

Geodynamics of Pluto

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In this article we summarize our understanding of Pluto's internal structure and evolution following the *New Horizons* mission. Pluto's density implies it is roughly 70% rock and 30% ice by mass, although it may plausibly also contain a sizeable fraction of carbon compounds. The lack of compressional structures indicates that it is fully differentiated, although this differentiation most likely cannot have been complete prior to the Charon-forming impact. Heat flux estimates are conflicting: one relaxed crater suggests high heat fluxes, while the absence of observed flexure suggests low heat fluxes. Pluto's energy budget is dominated by slow radioactive decay, and is sufficient to form and maintain a present-day subsurface ocean roughly 100 km thick beneath an ice shell. Four lines of circumstantial evidence point towards such an ocean; although none is definitive, taken together we think it probable that an ocean existed, and may still be present. These are: surface extension and possible cryovolcanism (both likely due to a thickening ice shell); an absence of a detectable fossil bulge; and reorientation driven by the nitrogen-filled Sputnik Planitia basin. If an ocean exists, the ice shell above must be cold and rigid. These conditions could be maintained if the ocean is ammonia-rich, or if there is a layer of clathrates at the base of the ice shell. At least the second half of Pluto's history consisted of slow cooling and thickening of an ice shell and continued reactions between the warm silicate core and the overlying ocean.

1. INTRODUCTION

The *New Horizons* mission promoted Pluto from a pixelated blob – the province of astronomers – to a complex and active world. The aim of this chapter is to review what we now think about Pluto's geodynamics – its structure, its history, and what drives its activity. Many of the conclusions we draw will be uncertain or provisional, and in some cases we have scarcely improved on our pre-*New Horizons* knowledge. Nonetheless, a significant amount has been learned, in particular the strong (although circumstantial) evidence for a subsurface ocean. Such an argument could certainly not have been made before 2015.

The rest of this chapter is organized as follows. We will begin with the observational constraints (Sec 2) and then discuss inferences arising from these observations. The topics covered, in decreasing order of certainty, are: Pluto's bulk structure (Sec 3.1); whether it possesses a subsurface ocean (Sec 3.2); the properties of the ice shell (Sec 3.3); and Pluto's long-term evolution (Sec 3.4). With these results in hand, we will then discuss Pluto and Charon in the context of the menagerie of icy worlds elsewhere in the Solar System (Sec 4). A brief discussion of possible future studies (and future spacecraft exploration) follows (Sec 5). Finally we will summarize our findings.

Several other chapters in this book are relevant to the material presented here. In particular, Pluto's geology (WHITE ET AL.), impact history (SINGER ET AL.), and

surface composition (CRUIKSHANK ET AL.) are all covered more extensively than in Sec 2 below, while Sec 3.4 has overlaps with the chapter by MCKINNON ET AL.

2. OBSERVATIONAL CONSTRAINTS

New Horizons provided surface images, spectroscopic mapping data and topography, all of which provide constraints on Pluto's geophysical behaviour. Although separating observations from interpretation is never entirely possible, this Section attempts to summarize the former without delving too much into the latter.

2.1. Shape and density

The density and shape of Pluto and Charon give zeroth-order constraints on their interior structures (Sec 3.1). Prior to *New Horizons*, Pluto's relatively thick atmosphere and hazes (JESSUP ET AL.) inhibited confident determination of Pluto's radius in stellar occultation and mutual event campaigns (Lellouch *et al.* 2009; Tholen 2014, e.g.). Pluto and Charon's masses were already well-known thanks to the motions of the small satellites, which allowed accurate determination of the barycenter (Brožović *et al.* 2015).

Approach images taken by the *New Horizons* LORRI camera combined with occultation measurements from several instruments yielded a mean radius of 1188.3 ± 1.6 km, and revealed no sign of oblateness ($<0.6\%$; Sec 3.1.4) (Nimmo *et al.* 2017). Combined with its known mass, Pluto’s inferred density was 1854 ± 11 kg m⁻³; for Charon the results were 606.0 ± 1.0 km and 1701 ± 33 kg m⁻³ respectively; these are actual, as opposed to “uncompressed”, densities. The masses (and thus the densities) may change slightly following incorporation of the encounter observations (Jacobson *et al.* 2015), but it is unlikely that they will change enough to alter any of the discussion presented below.

2.2. Surface Geology

Descriptions of the surface geology and composition of Pluto may be found in Moore *et al.* (2016); more recent summaries are in WHITE ET AL and CRUIKSHANK ET AL. From the point of view of Pluto’s bulk structure and evolution, the following observations are the most pertinent.

Pluto’s rugged surface is judged to be composed primarily of water-ice (Moore *et al.* 2016). More volatile nitrogen and methane deposits are found in some areas, notably the Sputnik Planitia (SP) basin which is dominated by N₂ ice (Grundy *et al.* 2016; Protopapa *et al.* 2017; Schmitt *et al.* 2017). Ammoniated species are rare on Pluto’s surface, although some traces are found around Virgil Fossae (Cruikshank *et al.* 2019); ammonia signatures are much more common on Charon, especially associated with certain impact craters (Dalle Ore *et al.* 2019, PROTOPAPA ET AL.).

Much of Pluto is heavily cratered; although the impact flux is imperfectly known, the bulk of the surface has inferred ages of several Gyr (SINGER ET AL.). The principal exception is the nitrogen plains of SP, which show no craters at all and on this basis are likely <100 Myr old (Moore *et al.* 2016; but see also SINGER ET AL.). SP itself probably represents an impact basin (Johnson *et al.* 2016) which, given its size ($D \approx 1000$ km), is likely a very ancient feature.

Pluto shows a striking array of extensional tectonic features, some of which are stratigraphically young (cross-cutting impact craters) and have sharp edges suggesting only limited degradation. A degraded north-south trending “ridge-trough system” might be evidence of more ancient extension (WHITE ET AL.). There is very little evidence for compression, although ~ 100 km-scale Tartarus Dorsae ridges east of SP and the north-south methane-capped mountains of eastern Cthulhu could conceivably have a compressional origin (McGovern and White 2019).

Two enigmatic features south of SP, Wright and Piccard Montes, have elevated topography of several km, central depressions and a lumpy surface texture (WHITE ET AL.). These features do not show any unusual spectroscopic characteristics, but based on height and observed slopes (up to

30°), their bulk composition must be dominated by water-ice. Their origin is uncertain, but it has been argued that they may be “cryovolcanic” constructs (Stern *et al.* 2015; Moore *et al.* 2016). Similarly, the stratigraphically young fractures at Virgil Fossae are at the centre of an ammonia signature, and it has been argued that this signature is the result of a recent cryovolcanic eruption (Cruikshank *et al.* 2019), although discrete flow boundaries are not evident in panchromatic images. While present-day cryovolcanism at Enceladus evidently produces diffuse surface deposits (Scipioni *et al.* 2017), we remind the reader that initial identification of volcanic or cryovolcanic features using images alone has frequently been overturned when different or better data became available (Moore and Pappalardo 2011). As a result, these interpretations should be treated with caution.

2.3. Heat Flux

Geological activity is ultimately driven by heat from the interior. Accordingly, obtaining estimates of present-day (or ancient) heat flux is very important for understanding the geodynamics of a planet. On Pluto there are several ways of doing so.

2.3.1. Convecting nitrogen

One of the most unexpected discoveries of *New Horizons* was the existence of ~ 30 km wide cellular patterns in the nitrogen plains of Sputnik Planitia. These were immediately identified as evidence for thermally-driven convection (Stern *et al.* 2015; McKinnon *et al.* 2016; Trowbridge *et al.* 2016) and thus provided one potential avenue to determine the local heat flux.

