Exoatmospheres with CARMENES @ IAA

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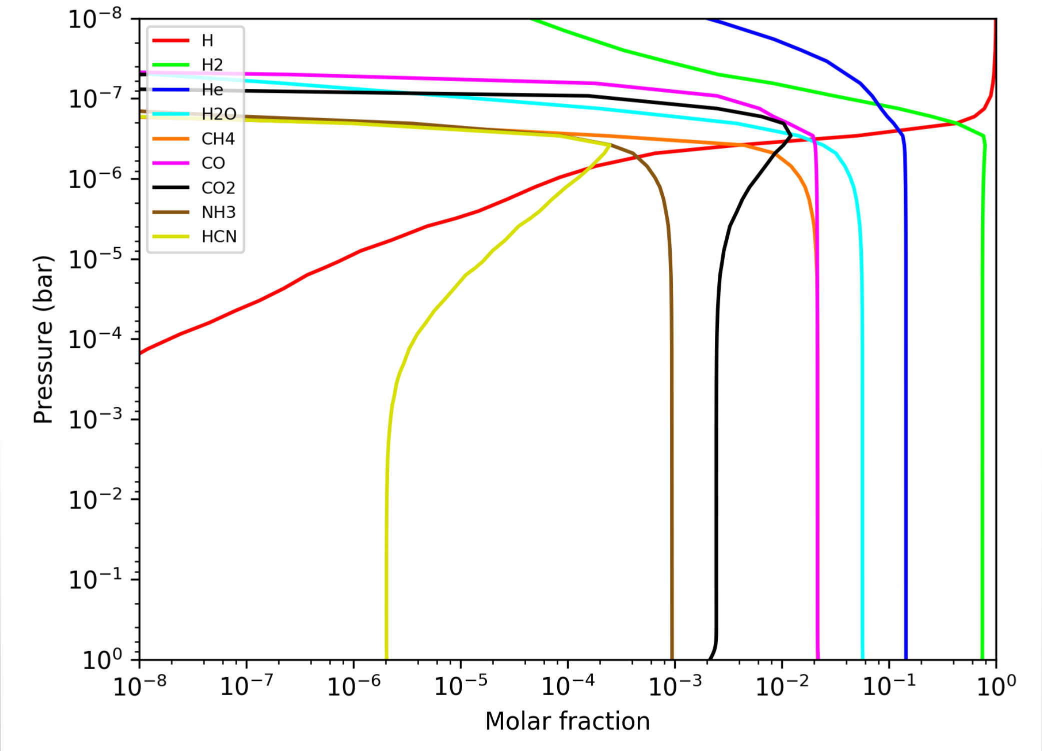
IAA-CSIC

Outline

- Exo-atmospheric modelling of chemical composition
- Helium triplet abundance modelling
- Radiative transfer modelling
- He triplet absorption
- High dispersion spectroscopy (HDS) (molecular detection)
- Earth's atmospheric studies (OH for the He absorption correction, Temp., Rot. NLTE)

1D Composition modelling

GJ 436b-like planet (0.07M$_J$, 0.372 R$_J$)



- Thermochemical equilibrium
- Non-equilibrium composition (photochemistry+vertical diffusion)

1D modelling of He triplet

- Processes included:

  Φ_1: He + hν => He$^+$ + e$^-$

  α_3: He$^+$ + e$^-$ => He(2^3S)

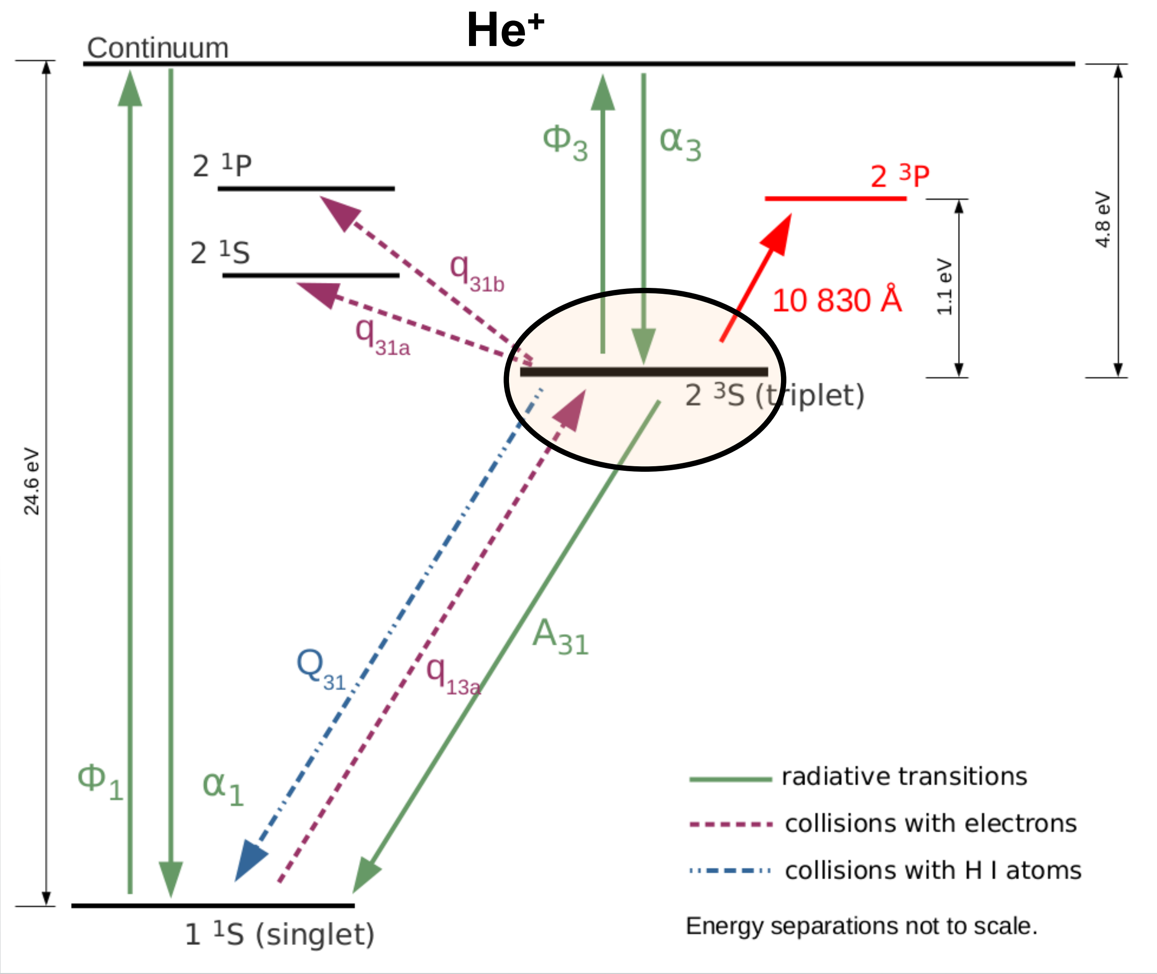
  q_{13}: He + e$^-$ => He(2^3S) + e$^-$

  Φ_3: He(2^3S) + hν => He$^+$ + e$^-$

  q_{31}: He(2^3S) + e$^-$ => He($2^1P, ^1S$)+ e$^-$

  A_{31}: He(2^3S) => He + hν

  Q_{31}: He(2^3S) + H => He + H



1D escape modeling of He and H exosphere

The different models/steps:

1. Hydrodynamics. Spherically symmetric. Parker-wind approx. T=cte.
   - Calculation of density (H (90%)+ He (10%)), v_escape
   - Inputs: Mp, Rp, T, Mass Loss Rate, Mean mol weight
2. Photoionization of H => [H], [H^+], [e^-]. UV stellar flux
   - $H + h\nu \Rightarrow H^+ + e^-$
3. Helium I triplet concentration; UV stellar flux

