Pluto's Heat Flow: A Mystery Wrapped in an Ocean inside an Ice Shell. William B. McKinnon[1], P.M. Schenk[2], M.T. Bland[3], K.N. Singer[4], O.L. White[5], J.M. Moore[5], J.R. Spencer[4], L.A. Young[4], C.B. Olkin[4], H.A. Weaver[6], S.A. Stern[4], and the New Horizons Geology, Geophysics & Imaging Theme Team; [1]Dept. Earth and Planet. Sci. & McDonnell Center for the Space Sci., Washington Univ. in St. Louis, Saint Louis, MO 63130 (mckinnon@wustl.edu), [2]LPI, Houston, TX 77058, [3]USGS Astrogeology, Flagstaff, AZ 86001, [4]SwRI, Boulder, CO 80302, [5]NASA Ames Research Center, Moffett Field, CA 94035, [6]JHUAPL, Laurel, MD 20723.

Introduction: One of the most significant discoveries of the July 2015 *New Horizons* flyby of Pluto was the high level of past and present geological activity on an icy dwarf planet that has not experienced tidal heating since mutual spin-orbit synchronism with its major satellite (Charon) was achieved [1], a tidal end-state presumably reached long ago and not long after the Charon-forming impact [2]. While much can be attributed to the geological mobility of volatile ices such N_2 and CH_4, other tectonic and (likely) cryovolcanic features attest to an active interior [3,4]. Tectonics, the orientation of Pluto (specifically, Sputnik Planitia) with respect to Charon, and theoretical models all suggest the presence of an internal liquid water ocean [5-8], which would need to be maintained by radiogenic heat release within Pluto. But what is this level of heat release, and is the resulting surface heat flow consistent and/or sufficient to drive the geological activity we see? Here we examine independent lines of evidence in an effort to constrain Pluto's heat flow today or in the geologic past.

Working on a Mystery: Pluto's density of 1.85 g/cm^3 implies a fair fraction of rock, about 2/3 by mass on an anhydrous basis [9]. As such, and presuming solar elemental abundances for rock accreted so far from the Sun, radiogenic heat release is nominally well known: abundances of ^{40}K, Th, and U are ostensibly well-determined at the 5-10% level [10]. Heat flow history depends, however, on how these elements are arranged in the interior and effective thermal conductivities. A rock core, once formed, can act as a sort of thermal battery, storing heat from earlier, higher radiogenic heat production, and releasing it later, effectively smoothing out the heat flow over time [11,12]. On the other hand, ^{40}K is soluble in water, and an internal ocean can transmit heat very efficiently across its depth. Cold water ice also has a very high thermal conductivity. If hydrothermal activity persists in Pluto's (outer) core, then the effective thermal conductivity of the core will also be high. While it is not clear that sufficient porosity and permeability can persist at the "high" pressures in Pluto's core, $\gtrsim$0.2 GPa, the gravity field evidence for underdense, porous cores within Enceladus and Ceres [13,14], admittedly smaller bodies, should give one pause. Steady-state heat flows for Pluto today could be close to 3 mW/m^2 (30 times less than the terrestrial average).

The above models [9], being solely ice+rock(+metal), neglect the potential role of bulk carbonaceous matter, almost certainly an important component of comets and Kuiper belt objects, Pluto being no exception. Mass spectrometer measurements at Halley highlighted the importance of CHON particles, and in situ *Rosetta* measurements at 67P (a Jupiter-family comet and thus one formed in the same region of the outer Solar System as Pluto) have only strengthened this inference. Post-*Rosetta* models of bulk cometary composition that essentially match Pluto's density have been proposed, and contain a substantial organic/hydrocarbon component [15,16].

Such compositions naturally contain less rock, and thus would predict lower heat flows overall for Pluto (see Fig. 1). E.g., [15] propose in their "composition A" that 67P is 25 wt% metal+sulfides, 42 wt% rock/organics, and 32 wt% ice, while [16] posit, *by volume*, 5±2% FeS, 28±5% Mg,Fe olivines+pyroxenes, 52 ± 12% low-density hydrocarbons, and 15 ± 6% ice. Radiogenic heat production would, respectively, be 0.77 and 0.9 times that of the Pluto models in [9]. The cores in these models would also be comparatively cooler, as light organics likely convect readily, whereas graphite has very high thermal conductivity (indeed, graphitization of core organic material in any scenario should markedly enhance core thermal conductivity).

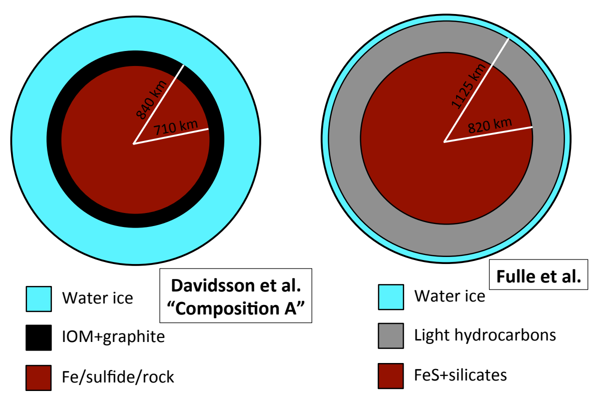

Figure 1. Alternative Pluto internal models based on proposed cometary compositions. Rock/sulfide, organics, and ice are depicted as if separated under the influence of gravity (differentiated). "Composition A" [15] proposes a 16.5 wt% contribution from graphite/amorphous carbon, equivalent to a deep 130-km-thick layer. The right-hand model is more radical, more than half light organics (1.2 g/cm^3) by volume.

