THE PLAUSIBILITY OF AN OCEAN ON PLUTO SHORTLY AFTER ACCRETION

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Introduction: Models of the thermal history of Pluto have generally started by assuming that shortly after accretion Pluto was a mix of silicates and cold water ice [1, 2]. These models then predict that Pluto would experience a period of warming and compression as a liquid ocean forms, followed by extension as the ocean refroze. With the wealth of data returned from the New Horizons flyby the first geologic interpretations have been performed [3, 4, 5]. These analyses have found evidence for widespread extension, but not the compression that is expected from the initial formation of a subsurface ocean. In this work we explore the implications and plausibility that Pluto developed an ocean during or shortly after accretion.

Thermal Models: In this work we use the Pluto thermal evolution model of Bierson et al. [6]. This model assumes a differentiated Pluto and conductive ice shell. We include long-lived radiogenic material and neglect second order effects such as mineral alteration, hydrothermal circulation through the core, and early tidal heating.

In this work we compare two different model initial conditions. The “Cold Start” case is comparable to previous thermal models. We use an initial temperature of 300 K in silicates and 200 K in ice. This is contrasted with the “Hot Start” case with 300 K in silicates plus an ocean that is just above the melting temperature. The model parameters used are those from Bierson et al. [6] except for the ice density ($920\ \mathrm{kg\ m^{-3}}$) and core density ($3000\ \mathrm{kg\ m^{-3}}$).

The resulting thermal evolution for these two different cases are shown in Figure 1. Both cases finish with an ocean of similar thickness since the conductive timescales are much less than the age of the solar system. The key difference between these two cases is the strain history shown in panels c) and d) of Figure 1. The “Cold Start” case has an initial period of compression as the ocean forms and later transitions to extension during refreezing. In contrast, the “Hot Start” case has an initial period of rapid extension, and then a pause, before a longer period of slower extension.

Geologic Observations: Given these two scenarios for Pluto’s evolution, we consider which is better supported by the existing geologic observations. Evidence of recent extension is abundant on Pluto. In particular, there are a set of prominent graben west of Sputnik Planitia that show little degradation and overprint other features such as craters [3]. One of these graben is associated with surface deposits of NH_3, which degrades over geological time [7]. This all supports recent extension on Pluto.

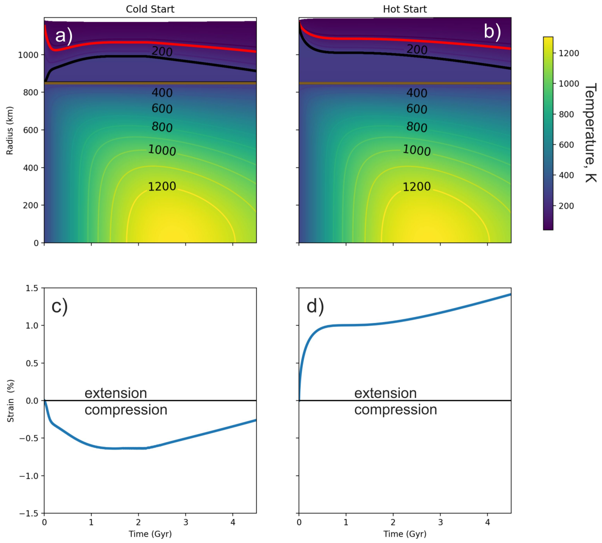

Figure 1: a) “Cold Start” Pluto model. Solid brown line indicates top of rocky core and black line top of ocean. Red line indicates the nominal base of the elastic layer, at 120 K (see text). b) “Hot Start” Pluto model with an initial ocean and an ice shell 6.5 km thick. c) Evolution of net linear strain due to thermal expansion/contraction and freezing/melting of ice, for the “Cold Start” model. Here compression is negative. d) Same as c) but for “Hot Start”.

