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Supplementary information

Potential long-term habitable conditions on planets with primordial H–He atmospheres

In the format provided by the authors and unedited

Supplementary Material

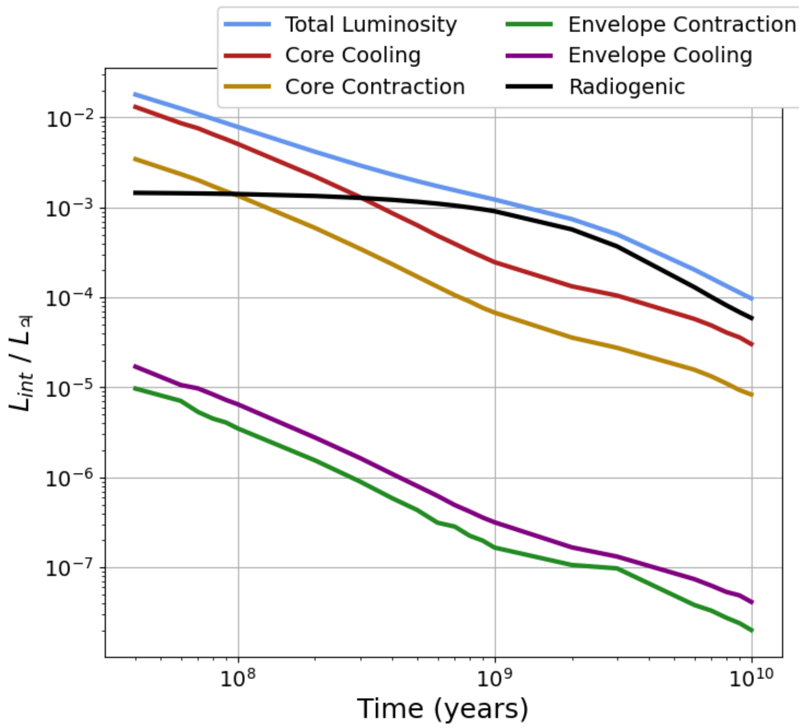

Figure 1: Evolution of the intrinsic luminosity (given in Jupiters current luminosity**?** of $3.35 \cdot 10^{25}$ erg s^{-1}) for a planet with a core of 3 $M_\oplus$ and a 0.001 $M_\oplus$ envelope. In the beginning of the evolution the cooling and contraction of the core are dominant components of the total luminosity. After ~300 Myr the radiogenic luminosity dominates.

