TRUE POLAR WANDER OF PLUTO. J. T. Keane[1] and I. Matsuyama[2]. [1]California Institute of Technology (Pasadena, CA 91125 USA; jkeane@caltech.edu); [2]Lunar and Planetary Laboratory (University of Arizona, Tucson, AZ 85721, USA).

Summary: One of the most important results of the *New Horizons* mission to Pluto was the inference that Pluto reoriented due to the formation and evolution of Sputnik Planitia (Pluto's "Heart"). This process, known as true polar wander, yields critical insight about Pluto's interior structure, and provides a framework for understanding Pluto's long-term geologic and climatic history. In this abstract, we summarize the evidence for true polar wander, and the broader implications for the Pluto system and other Kuiper Belt objects.

Sputnik Planitia (SP): In July 2015, the *New Horizons* flyby revealed Pluto to be an astonishingly active world (Fig. 1) [1–3]. Of all of the geologic features on Pluto, the largest and most dramatic is Sputnik Planitia (SP). SP is a 1,000 km diameter, tear-drop shaped topographic depression—likely formed early in Pluto's history by a giant impact [1–2, 4]. The interior of SP is characterized by a smooth, craterless plain, 3–4 km beneath the surrounding rugged uplands. The plains are the surface of a massive, actively convecting glacier of volatile ices (N_2, CH_4, CO) several kilometers thick [1–3, 5–6].

The Curious Location of Sputnik Planitia: SP is located very near the Pluto–Charon tidal axis (Fig. 1). The tidal axis is the line connecting the centers of Pluto and Charon (Pluto's large, tidally-locked moon), and it intersects the surface of Pluto at 0°E, 0°N (the sub-Charon point), and 180°E, 0°N (the anti-Charon point). For a tidally-locked world, like Pluto, the tidal axis corresponds to the largest minimum axis of inertia. SP overlaps the anti-Charon point, and extends to the NW. There is only a 5-10% probability of any feature on the surface being this close to the tidal axis.

True Polar Wander (TPW) of Pluto: The alignment of large geologic features with the principal axes of inertia of a body is often the hallmark of true polar wander (TPW) [7]. TPW occurs when geologic phenomena redistribute mass on/in a planetary body. This action changes the orientation of the body's principal axes of inertia. As energy is damped out of the system, the entire body will reorient to realign these principal axes with the tidal/spin axes—resulting in motion of the tidal/spin poles across the geographic surface.

To determine if SP could drive TPW, we calculated the inertia tensors of Pluto and for SP. The inertia tensor of Pluto was derived using viscoelastic Love number theory, assuming a four-layer interior structure (silicate-rich core, liquid water subsurface ocean, water-rich asthenosphere, and a water-rich elastic lithosphere), and constrained by Pluto's mass and radius [8]. Since the

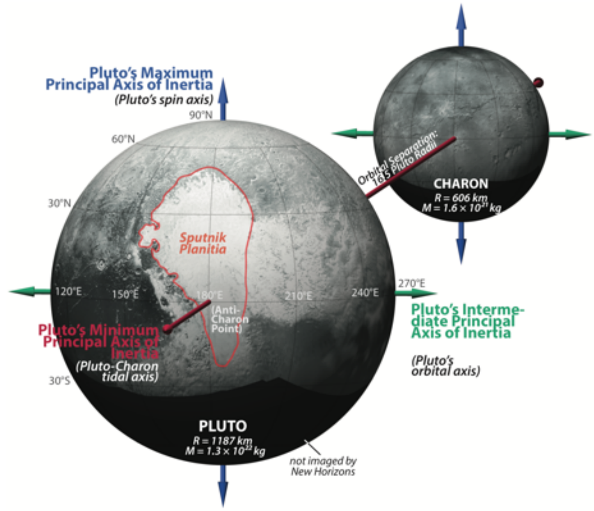

Fig. 1 | The geometry of Sputnik Planitia in the Pluto-Charon system. *Base-maps of Pluto and Charon: NASA/JHUAPL/SwRI.*

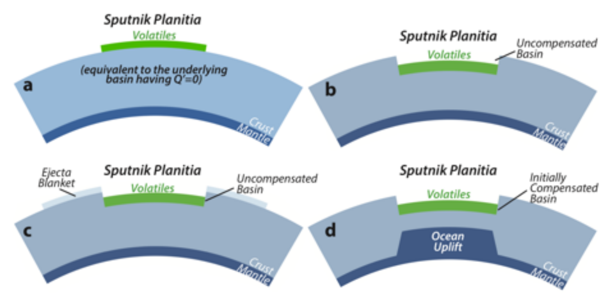

Fig. 2 | Models for the interior structure of Sputnik Planitia.

structure of SP is largely uncertain, we calculated the inertia tensor for a variety of different models (Fig. 2), and self-consistently accounted for the flexural response. TPW solutions were determined by combining the inertia tensor from our nominal Pluto model with the inertia tensors from our SP models, and determining the new lowest-energy configuration.

