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Compaction, cratering and collision frequency on chondritic parent objects

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Resumen / Calculamos el grado de compactación de un asteroide de 100 km de radio debido a un impacto con un asteroide pequeño para velocidades de impacto entre 3 y 5 km s^{-1}. Calculamos el radio del cráter producto del impacto. Obtenemos además el número de impactos sobre el asteroide de 100 km de radio con toda la distribución de asteroides pequeños durante la edad del Sistema Solar.

Abstract / We calculate the compaction of an asteroid with radius 100 km due to an impact with a small asteroid for impact velocities between 3 and 5 km s^{-1}. The crater formed on the target surface as a result of such an impact is calculated. The number of impacts on the target with the distribution of small asteroids during the age of the Solar System is computed.

Keywords / meteorites, meteors, meteoroids — minor planets, asteroids: general — interplanetary medium

1. Introduction

Among meteorites, chondrites represent the ~ 86 % of the falls, ~ 80 % of these being the so-called ordinary chondrites (OCs), while carbonaceous chondrites (CCs) account for the ~ 6 % of meteorite falls. Based on spectrographic studies, the best match for asteroidal analogs of OCs are S-type and M-type asteroids while for CCs are C-type and D-type asteroids.

The consolidation of pre-chondrites can be achieved during the collisional evolution of their parent bodies (targets) in the Asteroid Belt (AB). The successive impacts onto the targets over the age of the Solar System may be computed by using the collision frequency of the impactors, which can be derived from the number-frequency distribution of asteroids in the present AB. The present mean collision speed among bodies in the AB is $\sim$ 3.3–5 km s^{-1} and the timescales between collisions is of the order of a few Myr (de Elía & Brunini, 2007). In such a hyper-velocity collision, the smaller collision partner (projectile) is destroyed, whereas, a crater on the larger body (target) is formed and the material beneath the crater is compacted.

The present flux of meteorites might be explained from the dynamics of objects emerging from the AB via resonant phenomena (Morbidelli & Gladman, 1998). The collisional activity in the AB and the Yarkovsky thermal drag injects fresh collisional debris into the ν_6 3:1, 2:1, and 5 :2 resonances, which stay there for a few Myr, a fraction of it to be then transferred to the Earth and being released as meteorites. The typical cosmic ray exposer age (CREA), of a few 10 Myrs for OCs, determines the time since they became ejecta from the last collision on their parent body and reach the Earth. Thus, meteorites are fragments from recent collisions in the AB.

In this work, we compute the cratering and compaction of a target of radius 100 km due to an impact with a projectile with radius r between 0.1 m and 35 m. We also compute the number of collisions on the target during the age of the Solar System with the impactors in the AB that are not rapidly removed by Yarkovsky effect ($r > 0.1$ m) and that do not lead to a catastrophic disruption of the target ($r < 35$ m).

In Sec. 2.1., we show the compaction of an asteroid of 100 km due to an impact with a projectile of radius r. The crater formed on the target surface as a result of such an impact is calculated in Sec. 2.2.. The number of impacts on the target with the distribution of impactors in the AB during the age of the Solar System is computed in Sec. 2.3.. The discussion and conclusions are presented in Sec. 3..

2. Chondritic parent asteroids

2.1. Collisional compaction

Porosity (the percentage of pore space within the object) is a particular useful physical property, as it depends solely on the structure and not on the mineral composition of the meteorite. The structure is determined first by the formation mechanism of the rock, while the rock is compacted and consolidated by subsequent collisions. The volume filling factor ϕ (defined as 1-porosity) for CCs cover a range between $\phi = 0.58$ and $\phi = 1$ with a mean value of $\phi = 0.8$, while for OCs the range is between $\phi = 0.85$ and $\phi = 1$.

