Sputnik Planitia as an Impactor Remnant: An Ancient Mascon in a Frozen Ice Mantle. Harry A. Ballantyne[1], Erik Asphaug[2], C. Adeene Denton[3], Alexandre Emsenhuber[1,2,4] and Martin Jutzi[1], [1]Space Research & Planetary Sciences (WP), Universität Bern, Bern, Switzerland, [2]Lunar and Planetary Laboratory, University of Arizona, Tuscon, USA, [3]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, USA, [4]Universitäts-Sternwarte München, Ludwig-Maximilians-Universität München, Munich, Germany

Introduction: In 2015, the New Horizons space probe revealed Pluto's surface to be geologically complex [1], with perhaps the most striking feature being the high-albedo, ~1600km-wide basin known as Sputnik Planitia that forms the majority of Tombaugh Regio [1,2]. Observations show this feature to be amongst the deepest on Pluto at an elevation ~3-4km lower than its surroundings [2], however its original depth is obscured by a thick layer of N_2 ice thought to have been deposited soon after its formation [3]. Its quasi-elliptical shape and sharp, mountain-lined rim somewhat resembles a large degraded impact basin [4], leading to multiple impact-based investigations via the iSALE-2D grid-based shock physics code [5,6]. However, these works were limited to head-on collisions in two-dimensions, restricting their capacity to reproduce the simulated impact basin's precise geometry or explore the oblique impact angles predicted to produce Sputnik Planitia's elongated morphology.

Another common thread in these studies is the inferred presence of a subsurface ocean, as this could reconcile the seeming disparity between the basin's gravity contribution and its near-equatorial location. The negative gravity anomaly of such a large basin excavated from a solid mantle would induce true polar wander and drive its position towards one of Pluto's poles. A positive anomaly, on the other hand, would provoke the contrary, forcing the basin equatorward [7].

The currently accepted mechanism to produce such an anomaly is for Sputnik to form in an ice-crust above a global water ocean. The thinning of the crust leads to uplift of denser fluid [8,9], causing a mass concentration or "mascon" beneath the basin. This structure must be retained, for if the ice shell relaxes viscously, or the liquid ocean solidifies, the mascon disappears.

Retaining this structure is not a simple task; the ice shell must be cold (and therefore stiff) to avoid rapid viscous relaxation, while the ocean beneath must be warm enough to remain liquid to the present day. Such a scenario may require an unusually high ammonia content to reduce the ocean's freezing point [8] and/or a continually-replenished layer of clathrate hydrates to insulate the ice shell from the relatively warm ocean [9].

Here, we propose a new impact mechanism that introduces a long-lived rocky mascon beneath the Sputnik Planitia basin, while reproducing the topographical shape of the feature in three dimensions, without the need for a present-day subsurface ocean.

Method: We simulate the impact using the planetary-scale specialised SPHLATCH smoothed-particle hydrodynamics (SPH) code [10,11]. Shear strength and plasticity are included through a Drucker-Prager-like yield criterion, as such effects have been shown to be important even at planetary scales [11], with their prominence being particularly amplified by the very low temperatures of Pluto. Moreover, the sophisticated equation

