Effects of Thermal Emission on the Transmission Spectra of Hot Jupiters

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Received 2020 February 18; revised 2020 June 3; accepted 2020 June 4; published 2020 July 27

Abstract

The atmosphere on the dayside of a highly irradiated close-in gas giant (also known as a hot Jupiter) absorbs a significant part of the incident stellar radiation, which again gets re-emitted in the infrared wavelengths both from the day and the nightside of the planet. The re-emitted thermal radiation from the nightside facing the observers during the transit event of such a planet contributes to the transmitted stellar radiation. We demonstrate that the transit spectra at the infrared region get altered significantly when such re-emitted thermal radiation of the planet is included. We assess the effects of the thermal emission of the hot Jupiters on the transit spectra by simulating observational spectroscopic data with corresponding errors from the different channels of the upcoming James Webb Space Telescope. We find that the effect is statistically significant with respect to the noise levels of those simulated data. Hence, we convey the important message that the planetary thermal re-emission must be taken into consideration in the retrieval models of transit spectra for hot Jupiters for a more accurate interpretation of the observed transit spectra.

Unified Astronomy Thesaurus concepts: Radiative transfer (1335); Exoplanet atmospheres (487); Transmission spectroscopy (2133); Atmospheric effects (113)

1. Introduction

Transit spectroscopy is an essential tool for probing the upper atmospheres of the close-in exoplanets (Charbonneau et al. 2002; Sing et al. 2016; Sengupta et al. 2020). As an exoplanet transits across its parent star, a fraction of the starlight is transmitted through the planet’s upper atmosphere. Light at specific wavelengths is preferentially absorbed, depending on the atmospheric chemical composition and physical properties. An accurate interpretation of the observed transit spectra, however, requires a self-consistent theoretical model that must incorporate the physical and chemical properties of the planetary atmospheres in sufficient detail, including scattering albedo (e.g., de Kok & Stam 2012; Sengupta et al. 2020) and thermal re-emission from the nightside (this work). Theoretical models for the planetary transit spectra presented by various groups are described in articles by Brown (2001), Tinetti et al. (2007), Madhusudhan & Seager (2009), Burrows et al. (2010), Fortney et al. (2010), Line et al. (2012, 2015), Waldmann et al. (2015), Kempton et al. (2017), and Goyal et al. (2019), etc. All of these models have only considered the effect of the total extinction coefficient and ignored the effect of scattering albedo in calculating the transmission depth at different wavelengths. Recently, Sengupta et al. (2020) demonstrated that the diffused reflection and transmission due to scattering of the transmitted starlight by the atoms and molecules affect the transmitted flux and hence, the transit depth significantly in the optical. Therefore, modeling the transit spectra correctly and consistently requires one to solve the multiple scattering radiative transfer equations. However, Sengupta et al. (2020) show that effect of scattering albedo on transmission spectra is less than 10 ppm in the infrared region.

On the other hand, because of the extreme proximity to their parent stars, many gas giants are extremely hot. As they are tidally locked with their host stars, the dayside of such a planet is so hot due to the intense irradiation that its equilibrium temperature for zero albedo, $T_{eq0}$ can reach as high as $\sim 4000$ K (Gaudi et al. 2017). The heat is redistributed to the nightside by the advection process and the nightside of the planet facing the observer during transit also becomes hot depending on the heat re-circulation efficiency, $\epsilon$, of the planetary atmosphere. The average temperature, $T_n$, of the nightside of the planet can be estimated by the relation (Cowan & Agol 2011; Keating & Cowan 2017)

$$T_n = T_{eq0}(1 - A_B)^{1/4} + = T_{eq0}(1 - A_B)^{1/4}, \quad (1)$$

where $A_B$ is the Bond albedo of the atmosphere. We define $T_{eq0}$ as the nightside average temperature for zero Bond albedo. Even with a small value of $\epsilon$, the average nightside temperature, $T_n$, can be quite high if $T_{eq0}$ is high enough. Some previous studies provide an estimation of the nightside temperature of a few exoplanets. For example, Keating & Cowan (2017) report $T_n = 1080 \pm 11$ K for WASP-43 b; Demory et al. (2016) report a nightside brightness temperature of 1380 $\pm 400$ K for 55 Cancri e based on their observation in the 4.5 $\mu$m channel of the Spitzer Space Telescope Infrared Array Camera (IRAC); Arcangeli et al. (2019) report $T_n \leq 1430$ K for WASP-18 b at 3$\sigma$ level, etc. Such a hot region facing the observer would emit radiation in the infrared wavelengths, which should be added up with the transmitted stellar radiation. Thus, the transmitted flux would be affected by the re-emission of hot planets in the longer wavelengths.

