Deriving Gravity Profiles from SPH Simulations of Planetesimal Collisions

R. E. Melikyan[1], E. Asphaug[1], S. Cambioni[2], A. Emsenhuber[1,3], S. R. Schwartz[1], and M. Jutizi[4]
[1]Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, USA (*rmelikyan@lpl.arizona.edu*), [2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, [3]Physikalisches Institut, University of Bern, Gesellschaftsstrasse 6, 3012 Bern, [4]Switzerland, Space Research and Planetary Sciences, University of Bern, Switzerland.

Introduction: Current and upcoming NASA missions are uncovering the origin of the Solar System through the analysis of the minor body population. Due to strength, even the largest asteroids can support irregular shapes and interior structures, the consequence of the collisions that formed and shaped them. The Dawn mission orbited the massive asteroids (1) Ceres and (4) Vesta and returned stunning morphology, gravity and other data [1]. The Psyche mission [2] will use imaging, magnetometry, gravity and composition to determine whether 16 Psyche is the mantle-stripped core of a parent planetesimal.

Vesta's shape is dominated by an equatorial ridge and overlapping impact structures in the south, Veneneia and Rheasilvia [3]. Jutzi et al. [4] modeled the formation of these craters using simulations. Their goal was to see whether the impacts that formed Veneneia and Rheasilvia can explain Vesta's overall topography. According to these models the two overlapping impacts excavated material from at least 85 km deep [5].

Ultimately one wants to match not only the topography (the craters and their ejecta distributions) but also the global figure of Vesta, and to have the mass redistribution match the gravity data. These are challenging problems, so our first step is to derive the gravity field from the SPH simulations and see where that leads.

Methods and Analysis: The gravitational potential of a body at any given point is defined by Laplace's equations:

$$(1)\ \Phi_g(r,\phi,\theta) = -\frac{GM}{r}\left(1+\Delta\Phi_g(r,\phi,\theta)\right)$$

where $\Delta\Phi_g$ represents any deviations in the gravitational potential from that of a point-source signal.

$$(2)\ \Delta\Phi_g = \sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^n (C_{nm}\cos(m\phi) + S_{nm}\sin(m\phi))P_{nm}(\cos\theta)$$

r, ϕ, θ define position in spherical coordinates (θ is colatitude), $P_{nm}(\cos\theta)$ are the associated Legendre Polynomials of degree n and order m, and C_{nm} and S_{nm} are the Stokes coefficients and hold the information about the structure of the body.

Test Case: We construct a rotating equilibrium spheroid in SPH as a test case (Fig. 1). The values have been scaled to focus on the deviations relative to a point potential, as defined in Eq. 1. Small deviations from expected J2 symmetry show that the SPH model is not in complete hydrostatic equilibrium, revealing an initial limitation of the model, likely due to the packing method that was used to initialize the positions of each particle, combined with the strength that must be overcome before relative motion is possible.

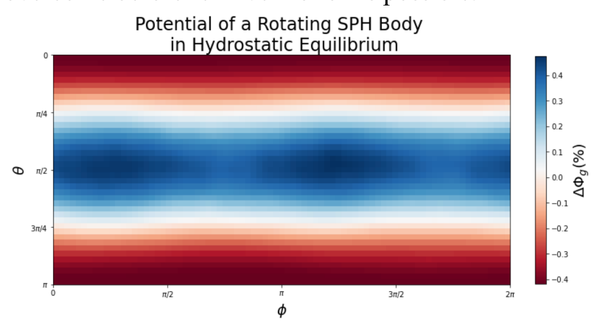

Figure 1. The gravitational potential map of the SPH rotating test body. The equator is at colatitude $\theta = \pi/2$ and the prime meridian at longitude $\phi = \pi$. The values of the map are normalized to the best focus on the $\Delta\Phi_g$ term of Eq. 2

SPH Vesta: To compare with the literature [6], the potential maps derived from the model of [4] (Vesta after 7000 sec of simulation time following the Rheasilvia collision) were converted into a radial gravity signal, and then converted into spherical harmonics with Pyshtools [7].

