INTERIOR RESPONSES TO IMPACTS BY DIFFERENT IMPACTOR TYPES Thomas Ruedas[1,2], Doris 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)

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, 3]). On the grounds that most observed craters seem to have been produced by collisionally evolved bodies, probably main-belt asteroids (e.g., [4, 5], 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. We show by analysing scaling laws how different impactors may result in the same final crater on a given planet and investigate some dynamical effects for different impactor types for several bodies in the inner Solar System.

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

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

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., [6]); 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 $D_\mathrm{f1} = D_\mathrm{f2}$:

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

for both simple and complex craters; this defines a set of isocrater impacts. Figure 1a 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., [7]), the depth of penetration is often found to be proportional to the square or cube root of the density ratio $\varrho_\mathrm{imp}/\varrho$, 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 [8] for the depth to the center of the isobaric core of the shocked volume into the relation

$$z_\mathrm{ic} = a_z D_\mathrm{imp} v_\mathrm{imp}^{b_z}\sqrt{\frac{\varrho_\mathrm{imp}}{\varrho}}; \qquad (3)$$

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:

$$\frac{z_\mathrm{ic1}}{z_\mathrm{ic2}} = \left(\frac{\varrho_\mathrm{imp1}}{\varrho_\mathrm{imp2}}\right)^{0.07}\left(\frac{v_\mathrm{imp1}}{v_\mathrm{imp2}}\right)^{b_z-0.56} = \zeta_{12}; \quad (4)$$

we use the value $b_z = 0.361$ from [8] (cf. Figure 1b).

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 [9, 10], and applying again the isocrater criterion eq. 2, the ratio of the isobaric cores of two isocrater impacts is

$$\xi_{12} = \frac{r_\mathrm{infl1}}{r_\mathrm{infl2}} = \delta_{12}\frac{\left(\frac{n_1-1}{n_1+1}b_1\right)^{\frac{1}{n_1}}}{\left(\frac{n_2-1}{n_2+1}b_2\right)^{\frac{1}{n_2}}}. \qquad (5)$$

The velocity dependences are complicated, because the parameters b and n are, in fact, 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

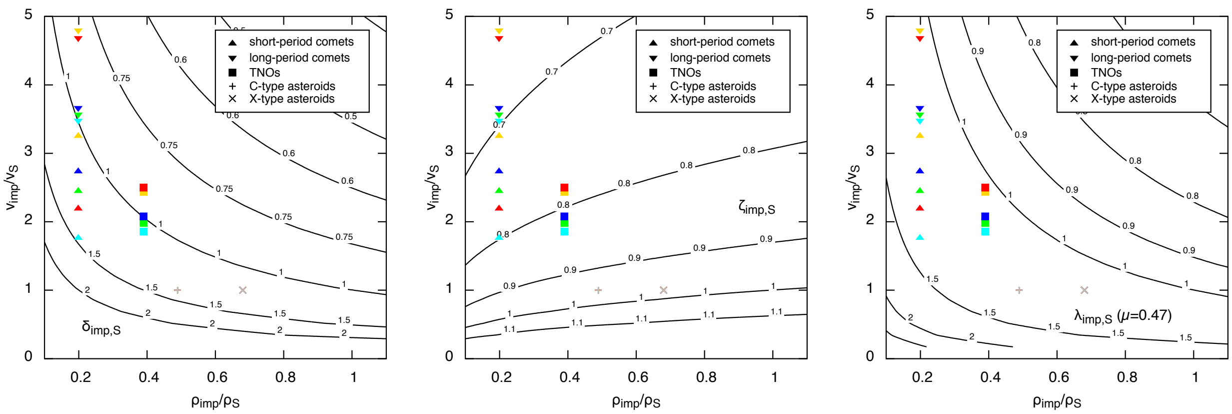

Figure 1: Ratios of impactor diameters (left), depth to the center of the isobaric core (center), and melt production (right) for impacts resulting in final craters of the same size as functions of the ratios of densities and impactor velocities according to eqs. 2, 4, and 6; the reference body for the ratios is an S-type asteroid. The symbols mark average values pertaining to the target planet (cyan: Mercury, green: Venus, blue: Earth, gold: Moon, red: Mars, grey: all target bodies), their shapes indicating the type of impactor being compared to the reference impactor. S-, C-, and X-type asteroids are assumed to have the same average velocities.

and the amount of melt produced in an impact. While we rather calculate melting in the framework of the thermal anomaly and the ensuing dynamics in the numerical models, applying the empirical scaling laws to the bulk amount of melt is a useful exercise for the purpose of a general comparison between different impactor classes. Combining a scaling law proposed by [11, 12], we have

$$\lambda_{12} = \frac{V_{\mathrm{m1}}}{V_{\mathrm{m2}}} = \left(\frac{\varrho_{\mathrm{imp1}}}{\varrho_{\mathrm{imp2}}}\right)^{\nu-1.29} \left(\frac{v_{\mathrm{imp1}}}{v_{\mathrm{imp2}}}\right)^{3\mu-1.68} \quad (6)$$

where V_{m} is the melt volume and ν and μ are constants related to the target. μ is experimentally found to lie between approximately 0.47 and 0.58 for commonly encountered materials [11]. Those authors chose $\nu = 0.67$, whereas the derivation by [12] implies $\nu = 1$, which is the value we adopt here; $\nu = 0.67$ would result in a slightly larger melt volume.

All plots in Figure 1 apply to impacts of impactors that differ in density, velocity, and size but result in a crater of the same final diameter. The isolines in Figure 1a 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; for instance, a C-type asteroid, which is about half as dense as an S-type asteroid but has the same velocity, would have to a have 1.4 times the diameter, regardless of the target, whereas a TNO-like impactor, which is even less dense but considerably faster, would have to be about 15% smaller on Mars or the Moon but almost the same size on Earth, Venus, or Mercury. Figure 1b shows that the center of the isobaric core would be shallower for all alternative impactor types, although only slightly so for asteroid impactors. On the other hand, the melt volume produced by alternative impactors would be larger by up to 40% (for $\nu = 1$), depending on impactor type and target. The differences in melt production might allow to resolve the non-uniqueness of the impactor type.

Models and results: We carry out numerical mantle convection simulations with a modified version of STAGYY [13, 14] 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.

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