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# A RADIATIVE-CONVECTIVE EQUILIBRIUM MODEL FOR YOUNG GIANT EXOPLANETS: APPLICATION TO GPI COMMISSIONING DATA

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**Abstract.** We developed a radiative-convective equilibrium model for young giant exoplanets, in the context of direct imaging. Input parameters are the planet's surface gravity (g), effective temperature ($T_{\rm eff}$) and elemental composition. Under the additional assumption of thermochemical equilibrium, the model predicts the equilibrium temperature profile and mixing ratio profiles of the most important gases. Opacity sources include the $H_2$-He collision-induced absorption and molecular lines from $H_2O$, CO, $CH_4$, $NH_3$, VO, TiO, Na and K. Line opacity is modeled using k-correlated coefficients pre-calculated over a fixed pressure-temperature grid. Absorption by iron and silicate cloud particles is added above the expected condensation levels with a fixed scale height and a given optical depth at some reference wavelength. Model predictions are compared with the existing photometric and spectroscopic measurements of $\beta$ Pictoris b and photometric data of HD95086 b recorded during GPI commissioning. This model was developed to interpret data of the instrument SPHERE at the VLT.

Keywords: radiative transfer, planets and satellites: atmospheres, planets and satellites: gaseous planets, stars: individual ($\beta$ Pictoris), stars: individual (HD95086)

## 1 SPHERE

SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch) is an instrument for the Very Large Telescope designed to study extra-solar planets by direct imaging. It is focused on spectroscopic and polarimetric characterization of giant planets. SPHERE combines extreme adaptive optics, coronography and spectroscopy, polarimetry and differential imaging.
We focus on young stars in the solar neighborhood to observe young planets just after their formation, thus having high temperature and self luminosity.

## 2 Model

We developed an atmospheric model based on radiative-convective equilibrium and thermochemical equilibrium. In this plane parallel model, the flux is thus constant with altitude and defined as $\pi F = \sigma {T_{\rm eff}}^4$.
The model includes absorption by eight molecular species and two different clouds. Molecular absorption is calculated using $k$-correlated coefficients computed on a grid of temperature profiles.
**$H_2O$ and CO:** for water and carbon monoxide we used the HITEMP line list from Rothman et al. (2010).
**$CH_4$:** for methane we used line lists coming from Albert et al. (2009) , Boudon et al. (2006) , Daumont et al. (2013) and Campargue et al. (2012), and for $CH_3D$ Nikitin et al. (2002), Nikitin et al. (2006) and Nikitin et al. (2013).
**$NH_3$:** for ammonia we used the Exomol line list from Yurchenko et al. (2011).
**TiO and VO:** for TiO and VO we used line lists coming from the website of B. Plez * (Plez (1998) with some

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update since the publication).
**Alkali Na and K:** for alkali lines we used line lists from the NIST Atomic Spectra Database[†] with lineshape profiles from Burrows & Volobuyev (2003).
**$H_2$-He CIA:** for $H_2$-He, the collision-induced absorption coefficients were obtained from the website of A. Borysow [‡] (Borysow et al. (1988) Borysow et al. (1989) Borysow & Frommhold (1989) Borysow et al. (2001) Borysow (2002) ). We considered absorption (and not scattering) by iron and silicate cloud particles, computed with the Mie theory for spherical particles, added above the expected condensation level with a fixed scale height and a given optical depth $\tau_{\rm ref}$ at some reference wavelength (1.2 $\mu$m).
The input parameters of the model are the effective temperature $T_{\rm eff}$, the acceleration of gravity $g$ at 1 bar. The other set of free parameters is the optical depth of the silicate and iron clouds $\tau_{\rm ref}$, assuming the same column density, for the two species for a condensation pressure level of 1.0 bar, and the mean radius $r$ of the cloud particles. Optical depths of the clouds are assumed to be proportional to the condensation pressure.
For output, the model then provides the radiative-convective equilibrium temperature profile $T(p)$, the corresponding vertical profiles of the absorbers at chemical equilibrium, and the spectrum at the resolution of the $k$-correlated coefficient distribution, i.e. 20 cm$^{-1}$.

We built some grids of surface spectra, corresponding to a range of $T_{\rm eff}$ and log($g$) (Fig. 1). Each spectrum was computed for a radius equal to one Jupiter radius ($R_{\rm Jup}$) and a set of cloud parameters. We used the five grids (five sets of cloud parameters) defined in Appendix C of Bonnefoy et al. (2014).

