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CHARACTERISING EXOPLANET ATMOSPHERES WITH SPHERE: THE HR 8799 SYSTEM WITH EXO-REM AND NEMESIS

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Abstract. The characterisation of the exoplanets evolved recently thanks to the beginning of the second generation of direct imaging instruments, especially with SPHERE. The resolution and wavelength range available currently give access to an increase of accuracy and on the number of physical parameters that can be constrain.

One of the first target of SPHERE was the HR 8799 system. The four planets was characterised using four different forward models including *Exo-REM*. We complete this paper buy using *NEMESIS*, a retrieval code.

Keywords: planets and satellites: atmospheres, planets and satellites: gaseous planets, radiative transfer

1 Introduction

In this presentation we characterise the planets of the HR 8799 system, using the data coming from Zurlo et al. (2016). We constrained these observations with one atmospheric forward model *Exo-REM* and one retrieval code *NEMESIS*.

The Exoplanet Radiative-convective Equilibrium Model (*Exo-REM,* Baudino et al. 2015) is an atmospheric model computing the radiative-convective equilibrium taking into-account equilibrium or non-equilibrium chemistry (parametrised by the eddy coefficient K_{zz}). The model uses 10 molecular and atomic absorbers (H_2O, CH_4, NH_3, CO, CO_2, TiO, VO, PH_3, Na, K) and H_2-H_2, H_2-He CIA. *Exo-REM* takes also into-account cloud absorption of Fe and Mg_2SiO_4 (with some recent update, see also Benjamin Charnay presentation).

This model computes the atmospheric structure (abundance and temperature profiles) and the emission spectrum of a planet.

The Non-linear optimal Estimator for MultivariatE spectral analySIS (*NEMESIS,* Irwin et al. 2008) is a retrieval code using the radiative transfer code Radtrans. This code directly retrieves what is the best combination of parameters to reproduce the observations without physical constrain (no equilibrium, chemistry ...).

First, we compare models generated by Exo-REM with the observations. Then we define the priors of NEMESIS using the results of Exo-REM. Finally, we apply NEMESIS retrieval on the data.

2 Characterising

The two externals planets of the system (b and c) are outside the field of view of the spectroscopic mode of SPHERE (IFS). So the data are restrained to five photometric bands J, H2, H3, K1, K2 (of IRDIS). For the two internal planets (d and e), we use observations of the two instruments including IFS in mode Y-H.

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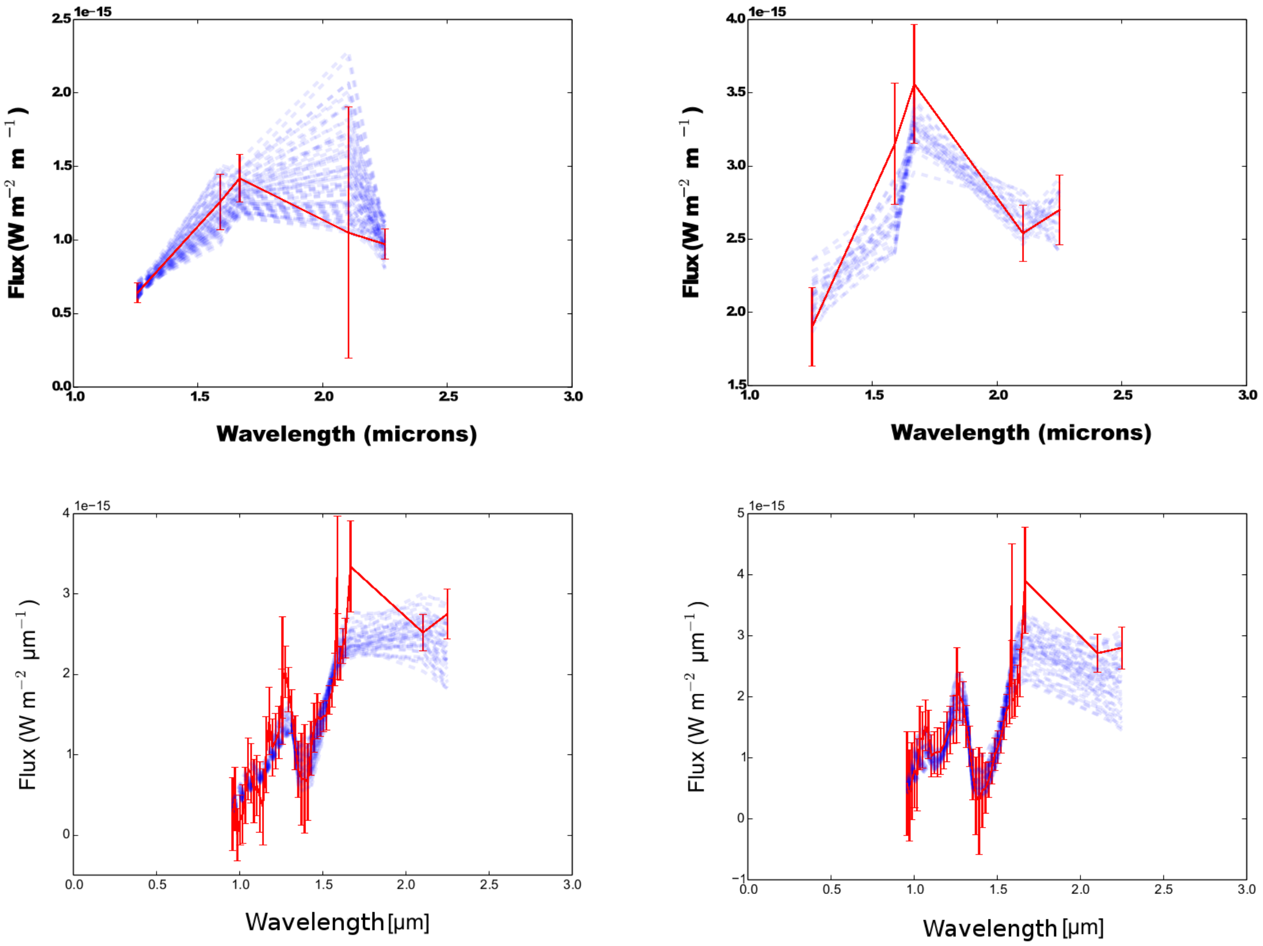

