Boletim da Sociedade Astronômica Brasileira, **34**, no. 1, 182-185

A study of the relationship between the chromospheric activity of host stars and atmospheric properties of hot Jupiters

M. G. C. Navia[1], L. Ghezzi[1], & P. Cruz[2]

[1] Observatório do Valongo - UFRJ. e-mail: `mariana18@ov.ufrj.br, luanghezzi@ov.ufrj.br`
[2] Centro de Astrobiología (CAB), CSIC-INTA, Madrid, Spain. e-mail: `pcruz@cab.inta-csic.es`

Abstract. To better understand the properties of exoplanets, it is necessary to comprehend how their atmospheres are affected by their host stars. In this scenario, we set out to analyze whether the stellar activity influences the thermal profile of hot Jupiters' atmospheres and to investigate the possible relationship between the presence/absence of thermal inversion and the stellar activity level. To start our work, we searched the literature and selected a sample of hot Jupiters that have secondary eclipses observed in infrared bands. Since hot Jupiters have higher temperatures (due to their proximity to the star) and larger radii, it is easier to detect them with the transit method and, consequentely, to obtain secondary eclipse data. Furthermore, the thermal emission of the planet is higher in the infrared (compared to shorter wavelengths) and favors the determination of the brightness temperature using the secondary eclipse depth. With the current sample of 93 hot Jupiters, we observed a linear relationship between the chromospheric activity, $\log(R'_{HK})$, and brightness temperature in the Spitzer bands 3.6, 4.5, 5.8 and 8.0 μm and in the Ks band. However, we did not obtain a clear separation between exoplanets with and without a thermal inversion layer in their atmospheres. Additionaly, we reproduced and expanded two new metrics that compare the stellar activity and both sets (exoplanets with and without thermal inversion) using Spitzer's 3.6 μm and 4.5 μm bands. As a future step, we will apply these new metrics to other photometric bands with data available in the literature, for example, H and Ks in the near infrared. Additionaly, we intend to use planetary atmospheric models to analyse of the effects of stellar activity on exoplanetary atmospheres.

Resumo. Para entender melhor as propriedades dos exoplanetas, é necessário compreender como suas atmosferas são afetadas por suas estrelas hospedeiras. Nesse cenário, propusemo-nos a analisar se a atividade estelar influencia o perfil térmico de atmosferas de Jupíteres quentes e investigar a possível relação entre a presença/ausência de inversão térmica e o nível de atividade da estrela. Para iniciar a pesquisa, realizamos uma busca na literatura e selecionamos uma amostra de Jupíteres quentes que possuem eclipses secundários observados na região do infravermelho. Uma vez que jupíteres quentes apresentam temperaturas mais altas (pela proximidade com a estrela) e raios maiores, é mais fácil detectá-los a partir do método de trânsito e, consequentemente, obter dados do eclipse secundário. Além disso, a emissão térmica do planeta é maior no infravermelho (em comparação com comprimentos de onda menores) e favorece a determinação da temperatura de brilho usando a profundidade do eclipse secundário. Com a amostra atual, observamos uma relação linear entre a atividade cromosférica, $\log(R'_{HK})$, e temperatura de brilho nas bandas 3.6, 4.5, 5.8 e 8.0 μm do Spitzer e na banda Ks. Entretanto, não obtivemos uma separação clara entre exoplanetas com e sem a camada de inversão térmica nas suas atmosferas. Ademais, nós reproduzimos e expandimos duas novas métricas que comparam a atividade estelar e as duas amostras (exoplanetas com e sem inversão térmica) usando as bandas 3.6 μm e 4.5 μm do Spitzer. Como passo futuro, iremos aplicar essas novas métricas para outras bandas fotométricas com dados disponíveis na literatura, por exemplo, H e Ks do infravermelho próximo. Além disso, pretendemos usar modelos atmosféricos planetários para realizar uma análise dos efeitos da atividade estelar em atmosferas exoplanetárias.

Keywords. Planet-star interactions – Atmospheric effects – Stars: activity – Astrobiology.