In this paper, we demonstrate the effect of thermal re-emission on the transit spectra of the hot Jupiters of different size and surface gravity and with equilibrium temperature ranging from 1200 to 2400 K. In Section 2 we provide the formalisms for calculating the transit depth with and without thermal re-emission. Section 3 outlines the detailed procedure followed to calculate the transmitted and the re-emitted flux from the hot Jupiters. In Section 4 we discuss the 1D pressure–temperature (P–T) grids calculated and the databases adopted.
for the calculation of abundance and absorption and scattering opacity for the modeling of the atmospheres of the hot Jupiters. In Section 5 we discuss the results from all the case studies as well as the results from the testing of detectability of the effect of thermal emission on the transit spectra of hot Jupiters by simulating observational transit spectroscopic data to be observed from the upcoming James Webb Space Telescope (JWST) using the open-source Pandexo code (Batalha et al. 2017) available in the public domain.\(^5\) In the last section, we conclude the key points.

2. The Transit Depth with Planetary Thermal Re-emission

The transit spectra of an exoplanet are expressed in term of transit depth \(D(\lambda)\), which is the difference in stellar flux out of transit and during transit of the planet and normalized to the unblocked stellar flux. When the planetary radiation does not contribute to the stellar flux, it can be written as (e.g., Kempton et al. 2017; Sengupta et al. 2020)

\[
D_{NE}(\lambda) = 1 - \frac{F_{in}}{F_{out}} = 1 - \left(1 - \frac{R_p^2}{R_s^2}\right) F_p + F_p
\]

where \(D_{NE}\) is the transit depth with no thermal radiation from the transiting planet, \(R_p^2\) is the sum of the base radius \(R_p\) and the atmospheric height of the planet, and \(F_{in}\) and \(F_{out}\) are the in-transit and out-of-transit stellar flux, respectively. In the case of pure transmission when thermal emission of the planet is ignored, \(F_{out}\) is the stellar flux \(F_s\). \(F_P\) is the portion of the stellar flux that is transmitted through the upper atmosphere of the planet and undergoes absorption and scattering through the medium. The above equation can also be written as:

\[
D_{NE}(\lambda) = \frac{R_p^2}{R_s^2} - \frac{F_p}{F_s}
\]

For a transiting planet with a hot nightside facing the observer, the re-emitted radiation flux \(F_{Th}\) is added to the observed fluxes. Hence, the transit spectra including the effect of the re-emission from the planet can be expressed as:

\[
D_{E}(\lambda) = 1 - \left(1 - \frac{R_p^2}{R_s^2}\right) F_p + \frac{F_{Th}}{F_s} \frac{R_p^2}{R_s^2} + \frac{F_P}{F_s}
\]

A transit spectrum is usually produced from observation by calculating the transit depth at different wavelengths normalized with respect to the baseline flux, i.e., the flux observed right before ingress or immediately after egress. One of the methods is to calculate the wavelength-dependent transit depth from the light curves at different wavelength bins extracted from the time-series spectra of the host stars observed during a transit event using space-based instruments like HST+STIS, HST+WFC3, etc. (Charbonneau et al. 2002; Berta et al. 2012; Gibson et al. 2012; Deming et al. 2013; Sing et al. 2016, etc.) or ground-based instruments like VLT+FORS, VLT+FOR2, Magellan+MMIRS, GEMINI-N+GMOS, GTC+OSIRIS, etc. (Bean et al. 2011; Stevenson et al. 2014; Nikolov et al. 2016; Pallé et al. 2016; Huitson et al. 2017, etc.). The wavelength-dependent transit depth can also be calculated directly from the photometric light curves at different wavelength bands observed using ground-based instruments or space-based instruments like Spitzer Space Telescope IRAC etc. during a transit event (Tinetti et al. 2007; Sing et al. 2016). In either case, the normalized wavelength-dependent transit depth (equivalently, the wavelength-dependent radius) can be more accurately modeled with the incorporation of the planetary thermal emission \(F_{Th}\). However, the impact on the accuracy by omitting the effect of \(F_{Th}\) might be, in some cases (e.g., at wavelength shorter than 2 \(\mu m\)), small compared to the uncertainties in the data. We discuss the significance of the effect of \(F_{Th}\) with respect to the uncertainties in the observational data elaborately in Section 5.

