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HOW TO CONSTRAIN THE PHYSICAL PROPERTIES OF VERY HOT SUPER-EARTHS WITH THE JAMES WEB SPACE TELESCOPE?

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Abstract. Space missions dedicated to exoplanet transit detection led to the discovery of the first super-earths with a measured radius. Surprisingly, the two first rocky planets discovered, CoRoT-7b and Kepler 10b (Léger et al. 2009; Batalha et al. 2011) show very similar parameters: their radius is respectively 1.7 and 1.4 $R_\oplus$ and they orbitate around (resp.) a K and a G star in 0.85 days. The properties of this two objects are expected to be very exotic (Léger et al. 2011). We expect them to be phase locked, with a large lava ocean on the irradiated face (with T reaching 2500 K and 3000 K, respectively) and cold hemisphere with a temperature lower than 50-75 K. We look for observational tests to validate this model among a larger family of models. We suggest to make an observation with the instrument NIRCam on the futur JWST. We investigate the amount of information that such an observation would provide on the physical and dynamical properties of CoRoT-7b, and we focus in particular on two parameters that could influence the surface nature of the very hot super-earth: the albedo, and the phase-locking.

Keywords: super-earth, CoRoT-7b , JWST, lava ocean

1 Introduction

Rocky planets are now detected and we can estimate with a very good accurancy (down to 5%) their mass, radius and then their density. The next steps are the caracterisation of their surface properties and their atmosphere, when there is one. Present and futur space missions will allow the study of exoplanets atmosphere and ground properties in the most favorable cases, using all the available signatures, from visible to infrared (IR) wavelengths. The Hubble Space Telescope (HST), Spitzer, the James Webb Space Telescope - here after JWST - (Gardner et al. 2006), or fully dedicated projects like EChO, Exoplanet Characterisation Observatory (Tinetti et al. 2012) gives or are going to give the first physical information on exoplanets surface nature. Obviously, the case of super-earths is more tricky because the planet to star size and mass ratios are not in favor of high amplitude signals. In this short paper, we will try to show that it is be possible to get some relevent quantitative measurement in some favorable cases. We will use, as an example, the case of the very hot super-earth (SE here after) CoRoT-7b, and simulate observationq with the JWST.

2 CoRoT-7b: A super-earth at 0.017 AU from it sun like star.

The detection of super-earth with the transit method gives a signal amplitude (relatively to the star) during the primary transit (the planet hides a part of the star from the point of view of the observer)

$$\epsilon_1 \approx \left(\frac{R_p}{R_\star}\right)^2, \tag{2.1}$$

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when R_p and $R_\star$ are the radius of the planet and the star respectively. The secondary transit signal (the star hides the planet) is proportionnal to $\epsilon_2 \approx \epsilon_1 \left(\frac{T_p}{T_\star}\right)^4 \sim \epsilon_1 \left(\frac{R_\star}{a}\right)^2$ so finally

$$\epsilon_2 \sim \left(\frac{R_p}{a}\right)^2, \tag{2.2}$$

where T_p and $T_\star$ are the temperature of the planet and the stars respectively, and a the planet to star distance. We understand that, if the small size of the super-earths makes difficult the detection, CoRoT-7b, Kepler-10b and more generaly the very hot SE show a particular advantage in term of planetary emission detection thanks to the unusual proximity of their host star ($<$ 0.02AU). Léger et al. (2011) and Rouan et al. (2011) have shown that the surface temperature of the substellar point of such objects is expected to reach 2500 to 3000K.

Furthermore, the star-planet distance and mass ratio will constrain the ability for the planet to hold an atmosphere or not, considering the surface temperature of the planet, the intensity of the stellar radiation, the stellar wind and more generaly the star activity, and the size of the roche lobe. In the special case of the very hot super-earths, a dense atmosphere is not really expected (Léger et al. 2011).

Moreover, the tidal interaction should have led to a quick circularisation of the orbit and a phase locking of the planet.

The very short distance between the planet and the star must have led, as illustrated by CoRoT-7b, to the absence of a dense atmosphere, and then to dramatically different thermal conditions between the two hemispheres of the planet: a frozen night face with a temperature that does not exceed 50 or 75 K, while the irradiated hemisphere can reach more than 2500 K, leading to the melting of a large part of the rocky surface, and giving birth to a large so called "lava-ocean" (Léger et al. 2011).