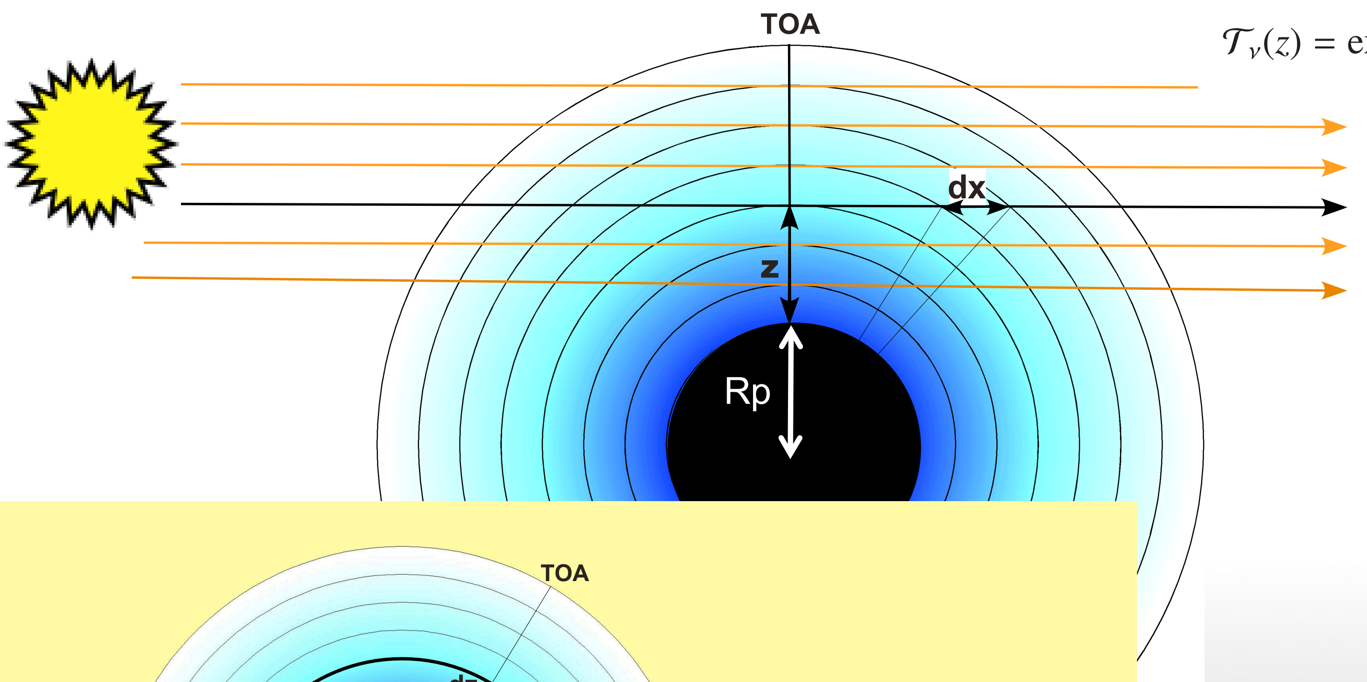
- Stellar flux from 0.1 to 300 nm (Sanz-Forcada, priv. comm., + Castelli and Kurucz models).

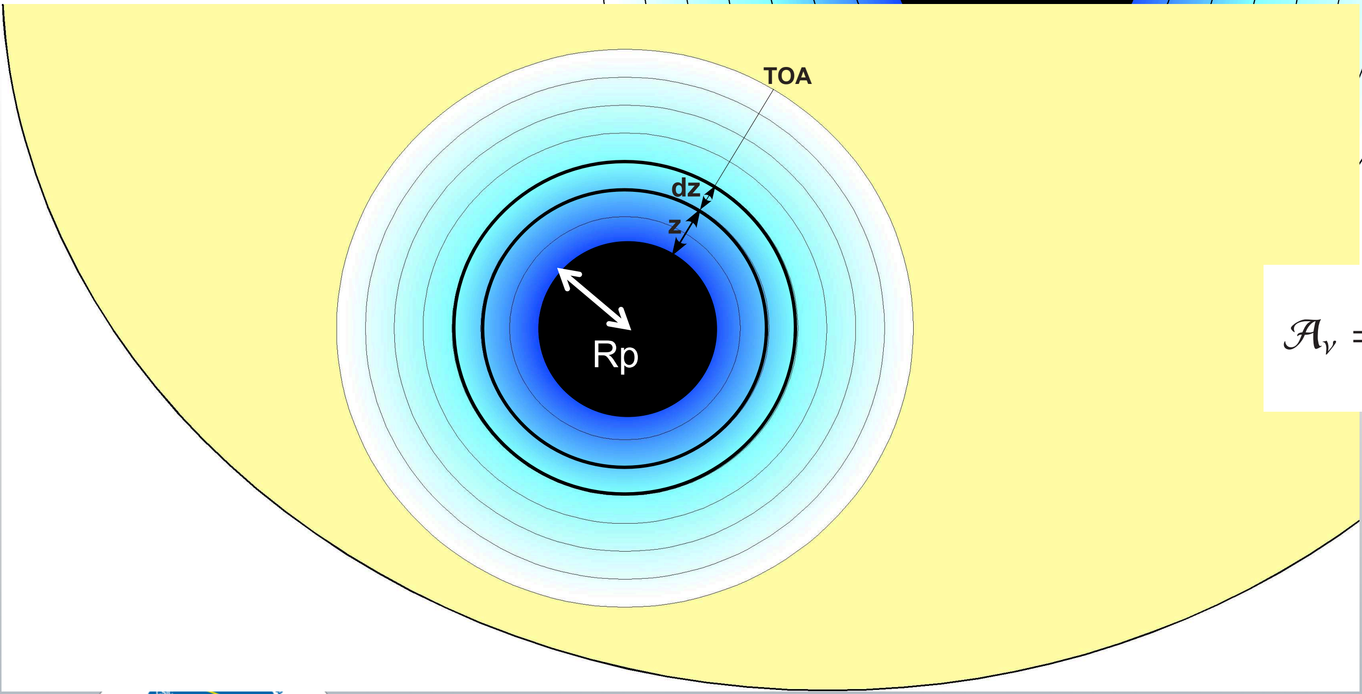
Radiative transfer modelling

- We can compute high resolution molecular transmission (1er transit) and emission (in LTE) (eclipse) spectra with KOPRA (adapted to exo-atmospheres).
  - Includes molecular transitions, Rayleigh scattering, Mie scattering (aerosols), atmospheric refraction, CIA, line-mixing, Lorentz, Doppler and Voigt line shapes, continuum, etc.
  - Spectral range: visible + near-IR.
  - Can accommodate atmospheric winds
  - Apply the CARMENES LSF
  - Still to be implemented high temp line-lists (CH_4, TiO, VO, hazes, …)
  - Some examples for CARMENES

Transmission, primary eclipse

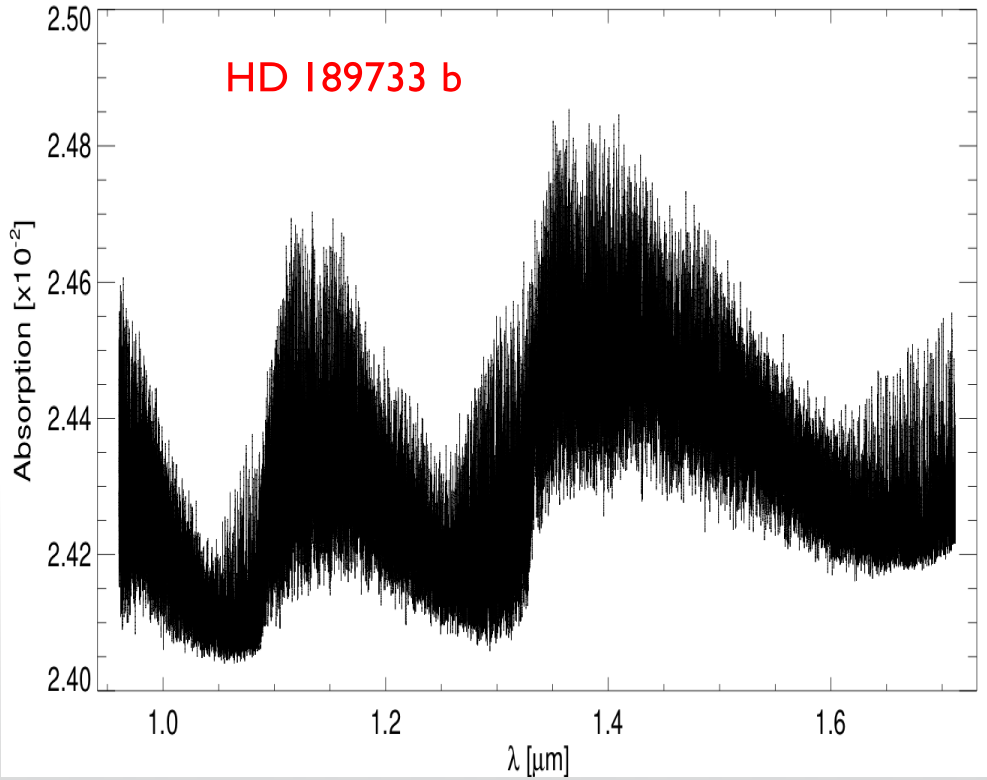
$$\mathcal{T}_\nu(z) = \exp\left[-\int_{-TOA}^{TOA} k_\nu(x)\, n(x)\, \mathrm{d}x\right]$$





