EPSC
European Planetary Science Congress

Interior responses to impacts by different impactor types

T. Ruedas (1,2), D. Breuer (2)
(1) Institute for Planetology, University of Münster, Germany, (2) Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany (t.ruedas@uni-muenster.de)

Abstract

We use scaling laws for impacts to estimate the differences in the effects on the interior of a planet that impactors with different parameters and properties have even if they produce impact craters with the same diameter at the surface. The long-term effects of such "isocrater" impacts on planetary evolution are then also studied with numerical models of mantle convection for different bodies, but especially for Mars. The results support the notion that the vast majority of large impacts was caused by asteroids rather than other bodies such as large comets.

1. Introduction

A number of numerical mantle convection studies from the past two decades have investigated the effects of very large meteorite impacts on mantle dynamics in terrestrial planets, especially Mars (e.g., [1, 2]). On the grounds that most observed craters seem to have been produced by collisionally evolved bodies, probably main-belt asteroids (e.g., [3, 4], the impactors were generally assumed to be rocky and have material parameters similar to those of the target. However, the statistical analysis does not imply that all craters derive from an S-type asteroid, as there is a significant fraction of impactors whose properties differ substantially from those of the target, and the dynamical effects in the interior may be quite different even if the final crater is similar; candidate alternative impactors include C-type asteroids and comets. It is generally not possible to deduce the nature of the impactor from the final crater, because the remnants of the impactor are rarely preserved.

2. Theory

The final crater results from the collapse of the transient crater, and their diameters D_f and D_{tr} are related by empirical scaling relations. The relation between D_{tr} and the characteristics of the impactor is derived by dimensional analysis. Combining both yields

$$D_f = 1.3836 \left(\frac{\varrho_{imp}}{\varrho} \right)^{0.377} \frac{D_{imp}^{0.88} \, v_{imp}^{0.497}}{D_{s2c}^{0.13} \, g^{0.249}} \quad (1)$$

for complex craters, where D_{imp} is the diameter of the impactor, ϱ and ϱ_{imp} the densities of the target and the impactor, v_{imp} is the velocity of the impactor (or rather its vertical component), D_{s2c} is the simple-to-complex transition diameter, and g is gravity (e.g., [5]); the numerical values of the coefficient and exponents vary with certain target properties and are chosen here to correspond to a frictionless, pore-free material. In this equation, ϱ_{imp} and v_{imp} are not known for a given crater and may vary widely between different impactor types. Hence the condition for two impactors 1 and 2 to produce a final crater of the same diameter on the same target is given by $D_{f1} = D_{f2}$:

$$\frac{D_{imp1}}{D_{imp2}} = \left(\frac{\varrho_{imp1}}{\varrho_{imp2}} \right)^{-0.43} \left(\frac{v_{imp1}}{v_{imp2}} \right)^{-0.56} = \delta_{12}, \quad (2)$$

for both simple and complex craters; this defines a set of isocrater impacts. Figure 1 shows the ratio of impactor diameters, δ_{12}, for isocrater impacts, whereby impactor 2 is chosen as a common reference impactor, namely an S-type asteroid. The isolines thus show how strongly the size of impactor 1 must differ from that reference in order to produce a crater of the same size, for any combination of density and velocity, which are also normalized to the reference.

For the dynamics of the interior, it is the subsurface features of an impact rather than the crater that are of primary interest, but their geometry and properties are more difficult to study and less well described in terms of an analytical model. In the literature (e.g., [6]), the depth of penetration is often found to be proportional to the square or cube root of the density ratio ϱ_{imp}/ϱ, and the impact velocity is taken to a power between 1/3 and 2/3. We combine the square-root relation for the density with the widely used formula by [7] for the depth to the center of the isobaric core of the shocked volume into the relation

$z_{ic} = a_z D_{imp} v_{imp}^{b_z} \sqrt{\varrho_{imp}/\varrho}$; future numerical impact simulations should test whether empirical fits yield an exponent of the density ratio that is significantly different from 0.5. The ratio of the depths of the isobaric cores for two isocrater impacts then follows by combination with eq. 2:

$$\frac{z_{ic1}}{z_{ic2}} = \left(\frac{\varrho_{imp1}}{\varrho_{imp2}}\right)^{0.07} \left(\frac{v_{imp1}}{v_{imp2}}\right)^{b_z - 0.56} = \zeta_{12}; \quad (3)$$

we use the value $b_z = 0.361$ from [7].