3 How to check the validity of the lava-ocean model?

These exotic predictions cannot be confirmed with the current available observations. In order to test the validity of the fundamental hypothesis of the model of Léger et al. (2011), we have tried to imagine what would be surface properties of CoRoT-7b like if, for an example, the complete phase-locking did not happen. We could imagine such a situation if a third body, such as CoRoT-7c (Queloz et al. 2009), could have excited the orbit of CoRoT-7b, and then prevented the circularization of the orbit. Other scenarios could be suggested, but our goal here is mainly to explore the discernability of a phase-locked situation from another, thanks the observations.

In this state of mind, we have modelled a rotating CoRoT-7b, with different planetary rotation periods, different albedos, and we have computed the reflected and emited thermal flux of the planet, taking into acount the particular surface temperature map that would results from the partial melting, the periodical warming and cooling drives by the violent irradiation variations undergone by the surface.

We found that a non phase-locked rocky planet, in the orbital condition of CoRoT-7b, would exhibit an ephemeral lava-ocean at its surface[i], appearing and desappearing every day as a kind of daily ice floe. The melted area would continuously follow the substellar point (Fig. 1), with a little delay from the noon stellar time, as a function of the rotationnal speed and the thermal inertia of the floor. This effect is stronger at long wavelengths, where the thermal emission of the planet dominates the reflected light from the star, than at shortest wavelengths where this is the opposite trend, as shown on Fig. 2. We have tried to see if we could take advantage of this feature to significantly detect a difference from the phase-loked case.

4 Observation with the JWST

We simulated the thermal and reflected emission from the planet surface during the orbit, thanks to the temperature map computed as explained in the previous paragraph. We choosed to simulate the observations with the instrument NIRSPEC on the JWST, wich covers a spectral range (600 nm to 5 μm) that allows to observe both reflected light from the star and thermal emisson of the planet.

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[i] For this study, we did not take into account the energy dissipation due to the tidal forces applied on the rotating planet. A study including this source of energy is on progress.

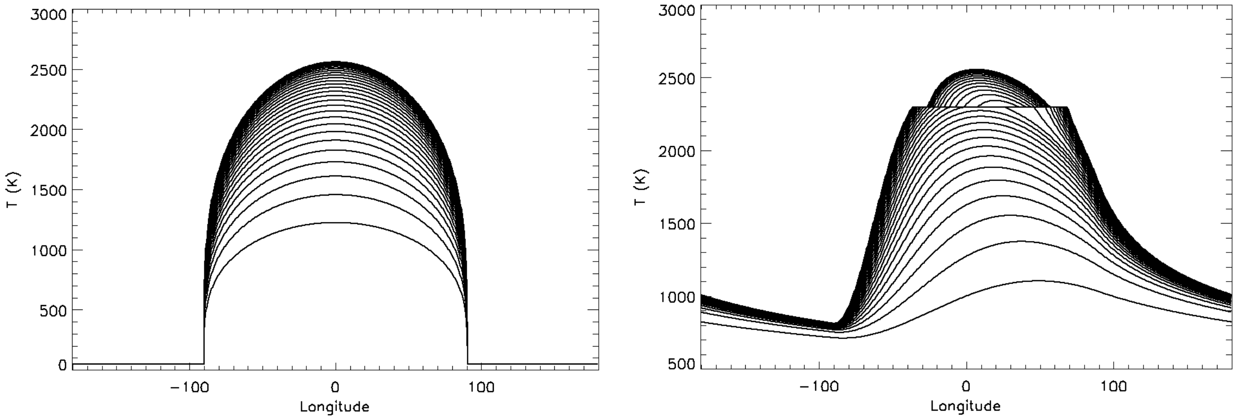

Fig. 1. Left: Temperature on the surface of a phase-locked CoRoT-7b, as a function of the longitude. From the top to the botom, each solid line represents a latitude, from the equator (lat= 0) to lat= 85. **Right:** The same situation, with a non phase-locked CoRoT-7b. The planetary rotation period is 10.5h long (more precisely, the stellar day is 10.5h long), which is one half the orbital period. The temperature threshold around latitude $-45°$and $60°$corresponds to the melting temperature, where the latent heat must be overpassed before the temperature can evolve.

