From Interacting Binaries to Exoplanets: Essential Modeling Tools
Proceedings IAU Symposium No. 282, 2011
Mercedes T. Richards & Ivan Hubeny, eds.

doi:10.1017/S1743921311028213

Day-Night Side Cooling of a Strongly Irradiated Giant Planet

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Abstract. The internal heat loss or cooling of a planet determines its structure and evolution. We address in a consistent fashion the coupling between the day and the night sides by means of model atmosphere calculations with heat redistribution. We assume that a strong convection leads to the same entropy on the day and night side and that the gravity is the same on both hemispheres. We argue that the core cooling rate from the two hemispheres of a strongly irradiated planet may not be the same and that the difference depends on several important parameters. If the day-night heat redistribution is very effective, or if it takes place at a large optical depth, then the day-side and the night-side cooling may be comparable. However, if the day-night heat transport is not effective, or if it takes place at a shallow optical depth, then there can be a big difference between the day-side and the night-side cooling and the night side may cool more effectively. If the stellar irradiation gets stronger e.g. due to the stellar evolution or migration, this will reduce both the day and the night side cooling. Enhanced metallicity in the atmosphere acts as a “blanket” and reduces both the day- and the night-side cooling. However, the stratosphere on the day side of the planet can enhance the day-side cooling since its opacity acts as a “shield” which screens the stellar irradiation. These results might affect the well known gravity darkening and bolometric albedo effects in interacting binaries, especially for strongly irradiated cold objects.

Keywords. binaries: eclipsing, stars: atmospheres, planets and satellites: general, convection

1. Calculations

We calculate detailed irradiated models of the atmospheres of the planet with the code COOLTLUSTY (Hubeny 1988; Hubeny, Burrows & Sudarsky 2003). Models represent separately averaged day- and averaged night-side models, start at 10^{-5} bars and go deep enough into the convection zone. At a specified depth, we take into account an energy sink on the day side and an energy source on the night side of the planet (Burrows, Budaj & Hubeny 2008). The amount the heat redistribution is parametrized by the P_n parameter, which is defined as a fraction of the stellar irradiation impinging on the planet that is transferred from the day to the night side and radiated out from there (Burrows, Sudarsky & Hubeny 2006).

We consider here a well known planet HD209458b. If not stated otherwise, we assume the solar chemical composition of the planetary atmosphere, energy sink/source at 0.03-0.3 bar, and $P_n = 0.3$. TiO and VO opacities were not considered. The opacities we use are those of Sharp & Burrows (2007), assuming chemical equilibrium composition with a rain-out but no cloud opacity. The Kurucz (1993) spectrum of the parent star HD209458 was used as a source of irradiation. The parameters of the star and planet were taken from Henry *et al.* (2000), Charbonneau *et al.* (2000), and Knutson *et al.* (2007).