Finally, Equation (2) and Equation (4) give

\[
\frac{D_{NE}(\lambda)}{D_{E}(\lambda)} = 1 + \frac{F_{Th} R_p^2}{F_s R_s^2}
\]

As evident from Equation (5) the contribution from the thermal re-emission of the planet reduces the transit depth.

3. Calculations of Transmission and Emission Flux

To calculate the transmitted stellar flux \(F_p\) that passes through the atmosphere of a hot Jupiter, we first calculate the reduced stellar intensity that suffers absorption and scattering in the planetary atmosphere and then integrate over the angle subtended by the annular region of the atmosphere. Sengupta et al. (2020) have shown that an accurate approach to calculate the reduced intensity is to solve the multi-scattering radiative transfer equations that incorporate the diffused reflection and transmission of radiation due to scattering. The radiative transfer equations including diffused reflection and transmission for a plane-parallel geometry can be expressed as (e.g., Chandrasekhar 1960; Sengupta et al. 2020)

\[
\mu \frac{dI(\tau_{LOS}, \mu, \lambda)}{d\tau_{LOS}} = I(\tau_{LOS}, \mu, \lambda) - \frac{\omega}{2} \int_{-1}^{1} p(\mu, \mu') I(\tau_{LOS}, \mu, \lambda) d\mu' - \frac{\omega}{4} F_s e^{-\tau_{LOS}/\mu_o} p(\mu, \mu_o)
\]

where \(I(\tau_{LOS}, \mu, \lambda)\) is the specific intensity of the diffused radiation field along the direction \(\mu = \cos \theta, \theta\) being the angle between the axis of symmetry and the ray path, \(F_s\) is the incident stellar flux in the direction \(-\mu_o\), \(\omega\) is the albedo for single scattering i.e., the ratio of scattering coefficient to the extinction coefficient, \(p(\mu, \mu')\) is the scattering phase function that describes the angular distribution of the photon before and after scattering and \(\tau_{LOS}\) is the optical depth along the line of sight to the observer. The detail method for calculating \(\tau_{LOS}\) is given in Sengupta et al. (2020). We adopt the Rayleigh phase function (e.g., Chandrasekhar 1960) for cloud-free atmospheres. For cloudy atmospheres, we use the Mie phase function. This is elaborated in Section 5.5. The planetary thermal emission is important only at longer wavelengths where the effect of scattering albedo is negligible, less than 10 ppm (Sengupta et al. 2020), even in the presence of atmospheric clouds. Therefore, in the present work, we have ignored the effect of scattering albedo in the calculation of \(F_p\).

On the other hand, to calculate the flux of the planetary thermal radiation \(F_{Th}\), we treat the planet as a self-luminous object and solve the radiative transfer equations in the

\(^5\) https://github.com/natalisabatalha/PandExo
following form:

$$\frac{dI(\tau, \mu, \lambda)}{d\tau} = I(\tau, \mu, \lambda) - \frac{\omega}{2} \int_{-1}^{1} p(\mu, \mu') I(\tau, \mu, \lambda) d\mu' - (1 - \omega) B(\tau, \lambda),$$

(7)

where, $I(\tau, \mu, \lambda)$ denotes the specific intensity of the thermal radiation field along the direction $\mu$, $\tau$ is the optical depth in the radial direction, $B(\tau, \lambda)$ is the Planck function corresponding to the temperature of the atmospheric layer with optical depth $\tau$ at a particular wavelength.

