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. 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 .

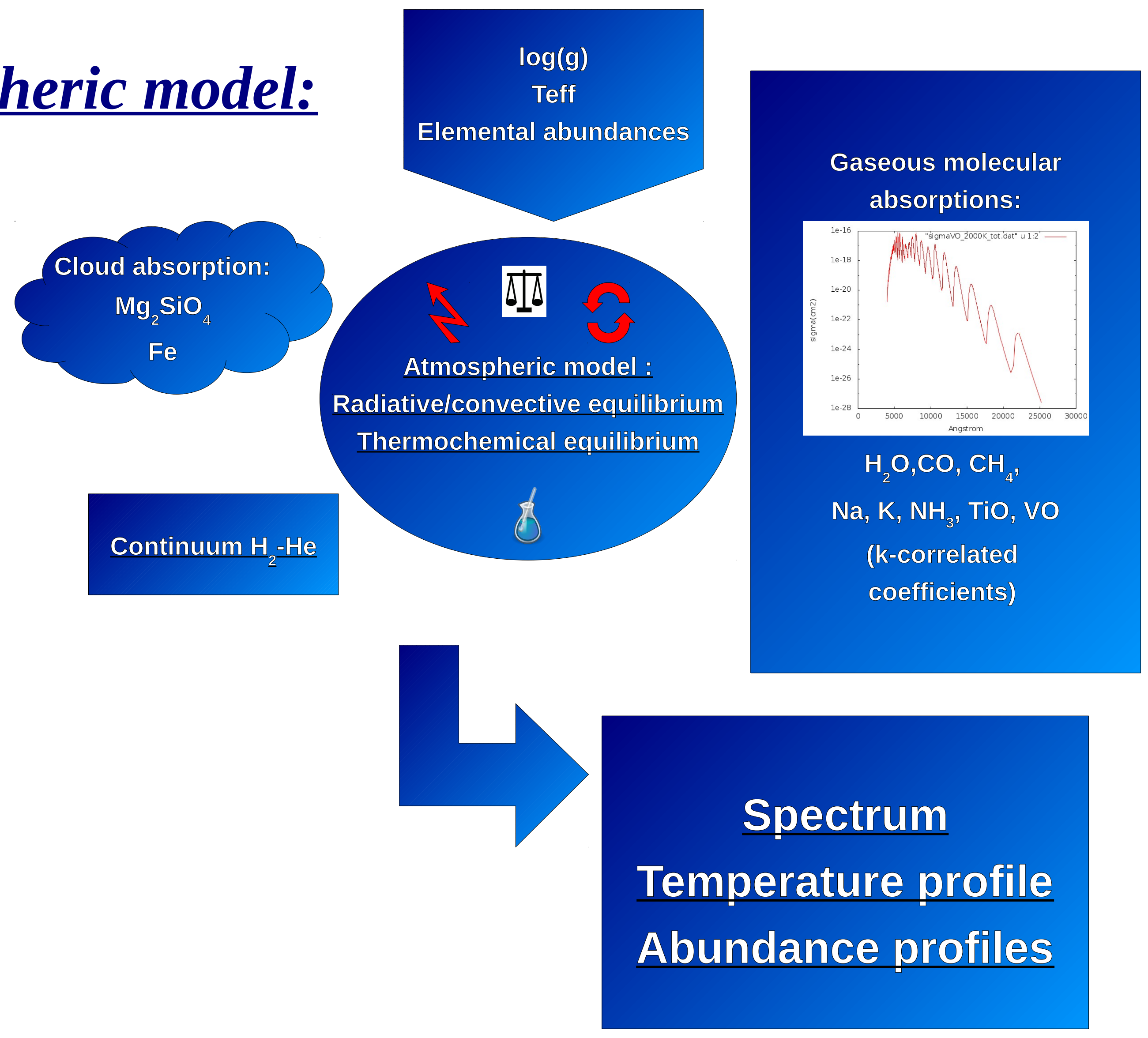
This model will be used to interpret future photometric and spectroscopic observations of exoplanets with SPHERE, mounted at the VLT with a first light expected in 2014.