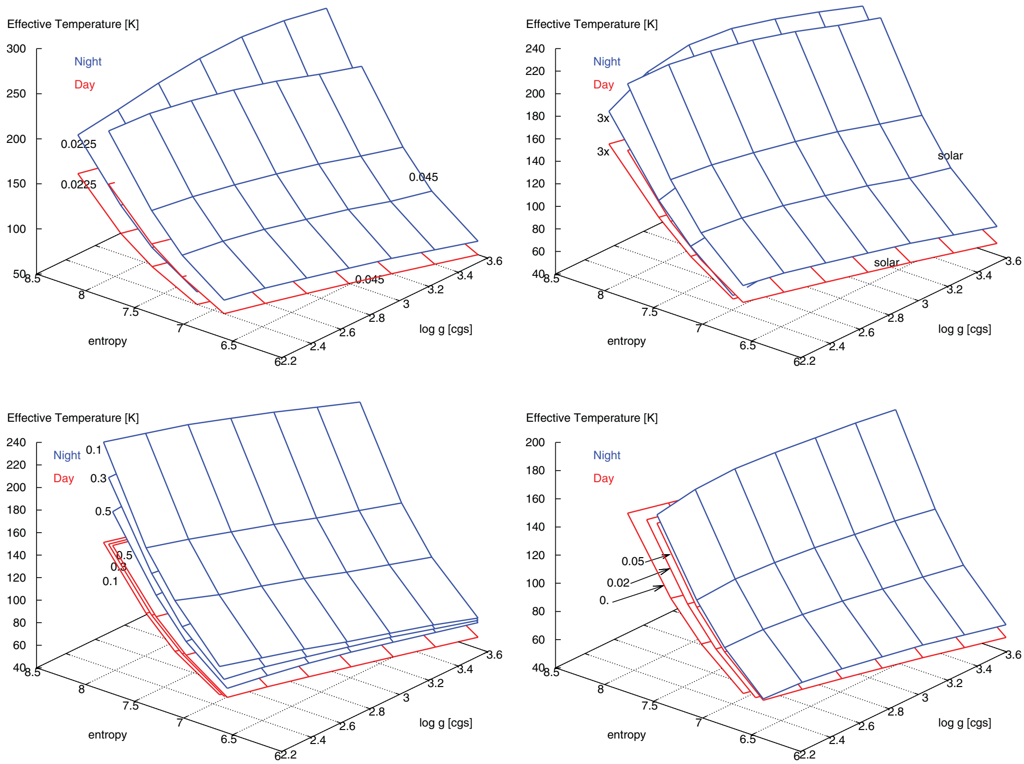

Figure 1. Top-Left: The effect of the planet-star distance or irradiation on the day-night side cooling of the planet. The cooling is expressed as the internal effective temperature in K as a function of the core entropy and the surface gravity. The day-side is red and night-side is blue. Calculated for two planet-star distances $0.045, 0.0225$ AU. The cooling from the day side is decreasing with the stellar irradiation (shorter distance). The cooling from the night side behaves in a similar way. Thus for the higher irradiation the total heat loss is lower. **Top-Right: The effect of varying the metallicity in the planetary atmosphere on the day-night side cooling.** Calculated for two metallicities: solar and 3x solar metallicity. The cooling from the day side is decreasing with the metallicity. The cooling from the night side behaves in a similar way. Thus for the higher metallicity the total heat loss is lower. **Bottom-Left: The effect of the P_n parameter (the effectiveness of day-night heat transfer), on the day - night side cooling**. Calculated for three different values of $P_n = 0.1, 0.3, 0.5$. The cooling from the night side is decreasing with the amount of the heat redistribution (P_n). The cooling from the day side behaves in the opposite way and is increasing with increasing P_n. However, the nights side is more sensitive to the P_n parameter and governs the total heat loss which is decreasing with increasing P_n. The difference between the night and the day side cooling is largest for smaller values of P_n. **Bottom-Right: The effect of the extra opacity in the stratosphere of the day side of the planet on the day - night side cooling.** Calculated for three different values of extra opacity $\kappa = 0., 0.02, 0.05$ $cm^2 g^{-1}$. (Extrasolar planets may have stratospheres due to high opacity at very low optical depth (Hubeny, Burrows & Sudarsky 2003; Fortney *et al.* 2008). The cooling from the day side is increasing with the value of the extra opacity. The cooling from the night side is the same since only the day side is changing. The difference between the night and the day side cooling is thus largest for smaller values of extra opacity. The total heat loss is increasing with increasing the extra opacity.