The above radiative transfer equations are solved by using the Discrete Space Theory method (Periaiah & Grant 1973). The numerical method is described in Sengupta et al. (2020) and in Sengupta & Marley (2009). $F_0$ and $F_{\text{th}}$ are calculated separately and used into Equation (2) and in Equation (4) to derive $D_{\text{NE}}$ and $D_{\text{E}}$, respectively.

4. P–T Grids and theOpacity and Abundance Data

The atmospheric P–T structure plays an important role not only in determining the optical depth of the medium but also in estimating the thermal radiation of the planet. In order to calculate the P–T profiles, we use the FORTRAN implementation of the analytical models of non-gray irradiated planets provided by Parmentier & Guillot (2014) and Parmentier et al. (2015). This code is available in public domain. It uses the functional form for Rosseland opacity derived by Valencia et al. (2013). The Rosseland opacities of Freedman et al. (2008) are adopted in the derivation. For $T_{\text{eq0}} \geq 1700$ K, the P–T profiles show temperature inversion when TiO and VO are included. Previous studies, including, e.g., Sengupta et al. (2020), find that the hot Jupiters are almost opaque to the transmitted flux at pressures level below 1 bar. Therefore, in the present work, we have considered the P–T profiles up to 1 bar pressure level such that the base radii $R_P$ of the hot Jupiters considered in the calculations of the transmission spectra are located at 1 bar pressure level.

However, the thermal radiation of a hot planet emerges from a deeper layer of the atmosphere and so we have considered the P–T profiles of hot Jupiters with $T_{\text{eq0}}$ ranging between 1200 and 2400 K and the surface gravity over a range of 15–100 m s$^{-2}$ at 10 bar pressure level. Figure 1 shows the P–T profiles for all the case studies with different $T_{\text{eq0}}$.

For all the calculations we have adopted solar metallicity and solar system abundance for the atoms and the molecules present in the atmospheres. We have considered 28 molecular and atomic species as mentioned in Sengupta et al. (2020). The abundance for all these atoms and molecules has been calculated using the abundance database given in the open-source package “Exo-Transmit” (Kempton et al. 2017) available in the public domain. In this package, the abundances for major atmospheric constituents as a function of temperature and pressure are calculated based on the solar system abundances of Lodders (2003). Also, to calculate the absorption and scattering coefficients we have used the opacity database from the same package. These opacities are based on the molecular databases of Freedman et al. (2008, 2014). The line lists used to generate the molecular opacities are also tabulated by Lupu et al. (2014). Both the abundance and opacity databases are available over a broad grid of pressure and temperature from which we have interpolated to our particular P–T profiles. We have adopted the equation of state for rain-out condensation. We have also calculated the opacity due to atmospheric clouds comprising mainly of amorphous Forsterite by using Mie theory (see Section 5.5).

Figure 1. Pressure–temperature profiles for different $T_{\text{eq0}}$ and $g$ adopted in this work. For all the cases, the effect of TiO and VO is included.
Modeling an atmosphere with a high day–night temperature contrast is not straightforward because a 1D P–T profile may not be adequate in such a scenario and therefore one requires a 3D P–T mapping using Global Circulation Model or a limb-averaged P–T profile (Kataria et al. 2015, 2016; Evans et al. 2018). In order to avoid such complications, we have assumed a hot-Jupiter atmosphere with \( \epsilon = 1 \) (\( T_{\text{eq}} = T_{\text{eq0}} \)) i.e., a globally averaged P–T profile in all the cases as our main motive is to demonstrate the effect of the nightside temperature \( T_n \). This corresponds to \( f = 0.25 \), where \( f \) is the flux parameter as defined in Burrows et al. (2003) and also used in Guillot (2010), Parmentier & Guillot (2014), and Parmentier et al. (2015), etc.

The nightside of the planetary atmosphere may also get warmed up by the release of the internal energy characterized by the internal temperature \( T_{\text{int}} \) and may cause thermal radiation (self-emission) but this radiation should be insignificant as compared to the thermal re-emission from planet older than 100 Myr (Burrows et al. 1997) in age.
5. Case Studies: Simulation and Testing of Detectability

We checked the detectability of the effect of thermal emission on the transit spectra by using the simulated data. We also investigate the extent to which the transit spectra depend on the planetary properties such as $T_n$, $R_p/R_*$, the atmospheric clouds and the surface gravity as well as the spectral types of the host stars. The following subsections describe the results from these case studies.