Sputnik Planitia (SP): The convective upwellings within SP naturally depend on heat flow, but uncertainties in the viscosity of the dominant ice (N_2) led [17] to work the other way around, adopting plausible chondritic heat flows and convection cell geometry to constrain the N_2-ice viscosity. Alternatively, [18] argue that the cell pattern is better explained by volumetric (as opposed to basal) heating of the ice sheet or by downwelling due to cooling from above. The former is implausible whereas the latter implies a limited role for basal heat flow at best. The N_2-ice sheet is also susceptible to melting at its base if conductive and deep (i.e., melting occurs at ~2-km depth for 3 mW/m^2 [4,17], a depth that seems shallow given the 20-to-40 km horizontal scale of the convective cells). Could Pluto's heat flow really be markedly lower, say, $\lesssim$1 mW/m^2?

One possibility is that the N_2-ice viscosity is much lower at the base of the SP ice sheet (as the N_2 melting temperature of 63 K is approached). In this case the proper cell geometry (upwelling centers and downwelling margins) is obtained for nominal chondritic heat flows, and efficient convective heat transport may draw down regional temperatures so as to prevent basal melting in nearby non-convecting SP regions.

Fossil Bulge (Or Lack Thereof): Despinning following the Charon-forming impact should have left Pluto with a residual equatorial bulge, in the manner of Iapetus but mediated by the minimum lithospheric thickness and strength over geologic time [12,19]. A plausible maximum early heat flow of 12-18 mW/m^2, corresponding to a minimum lithosphere thickness of ~50 km (~0.65T_m creep temperature), predicted a fossil bulge of >2–3 km [19]. No fossil bulge was detected, and though the 2σ upper limit on the flattening is 5-7 km [20], stereo topography has yielded no obvious flattening >2 km [21]. If Pluto's historical heat flow never exceeded 5 mW/m^2 [12], the corresponding *minimum* lithosphere thickness of ~140 km would not have permitted relaxation of Pluto's early oblate shape to today's nearly spherical one. The question then arises as to whether other geological/geophysical features on Pluto corroborate such heat flow estimates.

Viscous Relaxation of Impact Craters: Impact craters, with their well-defined initial shapes, have proven useful as heat flow probes of a number of icy bodies, provided characteristics of viscous relaxation can be identified (e.g., on Ganymede [22], Enceladus [23], and Ceres [24]). For Pluto's numerous craters this identification is hampered by infilling and erosion by mobile, volatile ices, but not in every case. Large craters offer relatively deep probes of rheological structure, and low-albedo regions are generally volatile-ice free. Two large, old craters in western Cthulhu Regio are probably the best examples for viscous relaxation on Pluto: Oort (120-km diameter) and Edgeworth (145-km diameter) (all informal names). They are similar enough in size, apparent age, and location that we suspect they resulted from the impact of a Kuiper belt binary (primary diameters of ~27 and 35 km, assuming an impact speed of 2 km/s and 500 kg/m^3 density). Edgeworth is particularly shallow (Fig. 2) and its floor appears bowed up above the original ground plane.

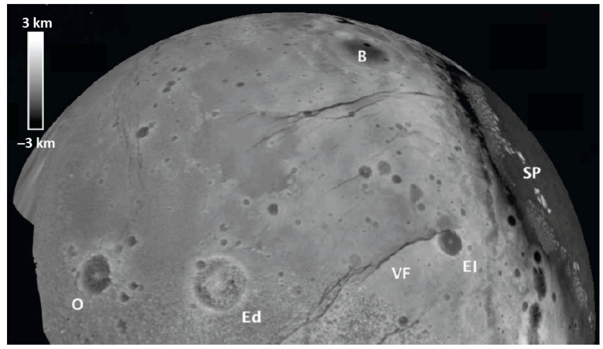

Figure 2. Orthographic projection of Pluto topography (western encounter hemisphere) [21]. Oort (O) and Edgeworth (Ed) are the largest craters known on Pluto after the Burney multiring (B) and Sputnik Planitia (SP) basins. Both Burney and Elliot crater (E) are deeper than Oort and Edgeworth. Also noted: Virgil Fossae (VF).

From smaller fresh craters on Pluto we estimate Edgeworth's original rim-to-floor depth at ≈3 km. Finite element calculations (50 K surface, 1-mm water-ice grain size) show that essentially no relaxation occurs over 4 b.y. for a constant heat flow of 3 mW/m^2, and little for 5 mW/m^2. The lithosphere is simply too cold and thick to relax or yield. To explain Edgeworth's floor as a product of viscous relaxation requires warmer ice temperatures at depth (higher heat flows). Oort, however, is obviously less relaxed.

Further: Additional observational constraints on Pluto's heat flow may also come from analysis of its extensional tectonic geometries, and from Burney's formation as a multiringed basin. Overall, most constraints indicate heat flows >3-5 mW/m^2 in the past.

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