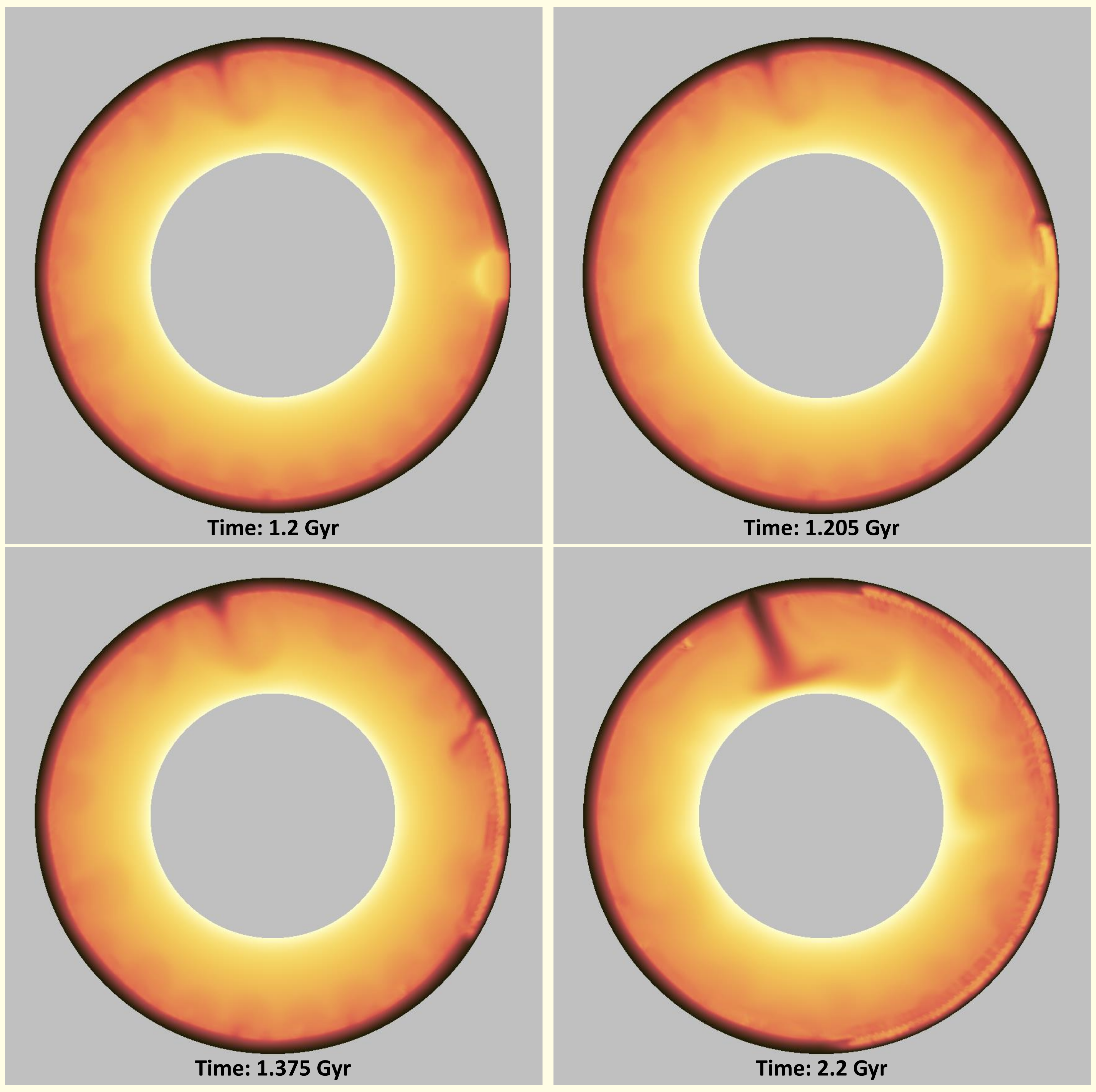
Venusian Impact: Starting a Mobile Lid

G. T. Euen (egrant93@vt.edu), S. D. King (sdk@vt.edu)
Dept.of Geosciences, Virginia Tech, Blacksburg, VA

Introducing an Impact to Venus

The surface of Venus shows evidence of a total resurfacing 500-700 million years ago [1]. Venus is hypothesized to be under stagnant-lid conditions, similar to hypothesized conditions of Hadean Earth. Using the geodynamics code ASPECT [2], cases were run varying the size of an impacting body onto a Venus-like planet.



