A radiative-convective equilibrium model for young giant exoplanets: Application to β Pictoris b

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1. 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 (Teff) 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. Scattering is not included at the present stage. Model predictions are compared with the existing photometric measurements of Planet β Pictoris b in the J, H, Ks, L', NB 4.05, M' bands .

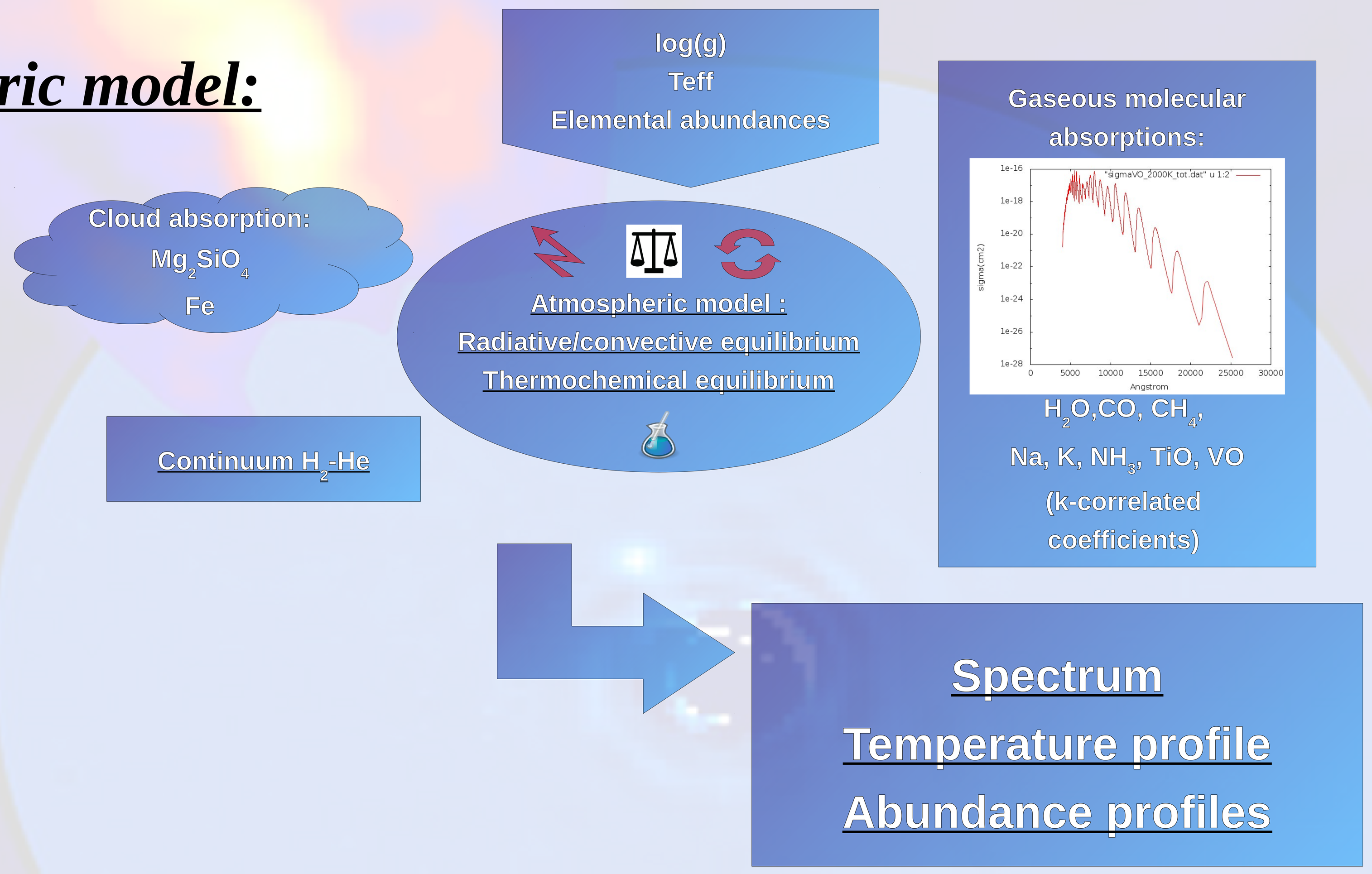
This model will be used to interpret future photometric and spectroscopic observations of exoplanets with SPHERE, mounted at the VLT with a first light expected in 2014.