1. Introduction

During the last three decades, many advances have been made in the area of exoplanets. Among them, the surprising discovery of an extreme class: the hot Jupiters. They are objects with size and mass similar to those of Jupiter, but unlike our Solar System gas giant, the orbital period of these objects is less than ten days. This causes them to receive a high amount of radiation from their stars and, consequently, to have higher temperatures.

The proximity and size make these objects easily detectable through the transit method. This method is characterized by the exoplanet passing in front of the star, causing a periodic decrease in the stellar brightness. Thus, the decrease in brightness is greater for larger planets. From the observation of the secondary eclipse, i.e., when the exoplanet is passing behind the star, we obtain other valuable information, such as the planet's brightness temperature and some characteristics of its atmosphere, such as the presence or absence of thermal inversion, when compared to planetary model atmospheres.

One of the main parameters studied in this research is the brightness temperature, which is obtained through the ratio between the total flux of the system (i.e., the stellar flux plus the flux emitted by the diurnal hemisphere of the planet) and the stellar flux measured during the secondary eclipse. Parameters such as opacity and the behavior of the temperature–pressure profile can influence the amount of flux emitted in each region of the electromagnetic spectrum. Thermal inversion, on the other hand, is an atmospheric phenomenon represented by the change in the temperature behavior with respect to the pressure (or altitude), that is, it can be a sudden increase in temperature in a behavior that once decreased or vice versa. This phenomenon can be associated with the chemical composition of the atmosphere studied, which can be affected by the stellar chromospheric activity.

More than 10 years have passed since the publication of the work by Knutson et al. (2010), which relates the presence of thermal inversion with stellar activity. During that period of time, there was a considerable increase in the number of exoplanets with secondary eclipse data. Therefore, we decided to revisit the possible relationship between stellar activity and the presence or absence of thermal inversion in the atmospheres of hot Jupiters.

2. Methodology

We searched the literature and collected brightness temperature data in the Spitzer (3.6, 4.5, 5.8 and 8.0 μm) and 2MASS (J, H and Ks) bands, as well as the information about thermal inversion, the chromospheric activity index $\log(R'_{HK})$ of the host stars and other planetary and stellar parameters that were necessary to determine the incident radiation and the equilibrium temperature of the exoplanets in our sample. When absent in the literature, we calculated brightness temperatures using the effective temperature of the star and the relative fluxes from secondary eclipses, i.e., the ratio between the flux from the planet and the star multiplied by the square of the ratio between the radii of the two objects. The total sample collected contains 93 hot Jupiters.

We chose to work with infrared bands, because, concerning hot Jupiters, the high temperature makes the contribution of the planet's thermal emission to the total flux of the system greater, allowing the detection of secondary eclipses. Thus, the planet-to-star flux ratio for this region of the electromagnetic spectrum is higher than for other bands, such as optical. We chose the chromospheric index $\log(R'_{HK})$ as an activity indicator, using the convention that stars with $\log(R'_{HK}) > -4.9$ are active and stars with $\log(R'_{HK}) < -4.9$ are considered inactive (Knutson et al. 2010).

We applied an approach based on the empirical index proposed by Knutson et al. (2010), which relates $\log(R'_{HK})$ and the difference between two slopes. The first is measured between the photometric points in the bands at 3.6 μm and 4.5 μm, for which values are taken from the literature. The second is the slope between the same photometric points, but calculated by a blackbody fit for the planet's emission and a theoretical spectrum for the stellar emission. We extended the initial sample by Knutson et al. (2010) by almost 4 times. To calculate the measured flux in each photometric band of interest, we need to estimate the ratio between the emission from the planet and the star. For this, we adopted the synthetic BT-NextGen spectra (AGSS2009) (Allard, Homeier & Freytag 2011) for about 60 stars in our sample that have information on the chromospheric activity index and whose planets have measured fluxes at the photometric points at 3.6 and 4.5 μm. We made an interpolation to obtain exactly the spectra according to the stellar effective temperature, surface gravity and metallicity. To calculate the exoplanet fluxes, we use the approximation of blackbodies, with a temperature that varies between 1000 K and 3400 K, with a step of 10 K. Finally, we calculated the relative fluxes for each planetary temperature and made a convolution with the response function of Spitzer's IRAC 1 and 2 filters to obtain synthetic photometric points at 3.6 μm and 4.5 μm, respectively. The blackbody temperature that best fits the observed photometric points is assigned to the planet.

