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Temperature inversion and the size of exoplanets

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Abstract

Most of the known exoplanets are Jupiter-size planets orbiting very close to their star. These planets are subjected to a high irradiation from their star. Atmospheres are the link between deep interior and outside of these planets. They control both the amount of energy that can be deposited by the star into the deep interior and the amount of internal heat allowed to escape from the planet.Their characteristic can influence the evolution of the planet. It has been proposed that two class of exoplanets might exist : with and without temperature inversion in their atmosphere [1]. Here, we implement a three-band analytical model for the atmosphere of giant planets which is coherent with the model interior. It allows us to solve both parts together and to study in detail the effects of atmospheric parameters on the global evolution of the planet. We first estimate that the plan-parallel approximation can lead to systematic errors in the model radius of up to 1%. We then study the influence of the presence of a temperature inversion on the planetary evolution. We find that planets with a temperature inversion should be smaller than planets without a temperature inversion by 2 to 10% depending on the irradiation flux they receive.

1. Introduction

Giant planet models are usually split in two parts : an atmosphere which absorbs and emits radiation and an interior for which the radiation field can be considered isotropic. These two parts are usually solved separately, the atmosphere being a boundary condition for the interior. We built a coherent model of the atmosphere and the interior of the planet which allows us to solve both parts together. This new model is used to study the influence of the classical plan-parallel approximation on the modeled transit radii. We then investigate how the the ratio of optical to infrared opacities affects the atmospheric profile and the evolution of the planet.

2. Model

2.1. Atmosphere model

We expanded the 1-dimensional plan-parallel two-stream model for the atmosphere from [3] to a three-stream model. This model solves the radiative transfer equation dividing the flux in three bands : an infrared flux from the planet and two visible flux coming from the star. The resulting analytical relation gives the temperature of the atmosphere in function of τ_{IR}, the infrared optical depth, $T_{\rm eq}$ the equilibrium temperature of the planet, $\sigma T_{\rm int}^4$ the intrinsic flux of the planet, γ_1 and γ_2 the ratio of the opacities in each visible bandpass to the thermal opacity.

2.2. Interior Model

In order to model the interior structure and evolution of fluid planets, we use the CEPAM code [4]. It is a 1-dimensional code solving the hydrostatics equations for the planet with a diffusion approximation for the radiation. We include into this code the propagation of the visible flux coming from the star. The flux is considered uncorrelated with the intrinsic flux of the planet so the diffusive approximation for the infrared flux remains valid. This allows us to place our atmosphere/interior limit at any depth inside the radiative zone of the planet.

2.3. Opacities

The opacities are taken from [2]. In order to facilitate the numerical integrations we use a polynomial fit of the opacities taking into account the temperature, pressure and metallicity dependencies. The same opacities are used for the model interior and the model atmosphere. This allows us to keep the coherence between the two models.

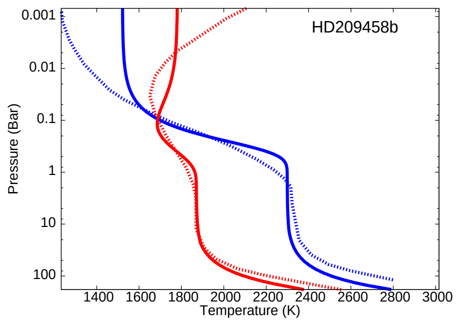

Figure 1: Temperature profile for HD209458b with and without temperature inversion. Dashed lines are from [1] whereas solid lines are from our model.

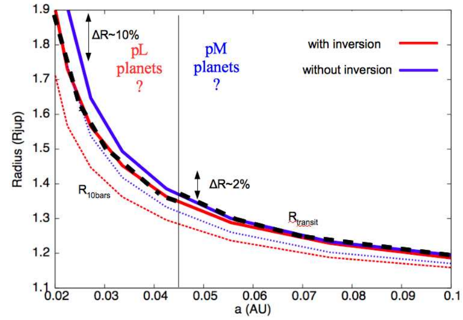

Figure 2: Final radius of a $0.69M_j$ at different distances from a solar-type star. Dashed line represent the 10bar radius of the planet whereas solid lines represent the transit radius of the planet. The vertical line is the hypothetical limit between pM and pL class planets as determined by [1]. The dashed black line represents the possible radius-distance relationship for the planet under the pM/pL planets hypothesis.

3. Results

3.1 Systematic error due to the plan-parallel approximation

When modeling giant planets, one has to choose R_{lim}, the depth of the boundary between the atmospheric, plan-parallel model and the spherical interior model. The limit between radiative and convective zones can be a natural choice to place the atmosphere/interior boundary. But for old and highly irradiated planets, the radiative zone can extend to great depth. The gravity and the $T_{\rm int}$ used in the atmospheric model are proportional to $1/R^2_{lim}$. This variations can affect the calculated transit radius. By changing the depth of this limit in our model we estimate that a $1M_j$ planet with $T_{\rm eq} = 1000K$ can have its modeled radius affected up to 1% by the plan-parallel approximation.

3.2 Consequence of a temperature inversion

When a strong absorber in the visible is present at low pressure, part of the stellar flux is absorbed on the high atmosphere resulting in a temperature inversion [1]. To mimic this behavior, we fit the temperature profiles from [1] to obtain realistic values of γ_1 and γ_2. These factors describe how opaque is the atmosphere in the two visible bandpass. For high values of γ, the flux is absorbed high in the atmosphere whereas for low values of γ the flux is absorbed deep in the planet. Figure 1 shows two possible temperature profile of HD209458b : one without temperature inversion ($\gamma_2 = \gamma_1 = 0.3$) and one with temperature inversion ($\gamma_2 = 3, \gamma_1 = 0.3$). Then we perform a set of evolution for planets with different irradiation with and without temperature inversion. The final radius of the planet is shown in figure 2. Planets with a temperature inversion appear to be smaller by 2 to 10% depending on the irradiation flux. When there is a temperature inversion, part of the incoming flux from the star is absorbed at the top of the atmosphere and is radiated to the space. That leads to a smaller amount of energy deposited deep in the planet. The cooling of the planet is more efficient, yielding a smaller planetary radius than for a planet at the same orbital distance but assuming no temperature inversion in its atmosphere.

References

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