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:



log(g)
Teff
Elemental abundances

Cloud absorption:
Mg_2SiO_4
Fe

Atmospheric model :
Radiative/convective equilibrium
Thermochemical equilibrium

Continuum H_2-He

Gaseous molecular absorptions:

H_2O,CO, CH_4,
Na, K, NH_3, TiO, VO
(k-correlated coefficients)

Spectrum
Temperature profile
Abundance profiles

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 :

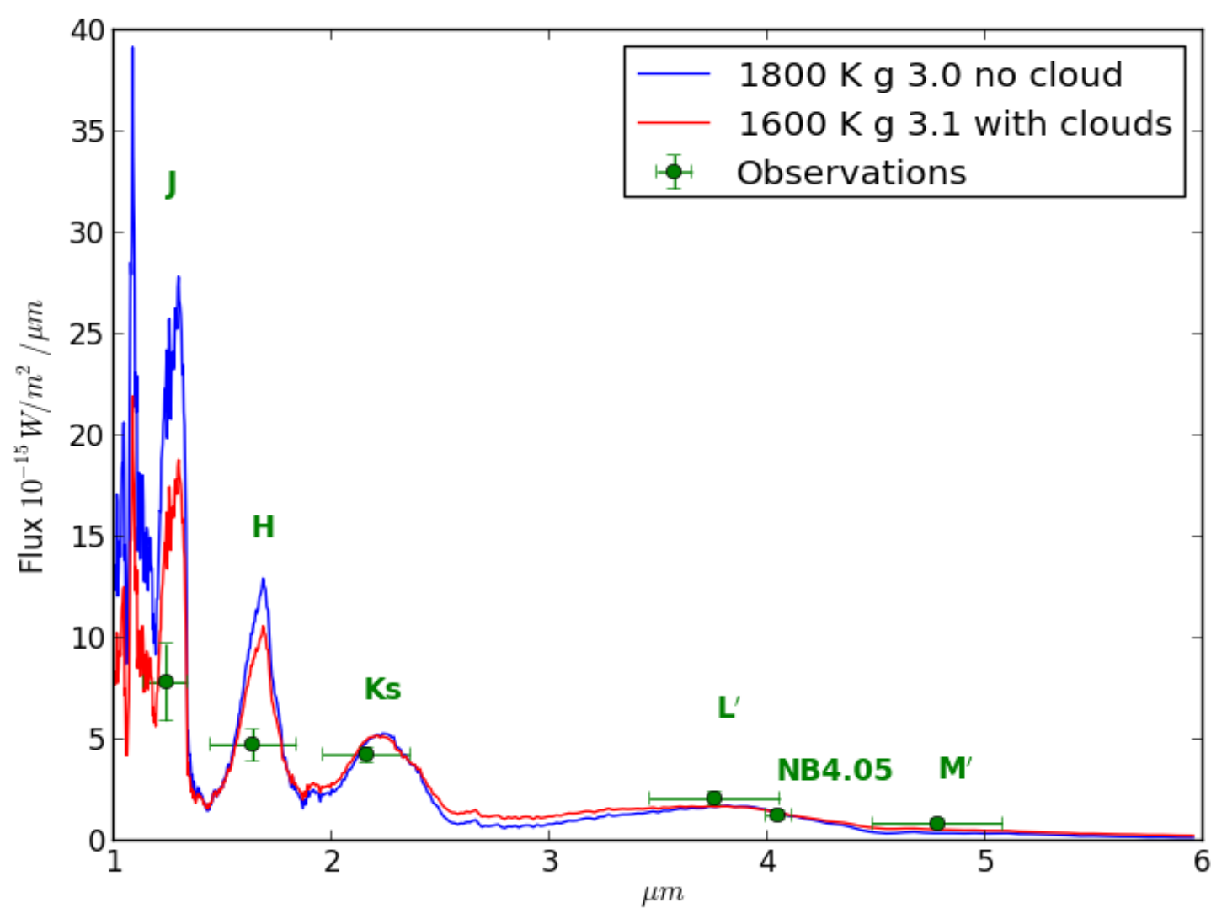


Figure1: Apparent flux of our model without (blue) and with cloud opacity (red), compared with measured apparent fluxes of β pictoris b (green dots)

We built 2 grids of models with:
- Teff between 1000 and 2500 K
- log(g[cgs]) between 3 and 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 χ^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]) and we define the acceptable range of parameters as those yielding χ^2 lower than 12.6 (Bevington 2003)[30]).

