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An Analytical Model for the 0.33 - 7.85 Micron Transmission Spectrum of HD189733b: Effect of Stellar Spots

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ABSTRACT

In recent years, the transit of HD189733b is the most observed among all known transiting exoplanets. The transmission spectrum of this planet has been measured with several instruments from Spitzer and Hubble (HST) Space Telescopes, and from several ground-based telescopes. In this paper an analytical theory is used to complete this spectrum from near-ultraviolet to infrared (0.33 - 7.85 μm). The model suggests a new approach which take into account the quantity of light transmitted through the planetary atmosphere and the thermal emissions from the night side of the planet, to describe the transmission spectrum of HD189733b in photometric study. The availability of measures in different wavelengths has allowed us to validate our model with more efficiency. We found an agreement between our transmission spectrum model of HD189733b and data from the infrared to the UV. The model predicts a value of $R_p/R_\star = 0.1516$ at $7.3\mu m$, which is a low value compared to all observations at different wavelengths. We interpreted this value by a fluorescence emission from sulphur dioxide (SO_2). Therefore, the likely presence of these molecules in the atmosphere of HD 189733b. The second objective of this paper is to study the effect of starspots on the transmission spectrum of this hot-Jupiter. To reach this goal, we developed an analytical theory considered as an extension of the approach proposed by Berta et al. 2011 [5]. The model shows clearly that the unocculted spots would significantly increase the transit radius ratio at visible and near-ultraviolet wavelengths, while having a minimal impact at infrared wavelengths. Therefore, the wavelength dependence of the spots effect has been clearly shown by this new model. At the end of this paper, we reported the way in which this model can provide an estimation of the percentage of the unocculted spots area relative to stellar disk area for an observation of HD189733 performed in a given epoch and at a given wavelength.

General Terms:

Transmission spectrum, atmosphere.

Keywords:

Planetary systems - starspots - stars: individual: HD 189733 - planets: atmospheres - techniques: photometric.

1. INTRODUCTION

The increasing of the number of exoplanets discovered during last years, revealing several types of systems with diffrent properties. Our understanding of planets outside the solar system is revolutionising from various studies on the transiting planets. The phenomenon of transiting planets is produced when the planet is located on the same plane containing the star and the earth, during this phenomenon, a part of the starlight is blocked by the planets and producing a specific light curve. The study of transiting planets gives an idea for their structure. Indeed, the transit technique can estimate the radius of the planet and its orbital inclination, and coupled with data from the radial velocity technique gives an estimate of the mass. Therefore, the density and structure can be inferred.

Two approaches are used to measuring the dependence of wavelength of a planetary radius. The first approach is by monitoring the transiting planets with spectroscopic measurements, which allow a measurement of transit depth at each wavelength by making a separation of light curves for each channel of wavelength. The second approach, is to perform multi-wavelength photometric observations of planetary transits, and estimate the transit depth for each. The model presented in this paper is focused on this second method.

A new class of planets having masses identical to Jupiter and on orbits of very short-period are called Hot Jupiters, their atmospheres are very hot because they are intensely irradiated by their stars. Therefore, the large atmospheric heights of these planets make them specially good targets for the measurements described above. Typically, HD189733b represents a good example for these measurements. The planet orbits a bright K2V star and characterized by a transit depth of $\sim 2.5\%$ ((Bouchy et al. 2005) [3]). Following Knutson et al. 2007(a,b) [13, 14] the planet has a brightness temperature varies between 960 and 1220 K. The large scale height of the atmosphere allowing transits to measure its chemical composition. The two approaches of measurements described above have been used to detect several species in the atmosphere of this hot-Jupiter, for example, the presence of H_2O has been inferred from Spitzer observations ((Tinetti et al. 2007) [21]). The observations also suggested the existence of a haze in the upper part of the atmosphere of this hot Jupiter at optical wavelengths ((Pont et al. 2008) [16]).

Note that HD 189733 is an active star. In general, the presence of stellar magnetic variability, caused by bright faculae or cool spots, may modify the transit depth and have an important influence on the derivation of the planetary radius ((Berta et al. 2011) [5]; (Sing et al. 2011a) [19]; (Pont et al. 2008) [16]; (Désert et al. 2011a) [10]; (Agol et al. 2010) [1] ; (Czesla et al. 2009) [9]; (Sing et al. 2009) [20]). In visible light, the presence of spots in the photosphere of HD 189733 causes a variation of its flux by $\pm 1.5\%$ over its 11.953 ± 0.009 days period of rotation ((Henry et al. 2008) [11]; (Winn et al. 2007) [23]; (Miller-Ricci et al. 2008) [15]; (Croll et al. 2007) [7]). Therefore, the existence of such spots during the transit of its planetary companion, affect the determination of the radius of the planet and the analysis of its transmission spectrum. Several models have been developed by Czesla et al. 2009 [9], (Ballerini et al. 2012) [2], (Berta et al. 2011) [5], (Désert et al. 2011a) [10] to estimate the starspots effects on the exoplanet sizes determination.

