

# Thermal and Tidal Evolution of Neptune with a Growing Frozen Core

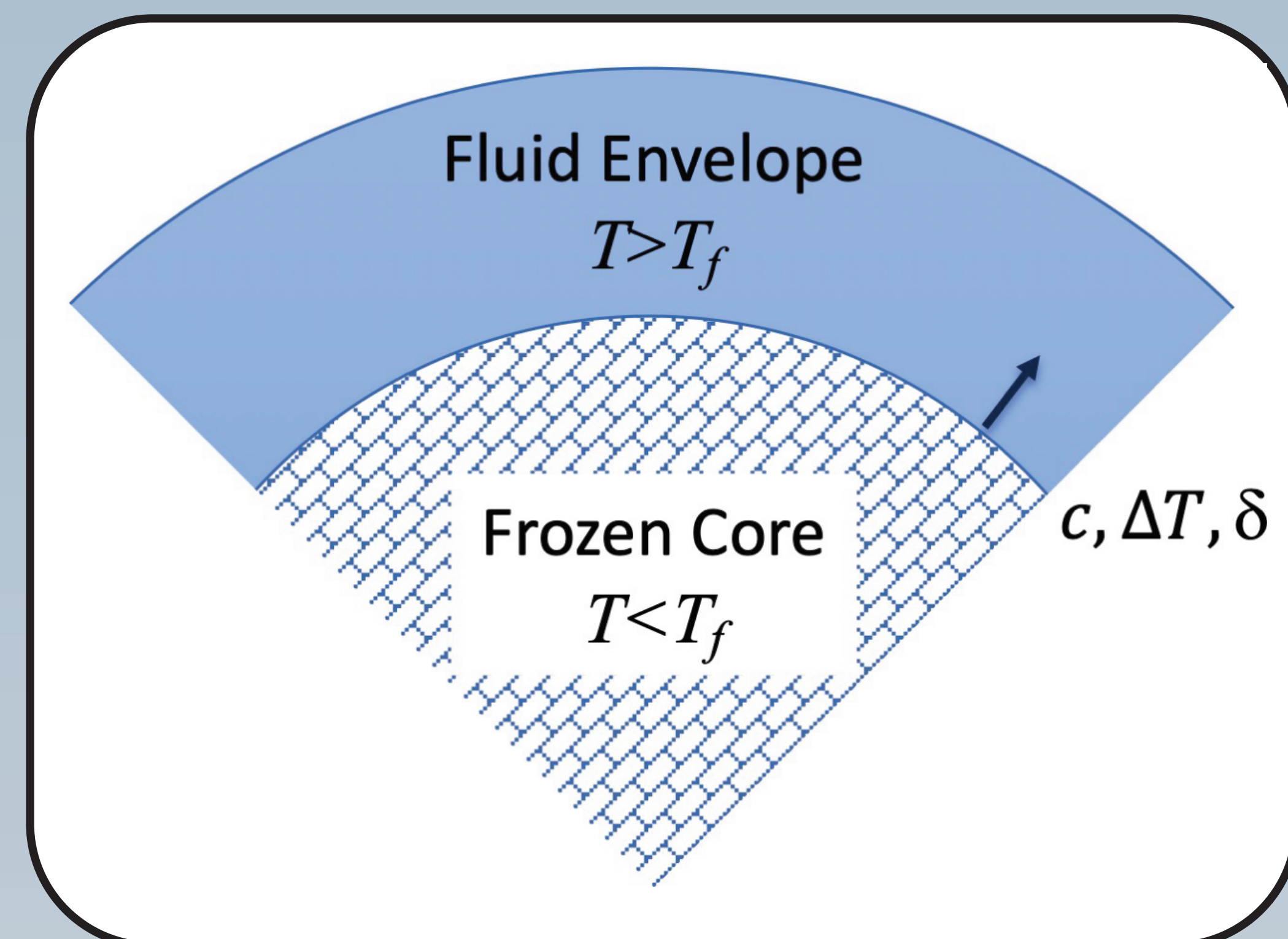
David James and Lars Stixrude  
djames@epss.ucla.edu



## Background

- Most models are inviscid and can explain thermal evolution
- Such models fail to explain tidal evolution
- Thermal and tidal evolution of Uranus can be explained with a growing frozen core
- Does Neptune also have a growing frozen core?