This TPW analysis reveals several important details about SP and Pluto's interior structure [9–10]. The most significant is that SP must be a positive mass anomaly (i.e., a mass excess). This is seemingly in contrast with the large negative topography associated with SP [11], which should yield a large negative mass anomaly. While the SP glacier is expected to be denser than the average crust of Pluto, it is insufficient to create the requisite mass anomaly. Nonetheless, there are other ways to make SP a larger positive mass anomaly, including: making the underlying basin isostatically compensated, incorporating an ejecta blanket around SP, or adding an uplift of the subsurface ocean. The latter was favored by [10], and is the primary piece of evidence for an extant subsurface ocean on Pluto.

Tectonics from TPW: As an object reorients by TPW, each surface location experiences a change in the tidal-rotational potential, which generates stress in the lithosphere with a characteristic pattern determined by the TPW geometry. We calculated the expected tectonic stresses arising from SP-driven TPW and global expansion from the freezing of a subsurface ocean [9]. Amazingly, the predicted tectonic stresses closely match the observed tectonic patterns on Pluto (Fig. 3). Proximal to SP, loading stresses dominate—resulting in predominantly radial extensional faults. Far from SP, the TPW stresses dominate—resulting in extensional faults that are roughly circumferential to SP in the regions imaged by *New Horizons*. This hypothesis provides the single most comprehensive explanation for the global pattern of faults on Pluto. Alongside SP's location, Pluto's tectonics is the second critical piece of evidence for TPW.

Implications for Cryovolcanism: TPW-generated tectonic stresses can enable the ascent of subsurface cryomagmas. There are several plausible cryovolcanic constructs on Pluto, including constructional mounds south of SP, Piccard and Wright Mons [12], and flow-like deposits west of SP associated with Virgil Fossae and other tectonic fractures [13–14]. These putative cryovolcanic features are all located in an annulus around SP associated with the maximum extensional stresses arising from TPW and volatile loading [9, 15]. The formation and evolution of SP may have indirectly enabled cryovolcanism across Pluto.

Implications for Pluto's Volatile Cycle and Climate: Since the orientation of Pluto depends on the mass anomaly of SP (which is partly controlled by the volatile content of the basin) it is plausible that Pluto experiences a feedback between volatile transport, climate, and rotational stability. While SP is located near the Pluto–Charon tidal axis, it is also located near the latitude of the minimum mean solar insolation [16]. TPW analyses suggest that SP initially formed at higher latitude, and was progressively loaded with volatile ices (Fig. 4) [9]. Depending on the rate at which volatiles migrate in and out of the basin, it is conceivable that Pluto undergoes small-amplitude wobbles (analogous to Earth's annual, atmospheric-pressure-driven wobbles) on a variety of timescales. This may provide an additional source of energy into the Pluto system.

Implications for Worlds: Beyond Pluto, volatile-driven reorientation may be active on a variety of planetary bodies. Neptune's large moon, Triton, possesses a comparable volume of volatiles and has an orbital/rotational configuration more susceptible to these processes [17]. Analogous processes may also occur on hot, tidally-locked exoplanets with large quantities of mobile volatiles (where volatiles in this case are silicates).

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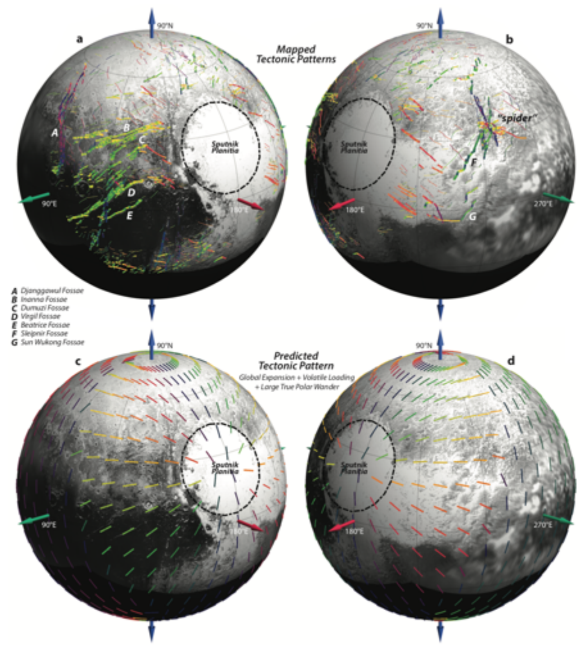

Fig. 3 | Observed and predicted tectonic patterns on Pluto. *Base-map of Pluto: NASA/JHUAPL/SwRI.*

Fig. 4 | The complicated interplay between volatiles and rotation on Pluto. *Sketch by J. T. Keane.*