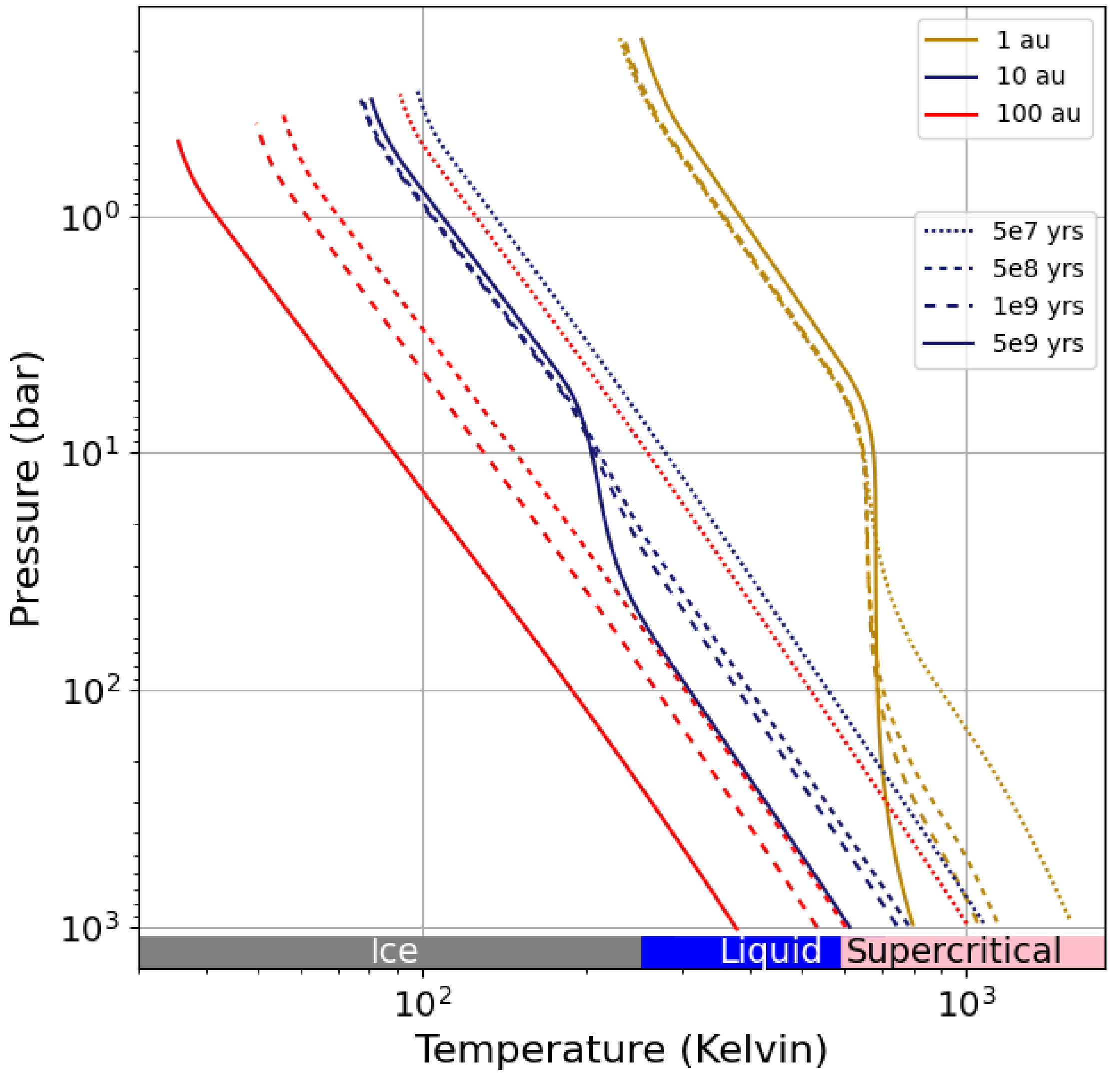

Figure 2: Evolution of the atmosphere structure of 3 planets between 50 Myr and 5 Gyr, without atmosphere loss. All planets have a core mass of 3 $M_\oplus$ and an envelope of 10^{-3} $M_\oplus$ and are at 1, 10 and 100 AU separation from their sun-like host-star. The bar in the bottom of the figure shows the state of water for the temperature range of the figure and at a fixed pressure of about 1 kbar, the resulting surface pressure.