In this paper, we present a new approach to study the effect of starspots on the planetary transmission spectrum. This approach based on the representation of the stellar spectrum by the blackbody radiation described by the Planck function. In general, when working with photometry (and not with spectroscopy) we observe a deviation of the stellar spectrum from a blackbody, but to model the planetary transmission spectrum by considering the stellar spectrum as a blackbody radiation, we need to search the analytical expression of planetary optical depth consistent with these radiation, and the combination of both can compensates the deviation observed initially and provides finally a correct expression describing the planetary transmission spectrum.

In the Sect. 2, we present a summarized of the recent main approaches studying the starspots effects on the exoplanet sizes determination. The Sect. 3 give a detailed description of the model for both cases : with and without stellar activity. A comparison with observations will be presented in Sec. 4 in order to check the validity of our model. The analyze of the impact of starspots on the planetary transmission spectrum is carried out also in this section. We give a conclusion in Sect. 5.

2. THE RECENT MAIN APPROACHES STUDYING THE STARSPOTS EFFECTS ON THE EXOPLANET SIZES DETERMINATION

Several approaches have been developed to study the effect of starspots on the exoplanet sizes determination. A remarkable approach treating this effect was developed by Czesla et al. 2009 [9] on the active star CoRoT-2. They proposed a method to extract the unperturbed transit light curve from the observed profiles. They reported also that it is important to normalize the transit profile to a common reference level in order to compare different transits.

Ballerini et al. 2012 [2] proposed a systematic approach allows the quantification of the flux variations of the star due to its magnetic activity. In their approach, they assumed a star with spots covering a given fraction of its disc and model the variability in both the $UBVRIJHK$ photometric system and the IRAC/Spitzer wavebands for dwarf stars. Thereafter, they compare the planetary transits with activity-induced flux variations in different passbands and quantify how they affect the determination of the planetary radius.

Another active star GJ1214 studied by Berta et al. 2011 [5]. They used a simple model to estimate the transit depth variations $\Delta D_{spots}(\lambda, t)$ induced by the unocculted spots. They assumed a fraction $s(t)$ of the visible stellar surface covered with spots, this fraction will change as the star rotates and the spots evolve. They introduced the following definition to derive the transit depth variations due to spots

$$D(\lambda, t) = 1 - \frac{F_{i.t.}(\lambda, t)}{F_{o.o.t.}(\lambda, t)} \tag{1}$$

where $F_{o.o.t.}(\lambda, t)$ and $F_{i.t.}(\lambda, t)$ are the observed out-of-transit and in-transit spectra, respectively, defined as

$$F_{o.o.t.}(\lambda, t) = [1 - s(t)]F_{\circ}(\lambda) + s(t)F_{\bullet}(\lambda) \tag{2}$$

$$F_{i.t.}(\lambda, t) = \left[1 - s(t) - \left(\frac{R_p}{R_\star}\right)^2\right]F_{\circ}(\lambda) + s(t)F_{\bullet}(\lambda) \tag{3}$$

where $F_{\circ}(\lambda)$ and $F_{\bullet}(\lambda)$ are respectively the spectrum of the unspotted photosphere and that of the presumably cooler spotted surface. In their calculations, they neglected limb-darkening and treated each of the two components presented in each above expressions ((2) and (3)), as having uniform surface brightness. In addition, they used the blackbody approximation for $F_{\circ}(\lambda)$ and $F_{\bullet}(\lambda)$, and considered that the planet blocks light across a spot-free transit chord. A limitation of this approach is that by considering a planet with no atmosphere. Therefore, the quantity of light transmitted through the planetary atmosphere has been neglected. The molecular species present in the atmosphere of the planet may absorb a quantity of the stellar radiation, and therefore, produce a variation in the apparent planetary radius as a function of the wavelength.

In this paper, we develop the above approach proposed by Berta et al. 2011 [5]. We will keep the same considerations used in this approach, except that we will take into account, in this time, the quantity of light transmitted through the planetary atmosphere to estimate the starspots effect on the planetary transmission spectrum (see Sect.3).

3. DESCRIPTION OF THE MODEL

In this study, we present a new approach describes the transmission spectrum of HD 189733b. Our goal is to model this spectrum by taking into account of two sources of radiation emitted by the planet when it passes in front of its star : the thermal emissions from the night side of the planet and the quantity of light transmitted through its atmosphere.
The model is focused on the study of this system in a wavelength range from near-ultraviolet to infrared (0.33 - 7.85 μm), where two cases could be taken into consideration. First, when the star presents no spots on its visible surface. Second, when the flux emitted by the star is perturbed by the stellar activity (with starspots).