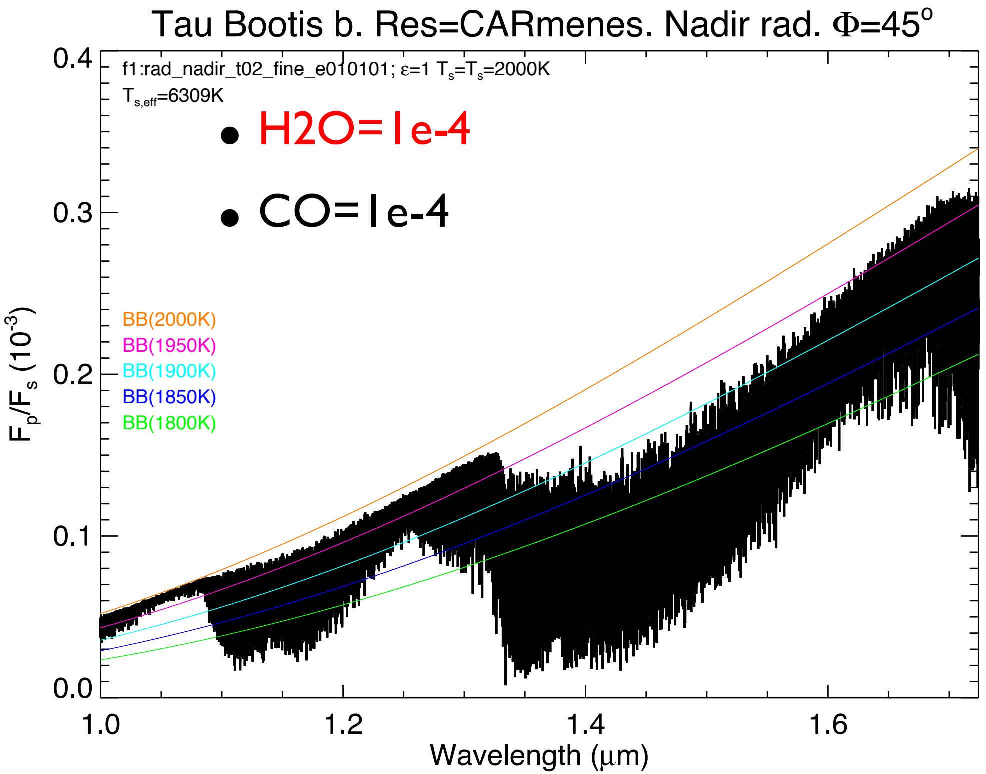
$$\mathcal{A}_\nu = 2\,\pi \int_{R_p}^{TOA} (R_p + z)\,[1 - \mathcal{T}_\nu(z)]\,\mathrm{d}z,$$

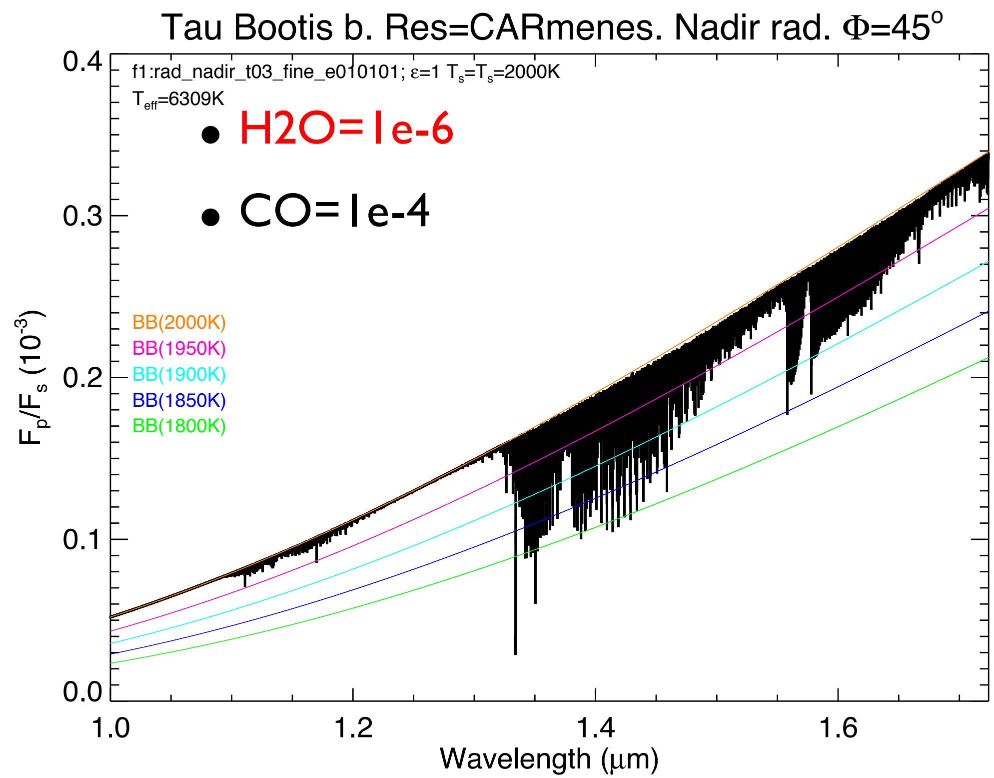
Transmission spectra.



Alonso-Floriano et al., 2019

Emission spec. (LTE) Tau-Bootis





Transmission simulations of He I triplet

Inputs:

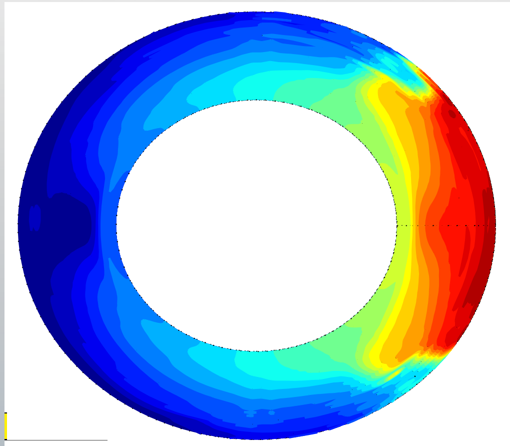
- Cross-sections (NIST)
- Concentration of He (2^3S) triplet from previous model.