## Interior of Neptune



The growing frozen core model showing the frozen core (brick pattern) with radius  $c$ , at the top of which develops a thermal boundary layer of temperature contrast  $\Delta T$  and thickness  $\delta$ , and overlain by a fluid envelope (blue). The black arrow indicates the growth of the frozen core with time. The fluid layer is assumed to be composed predominantly of  $H_2O$  over the range of radii occupied by the frozen core, and also includes an outermost gas (H/He) portion.

Larissa

## Thermal Evolution

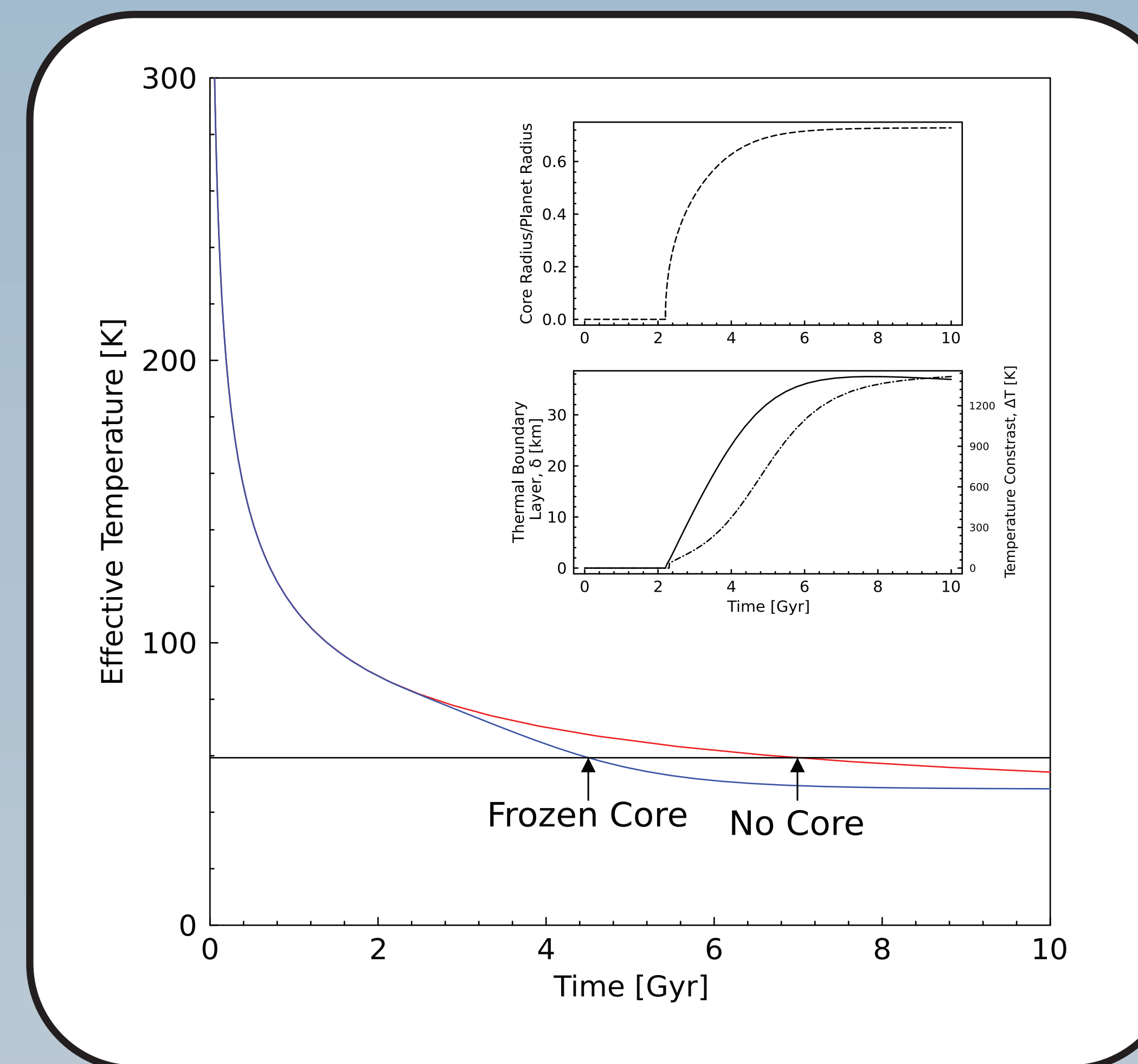
Presence of a frozen core leads to generalization of the thermal evolution equations