Beitz et al. (2013) studied the compaction of chondritic analog material in high-velocity impact experi-

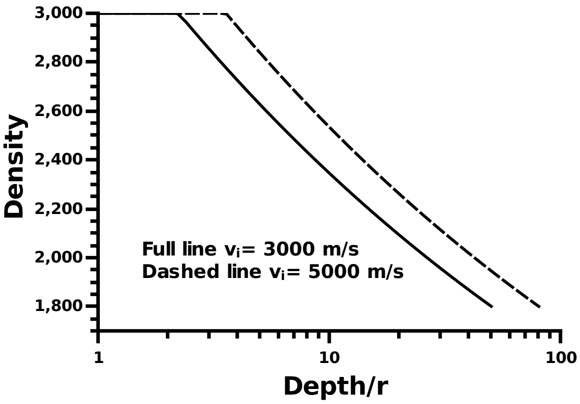

Figure 1: Target density (in kg m^{-3}) after an impact with a projectile with radius r vs. target depth from its surface in units of the projectile radius. $v_{\rm i}$ is the impact speed. The target radius is 100 km and its initial $\phi = 0.6$. The initial target density equals the projectile density, 1800 kg m^{-3}.

ments and determined the dynamic-pressure range under which these can be compacted to achieve porosities found in chondrites. The projectiles were aluminium rods with varying lengths. After the impact, the compacted target was analyzed using computer-aided X-ray tomography. The degree of compaction was analyzed as a function of depth and they found the highest consolidation close to the point of impact. To calculate the impact pressure, the impedance-matching method was adopted. In the experiments, they found that the degree of compaction decreases with increasing depth within the sample and that it is a function of the length of the projectile. We follow Beitz et al. (2013) to obtain a relation between dynamic-pressure range and impact velocity. We compute the compaction of a target of constant density $\rho_{\rm t}= \rho\phi$, where $\rho = 3000$ kg m^{-3} is the chondritic density. The target radius is 100 km and its initial $\phi = 0.6$. The compaction resulting from an impact with a projectile of radius r at the typical impact speeds $v_{\rm i}$ of 3 to 5 km s^{-1} (de Elía & Brunini, 2007) is shown in Fig. 1.

2.2. Crater radius calculation

The cratering law is calculated following the classical scaling of impact processes in planetary sciences developed by Holsapple (1993). The temporary cavity produced at impact is called the transient crater, which subsequently collapses under the influence of gravity to produce the final crater form. There are two radii in a transient crater that can be identified, $R_{\rm tr}$ and $R_{\rm tc}$. $D_{\rm tr} = 2R_{\rm tr}$ is the diameter of the transient crater measured from rim crest to rim crest, while $D_{\rm tc} = 2R_{\rm tc}$ is the diameter of the transient crater measured at the pre-impact surface. It was found that $D_{\rm tr} = 1.3D_{\rm tc}$. (Collins et al., 2005). The diameter of the transient crater decreases with increasing obliquity. Then, taking into account the impact obliquity θ, the radius of the transient crater in the gravitational regime, $R_{\rm tcg}$, is given by

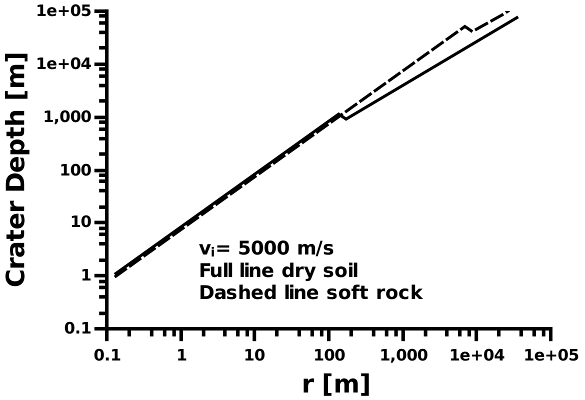

Figure 2: Crater depth $h_{\rm c}$ vs. impactor radius for an impact speed of 5 km s^{-1} for dry soil and soft rock.