Experimental measurements of solid nitrogen viscosity (Yamashita *et al.* 2010) show that it is mildly temperature- and stress-dependent; at stresses of 0.1 MPa the viscosities are 2.5×10^9 and 0.6×10^9 Pa s, respectively, at temperatures of 45 and 56 K. Such viscosities are very low compared to, for example, water ice, which has a viscosity of 10^{13-14} Pa s near its melting temperature (Goldsby and Kohlstedt 2001). Although there are many uncertainties in its rheology (see UMURHAN *et al.*), and new lab work is necessary, it is clear that nitrogen is very mobile at Pluto’s surface conditions.

Convection involving either small viscosity variations, or extreme variations in which the near-surface lid is immobile, results in cell widths roughly double the convecting layer thickness. However, if the viscosity contrasts are intermediate, such that the motion of the lid is non-negligible compared to the interior velocities, the cell aspect ratio can be much larger. This arises because larger aspect ratios minimize viscous dissipation in the system (Lenardic *et al.* 2006). Nitrogen convection on Pluto very likely falls in this intermediate regime and so the layer depth is probably significantly less than 30 km (McKinnon *et al.* 2016).

We can gain insight about the dynamics of convection in nitrogen ice by considering scaling arguments. The surface heat flux, velocity and dynamic topography can be written (Solomatov 1995)

$$F \sim \frac{k\Delta T}{\delta_0} \quad , \quad u \sim \frac{\kappa d}{\delta_0^2} \quad , \quad h \sim \alpha \Delta T \delta_0 \quad (1)$$

where d is the layer thickness, k and κ are the thermal conductivity and diffusivity, respectively, ΔT is the temperature contrast across the layer, α is the thermal expansivity and δ_0 is the thickness of the sluggish lid. The quantity δ_0 in turn depends on the vigour of convection as measured by the so-called Rayleigh number. The thickness of the lid depends on the heat flux; this factor also controls the rise speed of the convective flow, and the stress and topography it imposes on the lid.

Assuming that the surface temperature is 38 K (Gladstone et al. 2016, e.g.), and that the nitrogen is entirely solid (with a melting point of 63 K, UMURHAN CHAPTER), $\Delta T < 25$ K, but neither F nor d are known a priori. Guessing that $d \approx 5$ km (based on (McKinnon et al. 2016)) and taking the heat flux $F \approx 3 \text{ mW m}^{-2}$ (see Sec 3.3.2) we obtain $\delta_0 \approx 1.7$ km, $u \approx 0.7$ cm/yr and $h \approx 80$ m. Numerical simulations produce very similar results (McKinnon et al. 2016), with the exception of somewhat higher velocities (a few cm/year).

High-resolution images provide additional, albeit incomplete, constraints on the character of convection in SP. Photoclinometry-derived topography suggests that the cell centers are elevated by roughly 100-150 m (Schenk et al. 2018a), consistent with the numerical simulations. Small, km-scale pits are observed on many of the convection cells in SP (WHITE ET AL.). These pits increase in size with distance from the cell center. Assuming that these are sublimation pits, this trend has been used to infer surface velocities of ~ 10 cm/year, or cell ages of about 0.5 Myr (Buhler and Ingersoll 2018). This age is consistent with the total absence of impact craters on SP at *New Horizons* resolution. The inferred surface velocity hints at either a larger layer depth or a higher heat flux than assumed above, but uncertainties in nitrogen rheology preclude a definitive statement.

2.3.2. Elastic thickness

Because the heat flux determines the temperature gradient, it also controls the mechanical properties of outer layers of planetary bodies. Geological materials typically lose their elastic strength at roughly 50% of the melting temperature, depending on the strain rate. Hence, a higher heat flux implies a thinner elastic layer (Watts 2001). If the thickness of this elastic layer can be estimated, the heat flux can therefore be constrained (McNutt 1984, e.g.).

The large extensional graben west of SP impose upwards stresses on the surrounding lithosphere. In principle, the lithosphere should bend upwards in response, generating rift-flank uplift as observed at some rifts on Earth (Brown and Phillips 1999). Since no such uplift is seen,

the lithosphere must be thick enough to avoid detectable deformation. In practice, this places a lower bound on the lithospheric elastic thickness of about 10 km (Conrad et al. 2019).

Loading of an elastic plate (e.g., by deposition of nitrogen ice) results in extensional fractures which can be either radial or concentric depending on the elastic thickness and body radius compared with the load radius (Janes and Melosh 1990; Freed et al. 2001). Sputnik Planitia may be one area where this kind of analysis could be used to place further constraints on Pluto's elastic thickness (Keane et al. 2016; Mills and Montesi 2018), though as with many large basins it may prove difficult to distinguish any flexural topography from topography due to the ejecta blanket.

2.3.3. Viscous relaxation

The viscosity of water-rich ice crusts is strongly temperature-dependent, so that high heat fluxes result in relatively low viscosities at shallow depths. Topographic features like craters produce stress gradients in the subsurface; if the viscosity is low enough, lateral flow will occur, resulting in viscous relaxation (shallowing) of these craters (Kamata and Nimmo 2014, e.g.). Viscously-relaxed craters are observed on bodies like Enceladus and Ganymede and have been used to estimate local heat fluxes (Dombard and McKinnon 2006; Bland et al. 2012, e.g.). Areas of thinned crust are likewise expected to thicken due to lateral flow at a rate depending on the heat flux (Stevenson 2000).

To date, only one anomalously shallow crater (Edgeworth, $D=145$ km) has been identified on Pluto (McKinnon et al. 2018). If it is shallow because of viscous relaxation, numerical models for relaxation of similar-sized craters (e.g., Alcander on Dione) (White et al. 2017) suggest that the heat flux must have been in excess of roughly 50 mW m^{-2} . Although Edgeworth appears to possess the bowed-upwards shape typical of relaxed craters, it is puzzling that nearby Oort ($D=120$ km) shows no such signs of relaxation. It may simply be that Oort formed later, when heat fluxes had declined.

3. INFERENCES

3.1. Bulk Structure

A pre-*New Horizons* view of possible Pluto structures is given in McKinnon et al. (1997). This work presented a baseline Pluto model rather similar to the structure we infer below, but also considered possible alternatives, including carbon-rich, low-density, and undifferentiated versions. The latter two can now be ruled out.

3.1.1. Rock mass fraction

If Pluto is assumed to consist mostly of silicates and water/ice, then its bulk density of $1854 \pm 11 \text{ kg m}^{-3}$ indicates that it is roughly two-thirds rock and one-third water/ice by

mass. Taking the H₂O density to be 0.95 g/cc a rock density of 3.5 g/cc would imply a rock mass fraction of 67% and an H₂O layer 340 km thick. Similarly, a “rock” density of 2.5 g/cc (with the lower density implying a substantial non-silicate component) would yield 79% and 196 km, respectively. As illustrated by these end-member examples, precise estimates are difficult because of several uncertain factors.

1. “Rock” density. The Jovian moon Io (density 3.5 g/cc) is often assumed to represent the density of “rock” (actually silicates+iron) in the outer solar system. But at least for Enceladus, gravity measurements suggest that the “rock” interior has a density more like 2.5 g/cc, probably as a result of some combination of porosity and/or hydrothermal alteration (Hemingway *et al.* 2018, e.g.). The extent of hydrothermal alteration and/or porosity (presumably water-filled) in Pluto’s “rock” is unknown, but is expected on theoretical grounds (Vance *et al.* 2007; Neveu *et al.* 2017); analogous hydrothermal alteration has been suggested for Titan (Castillo-Rogez and Lunine 2010).

2. Ice Porosity. As argued below, the ice shell of Pluto may also have retained some porosity. If so, then the actual rock mass fraction would be higher than the estimates above. Much of the density difference between Pluto and Charon can be explained by Charon retaining more ice shell porosity (as a result of its lower heat flux and pressure) (Bierson *et al.* 2018).