Fig. 1. Spectra corresponding to the best fits (< 2 sigma) using Exo-REM models (blue) compared to SPHERE observations (red) of the planets (from the left to the right and from the bottom to the top) HR 8799 b, c, d and e.

	b	c	d	e
$\log_{10}(g[cgs])$	4.8 ± 0.4	4.95 ± 0.45	5.0 ± 0.4	4.7 ± 0.7
$T_{\rm eff}$	975 ± 225 K	1125 ± 225 K	1125 ± 75 K	1200 ± 150 K

Table 1. Constrained surface gravity and effective temperature of HR 8799 b, c d and e with *Exo-REM* (2 σ).

2.1 Exo-REM

First we analyse the observations with *Exo-REM*, using the method described in Baudino et al. (2015), with grids exploring $T_{\rm eff}$ = 400-1850 K, and log10(g[cgs])= 2.5-5.4, at equilibrium of with non-equilibrium chemistry (k_{zz}=10^8 cm^{2}s^{-1}), with clouds ($\tau_{\rm ref}$=0.5) or without, with a metallicity z=-0.4-1.5.

Fig. 1 shows the best result for each planet, the constrained parameters are listed in the Table 1. Additionaly to the $T_{\rm eff}$ and $\log(g)$ all the cases reproducing the observations are with clouds and non-equilibrium chemistry.

2.2 NEMESIS

As *NEMESIS* is a retrieval code, we need to define a prior. To do so we use the outputs of Exo-REM in an average case, i.e. the profiles generated by the atmospheric model.

The NEMESIS prior is $\log 10(g[cgs])$=4.8 ± 0.5 and $T_{\rm eff}$ = 1100 K. We use with also various clouds approaches: no clouds, grey clouds, same clouds as Exo-REM.

We retrieve the radius, gravity, location of the cloud, particule abundances, scale eight, and the abundances