3.1 The wavelength dependence of the transit depth

In this section, we consider that the flux emitted by the star is not affected by the stellar activity. Then, as considered by Berta et al. 2011 [5], we approximate the stellar spectrum (W/m^3) from the Planck law of blackbody radiation :

$$L_\star(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{exp\left(\frac{hc}{\lambda k_B T_\star}\right) - 1} \tag{4}$$

where $T_\star$ is the stellar effective temperature, λ is the wavelength, k_B, c and h are respectively the Boltzman constant, the light speed and the Planck constant.
In order to integrate the contribution of the thermal emissions from the night side of the planet in the transit depth calculation, these emissions can be represented by :

$$L_p(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{exp\left(\frac{hc}{\lambda k_B T_p}\right) - 1}\,\epsilon_p \tag{5}$$

where T_p is the surface temperature of the night side of the planet, ϵ_p the emissivity of the night side of the planetary atmosphere. In general, ϵ_p is wavelength dependent, but as first approximation we consider it invariant in the wavelength range studied in this model (0.33 - 7.85 μm).
From the above approximations, we define the relative transit depth as :

$$\left(\frac{\Delta F}{F}\right)_\lambda = \frac{F_{out}(\lambda) - F_{in}(\lambda)}{F_{out}(\lambda)} \tag{6}$$

where $F_{in}(\lambda)$ and $F_{out}(\lambda)$ are the radiations received on the Earth per unit surface of a detector and per unit of wavelength (W/m^3), during the transit (from both the star and the planet) and out of the transit (from the star only) respectively. The maximum of information on the planetary atmosphere is obtained when the planet is in the middle of the transit, i.e. when its atmosphere is entirely projected on the visible face of the star and that the limb-darkening effects of the star are minimized.
As considered by Berta et al. 2011 [5], we neglect the limb-darkening of the star and treat it as has uniform surface brightness. Therefore, $F_{in}(\lambda)$ and $F_{out}(\lambda)$ defined in Eq.(6) can be expressed as :

$$F_{out}(\lambda) = \frac{S_\star L_\star(\lambda)}{f_\star \pi d_\star^2} \tag{7}$$

$$F_{in}(\lambda) = \frac{(S_\star - S_p)L_\star(\lambda)}{f_\star \pi d_\star^2} + \frac{S_p L_p(\lambda)}{f_p \pi d_p^2} + \frac{S_p^{atm} F_T(\lambda)}{f_p \pi d_p^2} \tag{8}$$

where $S_\star$ and S_p are respectively the stellar and planetary disk areas. S_p^{atm} is the effective area allowing the transmission of light through the limb of the planet during a primary transit. $F_T(\lambda)$ is the quantity of light transmitted by the effective area S_p^{atm}, $d_\star$ and d_p are respectively the Earth-Star and Earth-Planet distances ($d_\star \sim d_p$). f is a factor which depends of the anisotropy of the radiation. For the star, we consider that the radiations are emitted isotropically from its surface. But for the planet, it should be noted that its atmosphere is not calm. However, the strong stellar gravity makes one hemisphere of the planet constantly faces the star, heating permanently only on one side. This probably creates fierce winds sweeping from the day side to the night side ((Knutson et al. 2007b) [14]). Therefore, the quantity of light traversing through the planetary atmosphere during the transit and the thermal emissions from the night side of the planet, may affected by these fierce winds which may cause a deviation of a part of these radiations, and leading to a non-isotropic emission from the planet.

The stellar and planetary surfaces appearing in Eq.(7) and Eq.(8), will be presented as a ratio $S_p/S_\star$ in the relative transit depth expression. Considering a circular orbit for the planet, this ratio can be expressed in terms of some parameters derived directly from the transit light curve using the following analytic approximations ((Carter et al. 2008) [6], (Seager et al. 2003) [18]):

$$b^2 \approx 1 - \frac{T}{t_0} \times \frac{R_p}{R_\star}, \tag{9}$$

$$\frac{a}{R_\star} = \frac{b}{\cos i} \approx \frac{P\sqrt{\frac{R_p}{R_\star}}}{\pi\sqrt{Tt_0}}, \tag{10}$$

where t_0 is the egress or ingress duration ($t_0 = t_{II}$ - t_I), t_{II} and t_I are the time of second and first contact, T is the total transit duration, $R_\star$ and R_p are the stellar and planetary radii, a is the orbital semi-major axis, i is the orbital inclination, P is the orbital period and b is the impact parameter.
From the Eq.(9) and Eq.(10), the planet-to-star surface ratio $S_p/S_\star$ is estimated by

$$\frac{S_p}{S_\star} \approx \left(\frac{P^2\cos^2 i}{\pi^2 T t_0} + \frac{T}{t_0}\right)^{-2} \tag{11}$$

