THE TIDAL-THERMAL EVOLUTION OF THE PLUTO-CHARON SYSTEM

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Introduction. The New Horizons mission found indications that Pluto is likely to harbour a subsurface ocean beneath its ice-covered surface, whereas this is no longer the case for Charon. The possibility that both bodies are able to sustain a liquid ocean beneath an icy cover enhances their status as prime targets for the search for extra-terrestrial life. For an ocean to form and remain liquid, the presence of long-lived heat sources is required, of which radioactive and tidal heating are the most significant contributors [1-2]. Consequently, understanding the long-term thermal and tidal evolution of planetary systems is a central tenet in evaluating the possibility for the existence of a present-day subsurface ocean and, in turn, the astrobiological potential of the outer Solar System [3,4].

The role of tidal heating in the evolution of Kuiper belt Objects, including Pluto-Charon, was found to be comparable to and even higher than the heat produced by the radioactive decay of long-lived isotopes. It was observed [2] that subsurface oceans containing a small amount of impurities and tidal heating due to initially high spin rates may enable liquid water and cryovolcanism to persist until the present [5-6]. Here, we study the evolution of the Pluto-Charon system by combining a comprehensive tidal model that incorporates a proper viscoelastic description of the tidal response of planetary bodies [7] with a thermal evolution model that tracks the temperature change in the interior over ~4.5 Gyr to assess the possibility for subsurface oceans in Pluto and Charon [8].

Methodology. The two bodies are presently tidally locked to each other, i.e., their spin periods are equal to their orbital period around their center of mass, ensuring that each always presents the same face to the other, and their respective orbits about the center-of-mass are almost perfectly circular.

Thermal evolution. The heat sources dominating the thermal evolution of Pluto and Charon are radiogenic heating in the silicate parts and tidal dissipation in the ice shell. The evolution of the ice shell is computed based on the energy balance between 1) the heat produced in the silicate part (radiogenics) and entering the ice shell from below; 2) the heat produced in the shell (tides and crystallization/melting of ice); and 3) the heat that can be transported from within the ice shell to the surface. In the ice and water layers we model thermal evolution using the parameterized convection model of [9]. This approach uses scaling laws derived from simulations of thermal convection to estimate the average temperature within the ice layer and the heat flux at its bottom. The growth of the ice shell (thickness) is then estimated from the difference between the heat flux coming from the silicate part (hereinafter core) and the heat flux entering the ice shell. We also take into account the presence of impurities within the subsurface ocean which can affect the thermal evolution of these bodies by lowering the melting temperature of the ice shell and thereby changing its crystallization behaviour. The heat flux at the top of the core is obtained by modeling its thermal evolution, which is governed by solving the time-dependent heat diffusion equation following the approach of [10]. We assume that the core has a carbonaceous chondrite composition and consider four radioactive elements: $^{235}$U, $^{238}$U, $^{232}$Th, and $^{40}$K. The averaged radial temperature profile of the core and the heat flux at its top are calculated by solving the heat diffusion equation.

Tidal evolution. The tidal evolution of Pluto and Charon consists of expansion of the post-impact orbit of the satellite around the dwarf planet, concomitantly with damping of the initially highly eccentric orbit and de-spinning of both objects from initially higher spin rates. Here, we extend the tidal evolution model of [7] to include the case of non-synchronous rotation, which builds upon the extension of the Darwin-Kaula tidal model [11] through the use of higher-order eccentricity functions and harmonic modes. We combine the tidal evolution model with a visco-elastic rheology (Sundberg-Cooper) to properly account for dissipation in ice and silicate core.

Results. A “nominal case” is chosen among the simulations that matches the present-day observed orbital parameters. Initial orbital parameters employed are eccentricity $e \sim 0.4$, semi-major axis $a \sim 0.65 a_p$, and ~5 times the initial mean motion, corresponding to a rotation period of ~10 hr, where $a_p$ is the present-day observed semi-major axis. Figure 1 shows the evolution of the spin rates of the two bodies, the semi-major axis of the orbit, the orbital eccentricity, and the tidal heat generated in each of the objects.

Figure 1a shows that the tidal evolution of the binary system occurs ($\theta/n = 1$) in $\sim 2 \times 10^5$ years. Charon
reaches the stable 1:1 spin-orbit resonance state ($\dot{\theta}/n = 1.5$) after $\sim 10^4$ years. Figure 1b displays the heat generated in the two bodies due to both tidal and radiogenic heating. Our results (Figure 2) show that for the nominal case, Pluto is very likely to harbor a present-day ocean overlain by a conductive ice shell, whereas the ocean on Charon, although present up until $\sim 3.5$ Gyr, has refrozen completely. Several parameters play an important role in the thermal evolution of Pluto and Charon, including reference viscosity, core size, initial thermal state, and ocean contaminants. Figure 2 shows the sensitivity of the results, i.e., the evolution of the subsurface oceans on Pluto and Charon, to these parameters. Convection is very sensitive to viscosity and its variations with temperature. A high viscosity opposes the flow, reducing the strength of convection, while temperature-dependent viscosity triggers stagnant-lid convection, which alters the heat transfer. In our computations, the reference viscosity $\eta_{\text{ref}}$ controls the bulk viscosity of the ice shell. Figure 2 displays the evolution of ocean thickness on Pluto and Charon for several different values of reference viscosity $\eta_{\text{ref}}$: $10^{12}$, $10^{14}$, and $10^{16}$ Pa s. Clearly, $\eta_{\text{ref}}$ has a strong impact on ocean thickness, in that larger viscosities generally result in a slower cooling as convection weakens, which increases the longevity and the thickness of the ocean layer. For all considered values of $\eta_{\text{ref}}$, Subsurface oceans on Pluto may survive until the present day, while the initially-formed oceans on Charon have all re-solidified.

The presence of impurities reduces the temperature at the bottom of the ice shell, which increases the bulk viscosity and thus reduces the vigor of convection. To evaluate the importance of this effect on the evolution of Pluto and Charon, we vary the initial fraction of ammonia in the range 1–5 wt%. The results are shown in Figure 2 for both bodies. Two conclusions may be drawn: 1) regardless of impurity content, a subsurface ocean is always present on Pluto at the present day, and 2) oceans also form on Charon, but completely solidify after $\sim 3.5$–4 Gyr. Between the various cases, ocean thicknesses on Pluto and Charon range from $\sim 10$–50 km and $\sim 40$–120 km, respectively.

References:[1] Robuchon and Nimmo, Icarus, 2011. [2] Saxena et al., Icarus, 2018. [3] McKinnon et al., Icarus, 2006. [4] Vance et al., Astrobiology, 2007. [5] Neveu et al., Icarus, 2015. [6] Beyer et al., Icarus, 2019. [7] Bagheri et al., Nat. Astronom, 2021. [8] Bagheri et al., Icarus, in press, 2022. [9] Deschamps and Vilella, JGR Planets, 2021 [10] Samuel et al., Nature, 2019. [11] Boué and Efroimsky, Celest. Mech. Dyn. Astron. 2019.