2. Observations:

Parameter	β pictoris b	References
d(pc)	19,44±0,05	[5]
Age (Myr)	12^{+8}_{-4}	[6]
J	14,0±0,3	[1]
H	13,5±0,2	[1]
Ks	12,6±0,1	[4]
L'	11,0±0,2	[1][4]
NB 4.05	11.20±0,23	[3]
M'	11,0±0,3	[1]

Photometric measurements of the young planet β Pictoris b have been obtained at the VLT using the NaCo instrument, in several near-infrared bands, the derived apparent magnitudes are listing in the table. For more informations see [1].

3. Atmospheric model:



4. Opacity sources:

H_2O, CO line list: HITEMP[7]

CH_4 line list: Albert et al. (2009)[14] + Boudon et al. (2006)[15] + Daumont et al. (2013)[16] + Campargue et al. (2013)[17] + (CH_3D)Nikitin et al. (2002,2006,2013)[18,19,20]

Na, K line lists: NIST Atomic Spectra Database[8]

Na, K, line profiles: Burrows & Volobuyev(2003)[21]

NH_3 line list :Yurchenko 2011[29]

VO, TiO line lists: Plez (1998)[22] (with update)

H_2-He continuum: Borysow et al. (2001, 2002, 1988, 1989a, 1989b) [9,10,11,12,13]

Mg_2SiO_4 optical constants: Jäger et al. (2003) [23]

Fe optical constants: Ordal et al. (1988) [24]

5. Results:

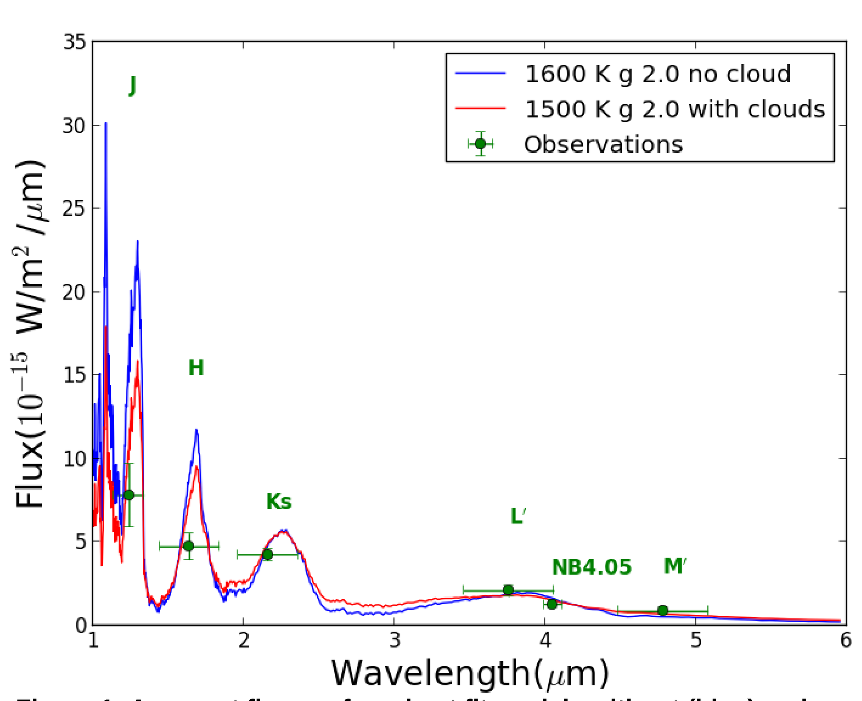


Figure 1: Apparent fluxes of our best fit models without (blue) and with cloud opacity (red), compared with measured apparent fluxes of β pictoris b (green dots)

We built 2 grids of models with:
- Teff between 1200 and 2200 K
- log(g[cgs]) between 2 and 4.5
- solar system abundances of the elements [26]
- one without clouds AND one with cloud particles located between condensation level and a pressure of 100 times less, with particle radius of 30 μm, scale height equal to the gas scale height and optical depths (τ_{cloud}) of 0.25 and 0.0375 at 1.2 μm for Fe and Mg_2SiO_4 respectively (assuming the same column density for both clouds).

For each model, we selected the radius that minimizes the χ2 between the observed and calculated apparent magnitudes.

We only kept models with a radius between 0.6 and 2 Jupiter radius (a realistic range derived from evolution models [28]) and we define the acceptable range of parameters as those yielding χ2 lower than 11.1 (Bevington 2003)[30]).