The initial conditions are of a stagnant-lid planet. The planet exists for roughly 1 billion years before impact. Maximum surface velocity is used as an approximation for any potential movement of the lithosphere. Effects after impact depend principally on the size of the impacting body. Impacts from relatively small bodies produce almost no effect on the stagnant lid. Larger impacting bodies can cause localized effects, with the possibility of subduction kicking in. This occurs as the yield viscosity begins to dominate viscous forces. It can also be seen in the maximum surface velocity, as a different baseline velocity is achieved post-impact. The largest impacts have dramatic consequences to the stagnant lid and cause large, immediate increases to the maximum surface velocities as the lid is broken.

What does this mean?

Shock waves penetrate deeper into the mantle the larger the impacting body. Based on the results shown here, a planet in stagnant-lid regime, such as Venus, can enter one of three evolutionary states after an impact:

1. The impacting body is "small" (radius < 75 km): The stagnant lid is not broken and continues to be the dominant regime of the planet. Maximum surface velocities are below 1 cm/yr.
2. The impacting body is "moderate" (radius > 75 km): The stagnant lid will be broken in the immediate area of the impact. This will trigger localized melting and subduction. As yield viscosity becomes the dominant force over geologic time, lithospheric overturn begins. Maximum surface velocities are around 1-2 cm/yr.
3. The impacting body is very large (radius > 500 km): The stagnant lid will be broken with large-scale heating of the mantle. Very large maximum surface velocities, 1-5 m/yr, will persist for millions of years.

References

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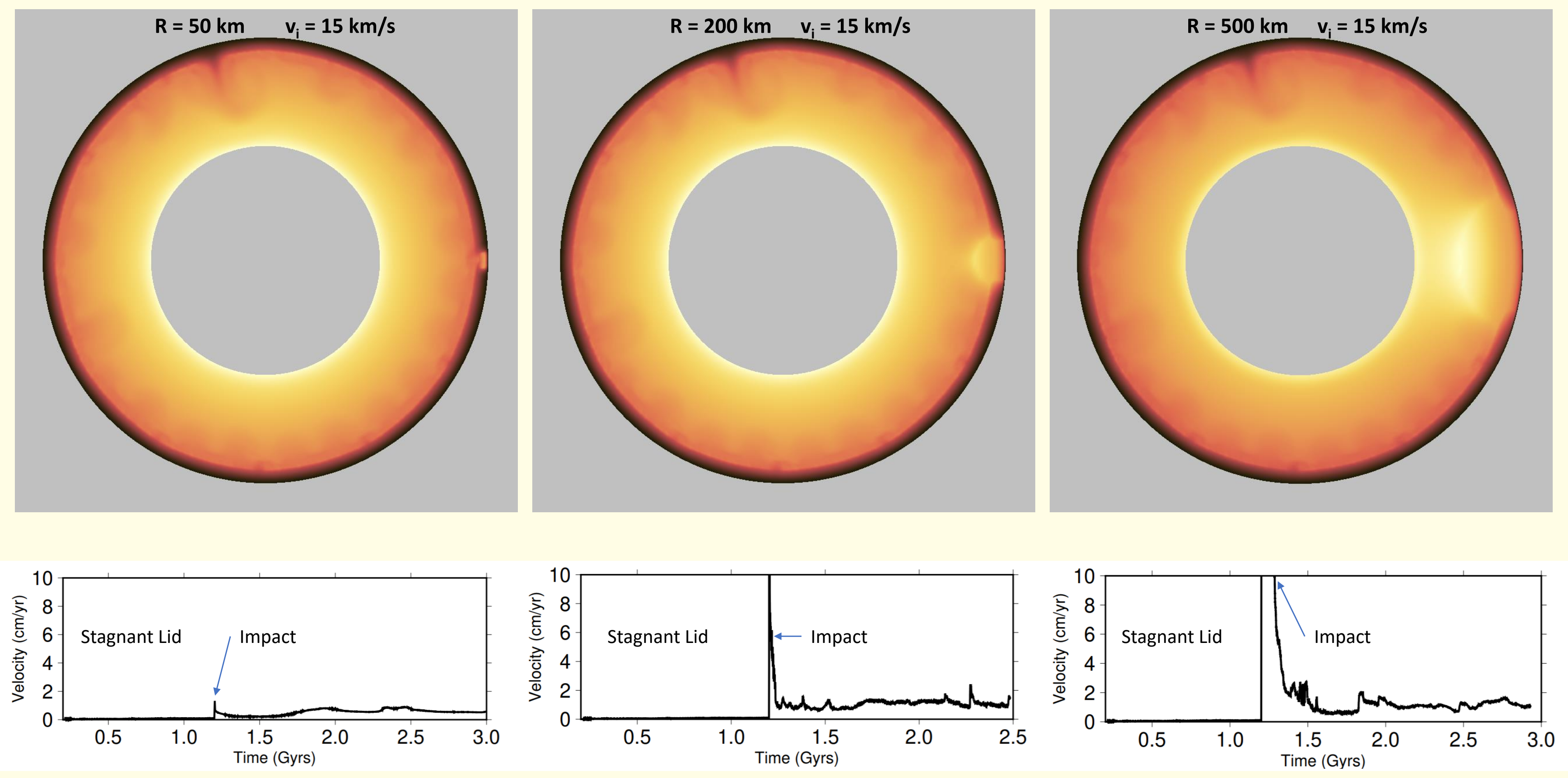
Why does this matter?