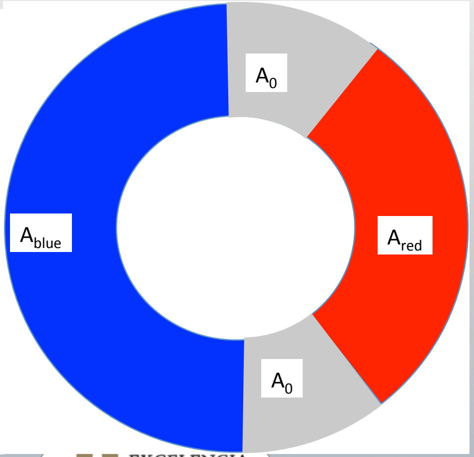
Assumptions:

- Only Gaussian (Doppler + turbulence) broadening. T constant. No Lorentz broad.
- Angle-integrated transmission assuming simple atmospheric ("winds") fields
- CARMENES LSF applied

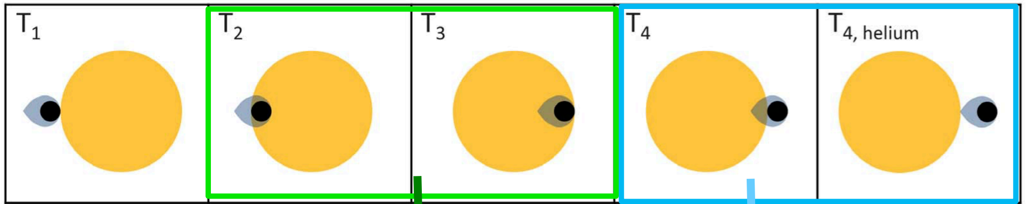
Fitting parameters:

- Scaling He I (2^3S) conc. prof.
- Temperature, Turbulence (Yes/No)
- v_blue, v_red,
- Area_blue, Area_red

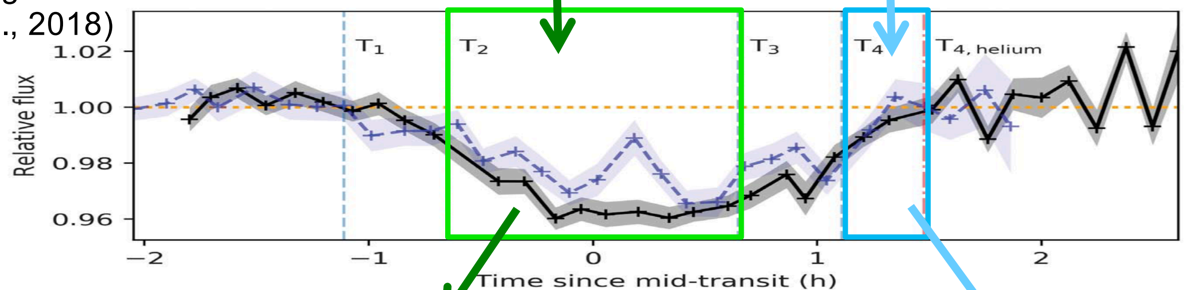




He triplet absorption analysis: WASP 69b



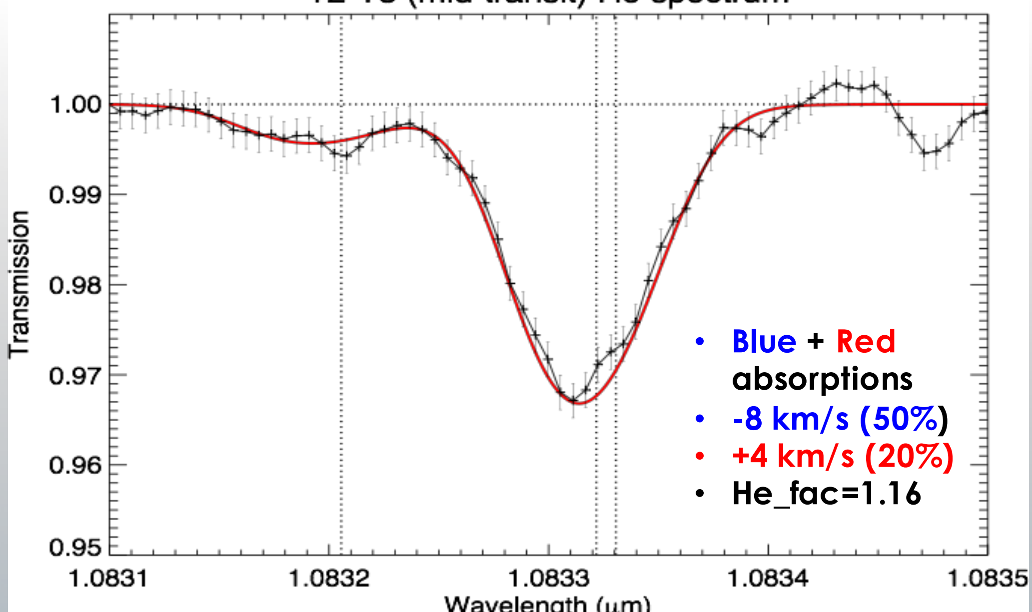
Helium transit light curve
(Nortmann et al., 2018)



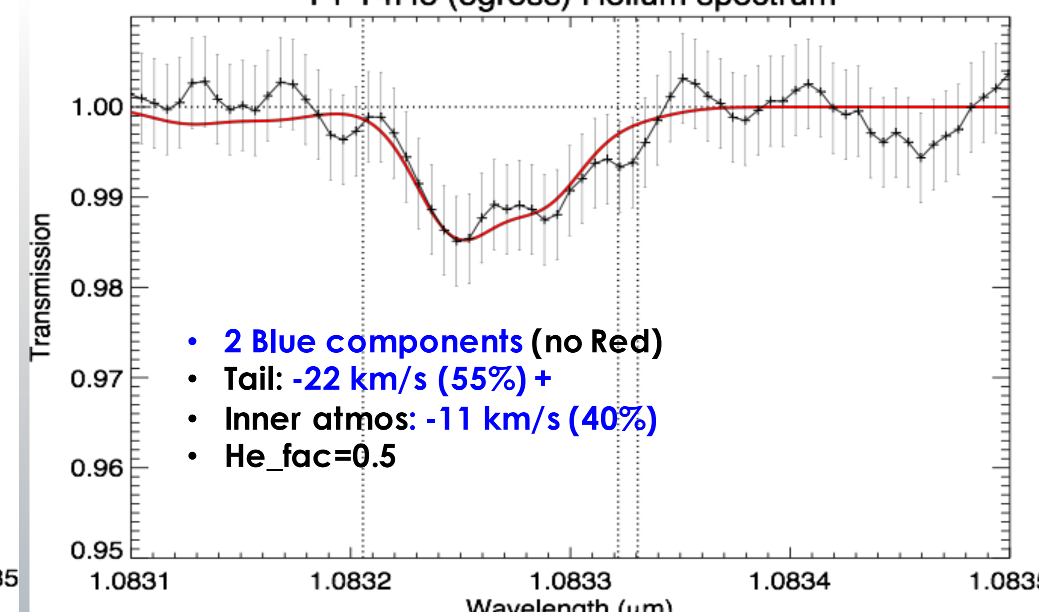
Helium modelling

- Helium triplet con. from 1-D model (T=10000K; MLR=5e10g/s; Mw=0.7; 10Rp)
- Turbulence broadening