For each set of observation and each synthetic planet in our grids, we selected the radius that minimizes the $\chi^2$ between the Spectral Energy Distribution (SED) of the planet and the calculated spectrum, which is given by:

$$5\log_{10}(R) = -\frac{\sum\left(\frac{X_{\rm Observed}-X_{\rm Computed}}{\Delta X^2_{\rm Observed}}\right)}{\sum\left(\frac{1}{\Delta X^2_{\rm Observed}}\right)} \tag{2.1}$$

where $R$ is the radius expressed in $R_{\rm Jup}$, $X_{\rm Observed}$ the observed apparent magnitudes bearing an uncertainty $\Delta X_{\rm Observed}$ and $X_{\rm Computed}$ magnitudes calculated at the distance of the planet from our model spectrum multiplied by the appropriate filter transmission. Then we multiplied our synthetic spectra by $R^2$ and computed the $\chi^2$ between observed and calculated magnitudes.

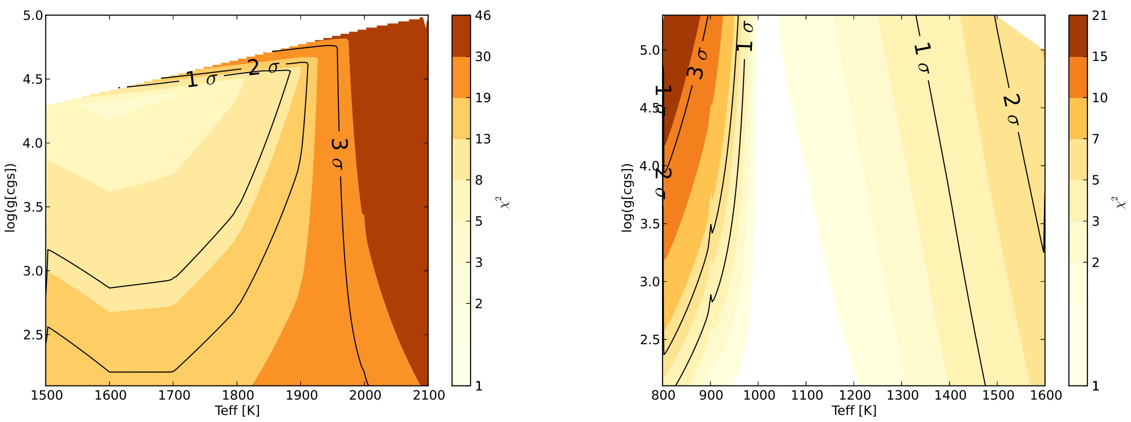


**Fig. 1. Left:** Example of grid for $\beta$ Pictoris b SED with selection on radius and mass. **Right:** Example of grid for HD95086 b SED with selection on radius and mass.

We used the published age of the star and hot-start formation model from Spiegel & Burrows (2012) and classical core accretion formation model from Mordasini et al. (2012) to exclude synthetic planets with radius

[†]http://www.nist.gov/pml/data/atomspec.cfm/
[‡]http://www.astro.ku.dk/~aborysow/programs/

outside of the predicted ranges.
The mass is related to the radius $R$ and the gravity $g$ through the relation $g = \frac{GM}{R^2}$. In some cases, we made use of existing informations on the mass (e.g. through velocity measurements) to limit the range of allowed parameters $R$ and $g$.

## 3 Planets

### 3.1 HD95086 b

In Galicher et al. (2014), we used apparent fluxes coming from NaCo and GPI (Gemini Planet Imager) observations in filters H, K1, L'.
To derive the planet parameters, we compared observations with BT-SETTL/Dusty/Cond models and our model.
Due to the lack of data it was difficult to obtain good constraints. In Galicher et al. (2014) we could still conclude that $T_{\rm eff} < 1500$ K and log(g[cgs])$< 4.5$ while with our model alone, we found $T_{\rm eff} = 1100 \pm 300$ K and no constraints on gravity.