$$R_{\rm tcg} = g^{-\frac{\mu}{\mu+2}} v_{\rm i}^{\frac{2\mu}{2+\mu}} r^{\frac{2}{2+\mu}} (\sin\theta)^{\frac{1}{3}}, \tag{1}$$

where g is the target surface gravity, $v_{\rm i}$ is the impact velocity, r the impactor radius, and μ a fitting parameter. In the strength regime the radius of the transient crater, $R_{\rm tcs}$, is

$$R_{\rm tcs} = \left(\frac{\bar{Y}}{\rho_{\rm t} v_{\rm i}^2}\right)^{-\frac{\mu}{2}} r(\sin\theta)^{\frac{1}{3}}, \tag{2}$$

being $\rho_{\rm t}$ the target density and $\bar{Y}$ the effective material strength. The values of μ and $\bar{Y}$ depend on the material properties. We take the mean value of $\sin\theta$, then $\langle\sin\theta\rangle^{1/3} = (\pi/4)^{1/3}$. For dry soil, we take $\mu = 0.41$ and $\bar{Y} = 0.18$ MPa and for soft rock, $\mu = 0.5641$ and $\bar{Y} = 7.6$ MPa (Holsapple, 1993).

The depth $d_{\rm tc}$ and rim height $h_{\rm tr}$ of the transient crater measured from the pre-impact surface are $d_{\rm tc} = R_{\rm tc}/\sqrt{2}$ and $h_{\rm tr} = 0.07R_{\rm tr}$ (Collins et al., 2005).

For impactors in the strength regime, we asume that the final crater radius $r_{\rm c}$ is $R_{\rm tcs}$ given by Eq. (2) and the crater depth $h_{\rm c} = d_{\rm tc}$, i.e., $h_{\rm c} = R_{\rm tcs}/\sqrt{2}$.

In the gravitational regime, the rim to rim diameter of the final simple crater $D_{\rm fr}$=1.25 $D_{\rm tc}$. For impactors in this regime, we then asume that the final crater radius $r_{\rm c} = 1.25R_{\rm tcg}$, with $R_{\rm tcg}$ given by Eq. (1). The rim height $h_{\rm fr}$ above the pre-impact surface is given by

$$h_{\rm fr} = 0.07\frac{D_{\rm tc}^4}{D_{\rm fr}^3}, \tag{3}$$

and the unbulked breccia lens volume $V_{\rm br}$

$$V_{\rm br} = 0.032D_{\rm fr}^3. \tag{4}$$

Then, the breccia lens thickness $t_{\rm br}$ may be expressed in the following form (Collins et al., 2005)

$$t_{\rm br} = 2.8V_{\rm br}\left(\frac{d_{\rm tc} + h_{\rm fr}}{d_{\rm tc}D_{\rm fr}^2}\right). \tag{5}$$

For impactors in the gravity regime, we asume that the final crater depth $h_{\rm c} = d_{\rm fr} - h_{\rm fr}$, where the crater depth $d_{\rm fr}$ is measured from the crater floor (above the breccia lens) to the rim crest $d_{\rm fr} = d_{\rm tc} + h_{\rm fr} - t_{\rm br}$. In Figs. 2 and 3, we show the final crater depth as function of the impactor radius.

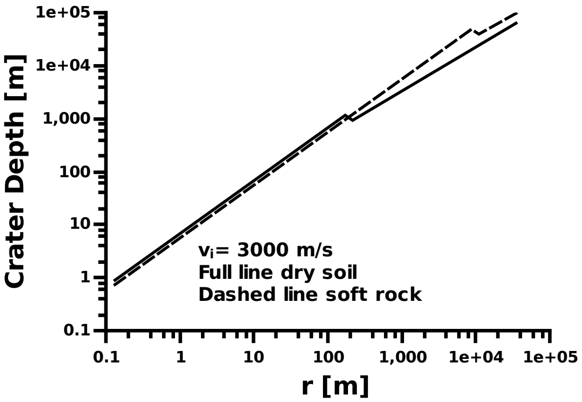

Figure 3: Crater depth h_c vs. impactor radius for an impact speed of 3 km s^{-1} for dry soil and soft rock.

