Coupled Atmospheric-Ocean-Tidal Evolution of Proxima Centauri b,

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Introduction: Planets orbiting in the habitable zone of M-dwarfs like Proxima Centauri b are likely to have undergone tidal evolution given the proximity to the host star. Any assessment of such a planet's habitability must consider tidal forces as they can circularize orbits, damp obliquities, tidally heat a planet and induce a 1:1 spin-orbit resonance which all can have a profound impacts on the global climate over time.

An additional potential obstacle to habitability for M dwarf planets identified by [2] is the high stellar luminosity during the star's pre-main sequence evolution which can cause total planetary desiccation. However, [2] noted that if the planet forms with a thin hydrogen envelope, the envelope shields the planet as it evaporates during the stellar pre-main sequence phase, protecting the surface water that is critical for life. When a planet possess a hydrogen envelope, however, surface water is unlikely to be present.

In this work [3], we simulate the tidal history of Proxima Centauri b if it formed with or without a hydrogen envelope and surface oceans. We find that the tidal and orbital evolution, dominated early on by the mantle, significantly depends on the presence of liquid surface oceans.

Methods: To simulate the complex tidal evolution of a planet with an evaporating envelope, we couple stellar, tidal and geophysical evolution models with an atmospheric escape model using the code VPLANET [3]. We account for the coupled tidal effects of a gaseous envelope, an ocean and a solid interior by summing the imaginary Love numbers, Im(k_2), of each respective component to compute a net tidal Q factor (see [4]). When either a hydrogen envelope is present or the planet is in the runaway greenhouse phase, we neglect the tidal impact of surface oceans as any water will not be present on the planetary surface as a liquid.

We model four cases: a constant tidal Q "CPL" case, a "No Ocean" case where the thermal interior drives the tidal evolution, an "Ocean" case which adds the impact of surface oceans to the "No Ocean" case, and an "Envelope" case which models the additional tidal effects of an evaporating hydrogen envelope to the "Ocean" case.

Results: In the figure from top-left to bottom-right, we show the evolution of the tidal heating surface flux, the tidal Q, the orbital eccentricity, semi-major axis, envelope mass and total water content. The mantle initially dominates the tidal evolution (e.g. the "No Ocean" case, red curve) as the envelope cannot efficiently dissipate energy leading to little change in both the eccentricity and the semi-major axis. For the "Envelope" case, the hydrogen envelope has evaporated after ~150 Myr by the time the planet enters the habitable zone (grey shaded region). Once in the habitable zone, the water condenses into surface oceans driving a dramatic decrease in the tidal Q. This in turn causes a large spike in tidal heating and rapid orbital evolution. We find that the "Envelope" and "Ocean" cases evolve similarly but the latter requires a larger initial water inventory for water to persist after the star's pre-main sequence phase. This demonstrates the importance of the initial hydrogen envelope for current habitability.

References: [1] Anglada-Escudé, G., et al. (2016), *Nature,* 536, 437-440, [2] Luger, R., et al. (2015), *Astrobiology*, 15, 57-88, [3] Barnes, R. et al. (2016) *Astrobiology.,* submitted., [4] Driscoll, P. & Barnes, R. (2015), *Astrobiology*, 15, 739-760