### 3.2 $\beta$ pictoris b

In Bonnefoy et al. (2014), we used observations coming from NaCo, NiCi, MagAO et GPI observations in filters Ys, J, $CH_{4_{S1\%}}$, H, Ks, L', NB4.05, M' and a J-band GPI spectrum (Figs. 2-3).
We begin to have a lot of data for the Spectral Energy Distribution (SED) of the planet and we have radial velocity measurements from Lagrange et al. (2012). With this last information, we can set a conservative upper limit on the mass of the planet of 25 $M_{\rm Jup}$.
We used either the SED alone or the normalized spectrum alone, and we considered upper limits on radius (2 $R_{\rm Jup}$) and mass (25 $M_{\rm Jup}$). In Bonnefoy et al. (2014), considering also other models BT-SETTL and Drift-PHOENIX, we derived $T_{\rm eff} = 1650 \pm 150$ K and log(g[cgs])$< 3.7$ for both cases, while, with our model alone we found $1650 \pm 150$ K and log(g[cgs])$= 3.7 \pm 0.9$ .

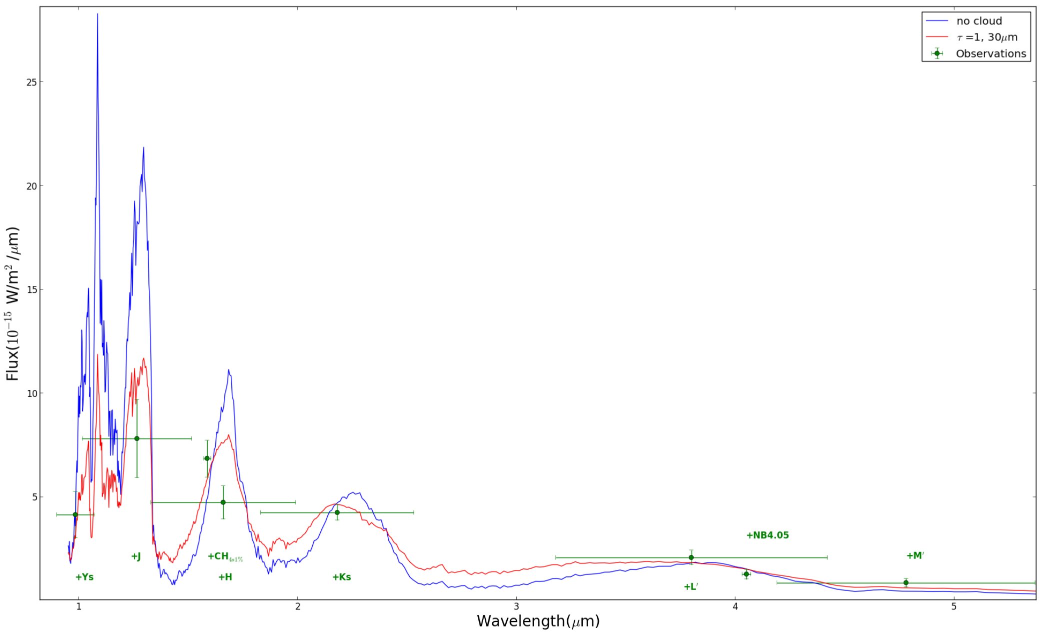


**Fig. 2.** SED of $\beta$ Pictoris b (green dots) compared to the best fit models without clouds (blue) and with clouds (red).

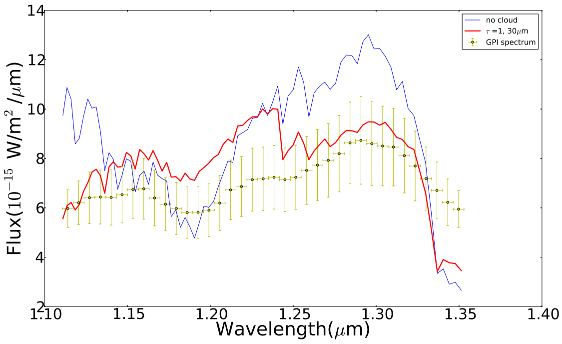


**Fig. 3.** $J$ spectrum of $\beta$ Pictoris b (yellow dots) compared to the best fit models without clouds (blue) and with clouds (red).

## 4 Conclusions and perspectives

We developed a very simple model that we compared with two sets of data. We derived constraints similar to those obtained from other models in the literature although our model is simpler.
We will obtain in a few months the first SPHERE data. Since the SF2A, we have updated our spectroscopic data for methane using the Exomol line list from Yurchenko & Tennyson (2014).
We begin to study the effect of metallicity on the derived parameters.

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