5.1. Detectability with JWST

To understand the significance of the effect of thermal emission from transiting hot Jupiters on the transit spectra, we need to compare the difference between $D_{\text{NE}}$ and $D_E$ with the noise levels of the actual observed data. For that purpose, we have focused on the observing capability of the upcoming JWST as this mission is going to be at the forefront of exoplanet characterization. Considering the contribution of thermal emission from hot Jupiters to the transit spectra, we use our model calculations for $D_E$ and simulate some observational transit spectra with error bars that can be observed using the infrared instruments of JWST. The simulation is done by using the open-source code Pandexo (Batalha et al. 2017). A host star of spectral type G2V with $J$-mag = 8 and a saturation level equal to 70% of the full well potential are considered for this simulation. The spectra with noise levels with a resolution of $R \sim 50$ are calculated by combining the data over four observed transit events, each with a duration of 2 hr ($T_{14}$). We have considered the instrument modes viz. NIRSpec G140M and G235M for the wavelength region 1–3 $\mu$m and G395M and MIRI LRS (slitless) for the wavelength region 3–8 $\mu$m (see Table 1 of Batalha et al. 2017).
Figure 4. Simulated observational data of transit depth with emission combined over four observed transit events using instrument modes NIRSpec G395M and MIRI LRS (slitless) of JWST with error bars, viz. $D_{\text{G395M}} \pm \sigma_{\text{G395M}}$ (red) and $D_{\text{LRS}} \pm \sigma_{\text{LRS}}$ (blue) are shown in the top panels assuming a G2V host star with $J$-band magnitude = 8. Models without and with thermal emission ($D_{\text{NE}}$ in magenta and $D_{\text{E}}$ in green, respectively) for different values of $T_n$ and $R_*$ with $R_0 = 1\, R_j$ are shown with corresponding chi-square values, keeping $g$ fixed at $g = 30\, \text{m s}^{-1}$. The bottom panels show the difference between the model without emission and the simulated observational data (red and blue circles with green error bars) as compared to the difference between the model with emission and the same simulated observational data (red and blue triangles with magenta error bars). Also, the mean of the ratio of the difference between the two models to the noise levels of the above modes, viz. $\left(\frac{D_{\text{NE}} - D_{\text{G395M}}}{\sigma_{\text{G395M}}}\right)_{\text{av}}$ and $\left(\frac{D_{\text{NE}} - D_{\text{LRS}}}{\sigma_{\text{LRS}}}\right)_{\text{av}}$, are shown in the bottom panels.

The corresponding simulated transit depth and noise levels are denoted by $D_{\text{G140M}} \pm \sigma_{\text{G140M}}$, $D_{\text{G235M}} \pm \sigma_{\text{G235M}}$, $D_{\text{G395M}} \pm \sigma_{\text{G395M}}$ and $D_{\text{LRS}} \pm \sigma_{\text{LRS}}$, respectively. For each pair of instrument modes we present the comparison of the models ($D_{\text{NE}}$ versus $D_{\text{E}}$), constructed using different sets of planetary parameters, with the simulated data along with their residuals in Figures 2–5. In Figure 2 and Figure 4 the model parameters are (i) $T_n = 1600\, \text{K}$, $R_p = 1\, R_j$, $R_* = 1\, R_\odot$, (ii) $T_n = 2000\, \text{K}$, $R_p = 1\, R_j$, $R_* = 1\, R_\odot$, (iii) $T_n = 1600\, \text{K}$, $R_p = 1\, R_j$, $R_* = 0.8\, R_\odot$, and (iv) $T_n = 2000\, \text{K}$, $R_p = 1.4\, R_j$, $R_* = 0.8\, R_\odot$. In Figures 3 and 5, the model parameters are (i) $T_n = 1600\, \text{K}$, $R_p = 1.4\, R_j$, $R_* = 1.4\, R_\odot$, (ii) $T_n = 2000\, \text{K}$, $R_p = 1.4\, R_j$, $R_* = 1\, R_\odot$, (iii) $T_n = 1600\, \text{K}$, $R_p = 1.4\, R_j$, $R_* = 0.8\, R_\odot$, and (iv) $T_n = 2000\, \text{K}$, $R_p = 1.4\, R_j$, $R_* = 0.8\, R_\odot$. The figures also show the chi-square values of the models (top sub-panels) and the mean of the ratio of ($D_{\text{NE}} - D_{\text{E}}$) to the 1$\sigma$ noise levels of the above modes (viz. $\sigma_{\text{G140M}}$, $\sigma_{\text{G235M}}$, $\sigma_{\text{G395M}}$, and $\sigma_{\text{LRS}}$).

