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

**Jean-loup Baudino[1], Bruno Bézard[1], Anthony Boccaletti[1], Mickael Bonnefoy[2], Anne-Marie Lagrange[3]**

*[1] LESIA, Observatoire de Paris, 5 place Jules Janssen, F-92195 Meudon, France,*

*[2]Max Planck Institut of Astronomy, Königstuhl17, D-69117 Heidelberg, Germany,*

*[3]UJF-Grenoble 1 / CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274, Grenoble, F-38041, France*

## 1. Abstract:

We developed a radiative-convective equilibrium model for young giant exoplanets. 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. Cloud absorption can be added above the expected condensation level (e.g. iron or silicates) with given scale height and 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 .

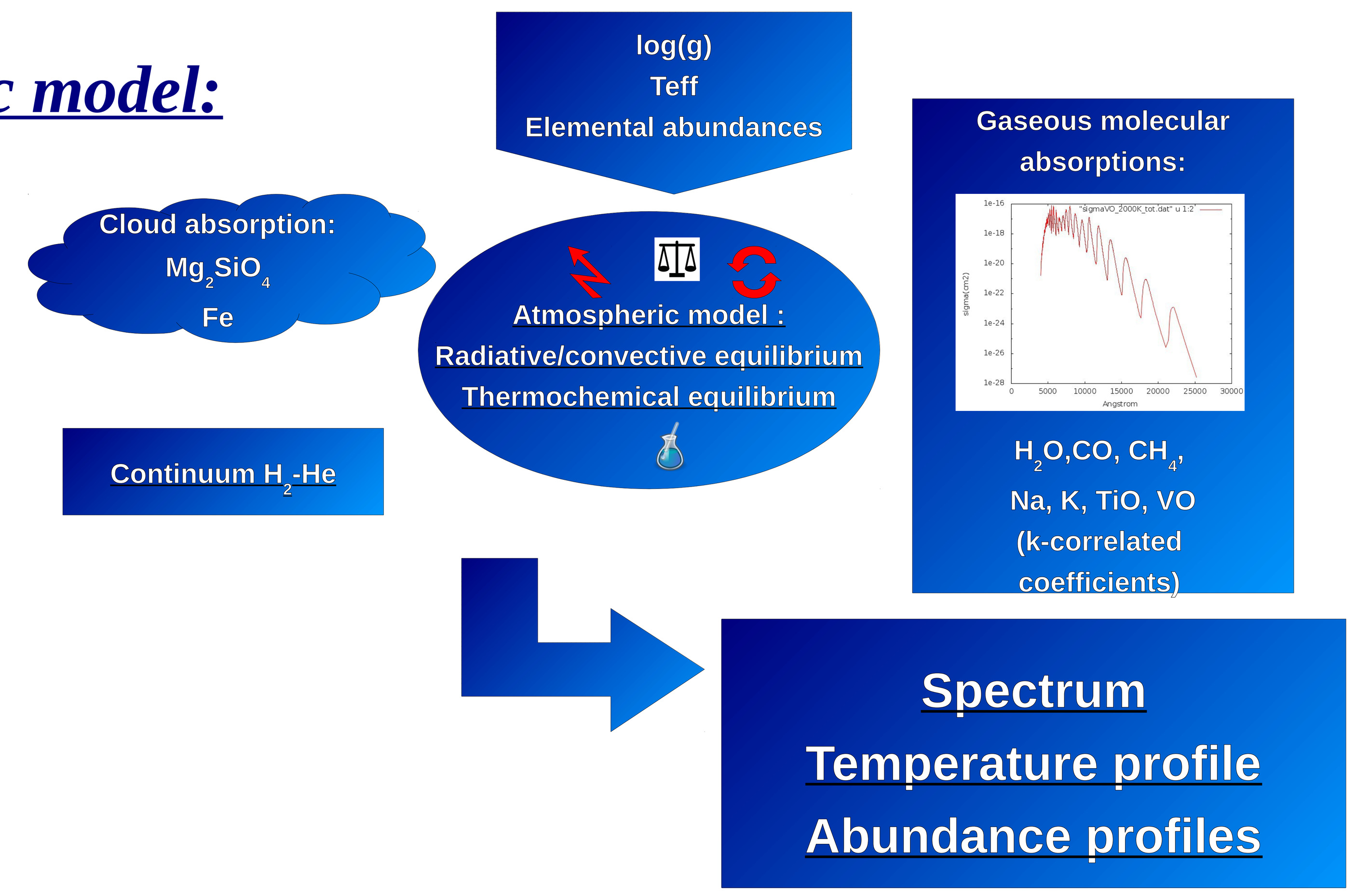
This model will be used to interpret future photometric and spectroscopic observations of exoplanets with SPHERE, mounted at the VLT with a first light expected end of 2013.