$$4\pi R^2 \sigma (T_{\text{eff}} - T_{\text{eq}}) = L_{\text{fluid}} + L_{\text{core}}$$

$$L_{\text{fluid}} = - \int_{M_c}^M C_p \frac{\partial T}{\partial t} dm$$

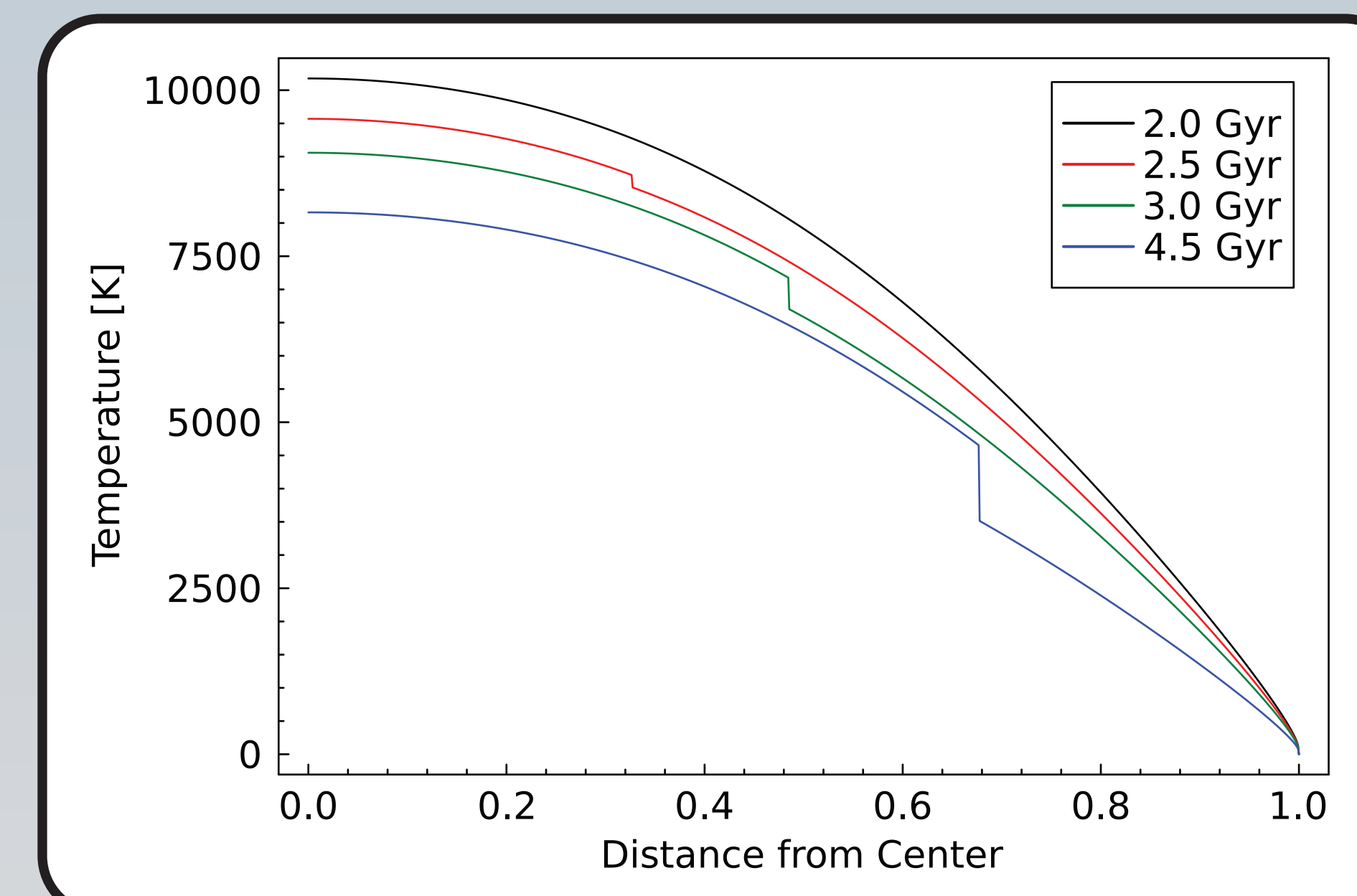
$$L_{\text{core}} = - \int_0^{M_c} C_p \frac{\partial T}{\partial t} dm - \int_S C_p \Delta T \frac{\partial c}{\partial t} \rho_c dS$$