These figures show that the difference between $D_{\text{NE}}$ and $D_{\text{E}}$ for $R_p/R_* = 1$ is of no or extremely low significance (<20 ppm and <4$\sigma$). Also, at wavelengths up to 2 $\mu$m, the difference between $D_{\text{NE}}$ and $D_{\text{E}}$ is significant (>25 ppm and}

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$\sim 22\sigma$) only for $T_n = 2000 \, \text{K}, R_p = 1.4 R_J, R_* = 0.8 R_\odot$. For all other combinations of $T_n, R_p$, and $R_*$, the difference is of no or low significance (<25 ppm and <4\sigma). However, for wavelengths longer than 2 $\mu$m, we find that the difference between the models increases with increasing $T_n$ and $R_p/R_*$ and reaches up to 500 ppm (330\sigma) for $T_n = 2000 \, \text{K}, R_p = 1.4 R_J, R_* = 0.8 R_\odot$. The chi-square values shown in these figures imply that for higher values of $T_n$ and $R_p/R_*$ and wavelength $\gtrsim 2 \, \mu$m, the simulated data are fitted well with the model transit spectra only when planetary thermal emission is incorporated. This demonstrates the fact that in order to achieve the precision level of the instruments on board JWST, the effect of thermal emission from hot Jupiters must be taken into consideration in the retrieval model for transit spectra.

Figure 5. Same as Figure 4 but with $R_p = 1.4 \, R_J$.

5.2. Host Stars of Different Spectral Types

The transit depth with no planetary thermal emission, $D_{\text{NE}}$, is absolutely independent of the stellar spectrum, as evident from Equation (6). The factor $F_{\text{FP}}^*$ solely depends on the physical and chemical properties of the planetary atmospheres and provides only the reduction in the stellar flux due to absorption. However, Equation (7) suggests that, when planetary emission is included, the transit depth, $D_E$, for planets with the same $T_n$ becomes dependent on the flux of the host star. Consequently, it depends on the spectral types of the host stars. Figure 6 displays the difference between $D_{\text{NE}}$ and $D_E$ for planets with $R_p/R_* = 1.4 R_J/R_\odot$ ($\sim 0.144$), $g = 30 \, \text{m s}^{-2}$ and $T_n = 1600 \, \text{K}$ orbiting stars of spectral types F5V, G5V, K5V, and M5V. Also, the 1$\sigma$ noise levels of the JWST instrument modes NIRSpec G140M, NIRSpec G235M, NIRSpec G395M, and
MIRI LRS (slitless) for number of observed transits equal to 2 and 4 and host stars with \( J \)-band magnitude of 8 and 10 are shown in this figure. The model spectra show that the transit depths \( D_E \) for stars of different spectral types differ significantly at wavelengths longer than 3 \( \mu \)m. The cooler the host stars are, the more significant the difference is between the models with respect to the noise levels, as evident from Equation (5).