The relative transit depth can thus deduced by combining the expressions (7) and (8) with the Eq.(11) :

$$\begin{aligned}\left(\frac{\Delta F}{F}\right)_\lambda = & \left[\frac{S_p}{S_\star}\left(1 - \epsilon_p \frac{f_\star d_\star^2}{f_p d_p^2}\frac{(exp(\frac{hc}{\lambda k_B T_\star}) - 1)}{(exp(\frac{hc}{\lambda k_B T_p}) - 1)}\right)\right. \\ & \left. - \frac{S_p^{atm}}{S_\star}\frac{f_\star d_\star^2}{f_p d_p^2}\frac{F_T(\lambda)}{L_\star(\lambda)}\right]\end{aligned} \tag{12}$$

where $S_p/S_\star$ is estimated from the Eq.(11). For gaseous giant planets, the ratio between the area which can transmit light and area star-minus-planet is very low, of the order of 10^{-4} to 10^{-3} ((Batista 2011) [22]). This allows us to estimate the $S_p^{atm}/S_\star$ ratio as

$$\frac{S_p^{atm}}{S_\star} \approx 10^{-3}\left(1 - \frac{S_p}{S_\star}\right) \tag{13}$$

The quantity of light transmitted through the limb of the planet (W/m^3) is defined as

$$F_T(\lambda) = e^{-\tau(\lambda)} L_\star(\lambda) \tag{14}$$

where $\tau(\lambda)$ is the optical depth of the planetary atmosphere as a function of the wavelength. We know that the way exoplanet atmospheres transmit light depends (a) on their chemical composition and (b) the temperature dependent way in which the species that make up atmosphere absorb and emit light. But when working with photometric models and considering the incident stellar flux as a blackbody radiation, we need in this case to search the transmission mechanism of this radiation and the corresponding optical depth expression which allow us to explain the transmission spectrum of HD189733b.

In this work, we consider that the transmission of light through the planetary atmosphere is done by the intermediate of the fluorescence phenomenon. With this in mind, we suggest that the temperature dependent way in which the species that make up atmosphere absorb and emit light should be represented by a power law of the quantity $\frac{k_B T_{pl}}{h\nu}$ when the stellar spectrum is considered as a blackbody radiation, where T_{pl} is the equilibrium temperature of the planetary atmosphere reached after a certain number of absorption and emission of photons each has an energy $h\nu$.

From the above considerations, the quantity $e^{-\tau(\lambda)}$,which represents the portion of the transmitted light, can be expressed as :

$$e^{-\tau(\lambda)} = \sum_{k=0}^{n} f_k \left(\frac{k_B T_{pl}}{h\nu}\right)^k \qquad (15)$$

where n is a integer number ($n \in N^{\star}$), f_k are proportionality coefficients correspond to different values of k. From the above expression, the optical depth $\tau(\lambda)$ can be written as :

$$\tau(\lambda) = -log\left[\sum_{k=0}^{n} f_k \left(\frac{k_B T_{pl}}{h\nu}\right)^k\right] \qquad (16)$$

Both expressions (15) and (16) are valid mathematically only when the quantity $\sum_{k=0}^{n} f_k \left(\frac{k_B T_{pl}}{h\nu}\right)^k$ is strictly positive. To examine the sign of this latter, we suggest the following polynomial form of variable k for the proportionality coefficients f_k, which, at the same time, must verifies the mathematical condition and has a physical signification

$$f_k = (-10)^k \sum_{i=0}^{5} \beta_i k^i \qquad (17)$$

with this expression of f_k, the quantity $\sum_{k=0}^{n} f_k \left(\frac{k_B T_{pl}}{h\nu}\right)^k$ satisfied to both above conditions, in the wavelength range considered in this model (0.33 - 7.85 μm), for $k \leq 5$ ($n = 5$) and for the following values of the coefficients β_i : $\beta_0 = 2.053$, $\beta_1 = -15.7469$, $\beta_2 = 26.8868$, $\beta_3 = -13.4712$, $\beta_4 = 2.68125$, $\beta_5 = -0.18793$.

3.2 Impact of starspots on the transit depth

In this section, we present a development of the approach proposed by Berta et al. 2011 [5] (and by Ballerini et al. 2012 [2] that they have used almost the same concept) to estimate the starspots effect on the planetary radius determination. We will take into account, in this estimation, the quantity of light transmitted through the planetary atmosphere (described in the last section) neglected by Berta et al. 2011 [5]. As considered by these authors, we study the effect of starspots unocculted by the planet which blocks light across a spot-free transit chord (Fig. 1).

Previous HST ACS observations of HD 189733 have established that the effective temperature of starspots is approximately 1000 K cooler than that of the stellar photosphere ((Pont et al. 2008) [16]) with a spot size of $\sim$ 3% of the stellar disk area. According to the approach proposed by Berta et al. 2011 [5], we will take into account in our expressions that the spot size parameter is expected to evolve in time by introducing the parameter α which represents the percentage of the spots area relative to stellar disk area. The starspots have a different temperature, so to estimate their effect on the relative transit depth, we consider an average temperature T_{spots} corresponds to each of these spots, and we treat them as a blackbody with this temperature.