### Thermal Evolution of Neptune



Thermal evolution of Neptune with the growing frozen core model (blue) and fluid model (red) with parameters  $\nabla = 0.281$  and  $C_p = 5000$ . The top inset shows the core radius and the bottom inset shows the thickness (dashed curve) and temperature contrast (solid curve) across the thermal boundary layer.

### Temperature Profile

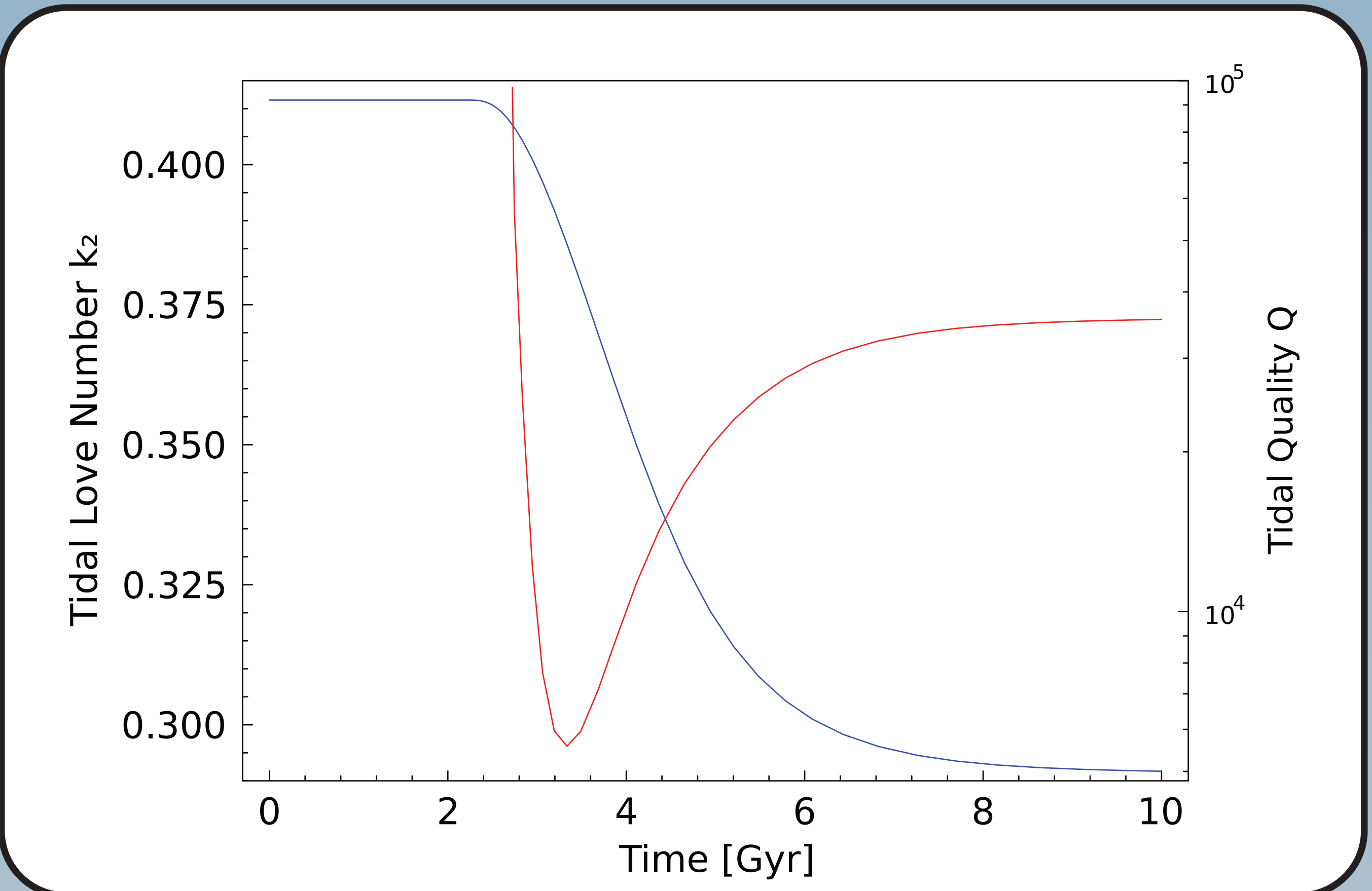


The temperature profiles of Neptune in the growing frozen core model at various snapshots in time as indicated.

