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Non-grey analytical models for exoplanets atmospheres

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Abstract

We present a new analytical model for irradiated atmospheres. Unlike previous models, we consider several bands both in the visible and in the infrared. Thus, we allow for the correct energy balance through the whole atmosphere. In particular, we show that infrared cooling of the upper atmosphere leads to much cooler temperatures than expected from simple, two bands, semi-grey models. We also highlight the role of non-grey thermal opacities in warming up the lower atmosphere. We provide a method in order to calculate the parameters of our model directly from the line by line opacities. Our method leads to PT profiles that deviates by no more than 10% from numerical profiles over a wide range of gravity and effective temperature. Such a fast and simple analytical solution is of great use to model the large diversity of those atmospheres at a small computational cost. It will be of great importance to interpret results of missions such as CoRoT, Kepler and the future TESS, CHEOPS and EChO.

1. Introduction

The last ten years of exoplanets detection and characterization unveiled the large diversity in their interior structure and atmospheric properties. The atmosphere regulates how much energy from the star can penetrate down to the deep layers of the planet and how much internal heat from the planet can escape to the outer space. Thus, characterizing exoplanets atmospheres is essential in order to understand their interior structure and composition. The large parameter space to explore (composition, gravity, irradiation etc) calls for the development of fast and accurate analytical models.

2. Non-grey analytical model

Most of atmospheric analytical models are either grey (using only the Rosseland mean opacity $\kappa_{\rm R}$) or semi-grey (using one or several bands in the visible and only one for the thermal emission [2]) and usually fail to represent the temperature structure at low optical depth (see fig. 1). Following [1] we develop a new analytical model considering thermal opacities that are the sum of a continuum and a comb of lines with a homogeneous spectral repartition. Our model uses 4 parameters (instead of 2 in the semi-grey model) to describe the opacities as a function of wavelength. $\kappa_{\rm R}$ is the Rosseland mean thermal opacity, $\gamma_{\rm v}$, the ratio of the visible opacity to the Rosseland mean thermal opacity, $R=\kappa_{\rm th2}/\kappa_{\rm th1}$ is the ratio of the thermal opacity in the first and second band and β is the relative spectral width of the two thermal bands.

The range of temperatures reached by our model is compatible with the profiles calculated with numerical integration of the radiative transfer equations (see fig. 2), a significant improvement over previous, semi-grey models. Atmospheric retrieval models based on the semi-grey model [4] should be revised with this new model.

We define a limit optical depth, $\tau_{\rm lim}$, that is a function of the thermal opacities only. We find that for $\tau_{\rm lim}<1$ non-grey effects are contained to $\tau<\tau_{\rm lim}$, whereas for $\tau_{\rm lim}>1$, non-grey effects can affect significantly the lower atmosphere by increasing the temperature down to the convective zone. This "line blanketing effect", important in stellar atmospheric models is shown to be important for irradiated planets [5].

3. Model parameters

Our model treats separately the thermal emission and the incoming stellar irradiation. For this last, we can take into account as many visible opacity bands as needed. In the case of two visible opacity bands we calculate their strength and width such that the absorbed flux in function of the thermal Rosseland optical depth matches the flux calculated using a direct, line by line, calculation. We then determine the val-

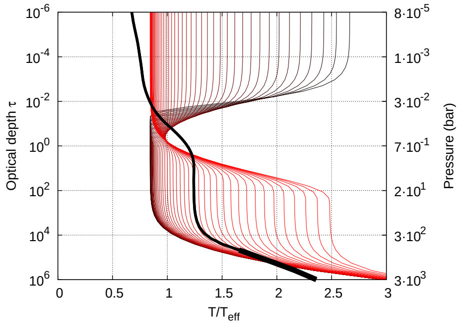

Figure 1: Optical depth vs. atmospheric temperature in units of the effective temperature. A numerical, solution obtained from [3] (thick black line) is compared to the semi-grey analytical solutions of [2] for values of the antigreenhouse factor $\gamma_{\rm v}=\kappa_{\rm v}/\kappa_{\rm R}$ ranging from 0.01 to 100 (black to red lines). Small values of $\gamma_{\rm v}$ are redder. This is for a dayside averaged profile. Note that, whatever the value of $\gamma_{\rm v}$, the semi-grey model is unable to reach the numerical model's cool temperatures at low optical depth.

ues of the thermal coefficients by fitting our solution to a set of PT profiles calculated using a state of the art radiative transfer model [3]. The models obtained matches the numerical profiles with an accuracy down to 10% at all optical depth over a wide range of effective temperature and gravity [6].

4. Summary and Conclusions

We developed a new analytical model for planetary atmospheres taking into account not only the non-grey structure of the visible opacities but also the non-grey structure of the thermal opacities. This model is a significant improvement over the commonly used semi-grey models. In particular, our model gives a good representation of the infrared cooling of the upper atmosphere, leading to accurate temperatures at low optical depth. We derive a parameter $\tau_{\rm lim}$ such that for small values of $\tau_{\rm lim}$, the non-grey effects are confined to low optical depth whereas for values $\tau_{\rm lim}$ larger than one, the non-grey effects can significantly warm up the lower atmosphere. An effect known as the “line blanketing effect”.

We derived a method to calculate the visible mean opacities relevant for our model from the line-by-line opacities and we obtain an analytical solution that

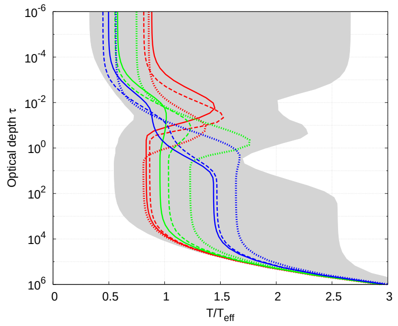

Figure 2: PT profiles for an irradiated planet with one visible opacity and two thermal opacities. The shaded area show the full range of parameters $0.1<\beta<0.9$, $1<R<10^4$ and $0.01<\gamma_{\rm v}<100$. The lines are profiles obtained for $R=10^3$ and $\beta=0.1$ (plain lines), $\beta=0.5$ (dashed lines), $\beta=0.9$ (dotted lines) and for $\gamma_{\rm v}=0.1$ (blue), $\gamma_{\rm v}=1$ (green) and $\gamma_{\rm v}=10$ (red). Note that the numerical profile of fig. 1 is now included inside the envelope of the analytical models. Note also that as β increases, the line blanketing effect warms up significantly the deep atmosphere.

matches the numerical profiles with a 10% accuracy over a wide range of gravity and effective temperature.

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