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A new energy balance model to map the habitability of tidally locked rocky planets: application to the Ariel target list

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Introduction: The hunt for biosignatures in the atmospheres of exoplanets is a central goal of many cutting-edge instruments currently in operation [1], under construction [2] or otherwise proposed [3]. The starting point of this search are the planets that can in theory support liquid water on their surfaces, i.e. inside the Circumstellar Habitable Zone (CHZ, [4]). Around two thirds of the 72 known rocky exoplanets in the CHZ orbit M-type dwarfs [5]. The HZ of this class of stars is well within the region of the system where the gravitational interaction of the central body force the planet into a 1:1 spin-orbit ratio [6]. The climate of these planets cannot be studied using standard 1-D Energy Balance Models (EBM, [7]) and most investigators rely on computationally expensive 3-D General Circulation Models (GCM, e.g. [8]). This severely limits the number of combinations of unconstrained or poorly constrained planetary parameters that can be tested to determine how much robust the habitability of these planets actually is.

Model: Here, we present a new 1-D EBM specifically tailored for the study of tidally locked rocky temperate exoplanets. This model discretizes the surface of the planet in a number of zones defined with respect to the substellar point. The surface temperature profile as a function of the angular distance with the terminator is determined by the equilibrium between the absorbed stellar radiation, the outgoing longwave radiation and the horizontally transferred heat, treated as diffusive. By defining an interval of temperatures suitable for the survival of life (here, 0-100°C, [9]), it is possible to derive the fraction of the planetary surface that is habitable. This model is coupled with a state-of-the-art radiative transfer model (EOS, [10]), and takes into account the contribution of clouds, the surface albedo and the atmospheric CO2 condensation on the nightside on the surface temperature [11,12]. Finally, the emission temperature of the planet at different points of the surface can be used to produce synthetic infrared phase curves. The free parameters of the model have been calibrated against both 3-D GCMs [13] and a priori theoretical calculations [14]. While the use of 1-D EBM on tidally locked planets is not entirely new (see e.g. [15,16,17]), previous models were simpler and generally focused on a specific climatological aspect.

Results: We have applied our new EBM for tidally locked planets to the eight temperate Earths and Super-Earths of the ESA Ariel Mission Target List (TRAPPIST-1c, -1d, -1e, -1f and -1g, LHS 1140b, K2-18b and TOI-1468c), all of which orbit M-type stars. In particular, we mapped the fractional habitability as a function of the surface pressure (Ps) in the [0.1, 10] bar range, and the CO2 mixing ratio (xCO2) in the [-4, 0] dex range for a N2-CO2-H2O atmosphere. Both line and collisional induced absorptions of the involved gases were taken from the HITRAN2020 repository [18]. All the targets were modeled as aquaplanets. Our preliminary analysis showed that: (i) TRAPPIST-1c and

TOI-1468c enter a runaway greenhouse state under all the tested combinations; (ii) TRAPPIST-1f, -1g and LHS 1140 b are habitable only in presence of dense (> 10 bar) and CO2-rich (> 1-10 %) atmospheres, but for LHS 1140 b this is incompatible with the observationally derived upper limit on the xCO2 (see Fig.1); (iii) TRAPPIST-1d is habitable only for CO2-poor atmospheres, which might limit the action of Earth-like photosynthetic organisms and thus the production of detectable biosignatures [19]; (iv) TRAPPIST-1e and K2-18b are the best targets for astrobiological studies in the sample. However, in both cases there exist a limiting pressure above which these planets likely enter a runaway greenhouse state. For K2-18b this limiting pressure is ~3 bars for a xCO2≥1% , which clashes with interior structure models of the planet predicting a deep (albeit H2-dominated) atmosphere [20].

Figure 1: The fraction of the surface within the 0-100 °C interval as a function of Ps and xCO2, for the planet LHS 1140 b. The white dashed line represents the upper limit on the CO2 mixing ratio as derived by observations [21]. The hatched region identifies the cases in which the atmosphere is unstable against collapse, caused by the condensation of CO2 on the planetary nightside. The snowflake symbol identifies the region of no habitability as caused by the onset of a planetary Snowball state.

Future prospects: We plan to expand the atmospheric pressure range and to test different atmospheric compositions, including H2-dominated cases (for K2-18b) and atmospheres with a varying amount of CH4. Our habitability maps can be readily compared with observational data, as done in Fig. 1, to rapidly assess the astrobiological relevance of any target for very large sets of planetary parameter combinations.

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