Venus has very few craters for a planet of its size and age, so why talk about them anyway? Recent work by [3] suggests that in order to have a mobile-lid regime, as we experience on Earth, a component of degree-1 density structure is required. It has also been hypothesized by [4] that a large planetary impact was the trigger for the mobile-lid conditions on Earth.



A planetary impact could introduce the necessary conditions for a total resurfacing event or even trigger mobile-lid conditions on a previously stagnant-lid world. However, the hypothesized impact that triggered plate tectonics on Earth would have taken place in the Hadean. In this early Solar System, planetary impacts were far more common, and involved much larger impacting bodies compared to current conditions. Based on this work so far, a "moderate" impact (radius > 75 km) is necessary for a significant disruption of a stagnant lid. Catastrophic resurfacing due to a very large impact is highly unlikely in current Solar System conditions. "Moderate" impacts too are very unlikely, however, if they do occur their effects are spread over a longer period of time, potentially leading to longer episodes of mobile-lid conditions.

Want to know about the models?

We model the thermal convection problem in a 2D slice of a sphere assuming a compressible fluid, solving the equations for the conservation of mass, momentum, and energy using ASPECT [2]. Impacts are modeled based on the methods outlined by [5]. Heating of the mantle caused by the impacting body is calculated as a function of pressure due to the shock waves caused by the impact. These shock waves occur at depth given by

$$d_c = 0.305 R {v_i}^{0.361}, \tag{1}$$

where d_c is the depth of the shock wave, R is the radius of the impacting body, and v_i is the velocity of the impacting body. The pressure due to impact is calculated as a function of radius from the impact site. The interior of the impact crater, r_c, is called the isobaric core and is given by

$$r_c = 0.451 R {v_i}^{0.211}. \tag{2}$$

Within this radius the pressure is at a constant peak, while outside of this radius the pressure decays according to

$$P_s(r) = \begin{cases} \rho_0 (C + S u_c) u_c & \text{if } r \leq r_c \\ P_s(r_c) \left(\frac{r_c}{r}\right)^{(-a + b \log v_i)} & \text{if } r > r_c \end{cases}, \tag{3}$$

where $P_s(r)$ is the pressure due to impact, $P_s(r_c)$ is the peak pressure within the isobaric core, ρ_0 is the reference mantle density, C and S are material constants, r is distance from the impact, a and b are decay law exponents, and u_c is the particle velocity. In these models, the target and impacting body are assumed to have the same density, making $u_c = \frac{v_i}{2}$. The heating due to impact is therefore calculated by

$$\Delta T(P_s) = \frac{1}{C_p} \left[\frac{P_s}{C^2 \rho_0} (1 - f^{-1}) - \left(\frac{C}{S}\right)^2 (f - ln(f) - 1) \right], \tag{4}$$

where f is defined as

$$f = -\frac{2 S P_s}{C^2 \rho_0} \left(1 - \sqrt{\frac{4 S P_s}{C^2 \rho_0} + 1} \right)^{-1}. \tag{5}$$