The other principal geometrical characteristic of an impact is the size of the shocked volume, which is often measured in terms of the size of the isobaric core, where the shock pressure shows relatively little variation. We choose it to be the position of the inflexion point of the shock pressure decay curve defined by the "inverse-r" approximation for shock pressure decay [8], and applying again the isocrater criterion eq. 2, the ratio of the isobaric cores of two isocrater impacts is

$$\frac{r_{infl1}}{r_{infl2}} = \delta_{12} \left(\frac{n_1 - 1}{n_1 + 1} b_1\right)^{\frac{1}{n_1}} \Big/ \left(\frac{n_2 - 1}{n_2 + 1} b_2\right)^{\frac{1}{n_2}} .$$
$$(4)$$

The velocity dependences are complicated, because the parameters b and n are material-dependent functions of v_{imp} as well, and so the ratios become dependent on the target planet as well as on the impact angle.

Apart from the geometrical relations, there are also semi-empirical relations between impactor parameters and the amount of melt produced in an impact to which similar considerations can be applied.

Figure 1 applies to impacts of impactors that differ in density, velocity, and size but result in a crater of the same final diameter. The isolines show how much larger or smaller, relative to an S-type asteroid, an impactor of some chosen density and velocity has to be in order to produce the same crater. The center of the isobaric core would be shallower for all alternative impactor types, but the melt volume produced by alternative impactors would be larger by up to 40%.

3. Model

We also carried out numerical mantle convection simulations with a modified version of STAGYY [9, 10] in which the impact is represented as an instantaneous thermal anomaly. The models show that the effects on the interior of isocrater impacts by impactors of different types can vary considerably, especially between rocky impactors with low to intermediate velocities and fast, ice-rich impactors.
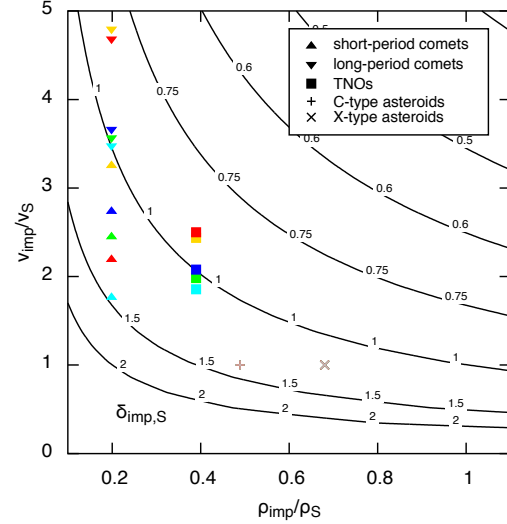

Figure 1: Ratio of impactor diameters for isocrater impacts as functions of the ratios of densities and impactor velocities (eq. 2). The symbols mark averages pertaining to the target (cyan: Mercury, green: Venus, blue: Earth, gold: Moon, red: Mars, grey: all targets).

Acknowledgements

References

[1] W. A. Watters, et al. (2009) *JGR* 114:E02001.

[2] J. H. Roberts, et al. (2012) *Icarus* 218(1):278.

[3] B. A. Ivanov, et al. (2002) in *Asteroids III* 89–101 University of Arizona Press, Tucson, Arizona.

[4] R. G. Strom, et al. (2005) *Science* 309(5742):1847.

[5] S. C. Werner, et al. (2015) in *Treatise on Geophysics* (2nd edn.), vol. 10, Elsevier.

[6] J. K. Dienes, et al. (1970) in *High-Velocity Impact Phenomena* chap. 3, Academic Press.

[7] E. Pierazzo, et al. (1997) *Icarus* 127(2):408.

[8] T. Ruedas (2017) *Icarus* 289:22.

[9] P. J. Tackley (2008) *PEPI* 171(1–4):7.

[10] T. Ruedas, et al. (2013) *PEPI* 216:32.