EPSC Abstracts
Vol. 13, EPSC-DPS2019-93-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Towards the detection of the runaway greenhouse radius inflation effect

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1. Introduction

Planets similar to Earth – but slightly more irradiated – are expected to experience a runaway greenhouse transition, a state in which a net positive feedback between surface temperature, evaporation, and atmospheric opacity causes a runaway warming [1,2]. This runaway greenhouse positive feedback ceases only when oceans have completely boiled away, forming an optically thick H_2O-dominated atmosphere. Venus may have experienced a runaway greenhouse in the past [3,4], and we expect that Earth will in around 600 million years as solar luminosity increases by ∼ 6% only compared to its present-day value [5]. However, the exact limit at which this extreme, rapid climate transition from a temperate climate (with most water condensed on the surface) to a post-runaway greenhouse climate (with all water in the atmosphere) would occur, and whether or not a CO_2 atmospheric level increase would affect that limit, is still a highly debated topic [6,7,8,9]. This runaway greenhouse limit is traditionally used to define the inner edge of the Habitable Zone [10,11].

Here we take advantage of this runaway greenhouse process to propose a new, innovative observational test of the Habitable Zone concept, that could also be used to diagnose the presence of water in temperate, Earth-size exoplanets.

2. Method

We first use the 1-D 'inverse' radiative-convective version of the LMD Generic model to simulate a post-runaway greenhouse planetary atmosphere, following the same approach as in [4,11,12]. The atmosphere is decomposed into 200 logarithmically-spaced layers that extend from the ground to the top of the atmosphere arbitrarily fixed at 0.1 Pascal. The atmosphere, assumed here to be composed of 1 bar of N_2 and a variable amount of H_2O, is divided in at most three physical layers (a dry convective layer, a moist convective layer, and an isothermal stratospheric layer) constructed as in [13,14,15].

We then compute the high resolution wavelength dependent transit depth of the post-runaway greenhouse, steam atmosphere using the line by line radiative transfer model PUMAS, integrated in the Planetary Spectrum Generator [16], for both cloud-free and cloudy atmospheres.

3. Results

Our main finding is that as an Earth-like planet experiences a runaway greenhouse transition, the apparent thickness of its atmosphere evolves from a few tens of kilometers [17,18] to possibly as high as over a thousand kilometers (i.e., a few tens of % of Earth radius), depending on the initial water content of the planet. We call this phenomenon the *runaway greenhouse radius inflation effect* [19].

This abrupt radius inflation – resulting from the runaway-greenhouse-induced transition – should produce a strong density change that could be detected statistically by ongoing and upcoming space missions such as TESS, CHEOPS and PLATO (combined with precise radial velocity mass measurements with ground-based spectrographs such as ESPRESSO, CARMENES or SPIRou).

It could also be detected in particular cases in multiplanetary systems such as TRAPPIST-1 (when masses and radii will be known with good enough precision). To explore this possibility, we carried out an analysis coupling simplified interior models with our 1-D radiative-convective model taking into account the runaway greenhouse radius inflation effect. The result of this exploration – which suggests a possible detection of the runaway greenhouse radius inflation effect within the TRAPPIST-1 system – will be presented in details at the EPSC-DPS Joint Meeting 2019.

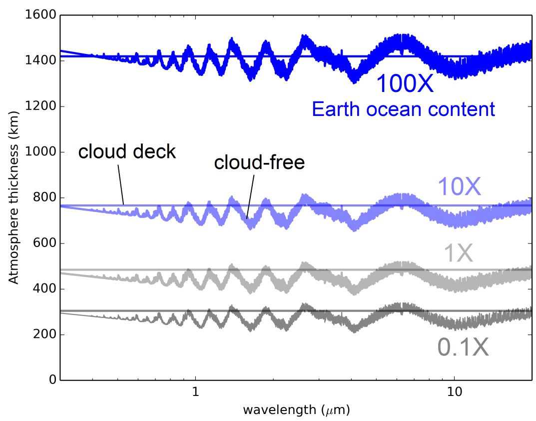

Figure 1 – Transit atmospheric thickness of a post-runaway greenhouse planetary atmosphere as a function of wavelength (from 0.3 to 20 μm), and for different total water content (from 0.1 to 100× the Earth ocean content). Atmospheric thickness is plotted for cloudy (horizontal lines) and cloud-free scenarios, for comparison.

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