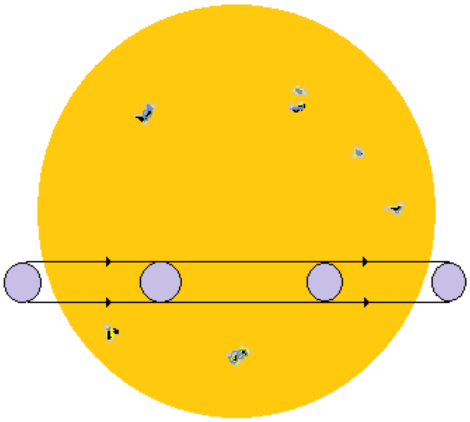

Fig. 1. Geometrical view of the HD189733 system considered in this model to study the effect of stellar spots on the transmission spectrum of HD 189733b.

From the above considerations, the expressions of $F_{out}(\lambda)$ and $F_{in}(\lambda)$ become :

$$F_{out}^{spots}(\lambda) = (1-\alpha)F_{out}(\lambda) + \frac{\alpha S_\star L_{spots}(\lambda)}{f_s \pi d_\star^2} \qquad (18)$$

$$F_{in}^{spots}(\lambda) = F_{in}(\lambda) - \alpha F_{out}(\lambda) + \frac{\alpha S_\star L_{spots}(\lambda)}{f_s \pi d_\star^2} \qquad (19)$$

where f_s is a factor depending on the anisotropy of the radiation emitted from the spots. This coefficient is assumed identical to $f_\star$ (the light is emitted isotropically from the spots). It is important to note that the present description neglects the limb darkening of the spots.

From the expressions (18) and (19), the relative transit depth defined by the Eq.(6) is given by :

$$\left(\frac{\Delta F}{F}\right)_\lambda^{spots} = \left[\frac{S_p}{S_\star}\left(\frac{\frac{1}{exp\left(\frac{hc}{\lambda k_B T_\star}\right)-1} - \epsilon_p \frac{f_\star d_\star^2}{f_p d_p^2}\frac{1}{exp\left(\frac{hc}{\lambda k_B T_p}\right)-1}}{\frac{1-\alpha}{exp\left(\frac{hc}{\lambda k_B T_\star}\right)-1} + \frac{\alpha}{exp\left(\frac{hc}{\lambda k_B T_{spots}}\right)-1}}\right) - \frac{\frac{S_p^{atm}}{S_\star}\frac{f_\star d_\star^2}{f_p d_p^2}\frac{F_T(\lambda)}{L_\star(\lambda)}}{(1-\alpha) + \alpha\frac{exp\left(\frac{hc}{\lambda k_B T_\star}\right)-1}{exp\left(\frac{hc}{\lambda k_B T_{spots}}\right)-1}}\right] \qquad (20)$$

where T_{spots} represents the effective temperature of the spots. We kept respectively for $S_p/S_\star$ and $S_p^{atm}/S_\star$ the expressions (11) and

Table 1. Planetary transmission spectrum measured by several instruments at different epochs from Spitzer and Hubble (HST) Space Telescopes, and corrected from starspots by a consistent treatment ((Pont et al. 2013) [17])

Wavelength (μm)	$R_p/R_\star$	σ
0.3300	0.15866	0.00043
0.3300	0.15734	0.00051
0.3950	0.15732	0.00026
0.4450	0.15701	0.00024
0.4950	0.15669	0.00023
0.5450	0.15672	0.00016
0.5750	0.15644	0.00014
0.5865	0.15638	0.00027
0.5895	0.15703	0.00011
0.5980	0.15631	0.00022
0.6095	0.15617	0.00036
0.6207	0.15600	0.00027
0.6321	0.15611	0.00019
0.6250	0.15610	0.00012
0.6750	0.15585	0.00011
0.7250	0.15572	0.00011
0.7750	0.15586	0.00012
0.8250	0.15552	0.00012
0.8750	0.15553	0.00013
0.9250	0.15546	0.00013
0.9750	0.15552	0.00016
1.0250	0.15496	0.00024
1.1050	0.15671	0.00084
1.1335	0.15549	0.00089
1.4920	0.15335	0.00129
1.5925	0.15608	0.00055
1.6070	0.15543	0.00082
1.6580	0.15516	0.00056
1.6650	0.15405	0.00079
1.7220	0.15424	0.00098
1.7790	0.15511	0.00068
1.8370	0.15490	0.00070
1.8740	0.15456	0.00048
1.8940	0.15572	0.00075
1.9510	0.15525	0.00069
2.0090	0.15370	0.00058
2.1810	0.15483	0.00068
2.2380	0.15490	0.00061
2.2960	0.15491	0.00073
2.3530	0.15432	0.00063
2.4110	0.15496	0.00070
2.4680	0.15520	0.00090
3.6000	0.15452	0.00059
4.5000	0.15543	0.00049
5.8000	0.15476	0.00067
7.8500	0.15510	0.00034

(13). Since the total transit duration (T) and the ingress/egress durations (t_0) are not affected by the unocculted starspots. On the other hand, Czesla et al. 2009 [9] found that no significant correction in the inclination i due to starspots effect. Note that for $\alpha = 0$, we find the expression of the relative transit depth given by the Eq.(12) when the star presents no spots on its visible surface.