3. Carbon (and other) compounds. As discussed by Simonelli and Reynolds (1989) and McKinnon *et al.* (1997), Pluto’s interior might contain a non-negligible quantity of carbon compounds. Cometary elemental abundances certainly suggest the existence of substantial amounts of carbon, far more than the amounts found in the most carbon-abundant chondritic meteorites (~5 wt%). As such, a major carbonaceous and/or graphitic component may exist within Pluto. Although there is no direct evidence for such a component, its presence would have potentially profound implications for Pluto’s structure and evolution (MCKINNON ET AL.).

3.1.2. Energy sources

To a large extent the evolution of a body is determined by the energy sources available. In particular, Pluto differs from many icy objects in that it is unlikely to have experienced significant tidal heating, if any, since it reached its synchronous state with Charon (Barr and Collins 2015). Given Pluto’s density and assuming that its silicate portion has chondritic radiogenic abundances (Robuchon and Nimmo 2011), the likely energy sources can be determined (Table 1). The accretion estimate is a lower bound, obtained by assuming zero velocity at infinity; the actual value could be somewhat higher. We also included an estimate for the mean energy delivered by a Charon-forming impact (Canup 2011), though in reality the temperature change due to such an impact will be highly spatially variable.

The main take-away from this Table is that Pluto’s evo-

lution is most likely dominated by radioactive decay. Other energy sources (accretion, despinning, even a Charon-forming impact) are smaller in comparison, though not negligible.

3.1.3. Differentiation state

Both Pluto and Charon are clearly ice-dominated at the surface (Grundy *et al.* 2016). There is no evidence supporting the suggestion that both bodies might possess an undifferentiated “carapace” consisting of a mixture of rock and ice (Desch *et al.* 2009). Prior to *New Horizons* it was unclear whether Pluto and Charon were fully differentiated, into a deep “rock” core and a shallower ice shell. Triton, a comparably-sized body, is certainly differentiated, but that is because it experienced extreme heating during its capture into Neptune’s orbit (Goldreich *et al.* 1989; McKinnon *et al.* 1995, e.g.). The moon Callisto, larger than Pluto but with a comparable density (1.83 g/cc) is sometimes referred to as only partially-differentiated (Anderson *et al.* 2001). However, we do not know this for sure; it is based on the assumption that Callisto is hydrostatic (see below), which has not been demonstrated and may not be correct (McKinnon 1997; Schubert *et al.* 2004).

The total gravitational energy released during Pluto’s accretion is larger than the amount required to heat it up to 250 K (Table 1 above). Radioactive decay releases more than twice as much total energy, but the rate of heat release is much slower. Because differentiation requires melting, all that theory can tell us is that differentiation of Pluto is plausible but not assured (McKinnon *et al.* 1997).

However, in addition there are three pertinent observational constraints. The first is that, if Pluto were undifferentiated then as it cooled over time, deeply-buried ice would convert from ice I to ice II (McKinnon *et al.* 1997). The accompanying reduction in volume would lead to compressional tectonics on the surface – which are not observed. Thus, a completely undifferentiated body can be ruled out (and the same goes for Charon).

Second, Charon and Pluto have roughly the same rock mass fraction (see above). Assuming that Charon formed via an impact, if Pluto had been totally differentiated at the time of impact then Charon would be mostly composed of ice (since the impact mainly excavates near-surface material). Because this is not the case, then assuming an impactor composition similar to Pluto’s, Pluto must have been at most partially-differentiated when the impact happened (Canup 2011). Subsequent differentiation could have happened either as a consequence of the impact itself, or due to later heating via radioactive decay.

Last, there is at least circumstantial evidence that Pluto has a subsurface ocean (see below). If so, the high temperatures required suggest complete differentiation.

Overall, it seems almost certain that Pluto consists of separate ice and “rock” layers. Whether a separate, central iron core is also present is unknown. There is no evidence for a core-generated magnetic field (McComas *et al.*

TABLE 1
LIST OF ENERGY SOURCES AND SINKS FOR PLUTO, MODIFIED FROM ROBUCHON & NIMMO (2011).

Energy	Value (J)	ΔT_{eff} (K)	Commentary
Radioactive	1.3×10^{28}	780	Released between 30 Myr and 4.5 Gyr after solar system formation
Accretion	5.7×10^{27}	340	$3GM^2/5R$
Thermal	3.3×10^{27}	210	To warm up Pluto from 40 K to 250 K
Charon-forming Impact	1.5×10^{27}	89	Collision between bodies with radii 1106 and 836 km and densities 1.8 g/cc (<i>Canup</i> 2011) Evaluated using $GM_1M_2/(R_1 + R_2)$
Despinning	9.2×10^{26}	55	To slow down Pluto from 3 h to the present-day period
Latent heat	9.5×10^{26}	55	To melt the top 200 km of water ice
Differentiation	8.4×10^{26}	49	To differentiate into a two-layer structure (<i>Hussmann et al.</i> 2010)

2016). A dynamo can operate if the heat flux extracted from the core exceeds the adiabatic value; scaling the results of *Nimmo and Stevenson* (2000) to the lower gravity of Pluto, the minimum heat flux required is thus roughly $1 - 4 \text{ mW m}^{-2}$. The expected deep mantle heat flux at present is roughly 3 mW m^{-2} (see Fig 2 below), so a dynamo is possible if a liquid iron core exists. More likely, given the relatively modest amount of heat generated during accretion and subsequently (Table 1), is that a dynamo is absent because separation of iron and silicates never occurred, or was sufficiently limited that whatever small core formed is now solid or nearly so.

3.1.4. Shape

In the absence of gravity measurements, the shape of a planetary body can sometimes be used to determine its moment of inertia, and thus constrain its internal structure (*Dermott and Thomas* 1988, e.g.). The main requirement is hydrostatic equilibrium, i.e. that the body has no long-term elastic strength and adopts the shape a fluid body would have.

The shape of a hydrostatic body, in terms of its ellipsoidal axes $a > b > c$, is determined by tidal and rotational parameters and its internal structure as described by the fluid Love number h_2 . Under the assumption of hydrostatic equilibrium, this fluid Love number can be directly related to the moment of inertia via the so-called Radau-Darwin relation (*Munk and MacDonald* 1960).

It can be shown that

$$\begin{aligned}
 a &= R_p h_2 \left[\frac{1}{6} q_{rot} + q_{tid} \right] \\
 b &= R_p h_2 \left[\frac{1}{6} q_{rot} - \frac{1}{2} q_{tid} \right] \\
 c &= R_p h_2 \left[-\frac{1}{3} q_{rot} - \frac{1}{2} q_{tid} \right]
 \end{aligned} \tag{2}$$

where $q_{rot} = R_p^3 \omega^2 / G m_p$ and $q_{tid} = R_p^3 m_s / a^3 m_p$ denote the rotational and tidal potentials. Here R_p and m_p are the body radius and mass, Ω_p is its angular rotation frequency,

m_s is the mass of the tide-raising body and a is its distance. For a synchronous satellite $q_{tid} = q_{rot}$.

In the absence of tidal effects, a hydrostatic planet takes the shape of an oblate spheroid with oblateness $\frac{(a-c)}{R} = \frac{1}{2} q_{rot} h_2$ and $\frac{(a-c)}{(b-c)} = 1$. For a hydrostatic synchronous satellite with $m_s \ll m_p$ the shape is that of a triaxial ellipsoid for which $\frac{(a-c)}{R} = 2 q_{rot} h_2$ and $\frac{(a-c)}{(b-c)} = 4$.