## 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]

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 :

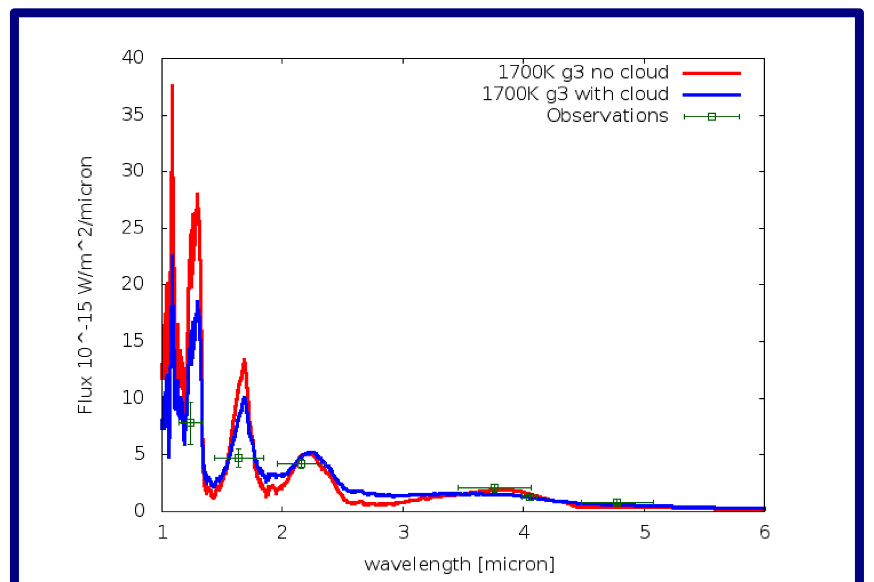



**Figure1: Apparent flux of our model without (red) and with cloud opacity (blue), compared with measured apparent fluxes of β pictoris b (green squares)**

We built a grid of models with:
- Teff between 1000 and 2500 K ,
- log(g[cgs]) between 3 and 5
- solar system abundances of the elements [26]
- no cloud opacity

For each model we selected the radius that minimizes the $\chi^2$ 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]).

The best one (cloud-free model) is a planet with an effective temperature of 1700°K, a log(g[cgs]) of 3 and a radius of 1.53 $R_{Jup}$ ($\chi^2$ = 21). This model clearly yields too much flux in the J and H bands.

In a second step, we added absorption from iron and silicates clouds. We used a particle radius of 30 microns and assumed the same particle column density for both clouds. For each cloud the opacity is distributed between the condensation level and the 0.1-mbar level with a particle scale height equal to the gas scale height.

For Teff=1700 K and log(g)=3, using a particulate optical depth ($\tau_{cloud}$) of 0.25 at 1.2 µm allows us to obtain a $\chi^2$ of 7.5 for a radius of 1.43 $R_{Jup}$. Compared with the cloud free case, the flux in the J and H bands is lower and that in the Ks, L', NB4.05 and M' bands is higher.

Adding cloud opacity in the model is required to reproduce the data within uncertainties.

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.

In Figures 3 and 4 are shown the mixing ratio profiles for the cloud-free and cloudy model computed with the temperature profiles of Figure 2.