## Tidal Evolution

As the frozen core grows, tidal response of Neptune will evolve

$$Q = \frac{|k_2|}{\text{Im}(k_2)}$$



The tidal evolution of Neptune

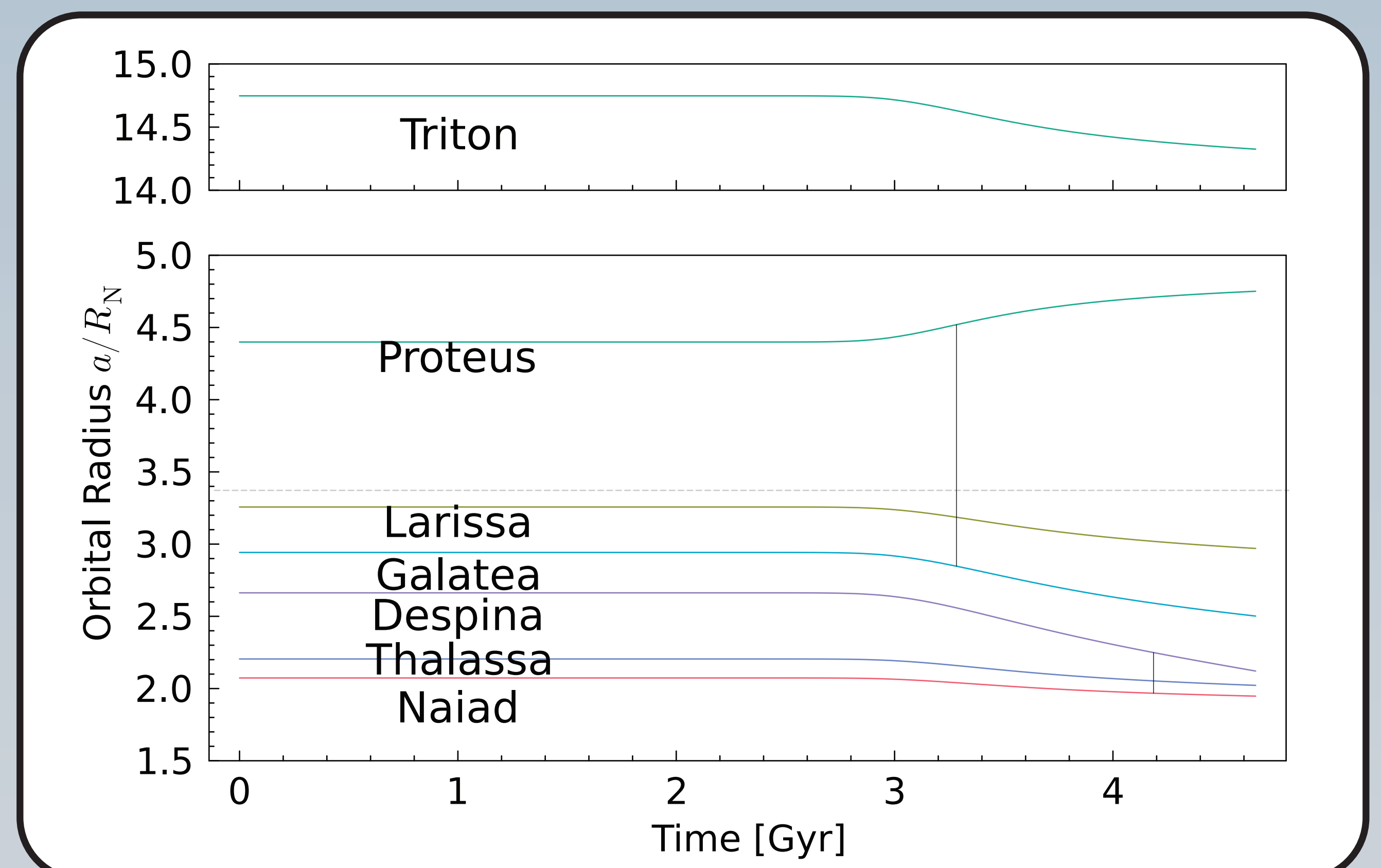


Triton

## Orbital Migration

The moons migrate due to tidal responses from the frozen core

$$\frac{\dot{a}}{a} = \pm 3 \frac{k_2}{Q} n \frac{m}{M} \left( \frac{R}{a} \right)^5$$



Orbital evolution of Neptune's moons. The dashed line indicates co-rotation. The vertical black lines indicate resonances: Proteus-Galatea 1:2 and Despina-Naiad 9:11.

Proteus

[1] Banfield D, Murray N (1992) A dynamical history of the inner Neptunian satellites. Icarus 99:229-401. [https://doi.org/10.1016/0019-1035\(92\)90155-2](https://doi.org/10.1016/0019-1035(92)90155-2)  
 [2] Burret B, Thomas PC (2016) Planetary satellites. In: Encyclopedia of the Solar System, Elsevier, p 759-777. <https://doi.org/10.1016/b978-0-12-415845-0.00034-7>  
 [3] Fortney JJ, Weidemann N (2010) The interior structure, composition, and evolution of giant planets. Space Science Reviews 152:11-423-44. <https://doi.org/10.1007/s11214-009-9562-x>  
 [4] Goldreich P, Nicholson PD (1977) Turbulent viscosity and Jupiter's tidal  $q$ . Icarus 30:223-304. [https://doi.org/10.1016/0019-1035\(77\)90163-4](https://doi.org/10.1016/0019-1035(77)90163-4)  