We calculate a grid of models with/without the irradiation corresponding to the day/night side of the planet for a range of day and night side internal effective temperatures (T_d, T_n) and surface gravities ($\log g$). Each model has a certain entropy in the convection zone. In the next step, we match the entropy and gravity of the day and night

https://doi.org/10.1017/S1743921311028213 Published online by Cambridge University Press

sides which result in different T_d and T_n on the day and night side. Since T_d, T_n represent the total radiation flux on the day and night side, they represent the day and the night side internal heat loss or cooling of the interior. They do not refer to the real atmospheric temperatures on the day/night side. The total internal heat loss (cooling), L_{cool}, from the planet is then

$$L_{\rm cool} = 4\pi R_p^2 \sigma T_{\rm eff}^4 = 2\pi R_p^2 \sigma (T_d^4 + T_n^4), \tag{1.1}$$

where R_p is the radius of the planet, σ is the Stefan-Boltzmann constant, and $T_{\rm eff}$ is the internal effective temperature. The results are displayed in Figs. 1 and 2, where the cooling (intrinsic flux from the interior) of the day and the night side is expressed in terms of the internal effective temperature of the day and the night side as a function of the core entropy and the surface gravity.

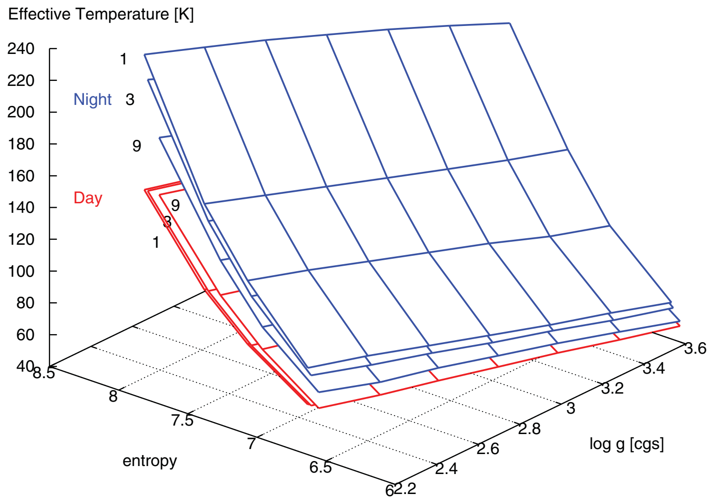

Figure 2. The effect of the depth of the day-night heat transport on the day - night side cooling. The day-side (red) and the night-side (blue) cooling of the planet for three different values of the day side Rosseland optical depth of the heat redistribution region $\tau_{\rm ross} = 1, 3, 9$. On the day side, the heat loss is increasing with increasing optical depth. On the night side, the heat loss is decreasing with increasing optical depth and this trend seems to overwhelm the opposite trend from the day side. As a result, the night-to-day difference is smaller for larger optical depth and the total heat loss decreases with increasing optical depth.

2. Conclusions

We studied the effects of several processes on the day- and night-side cooling of a strongly irradiated planet. The main conclusions are as follows:

• We have demonstrated that the cooling of a strongly irradiated giant planet is different on the day and night sides.

• An increased amount of planet irradiation leads to both reduced day- and night-side cooling and thus to the reduced total heat loss.

• An increased metallicity throughout the atmosphere leads to both reduced day- and night-side cooling and thus to the reduced total heat loss.

• An increased efficiency of the day-night heat redistribution reduces the heat loss from the night side while increasing the heat loss from the day side. The night side is more sensitive to the effect and the total heat loss is reduced.

• A possible extra opacity in the stratosphere of the day-side of the planet acts as a shade which screens the irradiation from the star. Consequently, it increases the day-side cooling as well as the total heat loss.

• If the day-night heat redistribution takes place at larger optical depths it increases the day-side cooling while the night-side cooling is suppressed. The total heat loss is also reduced.

• The night-side cooling is generally more efficient than the day-side cooling. However, this does not rule out a situation that there is a combination of parameters when the opposite case would take place.

These results may affect the evolution of the cold object and the well known gravity darkening and bolometric albedo in interacting binaries (von Zeipel 1924; Lucy 1967, Rucinski 1969, Vaz & Norlund 1985, Claret 1998) especially for strongly irradiated cold objects. It would be interesting to study these effects using data from the Kepler mission.

Acknowledgements

JB thanks the VEGA grants Nos. 2/0074/9, 2/007810, 2/0094/11. This work was partially supported also by SAIA.

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