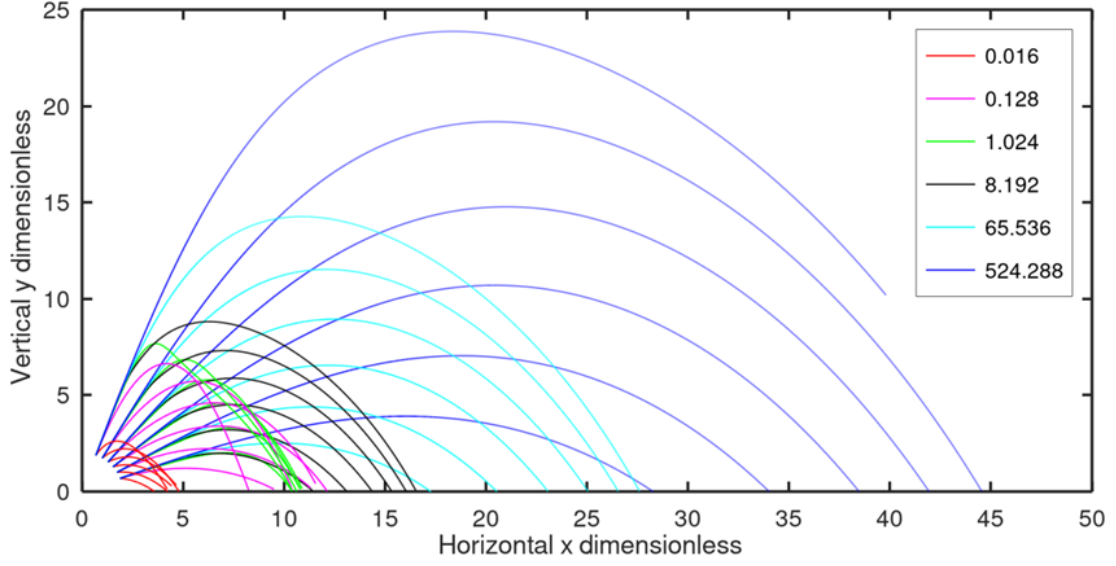


Figure 8. Trajectories of test particles for $C = 0.016-524$ (see the legend), $v'_{0gas} = 50$, $\mathbf{v}'_0 = (0, 0)$, and $R'_0 = 2$. The initial positions of the test particle are $x'_0 = 2 \cos \alpha_0$, $y'_0 = 2 \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, and 70° . Note zero initial velocity of the particles. Particles with $C = 0.128$ and 1.024 land close one to another. For other values of C , we observed that the smaller the C , the smaller the x'_{end} .

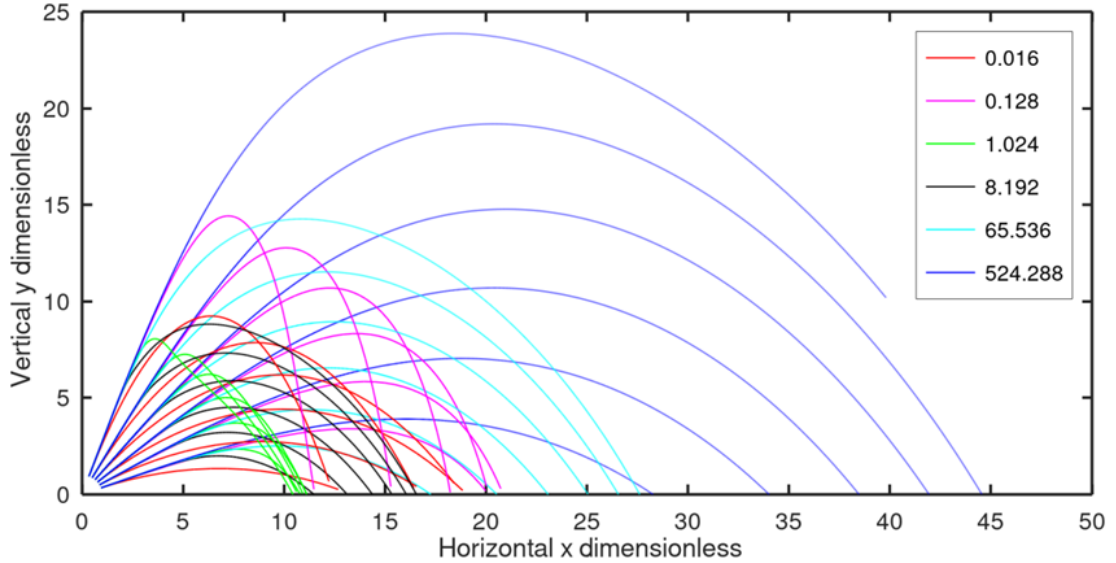


Figure 9. Another case with initial zero velocity of the test particles. However, the initial positions of these particles are closer to $(0, 0)$, so the initial acceleration is also higher than in Figure 8. Trajectories for test particles with $C = 0.016-524$ (see the legend), $v'_{0gas} = 50$, $\mathbf{v}'_0 = (0, 0)$, and $R'_0 = 1$.

The initial positions of the test particles are $x'_0 = \cos \alpha_0$, $y'_0 = \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ$. Particles with $C = 0.016 - 8.192$ land close one to another. Only for $C = 65.536$ and 524.288 , particles land further.