We also used a second metric, proposed by Wallack et al. (2021), which investigates the difference between the measured brightness temperatures in 3.6 μm and 4.5 μm, normalized to the predicted equilibrium temperature of the planet. Of the total sample of 93 hot Jupiters, 85 simultaneously have information about the brightness temperatures at 3.6 and 4.5 μm and the data needed to calculate the equilibrium temperature. With this sample, we performed the calculation using the same method as Baxter et al. (2020), assuming Bond albedo and an isotropic recirculation, i.e., equal redistribution of heat from the star in any direction of the atmosphere.

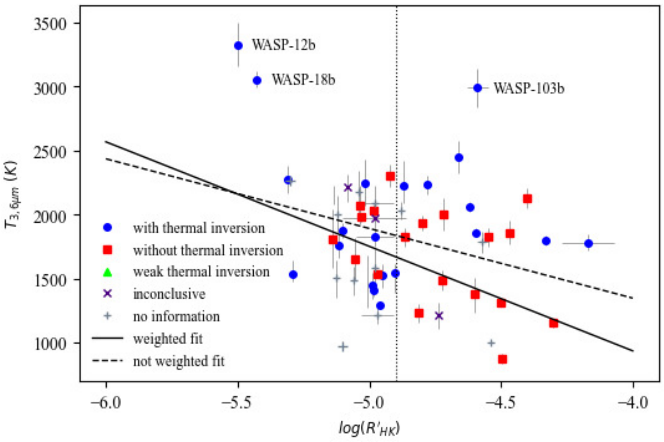

Figure 1. Relationship between the brightness temperature in 3.6 μm and the stellar chromospheric activity index. The dashed line at -4.9 $\log(R'_{HK})$ represents the separation between active and inactive stars. The weighted fit considers the uncertainties in the brightness temperature.

As an additional step, we calculated the incident radiation for our sample and compared it to the best fitted temperature according to our blackbody model.

3. Results

Of the 93 hot Jupiters in our sample, 60 simultaneously have information about stellar activity and brightness temperature in at least one of the chosen bands. From this sub-sample, we made a comparison with respect to stellar activity, represented by the $\log(R'_{HK})$ index, for four Spitzer bands (3.6 μm, 4.5 μm, 5.8 μm and 8.0 μm) and three 2MASS bands (J, H and Ks). It is worth mentioning that the Spitzer bands at 3.6 and 4.5 μm are the ones with the largest number of available data. For all photometric bands, we observed a linear correlation with negative slope, showing that the planet's brightness temperature tends to decrease for more active stars. An example for the band at 3.6 μm is shown in Figure 1. This result validates previous studies (e.g, Cruz et al. 2017) and proves to be important, since we are considering more photometric bands, in addition to a considerably larger sample. Nevertheless, we did not find a clear separation between exoplanets with/without inversion and inactive/active stars, contradicting previous hypotheses (Cruz et al. 2017).

Additionally, we analyzed stellar activity as a function of the empirical index defined by Knutson et al. (2010), explained in the previous section. We found that, on average, exoplanets without thermal inversion have more negative values for the empirical index, suggesting greater flux at 3.6 μm and lower flux at 4.5 μm (Figure 2), while exoplanets with thermal inversion tend to have more positive values, indicating the opposite behavior. This result is compatible with that obtained by Knutson et al. (2010).