4. RESULTS AND DISCUSSION

4.1 Model validation

In the framework of the approximations used in this model, the wavelength dependence of the planet-to-star radius ratio can be estimated as the square root of the relative transit depth defined in section 2 :

$$\left(\frac{R_p}{R_\star}\right)_\lambda = \left[\frac{S_p}{S_\star}\Big(1 - \epsilon_p \frac{f_\star d_\star^2}{f_p d_p^2}\frac{(exp(\frac{hc}{\lambda k_B T_\star}) - 1)}{(exp(\frac{hc}{\lambda k_B T_p}) - 1)}\Big) - \frac{S_p^{atm}}{S_\star}\frac{f_\star d_\star^2}{f_p d_p^2} e^{-\tau(\lambda)}\right]^{1/2} \quad (21)$$

The comparison with observations is necessary to validate our model. The ideal is to compare with simultaneous data, since the activity of the star allows the evolution in time of the spots size and their distribution on the stellar disk surface, leading to different impacts on the measure of the planetary radius. As we have no simultaneous data throughout the wavelength range considered in this work (0.33 - 7.85 μm), the comparison will be done with the planetary transmission spectrum measured by several instruments at different epochs from Spitzer and Hubble (HST) Space Telescopes, and corrected from starspots by a consistent treatment ((Pont et al. 2013) [17]).

In Figure. 2, we plot our transmission spectrum model of HD 189733b using the values presented in Table 2 correspond to its different parameters. In the same figure, the model was over-plotted by data from a new tabulation (Table 1) of the planetary transmission spectrum across the entire visible, near-ultraviolet and infrared range provided by Pont et al. 2013 [17]. In that table, the radius ratio in each wavelength band was re-derived, and a special care was taken to correct for, and derive realistic estimates of the uncertainties due to, both occulted and unocculted star spots. Details of the analysis of the data (and for the derivation of new error bars) can be found in Pont et al. 2013 [17]. In general we found a remarkable agreement between our model and the data. In the mid-infrared range, we have a total agreement with observations at 3.6 μm, 4.5 μm, 5.8 μm and 7.85 μm. Similarly for the observations in the near-ultraviolet range (0.33 μm, 0.395 μm, 0.445 μm and 0.495 μm). For the $0.625 - 0.925$ μm wavelength range, the model is on average over-predict the transit radius ratio by 0.25% compared to data. However, it is on average under-predict the transit radius ratio by 0.84% compared to observations in the $1.550 - 2.468$ μm wavelength range.

A remarkable prediction shown by this model at 7.3 μm, where the $R_p/R_\star$ ratio has a low value compared to all observations at different wavelengths presented in Figure. 2. The predicted value is $R_p/R_\star = 0.1516$. Note that no space or ground-based observations were acquired at this precise wavelength to test this prediction. Future observations of HD 189733 shall help verify this prediction. The interpretation of this low value of radius ratio at 7.3 μm should take into account the fluorescence process considered in this model. The molecules of the planetary atmosphere which can absorb and emit light at this wavelength will increase the total flux detected during a primary transit, which leads to have a decrease of the transit depth. Therefore, the radius ratio will decrease also. Among the gas-phase molecules, a strong possible candidate is emission from the SO_2 ν_3 band at 7.3 μm. Crovisier et al. 2002 [8] shows that the ν_3 band of SO_2 at 7.3 μm has a fluorescence emission rate of 6.6 × 10^{-4} s^{-1} at 1 AU from the Sun. An absorption feature of the ν_3 vibrational band of gas-phase SO_2 has been

