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Thermal light curves of Earth-like planets: 1. Varying surface and rotation on planets in a terrestrial orbit

I. Gómez-Leal[a,*], F. Codron[b], F. Selsis[c,d]

[a] Max-Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[b] Laboratoire de Météorologie Dynamique, Université de Pierre et Marie Curie-Paris 6, CNRS, Paris, France
[c] CNRS, LAB, UMR 5804, F-33270 Floirac, France
[d] Univ. Bordeaux, LAB, UMR 5804, F-33270 Floirac, France

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ABSTRACT

The integrated thermal emission of an exoplanet and its variations along the orbital motion can carry information about the climatic conditions and the rotation of the planet. In this study, we use the LMDZ 3D Global Climate Model (GCM) to simulate the climate of a synthetic Earth and three quasi-Earth configurations: a slowly rotating Earth, an ocean-covered Earth and its snowball counterpart. We also generate the time-dependent broadband thermal emission of the planet from these simulations. In a first step, we validate the model by comparing the synthetic Earth emission with the actual emission of our planet as constrained by observations. Then, we determine the main properties of the climate and emission of the three Earth-like planets and compare them to those of the Earth. We show that planets with an uneven distribution of continents exhibit a maximum of emission during the summer of the hemisphere with larger continental masses, and they may exhibit a maximum of emission at apastron. Large convective clouds might form over the continents of slow rotating planets, having an important effect over their climate and their emission. We also show that, in all the modeled cases, the equilibrium temperature, the Bond albedo and the rotation period can in theory be retrieved from the light curve by a distant observer. The values obtained at transiting geometries have a low deviation from the global values for cases with an axis tilt similar to that of the Earth, and we are able to distinguish between the four planets presented here by the data obtained from their light curves. However, this might not be the case under different conditions.

1. Introduction

Exoplanet surveys have shown that planets with low mass and small radius are common. The occurrence rate of Earth-like planets ($1–2R_\oplus$) in the *Habitable Zone* (HZ) of Sun-like stars (GK stellar types) is around $22 \pm 8\%$ for the *Kepler* survey (Petigura et al., 2013). Observations have reached a level of accuracy that allows the detection of such planets in the HZ, including Earth-sized planets (e.g. Borucki et al., 2013; Quintana et al., 2014; Jenkins et al., 2015). The bulk composition of these planets remains highly uncertain as few of them have both a mass and a radius that can be measured within a certain accuracy. This situation should improve with *TESS* (Ricker et al., 2009) and *PLATO* missions (Catala and PLATO Consortium, 2008; Rauer and Catala, 2011). The characterization of the atmosphere of nearby large and hot transiting planets will be achievable by *JWST*, but probably not for Earth-like planets (Belu et al., 2011), unless one is found around a nearby brown dwarf (Belu et al., 2013; Triaud et al., 2013). The use of ground-based missions, such as *E-ELT*, to probe the atmosphere of transiting Earth-like planets is under investigation (Pallé et al., 2011; Snellen et al., 2013). The systematic study of the atmosphere and climate of potentially habitable worlds around nearby stars is currently part of various space agencies programs, but we still do not know when and how it will be possible.

Modeling Earth-like atmospheres is of great importance, although their characterization seems a long term objective. Earth General Circulation Models (GCM) have reached an incomparable robustness and sophistication and allow for the study of the climate in great detail. These models can be used to explore the diversity of possible climates on Earth analogs, as well as the evolution of the properties of the planet through time, and the climatic response to particular changes. We can also use GCMs to generate

* Corresponding author.
E-mail addresses: gomez@mpia.de, ig238@cornell.edu (I. Gómez-Leal), f.codron@lmd.jussieu.fr (F. Codron), selsis@obs.u-bordeaux1.fr (F. Selsis).

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observables and analyze how they are connected with the properties of the planet. The conclusions reached on Earth-like planets may also provide new ways to study bigger worlds such as Super-Earths.

In this work, we study the influence of some characteristics over the climate, the emission and the light curve of Earth-like planets. We have used an Earth GCM to simulate four different planets. They have the same orbital characteristics and atmospheric composition as the Earth, but some parameters, such as the rotation rate, the ocean cover, or the insolation, have been varied with the aim of obtaining different climates. First, we have characterized the climate by the calculation of the parameters related with the radiative balance of the planet and the circulation of the atmosphere. Second, we have built the light curve of the planet at different geometries of observation. Finally, we have compared the results obtained from the analysis of the light curve with the global values of the planet. Section 2 is an introduction to the main characteristics of Earth-like planets and the effect of these properties over the climate and the light curve of the planet. Section 3 gives a description of the GCM model and method used to simulate each planet. Section 4 presents the parameters used to study the climate and the construction of the light curves. Section 5 shows our results, the study of the properties of each planet, and the analysis of the light curves by the identification of the origins of the variability of the signal such as the diurnal cycle, the rotation of the planet, the relevance of weather patterns, the seasonality, or the continental distribution. Our conclusions are given in Section 6.