We also calculated the equilibrium temperature for all 85 hot Jupiters from our sample, that have brightness temperature information at 3.6 μm and 4.5 μm, using the same method described by Baxter et al. (2020). We made a comparison between the difference in brightness temperatures measured in the two bands (3.6 μm and 4.5 μm) normalized to the calculated equilibrium temperature of the planet and the equilibrium temperature itself, as done by Wallack et al. (2021). We can see in Figure 3 that, in the temperature range between approximately 1200 and 2000 K, there is no clear separation with respect to the presence/absence

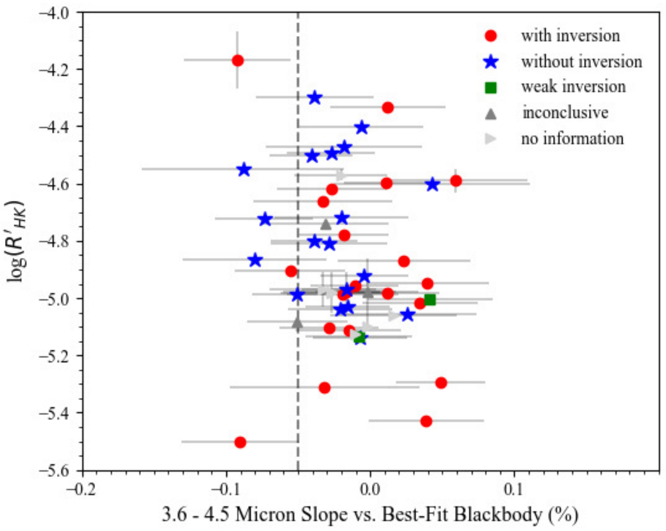

Figure 2. Reproduction of the empirical index from Knutson et al. (2010) with updated data. The dashed line represents the separation between inactive and active stars.

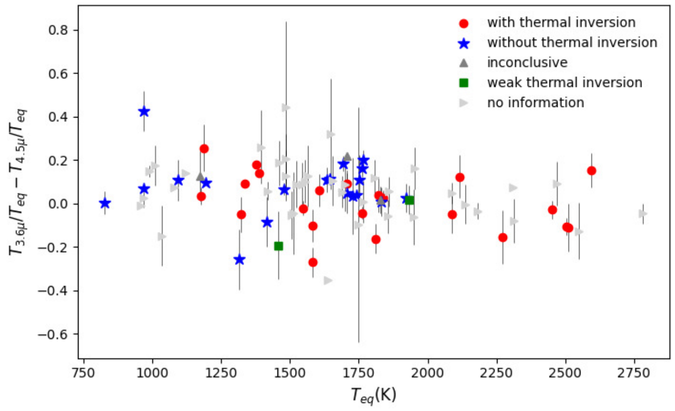

Figure 3. Comparison between the empirical index proposed by Wallack et al. (2021) and the equilibrium temperature.

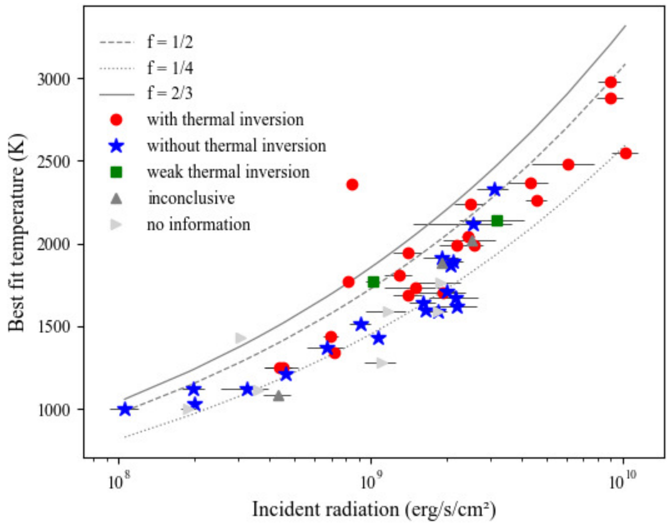

Figure 4. Comparison between the best fitted temperature using a blackbody model and incident radiation. The lines represent different atmospheric recirculation factors. Solid line: instant reradiation. Dashed line: redistribution in the diurnal hemisphere. Dotted line: isotropic redistribution.

of thermal inversion. For temperatures above 2000 K, we verified that there are no planets without inversion, in the same way that, for temperatures below approximately 1200 K, planets with inversion are not observed. According to our results, we believe that the gray points (without information on inversion) above 2000 K, as well as other planets eventually added in this interval, must have thermal inversion and the opposite must be observed for the interval with temperatures lower than 1200 K.