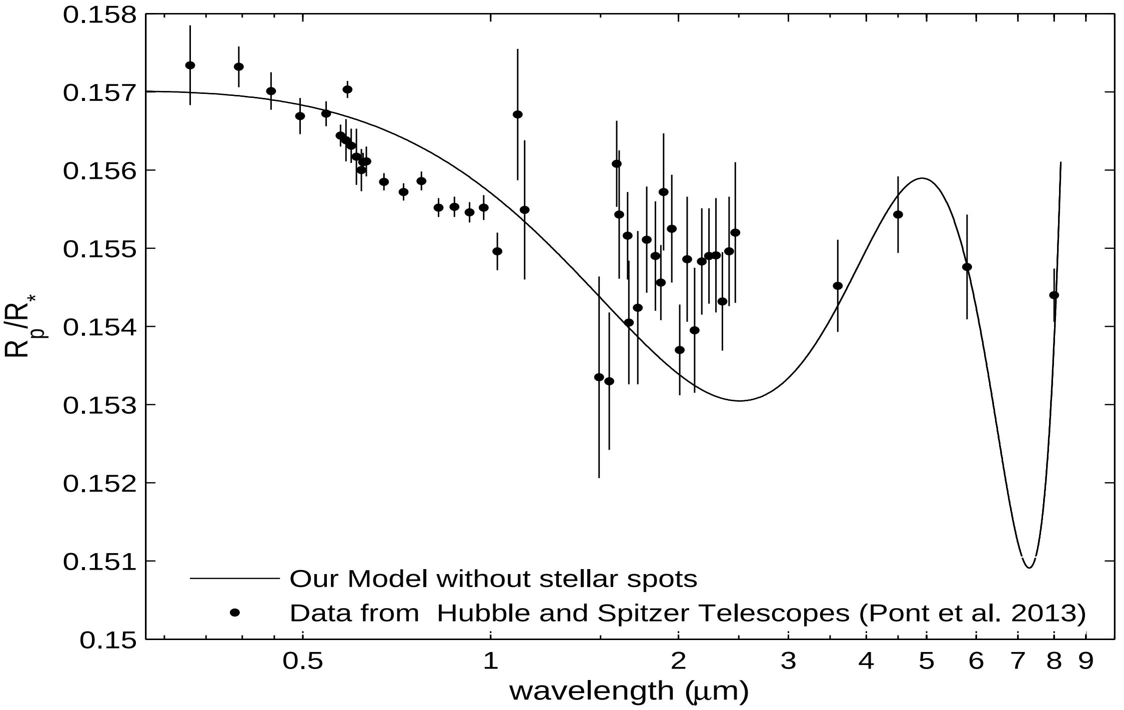

Fig. 2. Our transmission spectrum model of HD 189733b shown as the black curve and over-plotted by data from a new tabulation ((Pont et al. 2013) [17]) of the transmission spectrum across the entire visible, near-ultraviolet and infrared range. These data have been corrected from spots effect (see section 4.1)

Table 2. The values of different parameters used to plot the model

Parameter	Value	Reference
i	85.61 ± 0.04 degrees	Knutson et al. 2007b [14]
P	2.2 days	Knutson et al. 2007b [14]
T	1.8 h	Désert et al. 2011a [10]; Knutson et al. 2007b [14]
$T_\star$	$5000K$	Pont et al. 2013 [17]
T_{spots}	$4000K$	Pont et al. 2013 [17]
$T_p = T_{pl}$	$1000K$	Approximation used in this model
$f_\star/f_p$	$1/2$	inspired from our paper (Bouley et al. 2012) [4]
ϵ_p	$1/2$	hypothesis used in this model

detected in the mid-infrared spectral region around 7.3 μm from a sample of deeply embedded massive protostars (Keane et al. 2001 [12]). In addition, the SO_2 excitation temperature ranging up 700 K (Keane et al. 2001 [12]), which is in agreement with the equilibrium temperature (T_{pl}) considered in this model (see Table.1). A sufficient abundance of these molecules in the atmosphere of HD 189733b, can explain the low value of the radius ratio predicted by this model.

4.2 Impact of starspots on the transmission spectrum of HD 189733b

The transmission spectrum of HD 189733b derived from the Eq.(20) is strongly depends of the percentage, represented by α, of unocculted spots area relative to stellar disk area. Several independent approaches indicate that the background spot level is between zero and 3%, with lower values being more likely. In Figure.3, we plot the transmission spectrum of HD 189733b affected by the unocculted spots for different values of α from 0.5% to 3% with a step of 0.5%. In order to analyze the evolution of this transmission spectrum as a function of the wavelength and of α, we take for example the two extreme values of α considered in this paper. For $\alpha = 0.5\%$, and by comparing with our model without spots, the planet-to-star radius ratio is overestimated by 0.20% at 0.33 μm, by 0.13% at 0.6 μm and by 0.064% at 4.85 μm. Whereas for $\alpha = 3\%$, the radius ratio is overestimated by 1.34%, 1.02% and 0.45% at 0.33 μm , 0.6 μm and 4.85 μm respectively. The same figure shows that we have a lower impact on the transmission spectrum