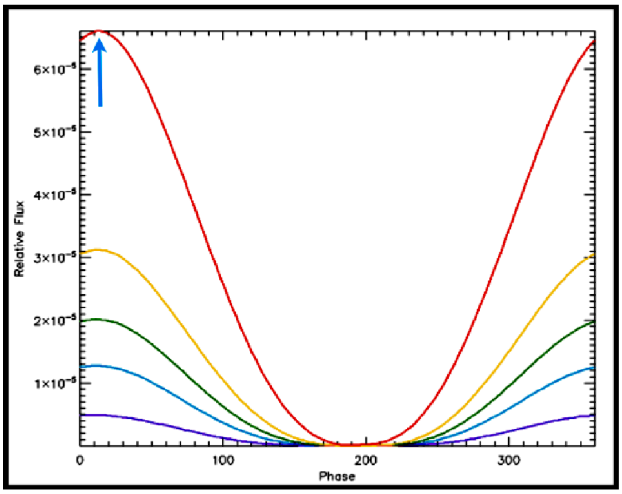

Fig. 2. We show the expected phase-curves of CoRoT-7b if it was not phase-locked. The five curves represent five different wavelengths, from 3.5 μm (red line) to 600 nm (purple line). The blue arrow points out the lag of the "hot point" alignment with the line of sight, in comparison to the phase zero (secondary transit). The shortest wavelength emission flux, dominated by the reflected light from the star, does not show this feature.

We divided the spectrum into five band centered from 800 nm to 3.5 μm and simulated the associated measurement including realistic simulated noise, using an online exposure time calculator tool `http://jwstetc.stsci.edu/etc/input/nirspec/spectroscopic/`.
We computed the phase curve of a full orbit of the planet at the different wavelengths, for the different scenarios. The near-IR channels mainly provide an information on the reflected light component from the planet (where the stellar flux dominates), while the mid-IR wavelength observation probes the thermal emission from the planet, where the planet to star flux ratio is less in favor of the star.

5 Results

In some favorable cases, the simulated observations allow to differenciate the phase-curves of a phase-locked planet from a rotating one. The confidence level is quite good when the rotation period (stellar day) of the planet is of the same order of magnitude than the orbital period ($P_{\rm orb} = 0.85$ days in this case) as shown on Fig. 3. When we simulate the observation of a phase-locked planet, we can assess a minimum value for the rotation period compatible with the observation. This is the way we should be able to constrain and confirm the nature of very hot SE as CoRoT-7b.

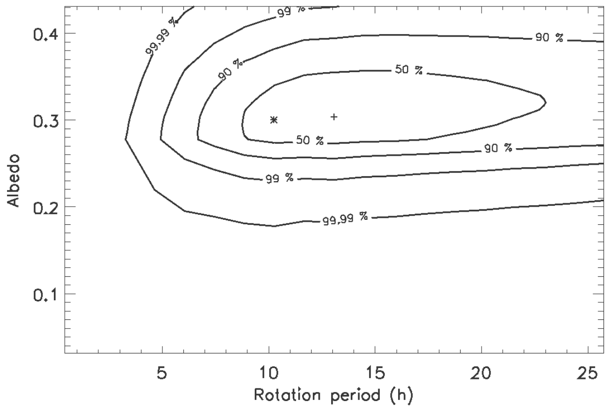

Fig. 3. On this figure, we show the result of a simulated observation of a rotating CoRoT-7b. The simulated rotation period is 10.5 hours ($P_{\rm orb}/2$) and the albedo is 0.3, as represented by the black star. This exercice shows that in this situation, we can find back the rotation period (we found $P = 13.0^{+7.7}_{-2.1}$h, and the albedo $a = 0.30^{+0.06}_{-0.02}$) as represented by the black cross. In this simulation, the phase-locked senario can be rejected with a confidence level of 13 σ.

6 Conclusion

The new generation of space telescopes with large mirrors and wide spectral range spectrographs will be a new milestone in the study of exoplanets. We already know that a lot of giant planets (and less massive planets in favorable situations) will reveal their atmosphere composition, using the differential light flux variations that occurs during the primary and the secondary transits. With this work, we show that will be able to set of information on planets, even of small radius and devoided of an atmosphere. We illustrate in this article how other interesting pieces of information will be provided by these instrument. In particular, this first study led us to the conclusion that the observation of a modulation of the emmited/reflected light from very hot super earths such as CoRoT-7b during their orbit can bring precise answers on the phase-locking, the rotation velocity, and the albedo of these objects. Studies in progress will investigate the possibility to probe the effect of an hypothetical more or less faint residual atmosphere on very-hot super earthes. Finally, we should be able to check step by step the validity of the lava-ocean planet model. Of course, we can hope that the future space telescope will lead to totaly different situations and surpring surface propertie that we did not even expected.

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