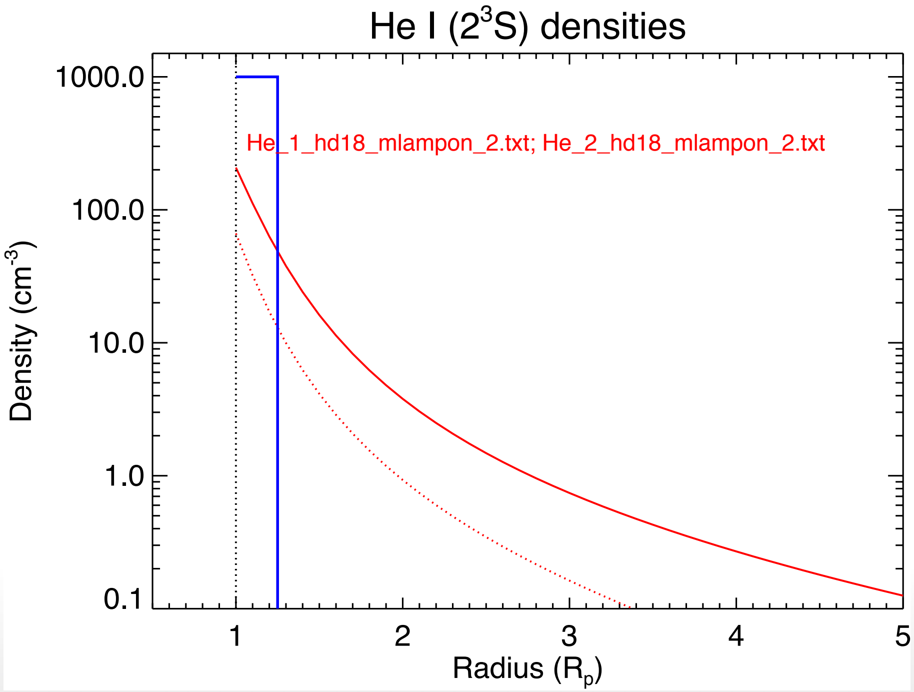
T2-T3 (mid-transit) He spectrum

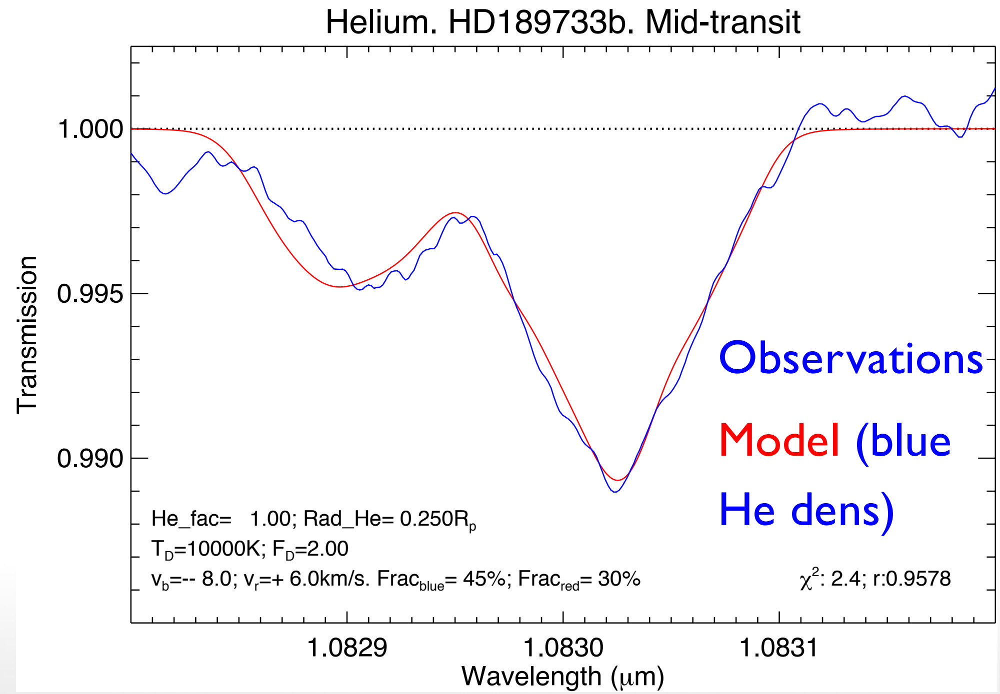


T4-T4He (egress) Helium spectrum



He triplet absorption analysis: HD 189733 b





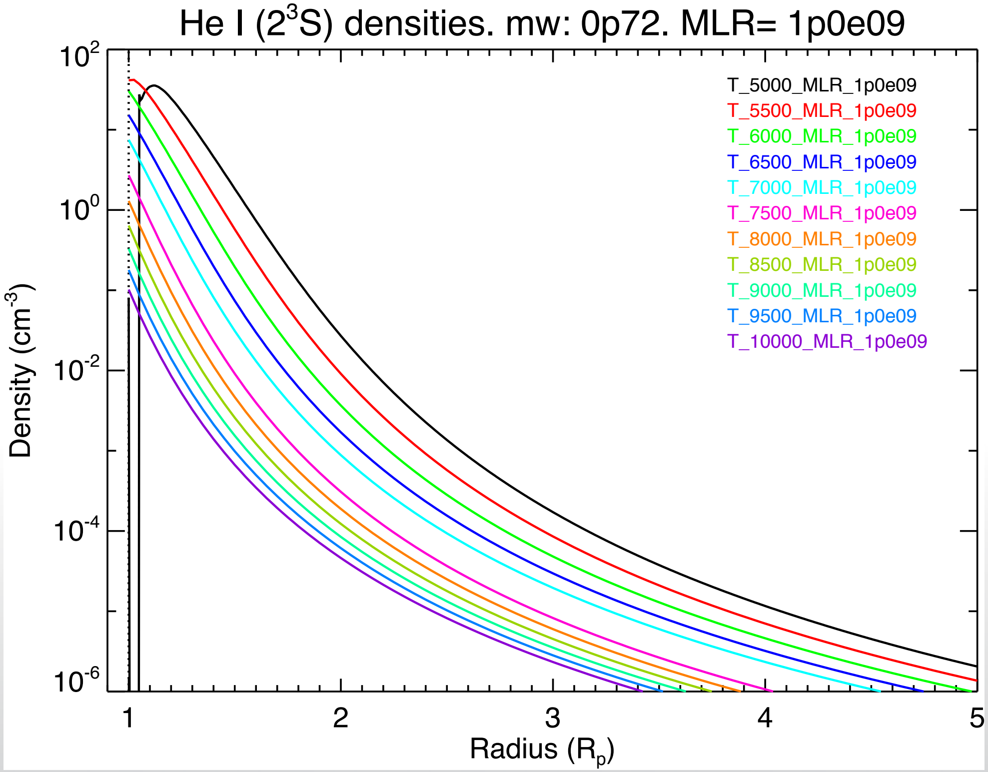
- [HeI triplet] compressed: 1e3cm^{-3} in 0.25Rp
- Doppler T=10000K + No Turb.
- Blue-winds v=-8 km/s; Frac=45%
- Red winds v=+6 km/s, Frac=30%

➢ Able to reproduce very well both lines!

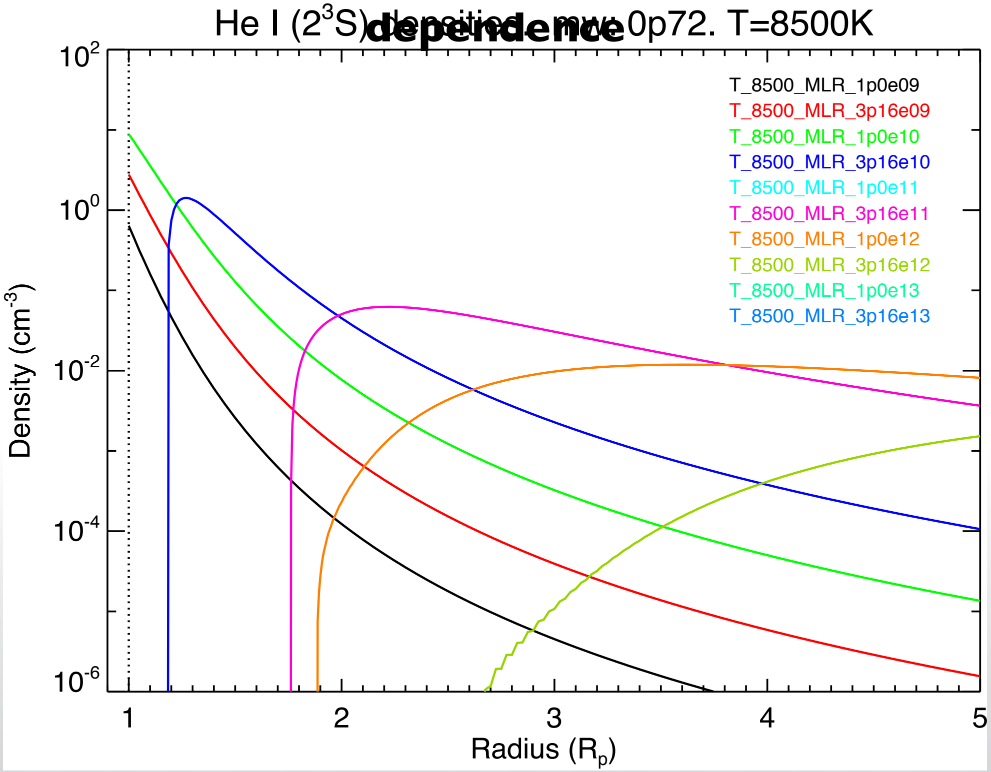
He triplet absorption analysis

- Helium triplet from the 1-D model.