Finally, we calculated the incident radiation for 60 hot Jupiters (out of our total sample of 93), those that simultaneously have information about stellar activity and brightness temperature in the 3.6 and 4.5 μm bands. We compared it with the best temperature obtained in the blackbody adjustment step, adding the thermal inversion information. Figure 4 shows that, on average, more irradiated exoplanets show thermal inversion, while less irradiated exoplanets do not, a result that confirms recent studies (Mansfield et al. 2021). In addition, we added information about the recirculation factors, and we saw that most exoplanets without inversion fall on the curve with $f = 1/4$ which represents isotropic recirculation, that is, independent of the direction, while exoplanets with inversion are better fitted by the recirculation curve in the diurnal hemisphere, with $f = 1/2$, showing that the heat redistribution in this case is efficient only in the hemisphere facing the star (assuming that, due to proximity, all these objects are gravitationally bounded by tidal effects, i.e., the period of rotation of the planet is equal to its period of translation around the star – a situation similar to what we observe for the Moon, for example). The recirculation factor $f = 2/3$, which considers an instant reradiation and an inefficient heat redistribution over the dayside, does not seem to fit any group present in our data, as can be seen in Figure 4.

4. Discussion and Conclusion

The comparisons made between the brightness temperature of exoplanets and the chromospheric activity of their host stars suggest that there is, indeed, a linear correlation between these two quantities, at least for all the infrared bands we analyzed (Spitzer: 3.6 μm, 4.5 μm, 5.8 μm and 8.0 μm; 2MASS: J, H and Ks). To study the relationship between the presence/absence of thermal inversion, we reproduced the empirical index by Knutson et al. (2010), applying it to a larger sample, and we saw that, despite not having a very clear separation, there is a larger population of exoplanets without inversion for more negative values of the index, while exoplanets with inversion have more positive values of the empirical index. According to Knutson et al. (2010), this behavior is due to the fact that there are carbon monoxide (CO) and water (H_2O) molecules in the planet's atmosphere that affect the exoplanet flux in the 4.5 μm band, but are not very significant in the 3.6 μm band. Depending on the conditions of the atmosphere, these molecules can produce thermal inversions, directly altering the relative flux of the planet in that given band and, therefore, reflecting in the calculation of the empirical index.

From the reproduction of the metric presented by Wallack et al. (2021), we found that the most irradiated exoplanets are those that have a thermal inversion layer in their atmospheres, while the opposite occurs for exoplanets without inversion, which is in agreement with works in the literature (e.g., Mansfield et al. 2021). We also noticed that exoplanets with thermal inversion are better described by recirculation models in the diurnal hemisphere, while exoplanets without inversion appear to have isotropic recirculation (considering Bond albedo).

We are currently working to refine the analysis using synthetic spectra also for exoplanets, in order to adequately reproduce the emission of the objects studied. As future steps, we intend to extend the analysis and calculate the empirical index of Knutson et al. (2010) and the metric by Wallack et al. (2021) using all available bands in our sample, ranging from 2MASS's J band to Spitzer's 8 μm band.

Acknowledgements. This work has been supported by CNPq, a Brazilian research agency. P.C. acknowledges financial support from the Government of Comunidad Autónoma de Madrid (Spain) via postdoctoral grant 'Atracción de Talento Investigador' 2019-T2/TIC-14760. This work makes use of the Virtual Observatory tool TOPCAT (Taylor 2005).

References

Allard, F., Homeier, D., & Freytag, B. 2011, 16th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, 448.
Baxter, C. et al. 2020, Astronomy & Astrophysics, 639, 15.
Cruz, P. et al. 2017, Proceedings of the IAU Symposium, 328, 363.
Knutson, H. A., Howard, A. W., & Isaacson, H. 2010, The Astrophysical Journal, 720, 1569.
Mansfield, M. et al. 2021, Nature Astronomy, 5, 1224.
M. B. Taylor 2005, Astronomical Data Analysis Software and Systems XIV, eds. P Shopbell et al., ASP Conf. Ser. 347, p. 29
Wallack N. L., Knutson, H. A., & Deming D 2021, The Astronomical Journal, 162, 14.