The **best χ^2 in the grid without clouds is 20.9** for an effective temperature of 1800 K, a log(g) of 3 and a radius of 1.38 Jupiter radius (R_J).
In the grid with clouds the best χ^2 is 6.9 for an effective temperature of 1600 K, a log(g) of 3.1 and a radius of 1.63 R_J, the base of the iron cloud is at 171 mbar and that of the silicate cloud at 122 mbar.
In the grid with clouds, we find that the effective temperature is well constrained and derive Teff = 1600±100 K while the gravity is poorly constrained: log (g) = 3.5±0.5 . For the radius (R) we obtain a range of 1.45-1.9 R_J.

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.

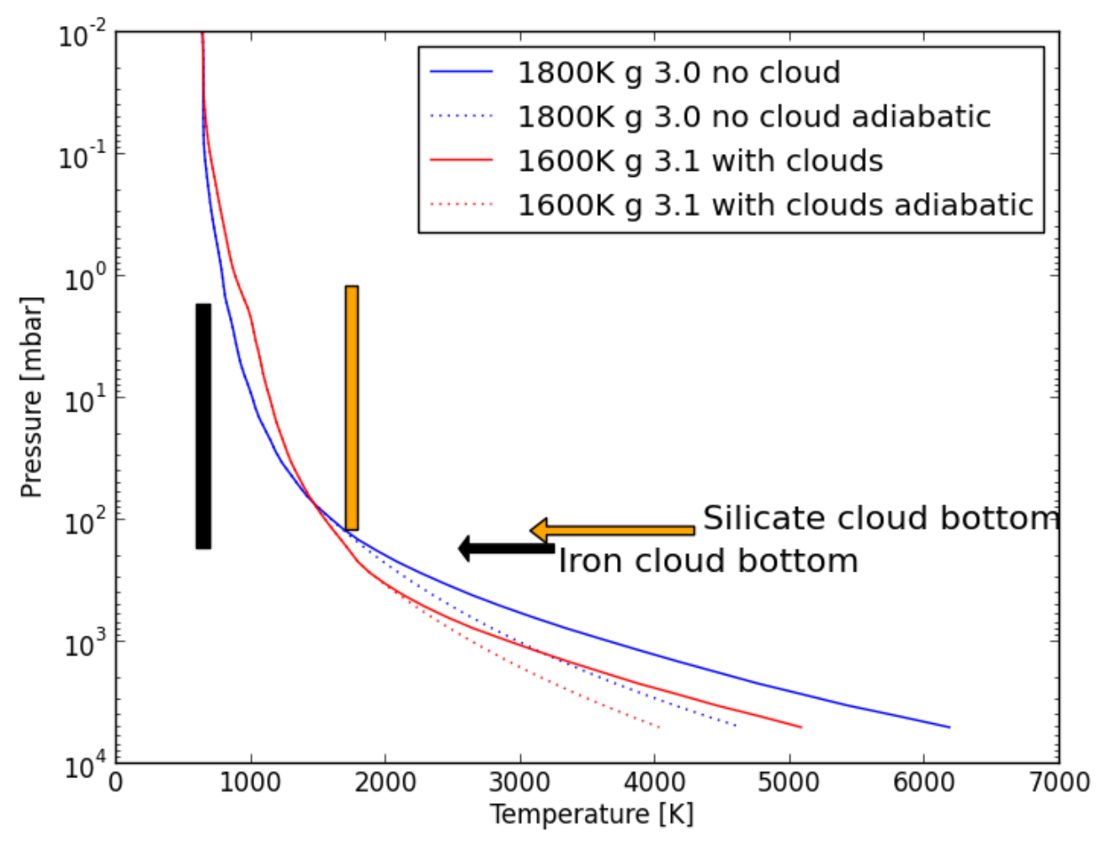


Figure 2: Pressure/Temperature profiles of our cloud-free (blue) and cloudy (red) models