In its present orbital and spin state, a hydrostatic Pluto should be only modestly triaxial with a predicted $\frac{(a-c)}{(b-c)} = 1.32$ and an oblateness of 539 m (0.05%) for $h_2 = 2.5$. The equivalent gravitational flattening, referred to as J_2 , would be about 2×10^{-4} , or roughly 12 mGal at the surface. The actual distortions will be smaller because h_2 is reduced by any degree of central mass concentration. For example, the high and low core density Pluto structures discussed in Sec 3.1.1 above would yield normalized moments of inertia of 0.323 and 0.345, respectively, and fluid h_2 values of 1.88 and 2.04.

The upper bound on Pluto's oblateness of 0.6% is thus consistent with the expected present-day oblateness. At earlier times, when Charon was closer and Pluto was spinning faster, the oblateness would have been larger. Charon's present distance to Pluto is 16.5 Pluto radii; any bulge locked in prior to Charon reaching ≈ 14 Pluto radii should have been detectable by this method (*Nimmo et al.* 2017). Either Pluto's interior was too soft to retain such a fossil bulge, or any initial bulge was later removed (e.g. by an ocean or failure of the lithosphere; see below).

3.1.5. Summary

Pluto has a "rock" mass fraction of $\approx 70\%$ and is probably fully-differentiated at the present day. Because its predicted present-day oblateness (flattening) is too small to detect, no direct estimates of its moment of inertia are available. Significant uncertainties in the silicate porosity, extent of hydrothermal alteration and abundance of organic compounds leave open a fairly wide range of acceptable structural models. **Figure 1** shows three possible models, including one in which an ocean is not present at all.

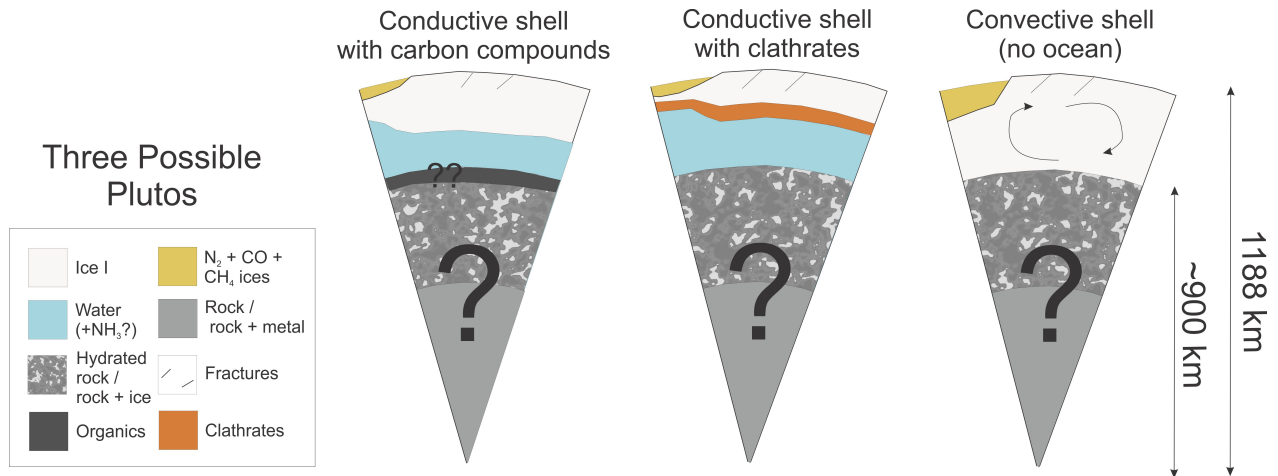


Fig. 1.— Schematic view of three possible Pluto interiors (Sec. 3.1). Interfaces are to scale, except the depth of the surface Sputnik Planitia basin is exaggerated for clarity. Question marks denote inferences (e.g., the presence of carbon compounds) which are uncertain (see text). In the absence of an ocean, the Sputnik Planitia basin would have to be deeper to explain its location (see text).

3.2. Is there an ocean?

Whether or not Pluto has a present-day subsurface ocean is a key question. As discussed below, direct evidence of an ocean is lacking, but there are several circumstantial lines of evidence which point towards such a feature. In Section 5 we discuss how confirmation of such an ocean’s existence could be obtained.

3.2.1. Theory

Table 1 shows that energy produced by radioactive decay comfortably exceeds that required to heat and melt Pluto’s entire ice inventory. The real issue is whether or not this heat can be removed rapidly enough to avoid melting. *Robuchon and Nimmo* (2011) investigated this question in some detail. They assumed a differentiated Pluto with an ammonia-free ice shell very similar to that shown in Fig. 2 and modeled its thermal evolution for different ice basal viscosities. If this viscosity were low enough ($< 2 \times 10^{16}$ Pa s), the ice shell underwent convection and removed heat rapidly enough to remain below the melting point, so that no ocean ever developed. Conversely, with higher ice viscosities the ice shell remained conductive throughout and experienced melting due to heating from below, resulting in an ocean surviving to the present day.

Other groups assumed convection was not operating and investigated whether an ocean could survive. For Pluto, a present-day ocean is a common outcome of models, especially if ammonia (which acts as an antifreeze) is present (*Husmann et al.* 2006; *Desch et al.* 2009; *Hammond et al.* 2016). Although *Hammond et al.* (2016) argued that a sufficiently conductive core could result in the ocean completely refreezing, this appears to be the result of a minor error in their code (see *Biersen et al.* (2018)).

Theory thus permits the existence of a subsurface ocean. But since the ice viscosity depends on the (unknown) grain size, the temperature at which melting begins, and the potential role of silicate fines in the ice (*Desch and Neveu* 2017), an ocean is not *required* (in the sense of being inevitable). Observations are thus required to resolve the issue.

3.2.2. Surface stresses

An important observation is the predominance of extensional tectonic features on Pluto (Sec 2.2). Such extension is commonly observed on icy satellites (*Collins et al.* 2010) and was mentioned as a possibility for Pluto (*Cruikshank et al.* 1997; *Moore et al.* 2015) prior to the *New Horizons* flyby. Particularly for bodies in which higher-pressure ice phases are not involved, a simple explanation of this extension is the partial refreezing of a subsurface ocean. Since ice takes up more volume than water, freezing of an ocean requires the icy surface to move outwards; because it is doing so on a spherical body, this outwards motion automatically produces extension. Thus, the existence on Pluto of relatively young extensional tectonics is consistent with a refreezing ocean.

Furthermore, *Hammond et al.* (2016) argued that complete freezing of an ocean would likely result in formation of ice II and young contractional features (see above); because such features are not observed, they concluded that a subsurface ocean is present now. We note, however, that for a sufficiently large (low-density) core, pressures would not be high enough for ice II stability and so this argument is not conclusive.

In the absence of an ocean, the dominant effect on surface stresses is cooling of the interior, which will lead to present-day compression. Similarly, progressive serpentinization of the silicate core will tend to increase the core

density (Beyer *et al.* 2017; Bierson *et al.* 2018) and lead to overall compression. The absence of recent compression strongly favors the existence of an ocean.

This conclusion is relatively insensitive to different thermal evolution scenarios. If Pluto starts cold, but differentiated, formation of an ocean leads to stresses that are initially compressional. They then switch to extensional as the ocean begins to freeze. If an ocean never develops, the stresses are comparable in magnitude but the sign is opposite: initial extensional followed by later compression, as the interior cools (Robuchon and Nimmo 2011). If Pluto begins life warm, the stresses are monotonically extensional (if an ocean develops), and monotonically compressional (if not). We remind the reader that recent tectonic features are certainly extensional (Sec 2.2), while older features are more ambiguous, and discuss the issue of Pluto’s thermal history further below (Sec 3.4). The apparently young nature of some extensional faults suggests ongoing ocean freezing.