 [5] Helled R, Anderson JD, Podolak M, et al (2011) Interior models of Uranus and Neptune. Astrophysical Journal 726(1). <https://doi.org/10.1088/0004-637X/726/1/15>  
 [6] Henning WC, Hurford T (2014) Tidal heating in multilayered terrestrial exoplanets. The Astrophysical Journal 789:30. <https://doi.org/10.1088/0004-637X/789/1/30>  
 [7] Hubbard WB, Podolak M, Stevenson DJ (1995) The interior of Neptune. In: Cruikshank DP (ed) Neptune And Triton. The University of Arizona Press, Tucson, pp 169-138  
 [8] Neutelmann N, Helled R, Fortney JJ, et al (2013) New indication for a dichotomy in the interior structure of Uranus and Neptune from the application of modified shape and rotation data. Planetary and Space Science 77:143-15. <https://doi.org/10.1016/j.pss.2012.06.019>  
 [9] Stixrude L, Barron S, Grossiello F (2001) Thermal and tidal evolution of Uranus with a growing frozen core. The Planetary Science Journal 200:222. <https://doi.org/10.3847/psj/ac2a7>  
 [10] Tittemore WC, Wisdom J (1989) Tidal evolution of the Uranian satellites. II: an explanation of the anomalously high orbital inclination of Miranda. Icarus 78:163-89. [https://doi.org/10.1016/0019-1035\(89\)90070-5](https://doi.org/10.1016/0019-1035(89)90070-5)  
 [11] Zhang K, Hamilton DP (2008) Orbital resonances in the inner Neptunian system. II: resonant history of Proteus, Larissa, Galatea, and Despina. Icarus 193:267-282. <https://doi.org/10.1016/j.icarus.2007.08.024>