Fig. 2 shows the deviations in Gals from that of a point source with the same mass, after removing the relatively small J2 component. The impact cavity is seen in the southeast quadrant.

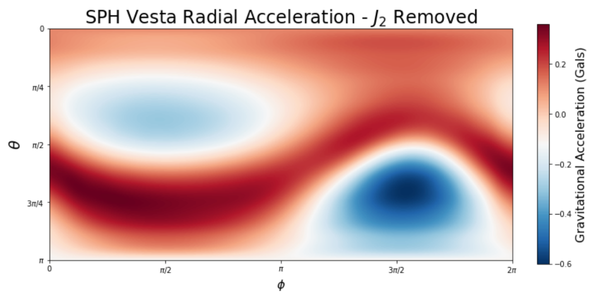

Figure 2. The radial gravity map of the SPH Vesta model with the J_2 term removed.

There is a strong offset wiggle that we originally suspected was the result of the body's spin vector being misaligned with the mapping coordinate frame; this was not the case, leading to a different conclusion. The Vesta simulation was only evolved for 7000 seconds after the Rheasilvia impact, leading us to believe that the offset bulge (green in the 3D point cloud; Fig. 3) is a remnant of the pre-impact rotating equilibrium state.

However, Dawn gravity results [6] do not show a strong signal like the one shown in Fig. 2. Further work (including dedicated SPH simulations and topography relaxation models) is needed to understand whether the relaxation of such signal over 1 Gyr time may match the data by Park et al.

Conclusions: We construct gravitational potentials from the outcomes of SPH simulations, in order to better connect simulations of planetesimal-forming collisions to spacecraft data. We identify key challenges in comparing SPH simulations of gravity with, e.g., the 3-layered shape models of Parket al.. Given how well the SPH simulations match the topography of Vesta, our interpretation is that this offset bulge from the prior spin state underwent relaxation over the remaining billion years and was not seen by Dawn.

SPH simulations may reliably indicate the end state following the collision, but a further analysis of low-order shape evolution is required before a more detailed analysis of gravity is possible.

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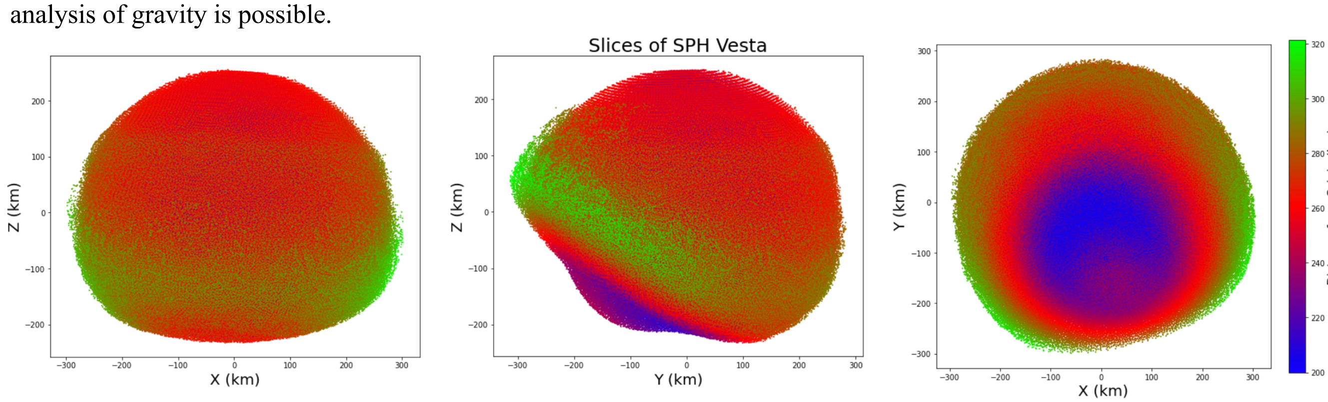

Figure 3. The Jutzi et al. Vesta SPH point cloud. This model is comprised of 783,502 particles.