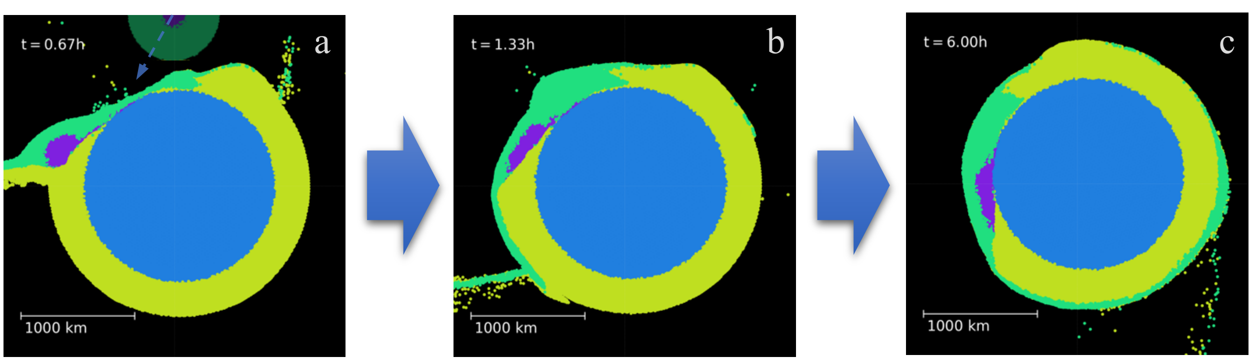

Fig. 1: *Example simulation of the impact mechanism. The initial impactor radius is ~375 km, core mass fraction 20%, impact angle 30°, impact velocity 1.35*v_{esc}*. Each image is a 300km slice centred on the impact plane. Colour represents the composition and parent body: purple is the impactor core, blue the target core, green the impactor mantle and yellow the target mantle. (a) Shortly after the impact, where the transient crater is still present and the impactor core's velocity has slowed to a near stop. The faded object indicates the impactor's initial size and velocity. (b) After the collapse of the transient crater, now filled with impactor mantle. The impactor core has begun falling back towards Pluto's core-mantle boundary, (c) The post-impact state of Pluto, 6 hours after the collision.*

of state ANEOS is used to accurately determine the physical environment in which such solid characteristics must be considered. The parameter space explored includes impactors of radii 250-500 km, with impact angles of 0-45° and impact velocities of 1.0-1.4 times the mutual escape speed (~1.2 km/s). We consider undifferentiated impactors of ice, and of rock, and differentiated impactors with core mass fractions from 20-66%.

Preliminary Results: Initial results reveal distinct trends in different regions of the parameter space. The most oblique (45°) impacts induce the rapid breakup of the impacting body upon contact with the target, redistributing most of its material downrange as a distinct ring of re-impacted ejecta in the impact plane. In more direct impacts, the undifferentiated ice impactor is often unable to penetrate deep into the target mantle, with its material spreading across the surface to form a characteristic "splat" distribution similar to that of Jutzi & Asphaug 2011 [12]. By contrast, undifferentiated rock impactors are capable of piercing much further through the mantle, easily reaching the core-mantle boundary in the near head-on cases before being buried by the collapsing ice walls of the transient crater.

The most promising cases lie in the intermediate parameters: core masses 5-30%, impact angles 15-30°, and an impactor radius ~375 km. An example simulation in this range is shown in Fig. 1. Here the impactor initially excavates the material of the immediate impact site (Fig. 1a) before sufficiently slowing such that it can no longer overcome the shear strength of the cold ice and begins to slide along the target mantle towards its surface. While much of the impactor's ice is displaced during this first phase, the rocky impactor core remains mostly intact due to its much higher density, melting temperature and strength, forcing out any impactor ice that was initially on the target-facing hemisphere. Most of the transient crater is then filled with infalling impactor ice while the impactor core slides back down towards the target core, losing some of its spherical shape as it does so (Fig. 1b).

Finally the site relaxes, settling into the desired teardrop shape of Sputnik Planitia, with the impactor core remaining as a buried mascon near Pluto's core-mantle boundary (Fig. 1c). Fig. 2 shows the final distribution of the impactor material, with a remarkable resemblance to Sputnik Planitia. The near-spherical shape in the northern hemisphere corresponds to the initial point of impact where a more classical crater forms and collapses, whereas the pointed, triangular shape in the south corresponds to the sliding region of the impactor core.

We propose that the overall shape of this feature could remain intact if the impactor mantle's precise composition had a slightly higher density than that of the primordial Pluto, as its greater load on the silicate core would lead to a local depression via isostasy. Furthermore, the dense buried mascon provided by the impactor's rocky core would produce a significantly deeper region of the basin. N_2 ice would quickly accumulate in the basin [3], culminating in the positive mass anomaly that drove Sputnik Planitia into its current position through true polar wander. The region of the basin with the strongest positive anomaly – the southernmost, narrow section directly above the mascon – would be forced closest to the equator, matching present day observations. Finally, as true polar wander best explains the distribution of extensional features on Pluto [7], a more dominant positive anomaly provided by a differentiated impactor and a fully frozen ice shell may better fit the current observational constraints.

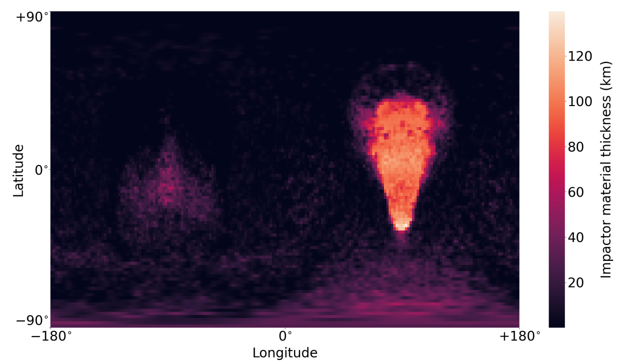

Fig. 2: *A global map of the final impactor material distribution down to depths of ~120km. This corresponds to the same simulation as Fig. 1.*

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