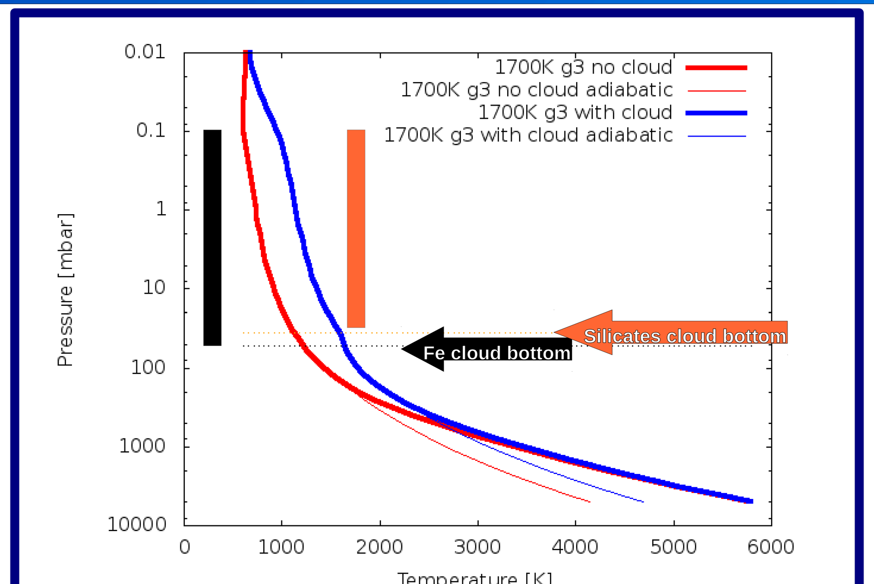



**Figure 2: Pressure/Temperature profiles of our cloud-free (red) and cloudy (blue) models**

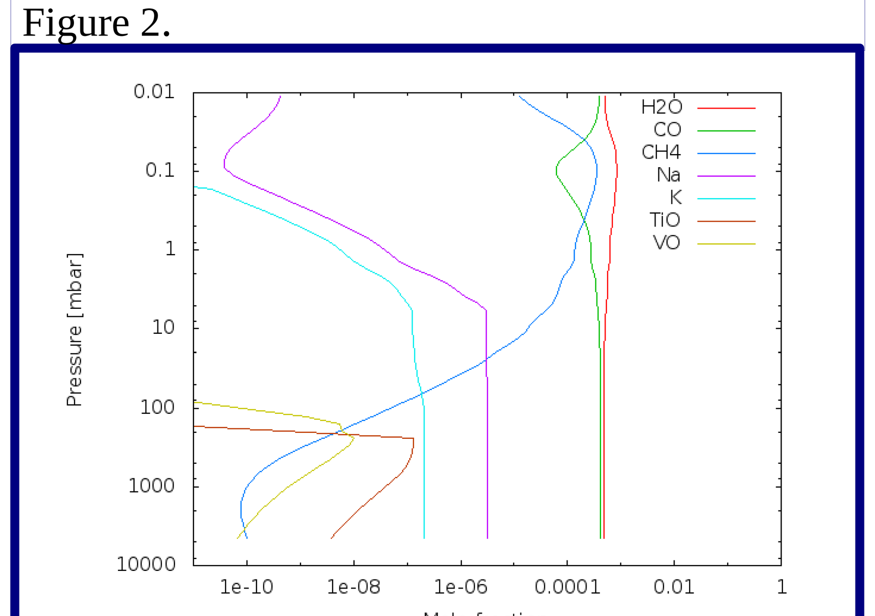



**Figure 3: Mixing ratio profiles of H2O, CO,CH4, Na, K, TiO, VO in our cloud-free model**

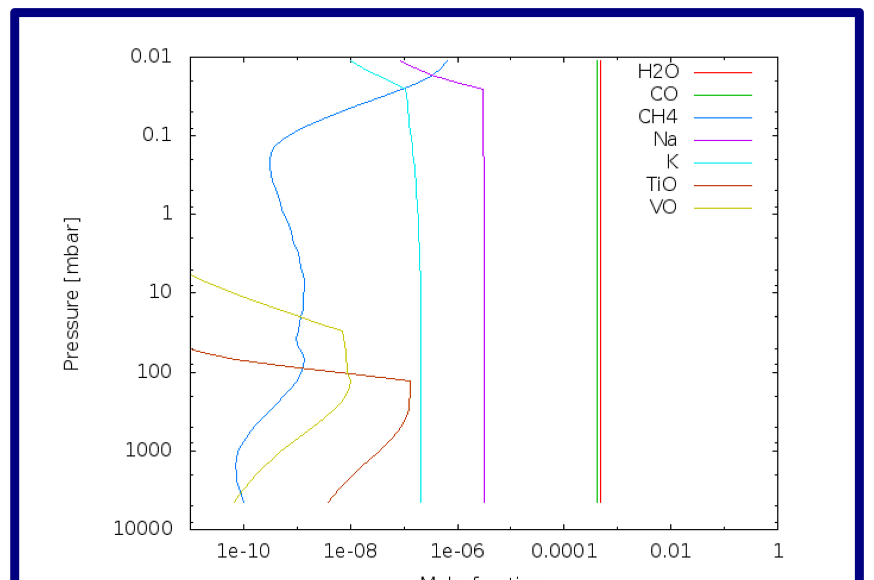



**Figure 4: Mixing ratio profiles of H2O, CO,CH4, Na, K, TiO, VO in our cloudy model**

## 6. Conclusions and perspectives:

In agreement with other models (see references in [1]) we found that cloud opacity is needed to reproduce the observations of β pictoris b.

A model with Teff = 1700K, g =1000cgs, and some cloud opacity agrees with observations within uncertainties, but other combinations of these parameters are probably possible.

We plan:
- to explore the parameter space (Teff, g, $\tau_{cloud}$) for cloudy models of β pictoris b
- to apply our model to planetary system HR8799 [26]
- to update methane opacity with the Exomol data base [27]
- to add $NH_3$ opacity

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