3.2.3. Fossil bulge

Prior to *New Horizons*, the possibility existed that Pluto and/or Charon might preserve a “fossil bulge”, a frozen relic of a distorted shape established earlier in their spin-orbit evolution similar to that seen at Iapetus (Castillo-Rogez *et al.* 2007) or the Moon (Garrick-Bethell *et al.* 2014; Keane and Matsuyama 2014). However, no such bulges were detected (Sec 2.1).

Maintaining a bulge imparted by an earlier, faster spin rate requires a body to be able to withstand the stresses associated with the bulge. This then depends on the thickness and strength of Pluto’s icy lithosphere, and the rigidity of its core if Pluto is differentiated (Robuchon and Nimmo 2011). That no fossil oblateness can be detected for Pluto implies that its icy lithosphere must have been thin and/or weak enough during or after spindown to relax (Singer and McKinnon 2011, *cf.*). Moreover, any oblate core must also have been soft enough to relax. Modelling by Robuchon and Nimmo (2011) showed that the development of an ocean always led to the loss of a fossil bulge. The presence of an ocean would also have accelerated Pluto’s tidal and spin evolution (Barr and Collins 2015); the reduced time available for cooling would have limited the ability of Pluto to freeze in a fossil shape during spin-down. Thus, the absence of an observed fossil bulge is consistent with the presence of an ocean, though it does not require it.

3.2.4. Cryovolcanism?

Cryovolcanic features are typically assumed to require the presence of liquid water, or an ice-water slurry (Kargel 1995), in which case a subsurface ocean would probably be required. However, liquid water is denser than the surrounding water ice crust, thus presenting a barrier to cryovolcanism. One result of partial ocean freezing is to pressurize the water beneath, which can in principle overcome the density barrier (Manga and Wang 2007; Mar-

tin and Binzel submitted). Thus, if the enigmatic features seen south of Sputnik Planitia are indeed cryovolcanoes (Sec 2.2), ocean freezing would be one way to explain their presence. Furthermore, the combination of stresses arising from ocean freezing, true polar wander and loading by the nitrogen ice of Sputnik Planitia shows that substantial tectonic stresses are generated within an annulus around Sputnik Planitia that incorporates Wright and Piccard Montes (Cruikshank *et al.* 2019; McGovern and White 2019), potentially explaining their location. The detection of ammonia at Virgil Fossae (Sec 2.2) could be explained by the eruption of NH_3 -rich material, perhaps driven by pressurization arising from partial ocean freezing.

In short, a present-day subsurface ocean provides a simple (though not unique) explanation for the proposed cryovolcanic features. However, since we do not know the origin of these features, this argument for a subsurface ocean remains provisional.

3.2.5. Sputnik Planitia

A final line of evidence arises from the location of the predominantly nitrogen-filled basin known as Sputnik Planitia (SP). The centre of this basin (roughly 175°E , 18°N) is located close to the anti-Charon point at 0° latitude, 180° longitude. Although this could simply be a coincidence (probability of roughly 5%), an alternative is that SP caused Pluto to reorient such that it moved closer to the anti-Charon point. This reorientation would have generated stresses which are approximately consistent with the orientation of tectonic features around SP (Keane *et al.* 2016). However, in order for such reorientation to occur, SP would have to represent a mass excess, or positive gravity anomaly, despite being a negative topographic feature. Nimmo *et al.* (2016) argued that the most likely way of making a positive gravity anomaly at SP was to invoke a subsurface ocean.

The argument proceeds as follows. SP is lower than the surrounding regions by at least 3 km, which would result in a negative gravity anomaly of about 110 mGal (assuming a surface density of 0.9 g/cc). Nitrogen ice is denser than water ice by about 0.1 g/cc, so this negative gravity anomaly could be just overcome if the nitrogen layer were about 27 km thick. As explained in Sec 2.3.1, such a layer would imply a convective aspect ratio significantly less than that expected based on the (admittedly poorly-known) nitrogen ice rheology.

Since the density contrast between water and ice is also about 0.1 g/cc, an ice shell thinned by 27 km beneath the SP basin can also provide the required gravity anomaly if an ocean is present. Numerical models (Johnson *et al.* 2016) show that shell thinning by 20–60 km is expected for an SP-forming impact. In this picture the SP basin is isostatically compensated immediately after the impact (*i.e.*, the gravity anomaly is ~ 0). The lithosphere then cools and is subsequently loaded with nitrogen, in a manner analogous to the mascon basins on the Moon. The final gravity anomaly then depends on the nitrogen thickness d and the lithospheric

elastic thickness. Although neither is known, a nitrogen layer 5 km thick would yield a surface gravity anomaly of about +200 mGal if the lithosphere were infinitely rigid.

Additional evidence that SP is a positive gravity load comes from the radial orientation of multiple normal fault valleys surrounding Sputnik (*Keane et al.* 2016). Such a fault pattern is expected for a positive load on a spherical shell or lithosphere when the horizontal scale of the load is sufficiently large (*Janes and Melosh* 1990).

Keane et al. (2016) point out that an impact redistributes mass from the centre to the periphery, in the form of an ejecta blanket and crustal thickening. Depending on the details of this redistribution, if no mass is lost it can result in a positive gravity anomaly at spherical harmonic degree-2 (which is what matters for reorientation), without requiring any additional effects. But mass can be lost (either vapourized, or ejected from Pluto). So whether or not an ocean is really required depends on how mass was redistributed during the impact, and the non-negligible mass contribution from the impactor itself. This question can be addressed using a combination of existing topographic data (*Schenk et al.* 2018b) and models (*Johnson et al.* 2016). At present, it seems almost certain that SP caused reorientation, and likely (but not certain) that an ocean was required.

3.2.6. Summary

Thermal evolution models permit a present-day ocean to exist, but do not require it. Four observations – extensional tectonics, cryovolcanism, absence of a fossil bulge, and the location of Sputnik Planitia – can all be explained if Pluto has a subsurface ocean. None of these observations *requires* such an ocean to be present, and each can be explained by alternative processes. Nonetheless, taken together it seems probable, although not certain, that Pluto does indeed possess a subsurface ocean at present. A corollary is that the ice shell above is conductive, rather than convecting.

3.3. What is the ice shell structure?

3.3.1. Temperature structure

Considering the range of possible interior models outlined above, it is possible to infer some aspects of the temperature structure of Pluto. **Figure 2a** shows one possible present-day Pluto temperature structure, taken from the model shown in Fig 1 of *Bierson et al.* (2018). In this model, the core is heated by radiogenic decay but is probably not convecting, though advection of heat via fluid circulation might be important (see below). The ice shell is about 200 km thick and conductive, with an ocean about 150 km thick beneath. The conductive core is close to the melting point (≈ 1400 K for peridotite) at its centre.

Fig 2b shows the ice shell temperature structure in more detail. The curvature of the profile arises because ice has a thermal conductivity that varies as $1/T$; the inflection point at 60 km depth (100 K) signals the transition from shallow, low-conductivity porous ice to deeper, pore-free ice. The main uncertainties in these models are the conductivity val-

ues assumed: that for ice depends on the porosity (discussed in more detail below), while that for the core is uncertain (*Hammond et al.* 2016) and may be effectively increased by hydrothermal circulation.

The profile shown in Fig 2b has two important implications. The first is that the ice shell of Pluto is strong. Ice typically behaves elastically at low temperatures and viscously at high temperatures. Calculations presented in *Conrad et al.* (2019) suggest that the base of the elastic layer on Pluto should occur at a temperature of 118 ± 15 K. Comparison with Fig 2b shows that the elastic layer will be roughly 100 km thick. This estimate is uncertain because of factors such as porosity (which will weaken the ice), yielding, and what strain rate to use. Nonetheless this result indicates that the present-day ice shell should have little difficulty in supporting topographic loads.