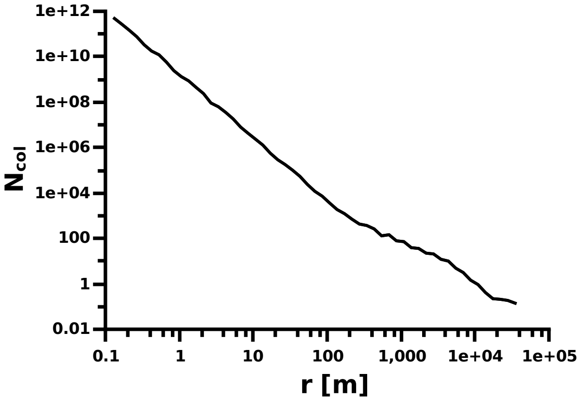

Figure 4: Number of impacts on a large asteroid of radius 100 km over the age of the Solar System vs. impactor radius.

2.3. Collisional evolution

We study the collision frequency on an asteroid of radius $R = 100$ km during the age of the solar system. The collision frequency of the impactors is derived from the number-frequency distribution of asteroids in the present AB given by de Elía & Brunini (2007). They found that the asteroid main belt population acquires its present structure during the first 5 Myr of evolution. Then, we take the present distribution of small asteroids obtained by de Elía & Brunini (2007) to compute the number of small objects impacting a target of radius 100 km during the age of the Solar System. Only impactors are considered that do not lead to a catastrophic disruption of the target (Parisi, 2013).

The projectiles in the size range $0.13264 \text{ m} \leq r \leq 34\,889$ m are distributed in 55 logarithmically equidistant size bins following $r_{i+1} = 1.26\, r_i$ for $i = 1, \ldots, 54$ (de Elía & Brunini, 2007). The total number of asteroids $N(r_i, r_{i+1})$ in each bin of impactor radius $[r_i, r_{i+1}]$ in the main belt extending from 2 au (approximate location of the ν_6 secular resonance) to 3.27 au (location of the 2 : 1 mean motion resonance), is given by de Elía & Brunini (2007). We compute the number of impacts on a target of radius $R = 100$ km per unit time

$$\frac{\mathrm{d}N_{\mathrm{p}}(r_i, r_{i+1})}{\mathrm{d}t} = \frac{N(r_i, r_{i+1}) \pi R^2 v_{\mathrm{i}}}{V}, \tag{6}$$

where v_{i} is the impact speed and the unit volume V is given by

$$V = 4\pi a_0 \Delta a_0 H, \tag{7}$$

where Δa_0 is the half width of the belt ($\Delta a_0 = 0.635$ au) and a_0 is the mean semiaxis of the AB ($a_0 = 2.635$ au). The height of the AB, $H = a_0 i$, where $i = v_{\mathrm{i}}/(\sqrt{5} v_{\mathrm{K}})$ is the mean orbital inclination of the asteroids and v_{K} the Keplerian speed (Parisi, 2013). Note that replacing Eq.(7) in Eq.(6), it results independent of v_{i}.

The total number of impacts in each impactor bin size over the age of the Solar System is then computed as (Fig. 4)

$$N_{\mathrm{col}}(r_i, r_{i+1}) = \frac{\mathrm{d}N_{\mathrm{p}}(r_i, r_{i+1})}{\mathrm{d}t} 4.5\,\mathrm{Gyr}. \tag{8}$$

3. Discussion and conclusions

We calculated the compaction of an asteroid of radius 100 km due to an impact with a projectile of radius in the range 0.1 m to 35 m. The resulting crater formed on the target surface was computed. We studied the frequency of these collisions during the age of the Solar System. The consolidation of pre-chondrites can be achieved during the collisional evolution of their parent bodies (large asteroids) until they are finally released as meteorites from the asteroid belt. The typical cosmic ray exposer age of a few 10 Myr determines the time since they became ejecta from the last collision on their parent object and reach the Earth. Thus, meteorites are fragments form recent collisions in the asteroid belt. The prediction of the porosity distribution of present large asteroids that might serve as parent bodies for meteorites may be obtained from the calculation of the compaction and cratering on the target from all the impacts over the age of the Solar System, which will be presented in a forthcoming paper (Beitz et al., 2016, ApJ, accepted).

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