Orbital Constraints on Exoplanet Habitability

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Implementing a 1-D energy balance climate model in order to investigate how changing certain orbital parameters can result in changes to habitability.

CONTENTS

1. INTRODUCTION

The climate of a planet such as the Earth is many dimensional.

The simplest climate model is a 0 dimensional energy balance model. The 0-D model is a simple equality of the input energy from the Sun (LHS) to the output energy from the Earth acting as a black body (RHS)

$$\pi r_{Earth}^2 S(1-A) = 4\pi r_{Earth}^2 \sigma T_{Earth}^4,$$

where r_{Earth} is the radius of the Earth, S is the incident solar radiation (insolation), A is the reflectance (albedo) of the Earth, and σ is the Stefan-Boltzmann constant. This 0-D model is essentially an average over all degrees of freedom of the Earth, including rotation and orbiting of the star.

A 1-D climate model attempts to resolve the surface of the planet into latitude bands. Since rotation of the planet would imply another dimension (namely longitude) the rotation of the planet is still averaged over. Each of these latitude bands is treated as balancing energy in from the sun and energy out via blackbody radiation, but an additional energy diffusion term is included in the equation for energy transport between latitude bands.

$$C(x,t)\frac{dT(x,t)}{dt} - \frac{d}{dx}\left(D(x,t)(1-x^2)\frac{dT(x,t)}{dx}\right) + I(x,t) - S(x,t)(1-A(x,t)) = 0$$

where $x = sin(\lambda)$, λ is the latitude, C is the heat capacity of the latitude band, D is the diffusion coefficient, I is the IR-emission of the band, S is the insolation, and A is the albedo.

In this analysis we adopt the form of the heat capacity given by !!!. In short: $C(x,t)$ varies with latitude through the ocean-land fraction, $f_o(x)$, and with Temperature through the ice-ocean fraction, $f_i(T)$, as

$$C(x,T) = (1-f_o(x))C_{land} + f_o(x)((1-f_i(T))C_{ocean} + f_i(T)C_{ice}(T)),$$

Where C_{land} =!!! and C_{ocean} =!!! are constant, and

$$C_{ice}(T) = \begin{cases} !!! & T < 263 \\ !!! & T >= 263, \end{cases}$$

We use a diffusion coefficient which is constant in space and time, but varies with orbital and atmospheric parameters as,

$$\frac{D}{D_0} = \frac{p}{p_0} * \frac{c_p}{c_{p,0}} * \left(\frac{m}{28}\right)^{-2} * \left(\frac{\Omega}{1day^{-1}}\right)^{-2}$$

where $D_0 = 0.56$ J s^{-1} m^{-2} K^{-1} from fitting to an Earth model (see !!!), p is the atmospheric pressure relative to $p_0 = 101$ kPa. c_p is the heat capacity of the atmosphere, relative to $c_{p,0} = 10^3$ g^{-1} K^{-1}. m is the (average) mass of the particles in the atmosphere, relative to the Nitrogen molecule. Ω is the rotation rate of the planet, relative to Earth's 1 rotation per day.

IR-emission and Albedo functions are taken from !!! and are given by

$$I(T) = I_2(T) = \sigma T^4/(1+0.5925(T/273)^3)A(T) = A_2(T) = 0.525 - 0.245\tanh\frac{T-268}{5}$$

where this IR-emission is a blackbody radiation term damped the optical thickness of the atmosphere. and the albedo is a smooth scaling from low to high reflectivity due to snow and water-vapour reflectance.

Insolation function is defined as the day averaged incident (based on latitude) radiation from the sun,

$$S(\lambda, t) = \frac{q_0}{\pi}\left(\frac{1AU}{a}\right)^2 (H \sin\lambda \sin\delta + \cos\lambda \cos\delta \sin H)$$

$q_0 = 1360$ W m^{-2}, λ is latitude,

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3. CONCLUSIONS

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REFERENCES

[1] A. N. Other, Title of the book, edition, publishers, place of publication (year of publication), p. 123.
[2] A. N. Other, Title of the article, journal title, volume, 123–456 (year of publication).