The second, paradoxically, is that the base of the ice shell is too warm. First, ice at 270 K typically has a viscosity of 10^{13-14} Pa s, less than the minimum required to permit ice shell convection (Sec 3.2.1) and implying that the lower portion of this shell could be convective (*McKinnon* 2006). Second, an ice shell this warm will flow rapidly so as to erase any lateral variations in shell thickness. The timescale for such lateral flow depends on the wavelength over which flow occurs, the viscosity at the base of the shell η_b , and the effective channel thickness over which flow occurs (*Stevenson* 2000). Because it was argued above that Sputnik Planitia represents an area of significantly thinner ice, we need to be able to maintain these shell thickness variations. This in turn requires a high ice viscosity at the base of the shell (where flow will occur).

One possible way of maintaining a high-viscosity shell is to require a very cold ocean. Because η_b depends on the temperature at the ice-ocean interface, a sufficiently cold ocean will shut down lateral flow. For the same heat flux, a thinner ice shell will also result. However, *Nimmo et al.* (2016) found that the ocean had to be 200 K or colder to avoid lateral flow (this would also prevent convection). Such a temperature requires an ocean with an NH_3 concentration of around 25 wt% (*Leliwa-Kopystyński et al.* 2002). Even for an initial NH_3 bulk composition of 5 wt% (*McKinnon et al.* 2008), such a high value is difficult to achieve and would require almost complete ocean freezing (at least 80%). In addition, such an amount of NH_3 would so reduce the ocean density that its ability to produce a positive gravity anomaly would be eliminated.

A perhaps more attractive alternative is to invoke a layer of clathrates (*Kamata et al.* 2019). Because clathrates have a thermal conductivity almost an order of magnitude lower than that of regular water ice, even a thin clathrate layer can greatly change the ice shell temperature structure. Fig. 2b shows that the result is a large temperature drop across the clathrate layer, resulting in a shell that is thinner (dotted line) and an ice portion that has a much lower basal temperature (in this case 150 K as opposed to 270 K for the clathrate-free case). Lateral flow in such an ice shell is not significant over the age of the solar system.

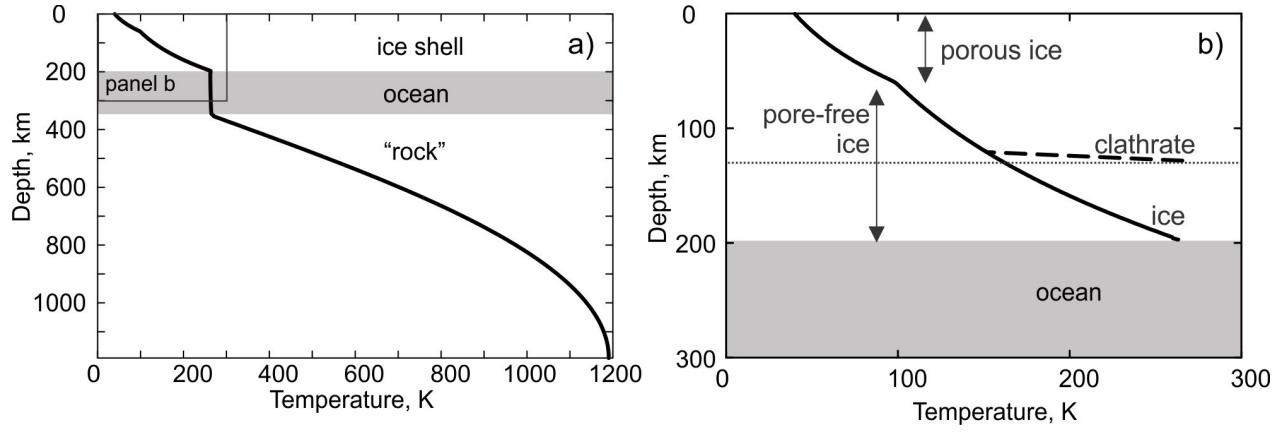


Fig. 2.— Possible present-day Pluto temperature structure, taken from the model shown in Fig. 1 of *Bierson et al.* [2018]. a) Overall view of temperature profile. b) Inset showing ice-shell temperature profile. The curvature arises because conductivity is temperature-dependent, and the slope break denotes the transition from porous to pore-free ice. The dashed line indicates the profile if a thin basal layer of clathrates is present (Sec. 3.3.1), resulting in a thinner ice shell overall (dotted line).

An additional implication of the clathrate hypothesis is that it may naturally explain the relative paucity of CO in Pluto’s atmosphere compared to N_2 (*Glein and Waite* 2018). Because CO clathrates form more readily than N_2 clathrates when multiple guest molecules are involved (*Mousis et al.* 2012), the low relative abundance of atmospheric CO may be a natural outcome of the clathration process (see MCKINNON ET AL.). Clathrates have also been invoked as a way of removing noble gases from Pluto’s atmosphere (*Mousis et al.* 2013).

3.3.2. Heat flux and elastic thickness

As noted above, the temperature structure of the shell depends on the heat flux and conductivity structure. For ice, which has a thermal conductivity that varies as roughly k_0/T with k_0 ($\approx 567 \text{ W m}^{-1}$) a constant (*Klinger* 1980), we may write

$$F = k_0 \frac{\ln(T_b/T_s)}{d} \quad (3)$$

where d is the total shell thickness, T_b and T_s are the surface and basal temperatures and here we are neglecting sphericity.

The mean effective thermal conductivity of the shell will be reduced in the presence of either a near-surface porous layer or a clathrate layer at the base. Porosity may gradually decrease due to annealing (*Bierson et al.* 2018). Independent of this effect, clathrates are likely to grow with time (*Kamata et al.* 2019). The consequences can be pronounced: a clathrate layer 10 km thick with a conductivity one-tenth of that of ice would reduce shell thickness from 200 km to 138 km (cf. Fig. 2b).

Once the temperature structure of the ice shell is known, its mechanical properties can be predicted. As argued above

(Sec 3.3.1), by taking the base of the elastic layer to be defined by a particular temperature, the elastic thickness T_e of the ice shell can be deduced from the heat flux, or vice versa.

Figure 3 plots the expected relationship between heat flux (log scale) and T_e . The shaded region shows the expected surface heat flux arising from radioactive decay, with the lower limit being the expected present-day value of $\approx 3 \text{ mW m}^{-2}$. For a Pluto with a porous, low-conductivity surface layer (dashed lines) the expected present-day elastic thickness is then roughly 100 km, which agrees with Fig. 2a, while it could have been as low as 50 km at earlier times.

Fig 3 also shows the lower bound on T_e of 10 km inferred by *Conrad et al.* (2019) based on the absence of rift-flank uplift observed (Sec 2.3.2). This is not a strong constraint, but is at least consistent with the expected (radiogenic) heat flux. Also shown on Fig 3 is the heat flux in excess of 50 mW m^{-2} indicated by the apparently relaxed 145 km diameter crater Edgeworth (Sec 2.3.3). This is not remotely consistent with the expected radiogenic heat flux, and only marginally (at best) with the absence of rift flank uplift.

3.4. How has Pluto evolved over time?

Icy satellites can experience complicated and non-monotonic thermal histories, because of tidal heating arising from proximity to a much more massive primary (*Hussmann and Spohn* 2004, e.g.). Pluto does not suffer from this complication. Nonetheless, our relative ignorance of its present-day structure and (even more so) its initial conditions make consideration of Pluto’s thermal evolution fraught with uncertainty.