Temperature-dependence



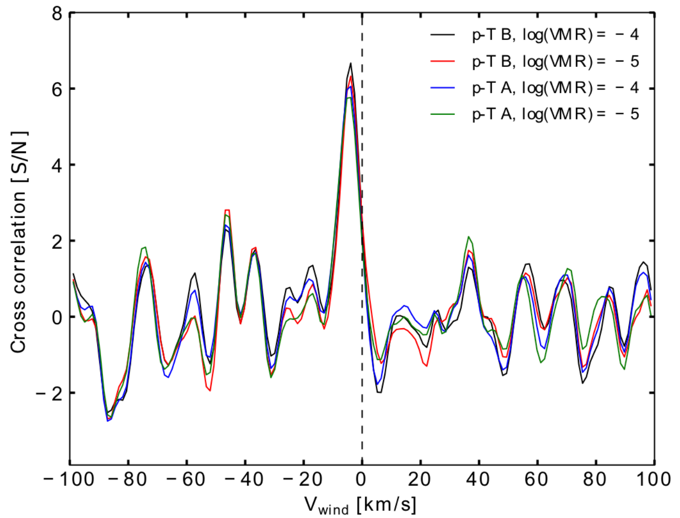
Mass loss rate-dependence

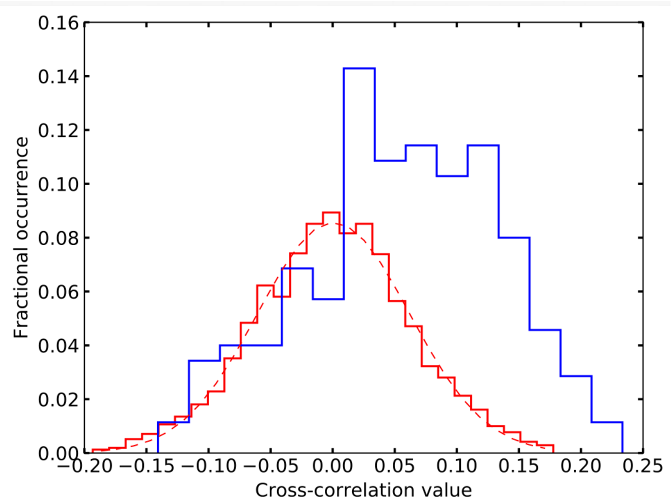


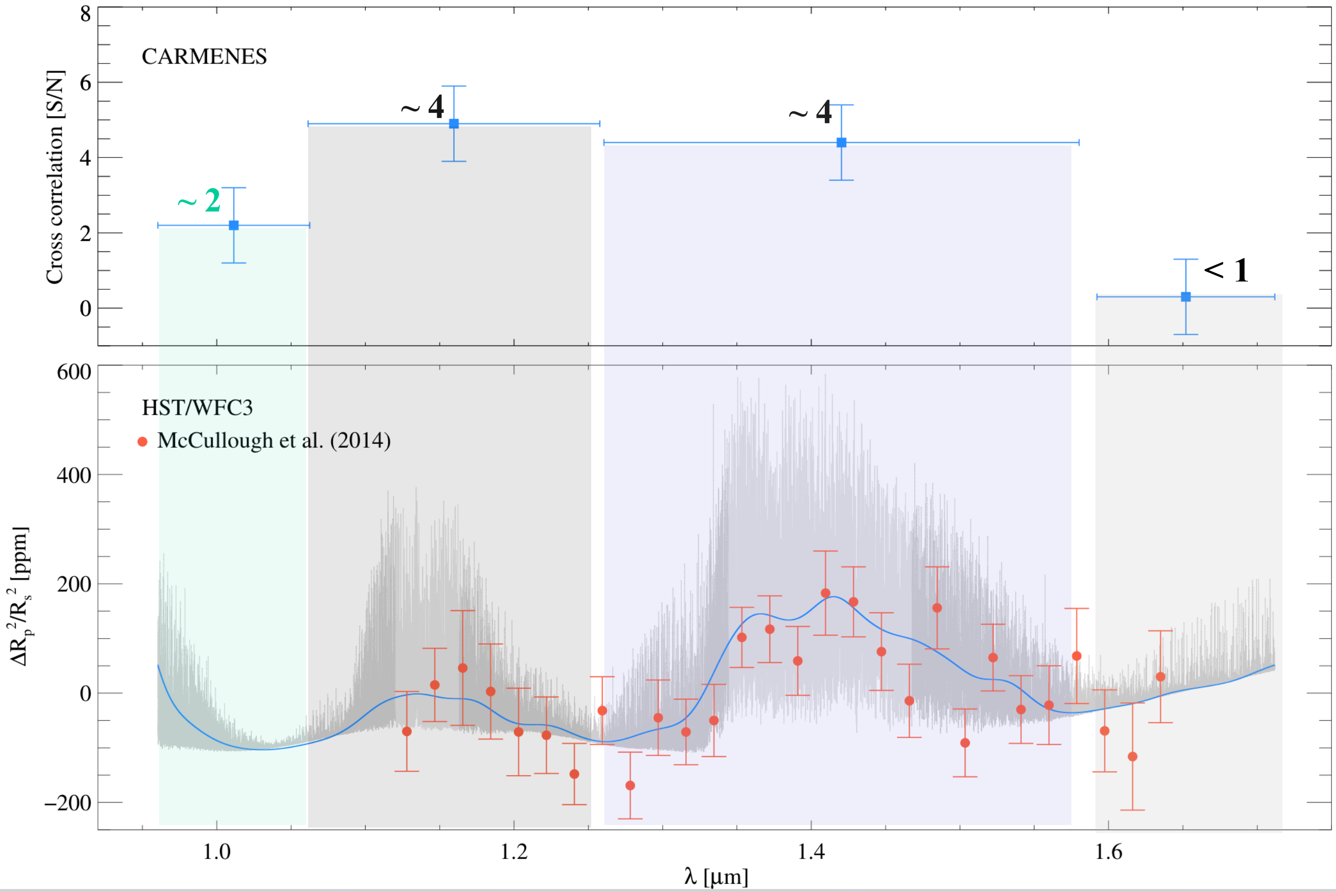
HDS: H2O detection in HD 189733 b

carmenes

- A major achievement.





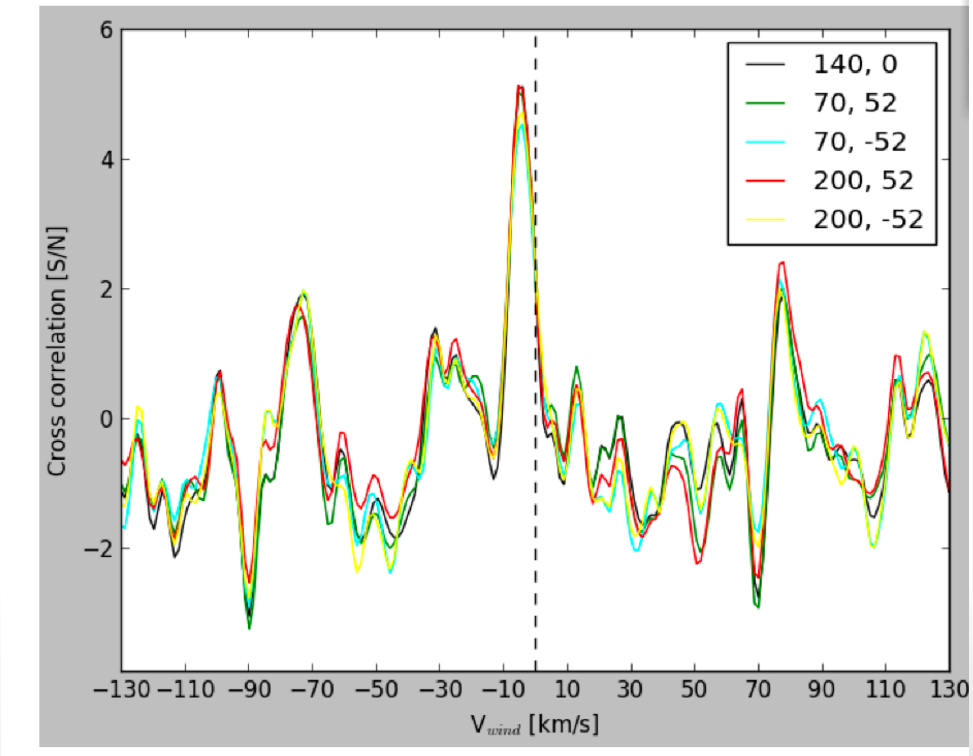


- First CARMENES NIR multiband detection of H_2O in the exo-atmosphere of the hot jupiter HD 189733 b.
- Evidence of strong winds flowing from the dayside to the nightside.