References: [1] Bonnefoy et al. 2013 A&A in press, [2] Lagrange et al. 2009 A&A 493 L21, [3] Quanz et al. 2010 ApJL 722 L49, [4] Bonnefoy et al. 2011 A&A 528 L15, [5] van Leeuwen 2007 A&A 474 653, [6]Zuckerman 2001 ApJL 562 L87, [7] Rothman et al. 2010 JQSRT 111 2139-2150, [8] http://physics.nist.gov/PhysRefData/ASD/lines_form.html , [9]Borysow et al. 2001 JQSRT 68 235-255 [10] Borysow 2002 A&A 390 779-782 [11]Borysow et al. 1988 ApJ. 326 509-515 [12]Borysow et al. 1989 ApJ 336 509-515 [13] Borysow and Frommhold 1989 ApJ 341 549-555 ,[14] Albert et al. 2009 Chem Phys 356 131-146, [15] Boudon et al. 2006 JQSRT 98 394-404, [16]Daumont et al. 2013 JQSRT 116 101-109, [17]Campargue et al. 2012 Icarus 219 110-128, [18]Nikitin et al. 2002 J Mol Spec 216 225-251, [19] Nikitin et al. 2006 J Mol Spec 240 14-25, [20] Nikitin et al. 2013 JQSRT 114 1-12, [21]Burrows & Volobuyev 2003 ApJ 583 985-995, [22]Plez 1998 A&A 337 495-500, [23] Jäger et al. 2003 A&A 408 193, [24]Ordal et al. 1988 Appl Opt 27 1203-1209 [25]Lodders 2010 Lecture Notes of the Kodai School 379-417, [26]Oppenheimer et al. 2013 ApJ 768 24, [27]http://www.exomol.com/, [28] Mordasini et al. 2012 A&A 547 A112

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

If you have any question ask me. Jean-loup.baudino@obspm.fr