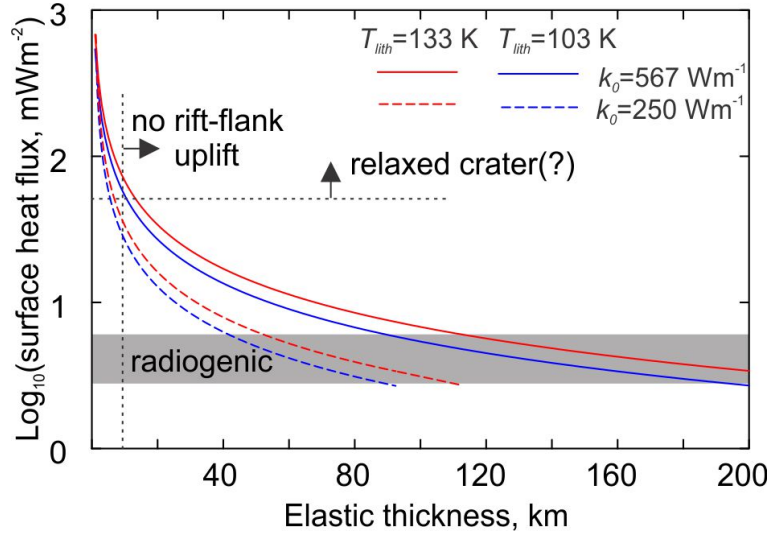


Fig. 3.— Relationship between heat flux and elastic thickness (Sec. 3.3.2). The temperature defining the base of the ice shell is denoted T_{lith} . Conductivity is calculated by k_0/T where k_0 is a constant chosen to represent either pore-free or porous ice. The shaded region denotes the expected heat flux range over Pluto’s history from radiogenic elements. The two dashed lines denote observational constraints derived from the absence of rift-flank uplift (Sec. 2.3.2) and the presence of one relaxed crater (Sec. 2.3.3).

Pluto probably experienced a fairly dramatic early history: a Charon-forming impact, followed by completion of differentiation, despinning and tidal bulge collapse (Barr and Collins 2015) as Charon moved outwards. However, we see no fossil bulge and no tectonic features obviously associated with despinning: in short, no evidence of this early history. This is most likely for three reasons. First, Pluto has a “short memory”: the conductive timescales of the core and shell are sufficiently short that present-day conditions are very insensitive to the initial conditions (Nimmo and Spencer 2015). Second, the energy budget of Pluto is dominated by radioactive decay, rather than these early processes (Table 1), so their influence would in any case have been limited. Third, Pluto’s active surface geology (WHITE et al.) has likely served to erase or obscure its earliest tectonic signatures.

Nonetheless, we can make two deductions. One relies on ^{26}Al : if Pluto had formed early enough (within roughly the first 5 Myr), heating from ^{26}Al decay would have ensured complete differentiation. But since Charon’s composition requires an incompletely-differentiated proto-Pluto (Sec 3.1.3), the Charon-forming impact would have to have occurred in a very narrow time window. More likely, Pluto formed after ^{26}Al was extinct, as Bierson and Nimmo (2019) concluded for Kuiper Belt Objects in general. The other deduction has to do with the absence of compressional features (Sec 2.2). A Pluto that began frozen and then formed an ocean would have experienced early compression, and then later extension (Robuchon and Nimmo 2011; Hammond et al. 2016). Although these early features might

have been overprinted, and in any case are often harder to identify than extension, the absence of compression hints that Pluto might have started hot and then gradually cooled down. On the other hand, Table 1 makes it clear that a hot start is not assured, and depends in particular on the details of Pluto’s accretion.

Figure 4 shows an example “cold-start” Pluto evolution (albeit one in which full differentiation is assumed), from Hammond et al. (2016). Radioactive decay warms the core; heat transferred out of the core causes the ice to melt, resulting in initial compression. The ocean reaches a maximum thickness at about 2 Gyr and then begins to refreeze, transitioning to extensional tectonics at about 1 Gyr B.P. In this model the present day heat flux is about 3 mW m^{-2} and the present-day ocean thickness about 50 km. If an insulating clathrate layer grew, this cooling and thickening will have been slower than in the clathrate-free models, delaying the onset of surface activity and resulting in a thicker ocean at the present day.

Assuming an ocean exists, the high temperatures predicted for Pluto’s core (Fig 2a) suggest that reactions would take place between the rock, water and any organics present, as long as there is some permeability present. By analogy with other ocean worlds like Enceladus or Europa, one would expect a salty ocean to develop (Zolotov 2007). Whether such salts could be detectable in any cryovolcanic deposits is an open question. Outgassing of gaseous species initially trapped in the interior is also likely, unless they were sequestered by clathration (Mousis et al. 2013; Kamata et al. 2019) or converted to other, more stable forms

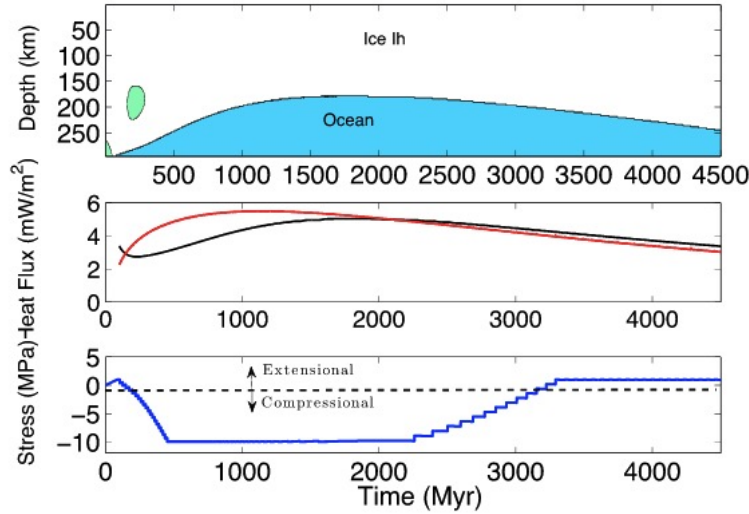


Fig. 4.— “Cold-start” Pluto thermal evolution model, from *Hammond et al.* [2016]. Top panel shows ice shell thickness evolution, with green blobs indicating where ice II is stable. Middle panel shows heat fluxes out of the core (red line) and at the surface (black line). Bottom panel shows predicted surface stresses.

(*Glein and Waite* 2018).

Another consequence of water-rock interactions is that the core might lose its heat more effectively than simple conductive models (Fig 2a) assume. The importance of such advection depends on the unknown permeability of the core, but the effect on Pluto’s overall evolution may be significant (*Gabasova et al.* 2018) and is certainly worth further study. Furthermore, if the core can dehydrate, then higher temperature processes may be possible (graphitization of organics, smelting of sulphides, etc.).

4. PLUTO AND CHARON IN CONTEXT

An important question is how Pluto and Charon compare with the icy moons orbiting the giant planets of the outer solar system. Perhaps the most important difference is that Pluto and Charon are not subjected to large tidal stresses and heating, which can be a major driver for geological activity among the moons. Triton is thought to be a captured dwarf planet from the Kuiper Belt, but it was exposed to massive tidal heating during the capture process (*Goldreich et al.* 1989).

Figure 5 is a summary plot of the inferred structures of a variety of icy worlds, including Pluto and Charon (for a review on how these structures are determined, see (*Nimmo and Pappalardo* 2016)). A rock:ice ratio of 2:1 by mass is roughly correct for many of the moons, as well as Pluto and Charon. Exceptions include Tethys, which appears to be almost pure ice and may be a relic of a disruptive impact (*Asphaug and Reufer* 2013), and Europa, which may have been volatile-depleted by tidal heating or forming in a warm part of the proto-satellite disk (*Canup and Ward* 2009). Triton is only slightly denser than Pluto, suggest-

ing that volatile loss driven by tidal heating was limited at least in this case. Although we have only very limited information on the structures of other KBOs, their inferred densities suggest a generally similar rock:ice ratio to that of Pluto (*Biersen and Nimmo* 2019).