2. Climate on Earth-like planets

Planetary climate is tightly related to the radiative balance and the circulation of the atmosphere. In the case of planets with small or moderate obliquity, the absorbed stellar radiation is greater at low latitudes resulting in an energy gain in the tropics and a deficit in the poles. This heat gradient is one of the primary drivers of the general circulation of the atmosphere (along with the Coriolis force). The Hadley cells are sustained by this mechanism, but zonal cells may also develop in the presence of east–west heating asymmetries, as is the case of the Walker cell over the Pacific ocean. The physical characteristics of the planet, such as the rotation rate, the orbital parameters, the atmospheric composition, the continental distribution and the albedo, have also serious effects on the circulation of the atmosphere and as a consequence, on the climate and the emission of the planet:

Rotation rate. Fast planetary rotation rates cause a large meridional scale of the stationary wave that produces equatorial jets (Edson et al., 2011), limiting the meridional extent of the Hadley cells, as the Coriolis force becomes large enough to balance stronger pressure gradients. The resulting temperature gradients and mean circulation can become unstable with respect to perturbations or eddies, which transport heat and moisture poleward as they develop (Held, 1999). The meridional temperature gradient increases with faster rotations, and as a consequence, the planet has warmer and wetter tropics and dryer and colder subtropics than on Earth. On the contrary, the Hadley cells extend further in latitude in slow-rotating planets, meridional transport is very efficient and temperatures are colder in general. Therefore, these planets may be still habitable at distances where rapid-rotating planets are in a runaway state, depending on the rotation rate and the planetary history (Yang et al., 2014). A superrotating equatorial flow may appear with rotation periods larger than 4 days (del Genio and Suozzo, 1987).

Emerged continents vs ocean. Continents play an important role in the radiative balance of the planet. Land heats up and cools down more quickly than oceans, because of its lower thermal inertia and its lower evaporation potential.[1] As a result, the Northern Hemisphere (NH) of the Earth, with larger continents, experiences lower winter temperatures and higher summer temperatures than the Southern Hemisphere (SH) (Cook, 2003). This phenomenon has an influence in the light curve of the planet, producing the highest emission at apastron (Gómez-Leal et al., 2012). Continental masses are also involved in other phenomena such as the production of monsoons and the increase on the oceanic circulation (and therefore on heat transport) by meridionally extended coastlines (Smith et al., 2006; Enderton and Marshall, 2009).

Water-planets. Planets completely covered by water are predicted by planet formation and evolution scenarios. These water worlds can be ocean planets, whose bulk composition consists in a large fraction of H_2O (Léger et al., 2004; Sotin et al., 2007; Kaltenegger et al., 2013); or aquaplanets, Earth-like planets where continents do not emerge, due to a different distribution of water between the surface and the mantle. The Earth itself might have been an aquaplanet in its early times (Flament et al., 2008). The distribution of temperature and wind fields on an aquaplanet are essentially zonal. Jets appear in the atmosphere and in the ocean, and the oceanic meridional heat transport is mostly due to a poleward Ekman flow in the subtropics, with a deeper, colder return flow (Codron, 2012). The mean surface temperature on an aquaplanet analogue is higher than on Earth, essentially due to the low albedo of water. There is a large potential influence of the sea ice-albedo feedback.

Snowball planets. The Earth may have suffered one or several global glaciations in the past (e.g. Hoffman et al., 1998; Hoffman and Schrag, 2002; Macdonald et al., 2010). In this situation, the ice-albedo feedback contributes to keep the cold temperatures and the dry atmosphere. In the case of a completely frozen planet (hard-snowball), surface temperatures may be between 170 K and 240 K, because of the low concentration of water vapor in the atmosphere (Pierrehumbert, 2005).

Here, we investigate how these conditions may affect the climate of the planet and its thermal emission.

3. Model and method

We have used the LMDZ GCM, an Earth Global Climate Model developed by the Laboratoire de Météorologie Dynamique[2] (Paris), to build the simulations of four Earth-like planets. This model has been previously used to study the climate of the Earth (e.g. Goubanova and Li, 2007; Risi et al., 2010; Charnay et al., 2013) and different versions of the model have been used to study the properties of Mars (e.g. Forget et al., 1998, 1999; Wordsworth et al., 2013), Titan (e.g. Charnay and Lebonnois, 2012), Earth-like planets (e.g. Leconte et al., 2013) or other types of exoplanets (e.g. Wordsworth et al., 2011). The version used has 48 grid points regularly spaced in latitude and longitude, yielding to a horizontal resolution of 3.75 by 7.5°, and 19 atmospheric pressure levels on the vertical dimension. Sub-grid scale processes such as radiative transfer, clouds (Bony and Emanuel, 2001), convection (Emanuel, 1991), and small-scale turbulence are parameterized as described in Hourdin et al. (2013). We have used an improved version of Emanuel's moist convection scheme coupled with a complex parametrization of clouds, which give a good representation of the Hadley and Walker circulations, the convective boundary layer, cumulus clouds, and the diurnal cycle. The 2-dimensional fields used to compute the thermal emission are output every 3 h (Figs. 3–6). The ocean in the different planets is modeled by a

[1] Evaporation allows a surface to lose energy with little change in temperature, whereas it needs to heat up significantly to increase sensible or thermal radiative heat fluxes.

[2] http://lmdz.lmd.jussieu.fr/?set_language=en.