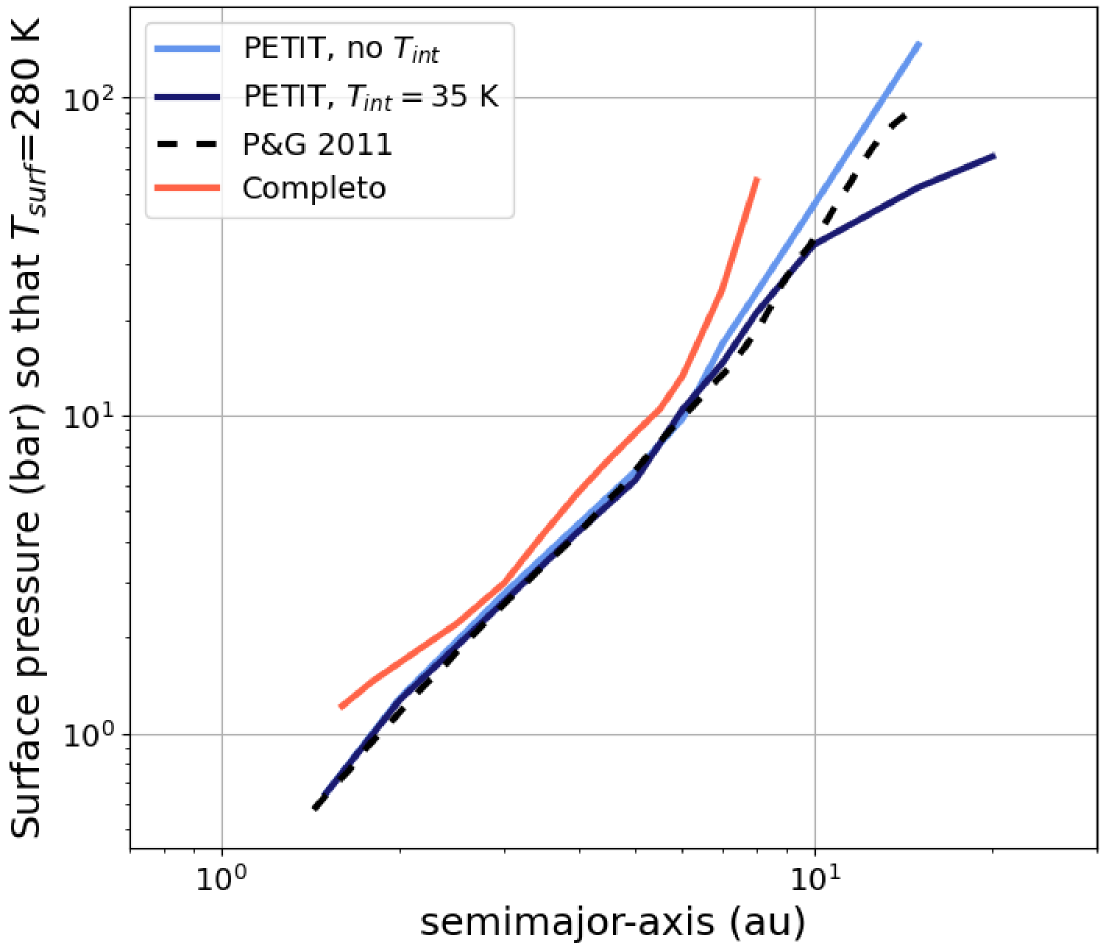

Figure 3: Comparison between the PETITcode models and the results from Pierrehumbert & Gaidos [1]. The figure shows the mass of a primordial, hydrogen-dominated atmosphere that is necessary for a surface temperature of 280 K, as a function of the semi-major axis around a sun-like star. The P&G models had a surface gravity of 1700 cm/s^2, which was constant through the coordinates of the model. To match this value at the surface, the models simulate a planet with a core mass of 3 $M_\oplus$.

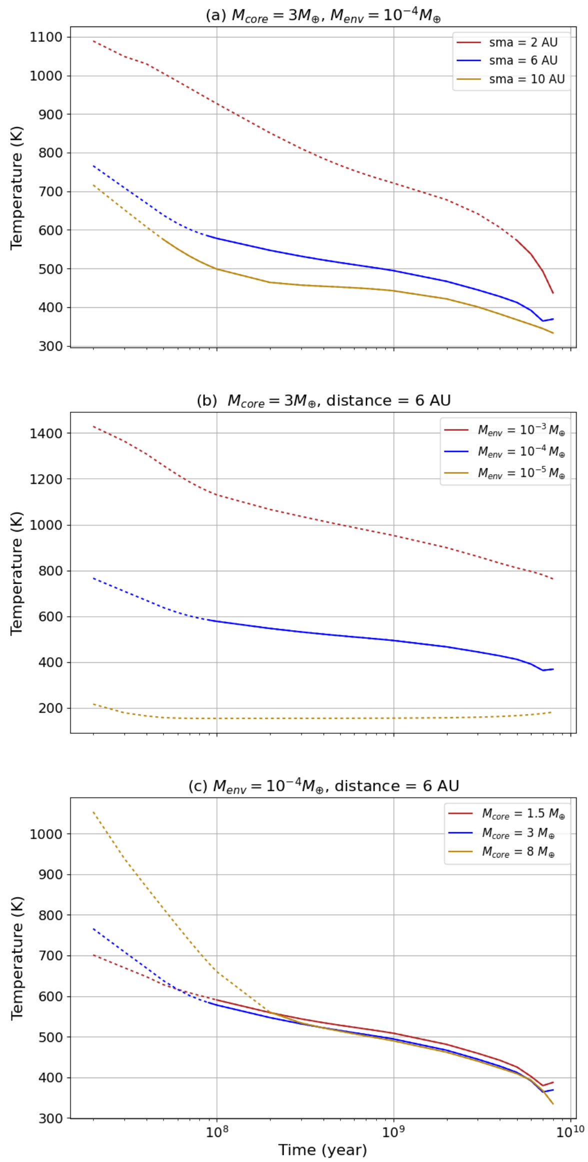

Figure 4: Evolution of the temperature at the envelope-core boundary for planets with different semimajor-axes (a), envelope masses (b) and core masses (c). The default values used are a distance of 6 AU, an envelope of $10^{-4}\ M_\oplus$ and a 3 $M_\oplus$ core. Dashed lines show when a layer of water between the envelope and core would not be in the liquid phase, solid lines show when it would. The simulations ran from 20 Myr to 10 Gyr. Our stellar model has no post Main-Sequence luminosity evolution and therefore we only consider our results until our model leaves the Main-Sequence at 8 Gyr. Atmospheric escape was not taken into account.