The most definitive test to discriminate between these two models would be clear, ancient, tectonic structures. Crater statistics suggests the oldest parts of Pluto’s surface have ages of >4 Ga [8], even given the uncertainties in the ancient impact flux. In these ancient terrains however, the evidence for extension is ambiguous. The best candidate is the degraded NNE-SSW trending “ridge-trough system” (RTS) [5] which is a likely an ancient tectonic feature. While this feature appears largely extensional, the high degree of degradation makes interpretation difficult. Further work should be done to characterize the strain history of Pluto as has already been done for Charon [9].

Process of accretion: In this section we examine the conditions during accretion and plausibility that Pluto could have developed an ocean shortly after formation. Numerical models of the Charon-forming impact produce only modest heating for Pluto, but these simulations only cover a small portion of parameter space[10]. During Pluto's accretion the main energy sources are gravitational energy and heat released by ^{26}Al decay. An important constraint on this is the very low observed density of small Kuiper Belt Objects (KBOs). In Bierson and Nimmo [11] we argued that these low densities require high porosity that could not be maintained if ^{26}Al had been present. This conclusion has been independently reached by other authors [12, 13]. This leaves the gravitational heat of accretion as the only likely energy source for an early ocean.

The gravitational energy ΔE deposited during accretion of a uniform body is given by

$$\Delta E = M\left(\frac{3}{10}v_{esc}^2 + \frac{1}{2}v_\infty^2\right) \tag{1}$$

where M is the final mass, v_{esc} is the final escape velocity ($= \sqrt{2GM/R}$), R is the final radius, G is the gravitational constant and v_∞ is the velocity of the impactors at infinity. If all this energy is retained as heat, the mean temperature change ΔT is

$$\Delta T = \frac{3}{10}\frac{v_{esc}^2}{C_p}\left(1+\frac{5}{3}f^2\right) = 330\text{ K }(1+\frac{5}{3}f^2) \tag{2}$$

where C_p is the mean specific heat capacity and the factor f compares v_∞ to v_{esc}: $v_\infty = f v_{esc}$. The numerical quantities are obtained by assuming v_{esc}=1.2 km/s and $C_p = 1300$ J/kg K [1]. In the late stages of accretion, excitation of planetesimal eccentricities by embryos results in $v_\infty \approx v_{esc}$ ($f \approx 1$) [14, e.g.], while in situations where gas or dynamical friction damps eccentricities, $f \approx 0$. Equation (2) shows that if all the energy is retained as heat, a Pluto possessing an initial liquid water ocean is inescapable.

In reality however, much of the delivered energy may be lost to space via blackbody radiation. We can construct a very rough estimate how fast accretion would have to occur to produce an initial ocean. We do this by calculating the amount of time it would take for the radiated energy to equal the energy of accretion for a given surface temperature (T_S). This is given by

$$\tau = \frac{R\rho v_{esc}^2}{10\sigma T_s^4}\left(1+\frac{5}{3}f^2\right) = 30kyr\left(1+\frac{5}{3}f^2\right) \tag{3}$$

where ρ is the bulk density, σ is Stefan's constant, v_{esc} refers to the escape velocity for the final mass and the numerical value was obtained by setting T_s=270 K. While this is only an order-of-magnitude level calculation at best, we can conclude that if Pluto formed with a timescale $<$30 kyr, then a hot start is assured. While the formation of Pluto likely occurred in several stages, such a fast accretion timescale is consistent with a scenario of initial gravitational collapse followed by pebble accretion [15, 16].

Conclusions: In this work we compare two possible initial conditions for Pluto's thermal state; a "Cold Start" where it initially formed with a mix of rock and ice and a "Hot Start" where it had a liquid water ocean shortly after formation. We argue that the observed extensional tectonics on Pluto, and lack of compressional features, favor this "Hot Start" scenario. We find that it is plausible that Pluto could have an ocean shortly after formation solely from the gravitational energy of accretion. This would imply that other large KBOs should also have had oceans shortly after formation.

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