Alonso-Floriano, A. Sánchez-López, et al., A&A, 2019

HDS: H2O detection

- Good S/N H2O signal ~5 =>

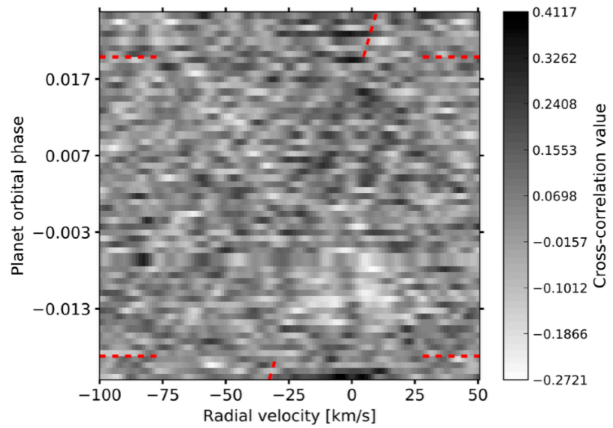


Sánchez-López et al., in prep.

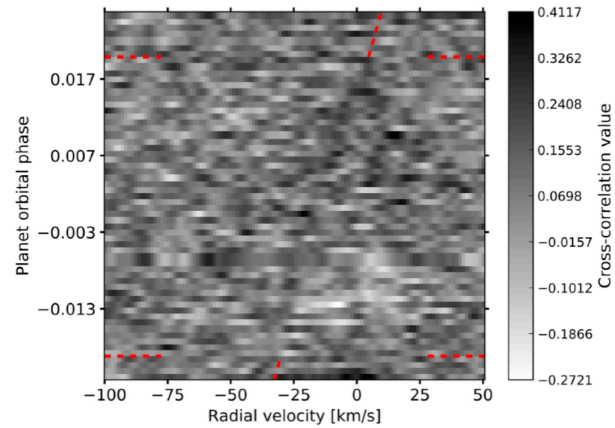
HDS: $H2O$ detection

- However, the signal from the 1.4 μm band (where we expect the larger signal) is very noisy, large residuals !

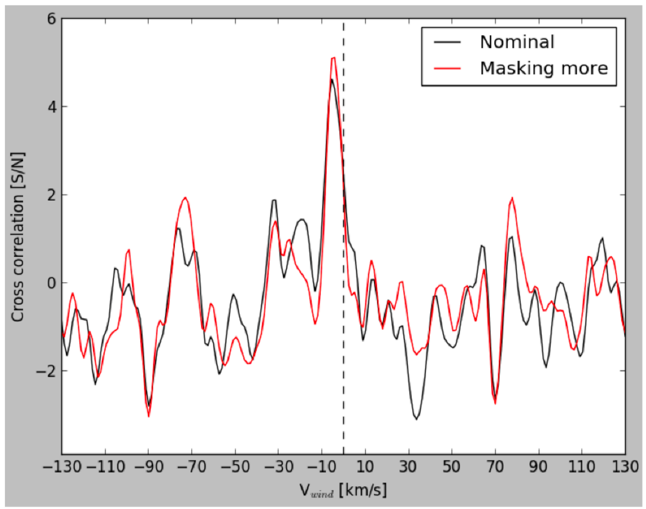
All H2O bands

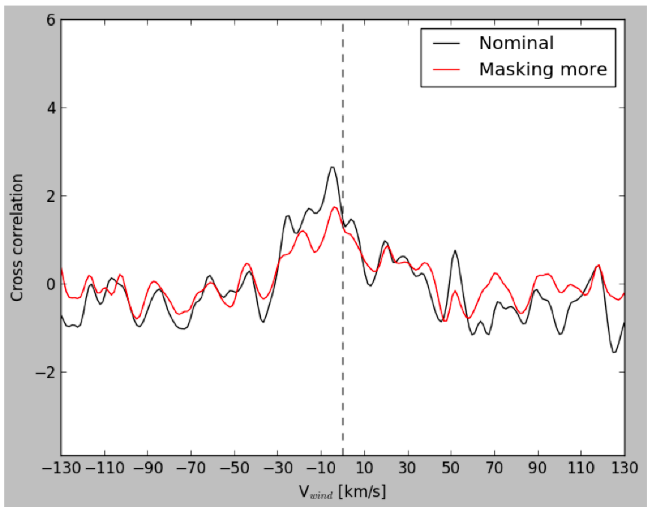


Without 1.4 μm band



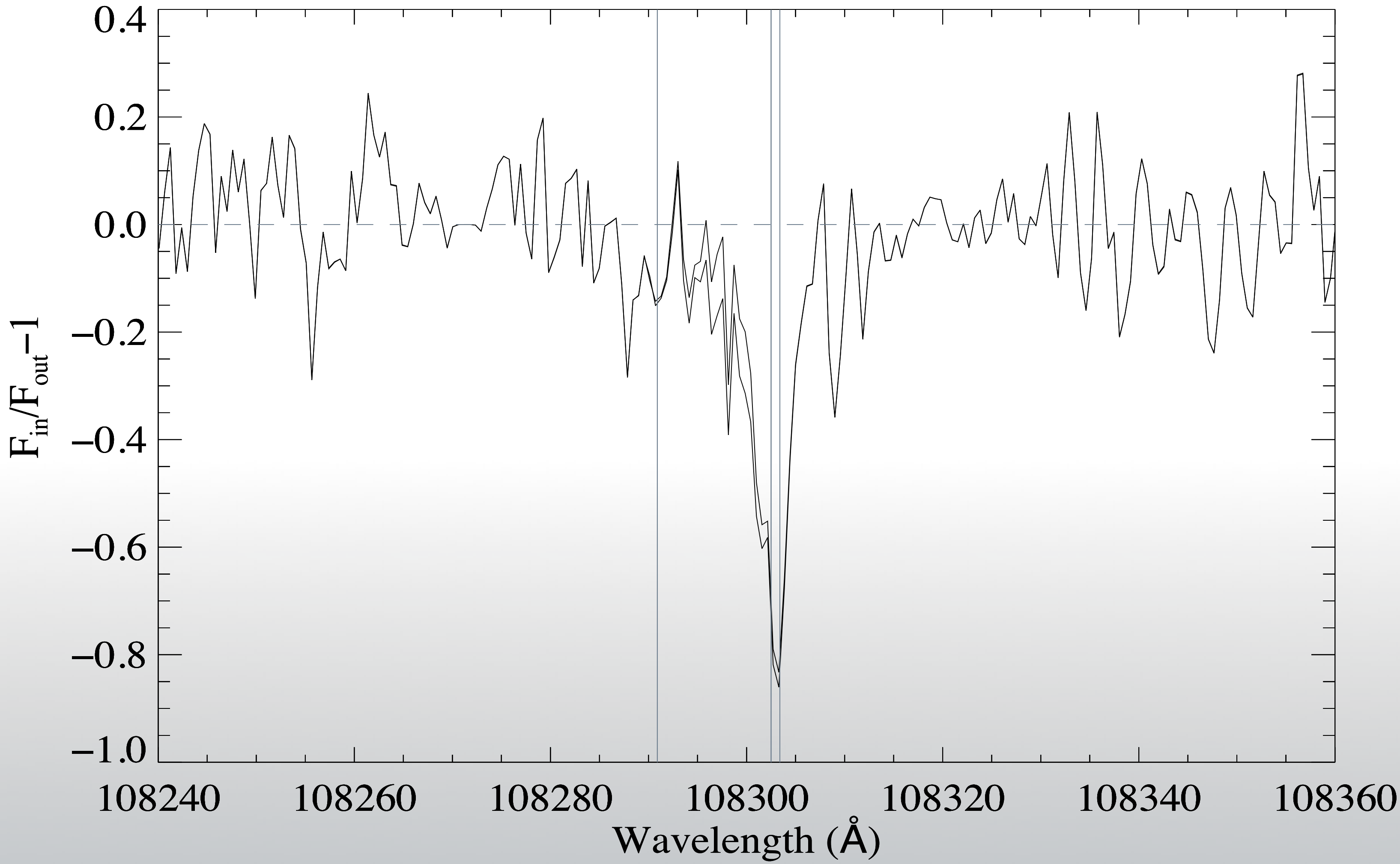
The signal increases both in S/N and sigma. 1.4μm band out (!)…
Residuals are less evident. More prominent planet signal by eye…





Sánchez-López et al., in prep.