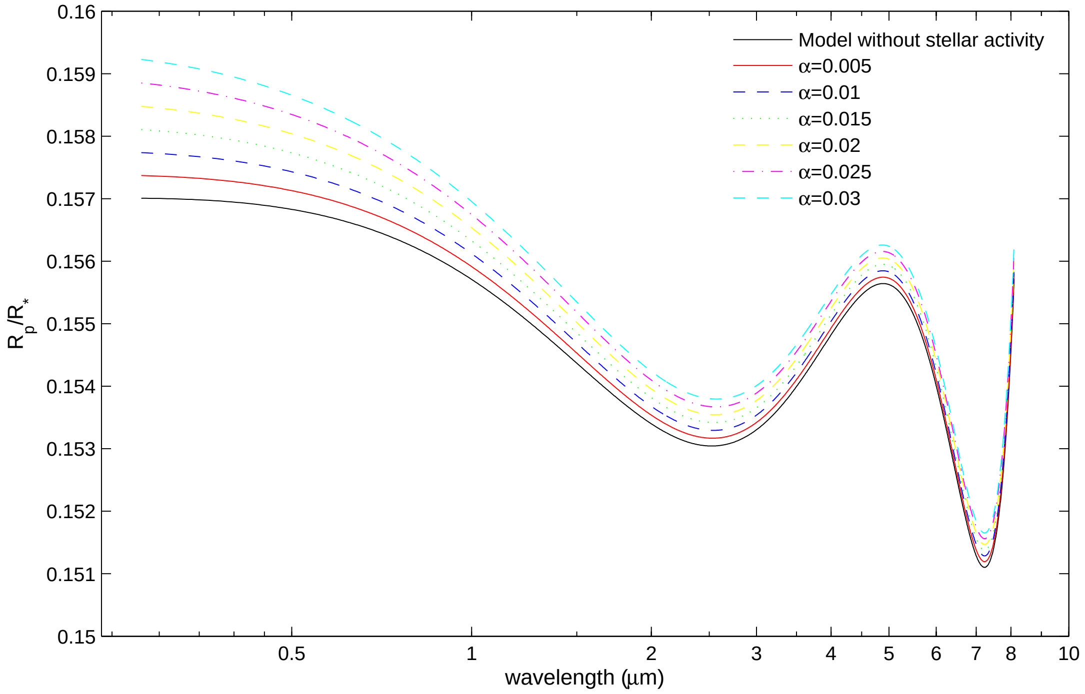

Fig. 3. Transmission spectrum of HD 189733b affected by the unocculted spots taking into account of different values of α from 0.5% to 3% with a step of 0.5%.

at the 5.5 - 8 μm wavelength range and this for all values of α considered in this work.

From these results, it is clear that for a given wavelength, the planet-to-star radius ratio increases with α. Therefore, the effect on the transmission spectrum of HD189733b becomes important when the star presents more spots on its visible surface. In addition, figure.3 shows also that this effect is wavelength-dependent, since the unocculted spots would significantly increase the transit radius ratio at visible and near-ultraviolet wavelengths, while having a minimal impact at infrared wavelengths.

This new analytical model was able to explain well the influence of unocculted starspots on the transmission spectrum of HD 189733b in the UV-to-IR wavelength range. One of the significant results showed by this model is that we have a negligible impact of starspots on the transmission spectrum of this planet for any observation made at wavelengths tending to 8 μm.

The model can also estimate the percentage of the unocculted spots area relative to stellar disk area (α). For an observation performed in a given epoch with a given instrument and at a given wavelength, this percentage can be deduced by knowing the value of the difference between the transit radius ratio uncorrected for the unocculted spots ($(R_p/R_s)_{uncorr}$) derived from the observation and its corresponding value corrected for spots ($(R_p/R_s)_{corr}$) from the data itself which can provide a constraint of the spots effect, independently of the models of spots correction. Thus, the same value of this difference, but this time found by making the difference between the transit radius ratio affected and not affected by spots derived from our model, can estimate the value of α.

5. CONCLUSIONS

An analytical model has been presented in this paper to explain the transmission spectrum of HD189733b from UV to IR (0.33 - 7.85 μm). We found a remarkable agreement between the model and the data. The model predicts a value of $R_p/R_\star = 0.1516$ at $7.3\mu m$, which is a low value compared to all observations at different wavelengths. We interpreted this value of the radius ratio by a fluorescence emission from sulphur dioxide (SO_2). Therefore, the likely presence of these molecules in the atmosphere of HD 189733b. Future observations of the transit of HD 189733b at $7.3\mu m$ should help to verify this prediction.

The current model represents an extension of the approach proposed by Berta et al. 2011 [5] to study the effect of stellar spots on the planetary transmission spectrum, and by using it we found that the unocculted spots have a remarkable influence on the transit radius ratio at ultraviolet and visible wavelengths, while having a minimal impact at infrared wavelengths. Therefore, the wavelength dependence of this effect is clearly showed by our analytical model. In the future, this model can be used to estimate the percentage of the unocculted spots area relative to stellar disk area for an observation of HD189733 performed in a given epoch and at a given wavelength.

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