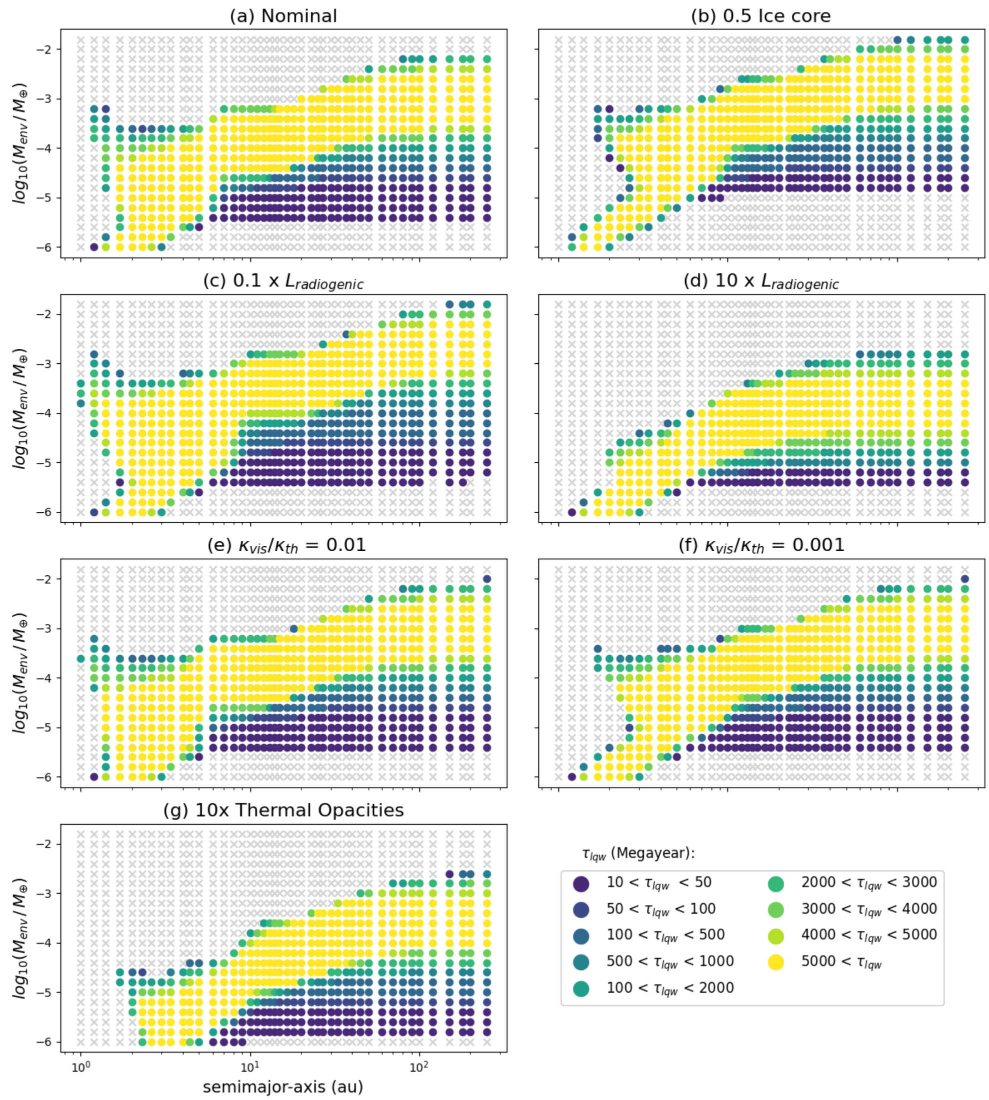

Figure 5: Comparison of τ_{lqw} for the nominal case and cases where a parameter has been changed. The semi-major axis and envelope masses are varied over a range of values on the x-axis and y-axis respectively. All cases have a total core mass of 3 $M_{\oplus}$. (a) The nominal case that is presented in Figure **??**. (b) The core has a 50% ice mass fraction, rather than 0% in the nominal case. In (c) and (d) the amount of assumed radiogenic abundances is scaled by a factor 10 lower (higher), leading to a 10 times weaker (stronger) radiogenic luminosity. In (e) and (f) the ratio of visible to thermal opacities is fixed to values of 0.01 and 0.001. For close-in planets where the irradiation is the main source of energy these are relatively high (low, respectively) compared to the nominal case. Finally in (g) the opacities are increased by a factor 10.

Supplementary Material References

1. Pierrehumbert, R. & Gaidos, E. Hydrogen Greenhouse Planets Beyond the Habitable Zone. *ApJl* **734**, L13 (2011). `1105.0021`.