### 5.3. Average Nightside Temperature and Planetary Size

In order to investigate the effect of \( T_n \), we calculate the difference between \( D_{NE} \) and \( D_E \) at different values of \( T_{a0} \) e.g., 1200, 1600, 2000 and 2400 K. Figure 13 of Parmentier & Guillot (2014) demonstrates that the Bond albedo of planets with high equilibrium temperature is extremely low (<0.01) for solar composition. Consequently, from Equation (1) it follows that, \( T_n \approx T_{a0} \). These values of \( T_n \) correspond to atmospheric scale heights of 138 km, 186 km, 254 km and 387 km, respectively. Figure 7 shows the difference between \( D_{NE} \) and \( D_E \) for these values of \( T_n \) and for different values of \( R_p \) and \( R_\infty \) e.g., (i) \( R_p = 1R_J \), \( R_\infty = 1R_\odot \), (ii) \( R_p = 1R_{J} \), \( R_\infty = 0.8R_\odot \), (iii) \( R_p = 1.4R_{J} \), \( R_\infty = 1R_\odot \), and (iv) \( R_p = 1.4R_{J} \), \( R_\infty = 0.8R_\odot \). It is clear from the figure that with the increase in \( T_n \), the difference between \( D_{NE} \) and \( D_E \) increases because the thermal re-emission from the planet increases. The factor \( R_p/R_\infty \) also strongly dictates the significance of the difference with respect to the noise levels. This happens due to the fact that, with increasing \( R_p/R_\infty \), the ratio of the thermal luminosity of the planet to the luminosity of the host star increases. Obviously, for a fixed planetary radius, the difference in \( D_{NE} \) and \( D_E \) increases with the decrease in the size of the host star.

Also, the 1\( \sigma \) noise levels of the JWST instruments NIRSpec G140M, NIRSpec G235M, NIRSpec G395M, and MIRI LRS (slitless) for number of observed transit equal to 2 and 4 and host stars with \( J \)-band magnitude of 8 and 10 are shown in Figure 7. This helps us comprehend the significance of the difference between the models with respect to the noise levels for different numbers of observed transits and different host star \( J \)-band magnitudes. However, it can be safely ascertained that for higher values of \( R_p/R_\infty \) (see bottom 2 panels of Figure 7) and for \( T_n > 1200 \) K, the deviation of \( D_E \) from the standard model of transmission spectra (\( D_{NE} \)) at wavelength beyond 2 \( \mu \)m is so significant that observed transit spectra can be misinterpreted by the standard model by 10–30\( \sigma \) (representing a change up to 0.5% in-transit depth).

### 5.4. Surface Gravity

We have calculated \( D_{NE} \) and \( D_E \) for \( g = 15, 30, 60 \) and \( 100 \) m s\(^{-2} \) as shown in Figure 8 for a fixed values of \( T_n = 2000 \) K, \( R_p = 1.4R_{J} \) and \( R_\infty = 1R_\odot \). These values of \( g \) correspond to atmospheric scale heights, estimated by using \( T_n = 2000 \) K of 508 km, 254 km, 127 km, and 76 km, respectively. We find that with increasing \( g \) the transmission flux \( F_T \) decreases. However, the value of \( g \) has almost no effect on the calculation of \( F_{TB} \) and hence, the difference between \( D_{NE} \) and \( D_E \) is almost independent of \( g \), the surface gravity of the planet.

### 5.5. Atmospheric Clouds

Clouds and hazes are a ubiquitous feature in the planetary atmospheres. For hot exoplanets, silicates may condensate in the upper atmosphere. Gas giant planets with comparatively
cooler night sides can have thick atmospheric clouds that may affect the spectra in the optical and near-infrared wavelength region. However, at higher day or night temperatures, clouds may either completely evaporate or may form a thin layer of haze in the uppermost atmosphere. As discussed in the previous subsection, the effect of thermal emission is significant only at wavelengths longer than 2 μm and for a nightside temperature $T_n > 1200$ K. Therefore, even in the presence of a thin layer of haze, we do not expect the transmission spectra of planets having $T_n > 1200$ K to be affected in the infrared region where thermal re-emission is important. Nevertheless, we have investigated the effects of the thin clouds on the transmission spectra of a planet with $T_n = 1600$ K. For this purpose, we have considered a simple model for thin haze in the uppermost atmosphere. The formalism is adopted from Griffith et al. (1998), Saumon et al. (2000). We consider grains of amorphous Forsterite ($\text{Mg}_2\text{SO}_4$) of mean diameter 0.5 μm as the dominant constituent of the cloud located within a thin region of the atmosphere bound by a base and a deck. Within this region, the sizes of the particles follow a log-normal distribution and the vertical density distribution of the cloud particles follows the relation

$$n(P) = n_0 \frac{P}{P_0},$$

where $n(P)$ is the number density of cloud particles at pressure level $P$, $P_0$ is the pressure at the base radius, and $n_0$ is a free parameter with the dimension of number density. The details of the model adopted can be found in Sengupta et al. (2020). The deck and base of the haze are fixed at 0.1 Pa and 100 Pa pressure levels, respectively. We use the Mie theory of