We show in Figure 2 the solution temperature profiles for the cloudy and cloud-free cases. The thick lines represent the purely radiative solutions. At deep levels, the lapse rates become super-adiabatic and the profiles are thus unstable against convection. The thin lines represent the profiles with adiabatic gradients set at these unstable levels.

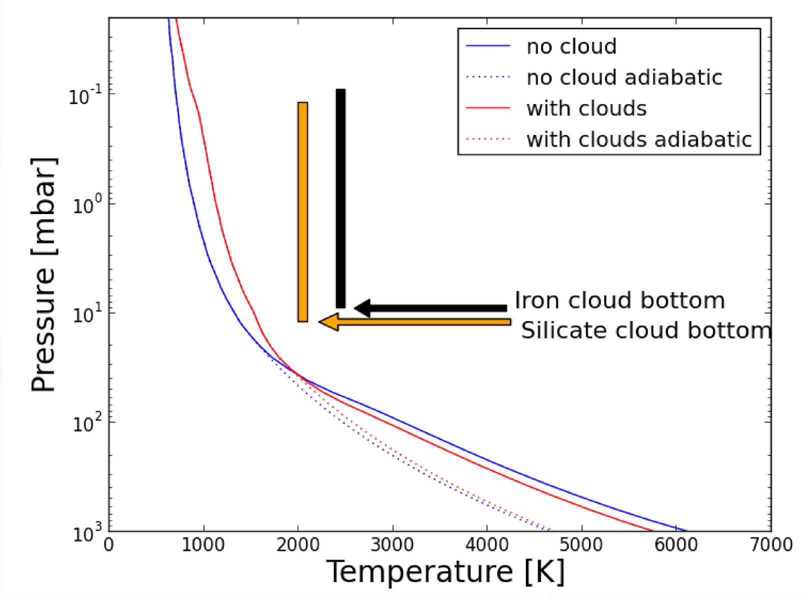


Figure 2: Pressure/Temperature profiles of our best fit cloud-free (blue) and cloudy (red) models

The <u>**best χ^2 in the grid without clouds is 9**</u> for an effective temperature of 1600 K, a log(g) of 2 and a radius of 1.63 Jupiter radius (R_J).

<u>**In the grid with clouds the best χ^2 is 2.8**</u> for an effective temperature of 1500 K, a log(g) of 2 and a radius of 1.79 R_J, the base of the iron cloud is at 12 mbar and that of the silicate cloud at 9 mbar.

In the grid with clouds, we find that the effective temperature is well constrained and derive Teff = 1650±150 K while the gravity is poorly constrained: log (g) <3.7 . For the radius (R) we obtain a range of 1.3-1.9 R_J and for the mass < 5.5 M_J .

6. Comparisons:

	This work	Bonnefoy et al.[1]	Currie et al.[32]
Teff	1650±150 K	1700±100 K	1575-1650 K
log(g)	<3.7	4.0±0.5	3.8±0.2
Radius	1.3-1.9 R_J	1.2-1.4 R_J	1.65±0.06 R_J
Best fit cloud model	Cloudy (2 thick clouds)	Cloudy Drift-Phoenix	Cloudy Modified AMES-Dusty (Thick clouds / small particles)

The different models yield consistent estimations of the effective temperature, in a range of 1500-1800K.
All models show that best fitting of the observations is achieved with cloud opacity.
We note that, in our model, gravity is very uncertain but that best fits are obtained for very low values, around log(g)=2.

7. Conclusions and perspectives:

In agreement with other models, we found that cloud opacity allows us to better reproduce the observations of β Pictoris b.
A model with Teff = 1650±150 K, log10(g[cgs]) < 3.7, and some cloud opacity agrees with observations within uncertainties.

We plan:
- to explore the influence of metallicity and departure from thermochemical equilibrium
- to constrain the range of cloud optical depths in β Pictoris b
- to apply our model to planetary system HR8799 [26]
- to update methane opacity with the Exomol data base [27]
- to include other condensation clouds [31]
- to use microphysical models predictions to constrain our cloud parameters (grains size,τ_{cloud}...)

This model will be used to analyze data from SPHERE after commissioning on the VLT in 2014.

PhD bursary founded by the Labex ESEP
http://www.esep.pro/

If you have any question ask me :
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