As reviewed in *Schubert et al.* (2004) and *Nimmo and Pappalardo* (2016), the only icy world known to be fully differentiated is Ganymede, with an active dynamo that indicates an iron core. Europa and Enceladus have ice shells overlying oceans, with a deeper interior that is presumed to be mostly rock; it is not known if an iron core is present. At both Titan and Callisto, it is possible that the rock and ice have not fully separated. However, this conclusion is quite uncertain: we don’t know if Callisto is hydrostatic (Sec 3.1.3), while Titan is close to, but not exactly, hydrostatic (*Durante et al.* 2019). Furthermore, a measured moment of inertia is non-unique in terms of possible internal structures. Triton is presumed to be differentiated due to ancient tidal heating, but there is no direct evidence for this.

As reviewed in *Nimmo and Pappalardo* (2016), the three Galilean satellites plus Titan are all thought to have subsurface oceans maintained by a combination of tidal and radiogenic heating. Enceladus’s ocean can only be maintained by tidal heating because the radiogenic contribution is negligible. Triton, being almost identical in size and density to Pluto, could in principle maintain an ocean, but there is no direct evidence for one. Smaller moons like Dione might also possess present-day oceans (*Zannoni et al.* 2019).

There is a general expectation that more volatile materials are likely to condense and survive at greater distances from the Sun. The Jovian satellites show no obvious signatures of NH_3 , while measurements of Titan’s atmosphere (*Niemann et al.* 2005) and the plumes of Enceladus (*Waite*

et al. 2009) indicate it is present in Saturnian satellites. The fact that Pluto possesses large surface reservoirs of volatile materials (N_2 , CH_4 , CO) not stable at the inner moons is in accordance with this expectation. Clathrates (Sec 3.3.1) have been proposed as a driver of Titan’s evolution (*Tobie et al.* 2006). Except at Enceladus, however, direct evidence of the chemistry of subsurface oceans is presently almost non-existent.

5. GOING FORWARDS

5.1. Near-term advances with existing data

Although a fair amount has already been gleaned from the existing observations, there are several areas where more work could be done.

Getting better constraints on heat flux, and how it has changed with time, is an obvious topic. Apparently relaxed craters (Sec 2.3.3) represent one option, and so does flexure at SP (Sec 2.3.2) or elsewhere. Perhaps other aspects of crater morphometry or topography can also be used to deduce surface heat fluxes and/or mechanical properties.

The interaction between atmospheric, geodynamic and rotational processes driven by SP over a variety of time-scales has seen some study (*Keane et al.* 2016; *Bertrand et al.* 2018) but more could be done. For instance, the fact that SP is so flat, despite removal and addition of nitrogen in different locations (*Bertrand et al.* 2018), might be used to deduce a lower bound on the thickness of the material there.

This of course raises another topic – that of nitrogen (and methane) rheology. Some of our current uncertainty arises from ignorance of how these materials deform; more measurements are critical (UMURHAN ET AL.).

Last, the interaction between chemistry and geophysics at Pluto is likely to be a fruitful field (*Neveu et al.* 2017; *Glein and Waite* 2018). For instance, the suggestion that clathration is responsible for the lack of atmospheric CO (*Kamata et al.* 2019) emphasizes the point that atmospheric evolution is tied to processes in the interior (*Stern* 1989). Similarly, the role of water-rock interactions on Pluto’s overall thermal evolution (Sec 3.4), and how they might influence the putative ocean (salts?) and atmosphere (outgassing) have so far barely been explored.

5.2. Future Missions

Looking further ahead, a Pluto orbiter would be desirable, and is achievable with current propulsion systems (*Finley et al.* 2019). However, as *Howett et al.* (2020) document, Pluto is a challenging geophysical target: standard ways of probing for an ocean, such as measuring the tidal response (*Moore and Schubert* 2000) or looking for an induction signature (*Zimmer et al.* 2000), will not work. On the other hand, the idea of SP being a positive gravity anomaly (Sec 3.2.5) is eminently testable, while measuring the static gravity or topography should yield a moment of inertia (Sec 3.1.4). Probing the N_2 plains with sounding radar could determine their thickness, while measuring

atmospheric ^{40}Ar (a decay product of ^{40}K) would place an important constraint on time-integrated outgassing from the silicate interior.

6. SUMMARY

Despite the wealth of data returned by *New Horizons*, studies of Pluto’s interior are still in their infancy, and we can say very little with certainty. Pluto is $\approx 70\%$ “rock” by mass with the remainder some mix of ice and carbon compounds, and Charon does not need to have a different bulk composition. We can rule out an undifferentiated Pluto based on the apparent absence of compressional features. Four lines of circumstantial evidence point towards a present day ocean roughly 50-150 km thick: extension; possible cryovolcanism; no detectable fossil bulge; and Sputnik Planitia. However, none of them is definitive. If an ocean exists (which we think is likely but not certain), the ice shell above must be cold and rigid. Although this could be due to an ammonia-rich ocean, a perhaps more likely possibility is a layer of clathrates at its base (or distributed throughout). The ocean may have been present since Pluto formed, or it may only have appeared hundreds of Myr later as radioactive heat built up. The ocean reached a maximum thickness mid-way through Pluto’s evolution; it subsequently slowly thinned and the ice shell thickened – driving extension and perhaps cryovolcanism – while reactions between the warm silicate core and the overlying ocean continued.

Our understanding of geodynamics on Pluto is still primitive. Nonetheless, Pluto has certainly shown itself to be far more interesting than expected, expanding the range of likely ocean worlds out to 40 AU. The Kuiper Belt is likely a menagerie of similarly fascinating worlds, and we eagerly await the next opportunity to take a close-up look.

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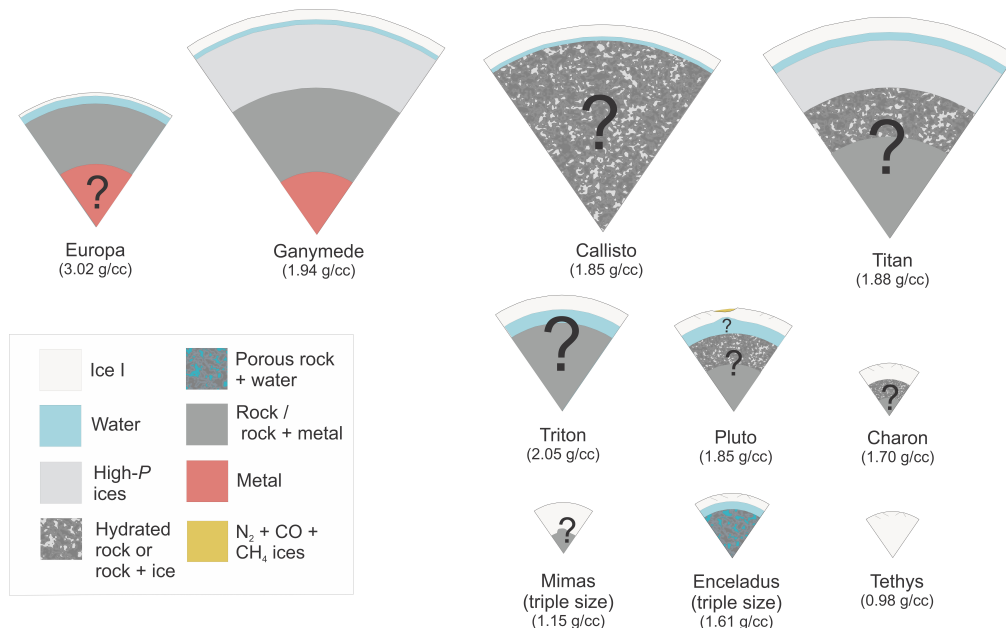


Fig. 5.— Pluto compared with other icy worlds. All these bodies are to the same relative scale, except for Mimas and Enceladus. Question marks denote uncertainties in structures depicted (see text).

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