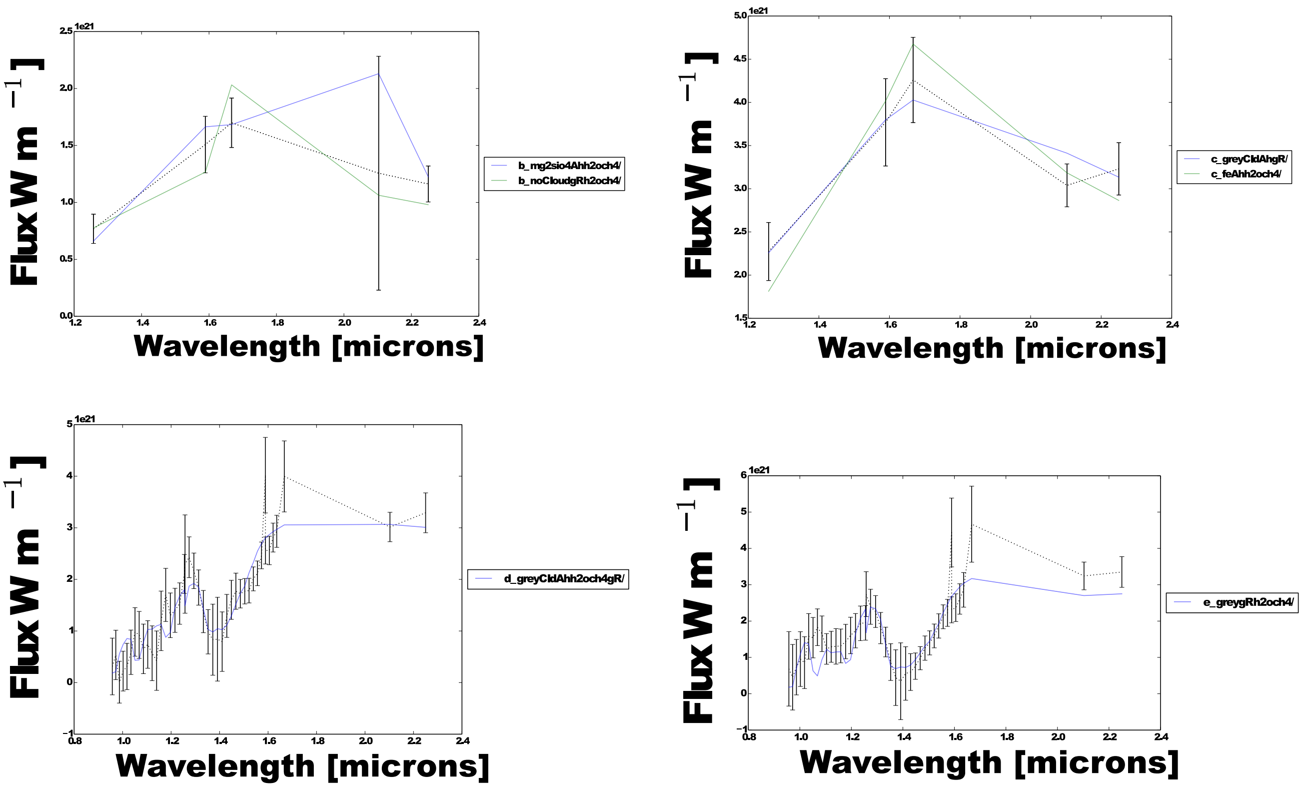

Fig. 2. Spectra corresponding to the best retrievals ($\chi^2 < 1$) on the data (black) of the planets (from the left to the right and from the bottom to the top) HR 8799 b, c, d and e with NEMESIS . For b the case in blue is with Mg_2SiO_4 cloud, the green is without cloud. For c the case in blue is with with grey cloud, the green is with Fe cloud. For d and e the case in blue is with with grey cloud.

	b	c	d	e
log10(g[cgs])	4.0 ± 0.2	5.1 ± 0.3	5.3 ± 0.2	5.1 ± 0.3
	$C/O_b < C/O_{sol}$	$C/O_b < C/O_c < C/O_{sol}$	$C/O_d < C/O_{sol}$	$C/O_e < C/O_{sol}$

Table 2. Constrained surface gravity and effective temperature of HR 8799 b, c d and e with *NEMESIS*

of H_20, CH_4, Na, K.

The temperature is not retrieved because *NEMESIS* needs to retrieve a temperature profile of 50 levels to do so properly, it corresponds to too much free parameters compared to the number of observations.

Fig. 2 shows the retrieved spectra of the four planets and the Table 2 shows the results. The low C/O of the planet b corresponds to what was announced in Barman et al. (2015).

3 Conclusion

The five IRDIS photometric points give already a first estimation (coming from the contrast between low and high wavelengths in H and K). SPHERE observations took into-account separately give a first idea of the temperature, surface gravity, and "reddening" (cloud effect). *Exo-REM* can be used to define prior of *NEMESIS*, such as a temperature profile as the radiative-convective equilibrium when the number of observation doesn't allow us to retrieve this profile. *NEMESIS* can give some information about H_2O and CH_4 abundances in the SPHERE wavelength (with similar results compared to studies using more high resolution data).

SPHERE targets are under study with *Exo-REM* and *NEMESIS*. We will publish the complete study of

HR8799 with NEMESIS. We benchmark and update *NEMESIS* using the protocol define in Baudino et al. (submitted to ApJ).

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