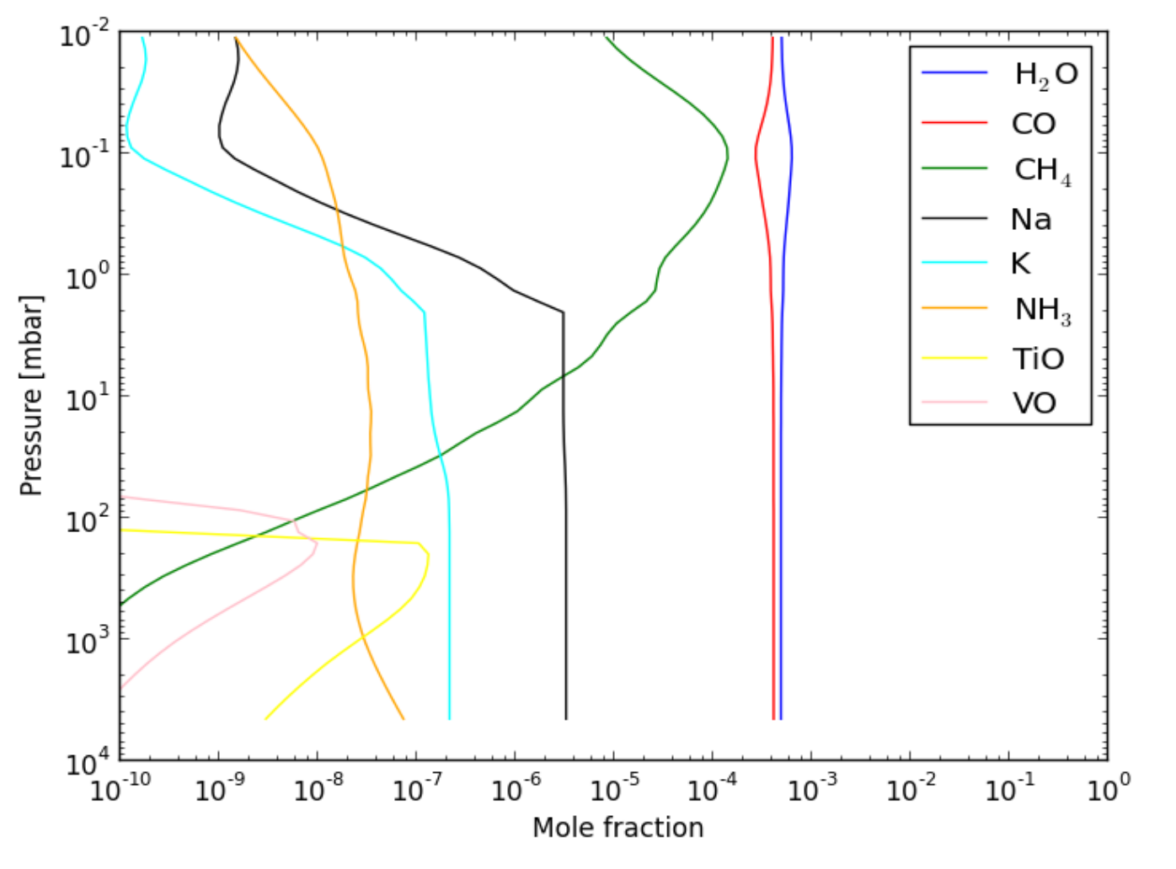


Figure 3: Mixing ratio profiles of H_2O, CO,CH_4, Na, K, NH_3, TiO, VO in our cloud-free model

