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Modeling the phase curve of hot rocky planets with 3D climate models

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Abstract

Using a 3D climate model, we study how the apparent emission of a hot terrestrial exoplanet varies with wavelength and orbital phase, for different atmospheric pressures, and inclinations, in the case of a tidally-locked planet. Based on these synthetic thermal phase curves, we investigate how the planet and its atmosphere could be characterized by spatially-unresolved spectro-photometry of the system with JWST and EChO.

1. Introduction

Thermal phase curves (variations of the planet apparent infrared emission with its orbital phase) have been observed for hot Jupiters in both transiting and non-transiting configurations, and could be observed for hot terrestrial exoplanets. We use a 3D climate model (GCM) to simulate the CO_2 atmosphere of a rocky planet on an 8-day circular orbit around a M3 dwarf and its apparent infrared emission as a function of its orbital phase. We estimate the signal to photon-noise ratio in narrow bands between 2.5 and 20 microns for a 10 pc target observed with a 6 and 1.5 m telescope, the sizes of JWST and EChO, respectively.

1.1. The model

The characteristics of the planetary system we model are summarized here:
The star is an M3 dwarf (0.31 $M_\odot$) with a luminosity of 0.0135 $L_\odot$. For flux and photon-noise calculations, the distance of the star is set to 10 pc.
The orbit is circular with a semi-major axis of 0.0535 AU and period of 8 days. As seen on Fig. 1, the inclination of the orbit on the line of sight is set to 60°, which the median value for randomly oriented systems.

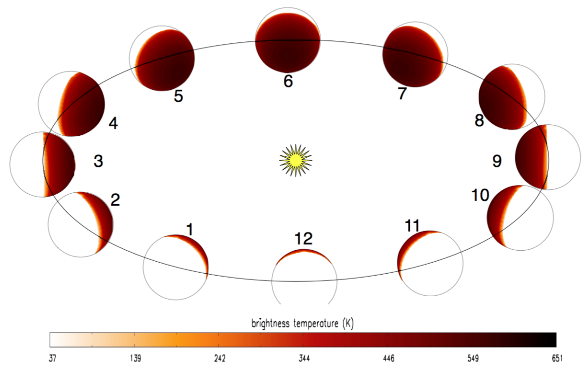

Figure 1: The orbit and phases as seen by the observer. The phases shown here are numbered from 1 to 12 and correspond to the phases presented in Fig.2. Temperature is given for the airless case.

The planet is a 1.8 $R_\oplus$ and 9.5 $M_\oplus$ terrestrial planet, consistent with a rocky composition. We set the surface albedo to 0.2. The rotation period is assumed to be equal to its orbital period (8 days).
The atmosphere is made of carbon dioxide (CO_2) as the unique constituent. We consider three atmospheric pressures: 0.1, 1, and 10 bars, as well as a case with no atmosphere (surface temperature is thensimply given by local radiative equilibrium).

For the three cases with an atmosphere, we used a new version of the LMD GCM that has been developed specifically for exoplanet and paleoclimate studies. It has already been used to study the early Mars climate [2] and possible climates on GJ581d [1]. The main improvement of the model is the radiative transfer scheme, which uses 36 bands between 0.3 and 5 μm for the incoming stellar radiation and 38 bands above 2.5 μm for the planetary infrared emission.

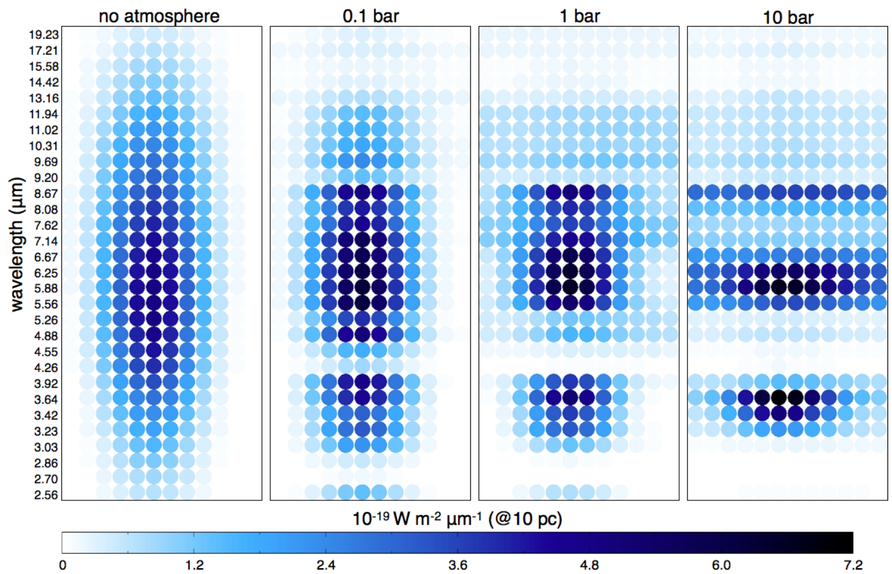

Figure 2: Disk-integrated flux as a function of wavelength (Y-axis) and phase (X-Axis) as a function of wavelength and phase. Phase refer to Fig. 1.

2. Results

Figure 2 shows the disk-integrated thermal emission, as seen by the observer at 10 pc, as a function of wavelength and phase. The variation of bond albedo with the atmospheric pressure being negligible, the global thermal emission of the planet does not change between the different cases, but its spectral and spatial distribution strongly depends on the pressure due to the effects of the atmosphere on the radiative and heat transport. With increasing pressure, the planet tends to radiate predominantly in the spectral atmospheric windows (where CO_2 absorbs less), while the emission in the dark hemisphere becomes more important thanks to the more efficient heat transport through atmospheric circulation.

3. Summary and Conclusions

An instrument of only 1.5 m with an extremely stable detector able to perform photometry at a level of 10^{-5} over several days simultaneously in several spectral bands could detect modulation by a nontransiting planet with a precision allowing the atmosphere to be characterized.

We find that atmospheric absorption bands produce signatures in what we call the variation spectrum. This is because the day-night temperature contrast changes with altitude, and different wavelengths probe different altitudes. Signatures of atmospheric molecules can thus be extracted from spectro-photometric observations of nontransiting planets. Planets with no atmosphere produce large variations and can be easily distinguished from dense absorbing atmospheres.

The stellar variability and photometric stability of the instrument are the main challenges when measuring the phase curves of nontransiting and spatially-unresolved terrestrial exoplanets. This characterization technique can, however, give access to one order of magnitude more targets than does transit spectroscopy.

Acknowledgements

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References

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