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Difference between the models of transit depth without and with planetary thermal emission for different values of $T_n$, $R_*$ and $R_*$, keeping $g$ fixed at 30 m s$^{-2}$. The 1σ noise levels are shown in dashed lines from left to right for the JWST channels NIRSpec G140M, NIRSpec G235M, NIRSpec G395M, and MIRI LRS (slitless), respectively. The red and black dashed lines correspond to noise levels for number of observed transits equal to 2 and 4, respectively. The thick and thin dashed lines correspond to noise levels for host stars with $J$-band magnitude of 8 and 10, respectively.
scattering to calculate the wavelength-dependent scattering coefficients, extinction coefficients, and the phase functions at different pressure atmospheric depth (van de Hulst 1957; Hansen & Travis 1974; Bohren et al. 1983; Fowler 1983; Sengupta & Marley 2009; Sengupta et al. 2020, etc.). Figure 9 shows $D_{\text{ne}}$ (in top panel) and the difference between $D_{\text{ne}}$ and $D_E$ (bottom panel) for cloud models with $n_0 = 1000 \text{ cm}^{-3}$ and $n_0 = 5000 \text{ cm}^{-3}$. We compare the results with that of a cloud-free atmosphere. Although the transit depth without thermal emission, $D_{\text{ne}}$, can alter depending on the cloud structure and opacity, the difference between $D_{\text{ne}}$ and $D_E$ does not change much as the emission flux ($F_{\text{th}}$) is not affected significantly in the infrared region by the presence of cloud. Figure 9 shows that the difference between $D_{\text{ne}}$ and $D_E$ does not change at all with clouds. Hence, the clouds do not play an important role in determining the transit depth at the infrared wavelength region of ultra-hot Jupiters.

6. Conclusion

We demonstrate that the effect of thermal re-emission from the nightside of hot Jupiters on the transit spectra can be significant at the infrared wavelength region if the equilibrium temperature of the planet is higher than about 1200K and if the planet is large enough in size such that $R_0/R_e > 0.1$. The contribution of planetary thermal emission to the transit spectra can significantly exceed the total noise budget (photon noise plus readout noise) of the infrared instruments on board the upcoming JWST that will perform transit spectroscopy. Hence, a retrieval model that does not include planetary thermal emission would overestimate the transit depth and thus can lead to a wrong interpretation of the planetary properties of the hot Jupiters. Therefore, for a consistent and accurate interpretation of the observed transit spectra, it is essential to include the diffused reflection and transmission due to scattering in the optical and near-infrared wavelength region and the thermal re-emission at the near and mid infrared region of hot gas giant planets. Both need the solutions of the multi-scattering radiative transfer equations.

We thank the reviewer for several valuable comments and suggestions.

Software: Exo_Transmit (Kempton et al. 2017), Analytical model for irradiated atmosphere (Parmentier & Guillot 2014; Parmentier et al. 2015), Pandexo (Batalha et al. 2017).

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Figure 8. Top: models of transit depth without and with thermal emission for different values of $g$ and for $T_e = 2000 \text{ K}$, $R_0 = 1.4R_J$ and $R_e = 1R_J$. Bottom: Difference between the above models for each value $g$ which shows no dependence on $g$. The $1\sigma$ noise levels are shown in dashed lines from left to right for the JWST channels NIRSpec G140M, NIRSpec G235M, NIRSpec G395M, and MIRI LRS (slitless), respectively. The red and black dashed lines correspond to noise levels for number of observed transits equal to 2 and 4, respectively. The thick and thin dashed lines correspond to noise levels for host stars with $J$-band magnitude of 8 and 10, respectively.

Figure 9. Top: models of transit depth with thermal emission with different cloud abundance as well as without any cloud for $T_e = 1600 \text{ K}$, $g = 30 \text{ m s}^{-2}$, $R_0 = 1.4R_J$ and $R_e = 1R_J$. Bottom: Difference between the models without and with thermal emission from the planets for the above cloud abundances as well as no cloud.
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