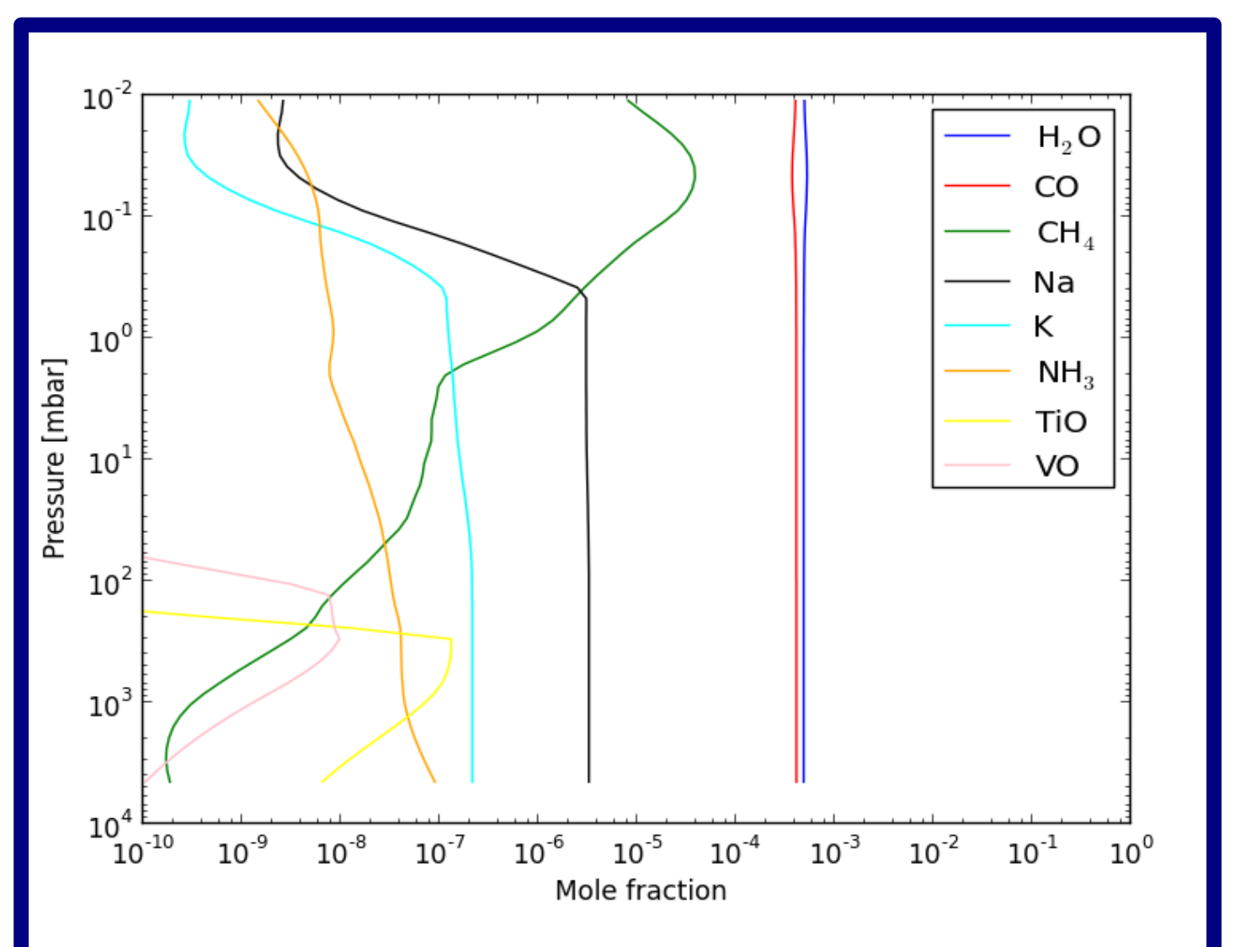


Figure 4: Mixing ratio profiles of H_2O, CO,CH_4, NH_3, Na, K, TiO, VO in our cloudy model

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 = 1600±100 K, log10(g[cgs]) =3.5±0.5, and some cloud opacity agrees with observations within uncertainties.

We plan:
- 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 microphysics models conclusions 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
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If you have any question ask me.
Jean-loup.baudino@obspm.fr

References: [1] Bonnefoy et al. 2013 A&A 555 A107 [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, [29] Yurchenko et al. 2011 MNRAS 413, 1828, [30] Bevington,Data reduction and error analysis for the physical sciences, Table C.4,[31]Morley et al. 2012 ApJ 756 17