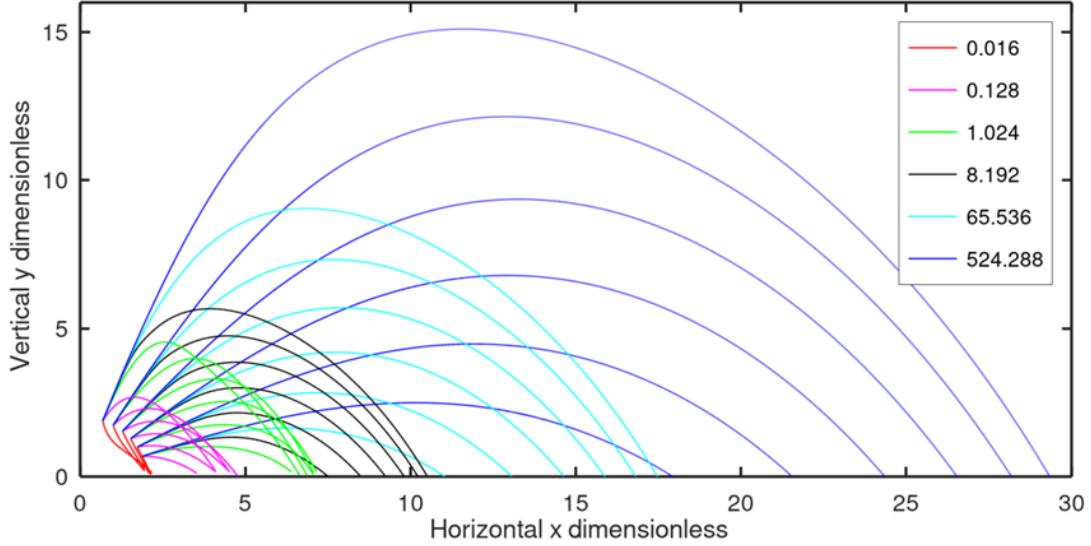


Figure 10. Next case with initial zero velocity of the test particles. Particles with a range of $C = 0.016$ –524 (see the legend), $v'_{0gas} = 20$, $\mathbf{v}'_0 = (0, 0)$, and $R'_0 = 2$. The initial positions of the test particles are $x'_0 = 2 \cos \alpha_0$, $y'_0 = 2 \sin \alpha_0$, where $\alpha_0 = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ$. The gas drag (lower than in Figure 9 because of lower gas velocity $v'_{0gas} = 20$ and $R'_0 = 2$) and gravity are the only accelerating forces. Note especially low acceleration of large particles (red lines). Their final velocity is low and landing points $x'_{end} = \sim 2$. Note that this is the only case where the distance of landing is monotonically increasing with parameter C .

7.2. Conclusions and future aspects

Based on the above results, we can formulate several more general conclusions:

- 1) In the tested range of parameters, we see a strong separation of grains, both depending on the parameters of the grains themselves and the gas movement parameters.
- 2) In one case reported here, the function $x'_{end}(C)$ increases monotonically with the value of C (Figure 10).
- 3) Most often (in our numerical models), however, we observe situations where the relationship $x'_{end}(C, \alpha_0)$ is more complicated. In Figure 4, the fractions with the largest and smallest C fall together far away, while the remaining fractions fall close together, so that their places of fall overlap. In Figures 5 and 6, there is a strong separation of the $C = 0.016$ fraction, which fell very far.

We obtained the above results for quite a simple model with a simple gas velocity field. Of course, for a more complicated model, the results may show an even more complicated separation picture. Also note that our hypotheses and those of other authors (see Section 3) are not mutually exclusive. It is possible that the processes proposed in both hypotheses are involved in the formation of faculae.

In further research, we will focus on the faculae models of type (c), that is, rim/wall faculae found on craters' rims or walls. In this case, the expansion of gas occurs below the planet's surface. Of course, it requires a different system of equations of motion of gas and fine fraction of regolith. Moreover, we must consider the possibility of large-scale mass motion in Ceres's interior (e.g., convection) (Czechowski, 2014; Turcotte and Schubert, 2002).

7.3. Application to other celestial bodies

Thanks to the use of dimensionless forms of equations and boundary conditions, our results can also be applied to other celestial bodies where volatiles in regolith and a rare atmosphere (or lack thereof) can be expected. For example, these are Mars, medium-sized satellites of Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Iapetus), similar satellites of Uranus, etc.

The ranges of parameter values in Table 1 should be adjusted to the situation on a given celestial body. For ice-rock bodies, some of these ranges may be similar. The main parameter requiring change will probably be the gravitational acceleration g . For the mentioned celestial bodies, we have different values of gravity on the surface (from 0.064 m/s² on Mimas to 3.72 m/s² on Mars). However, the values of dimensionless gravity are the same (equal to $g = 1$ n.u.; Table 2). If the values of the remaining parameters could be chosen to be the same as in the case of Ceres, then the dimensionless solutions given in Figures 4–10 can be used.

Of course, to obtain values in SI units, dimensionless results should be multiplied by the values of n.u. If the unit of length L is the same, then the units of time and velocity will depend on the acceleration due to gravity g (Table 2). In the case of Enceladus, gravity is about 0.22 times smaller than on Ceres; so, if the unit of length L remains unchanged, the natural unit of time will be about 2.1 times larger and the unit of velocity will be about 2.1 times smaller according to the formulas in Table 2: ($\tau = (L/g)^{1/2}$ and $\varepsilon = (Lg)^{1/2}$). It means that the trajectory of test particle with velocity 100 m/s on Enceladus corresponds to the trajectory of test particle with velocity 210 m/s on Ceres.

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