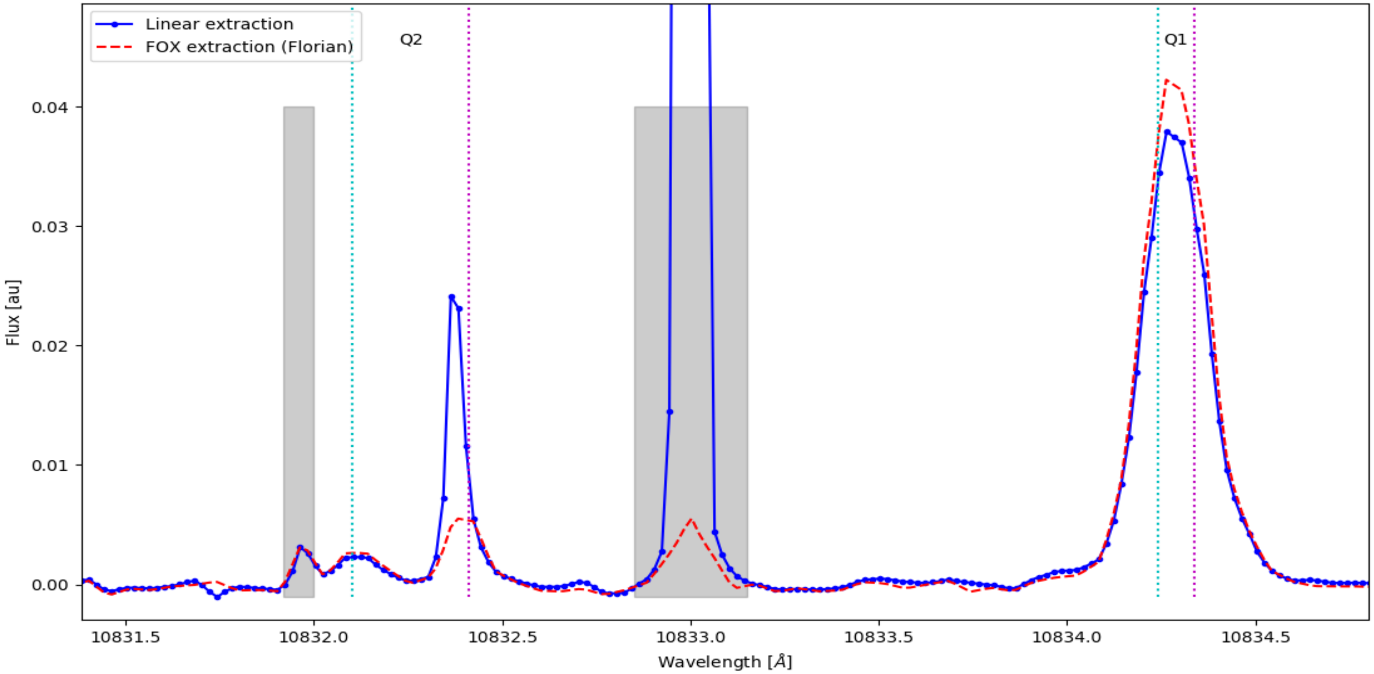
OH atmospheric emission correction for He absorption



OH atmospheric emission correction for He absorption

The OH lines

car-20181209T23h05m26s-sci-czeS-nir_B



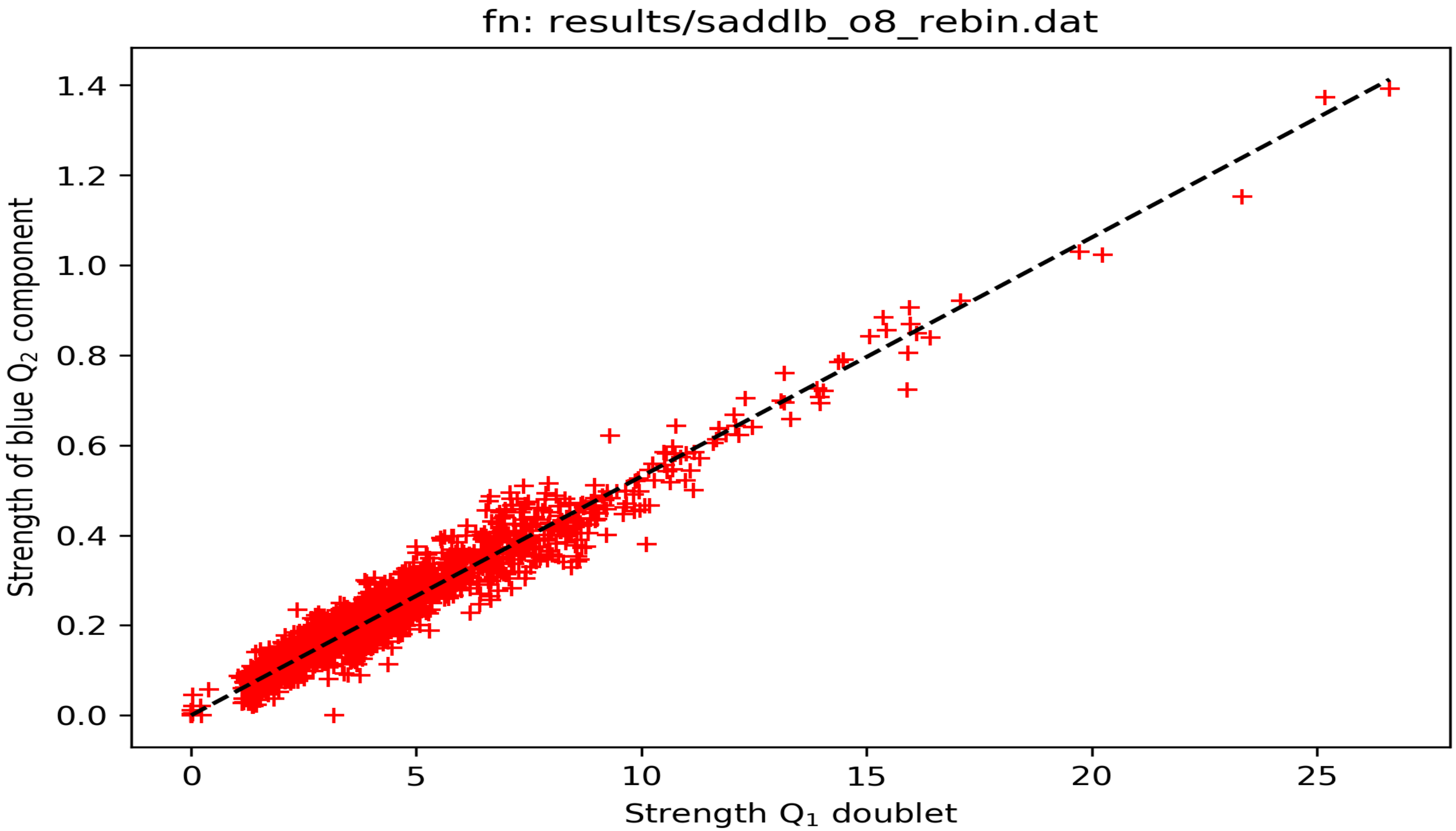
Telluric emission lines of OH with line identifications as specified by Oliva 2015

Wavelength [Å]	Line identification	Wavelength [Å]	Line identification
10832.412	(5-2)Q_2(0.5)e	10832.103	(5-2)Q_2(0.5)f
10834.338	(5-2)Q_1(1.5)e	10834.241	(5-2)Q_1(1.5)f

From Stefan Czesla

OH atmospheric emission correction for He absorption

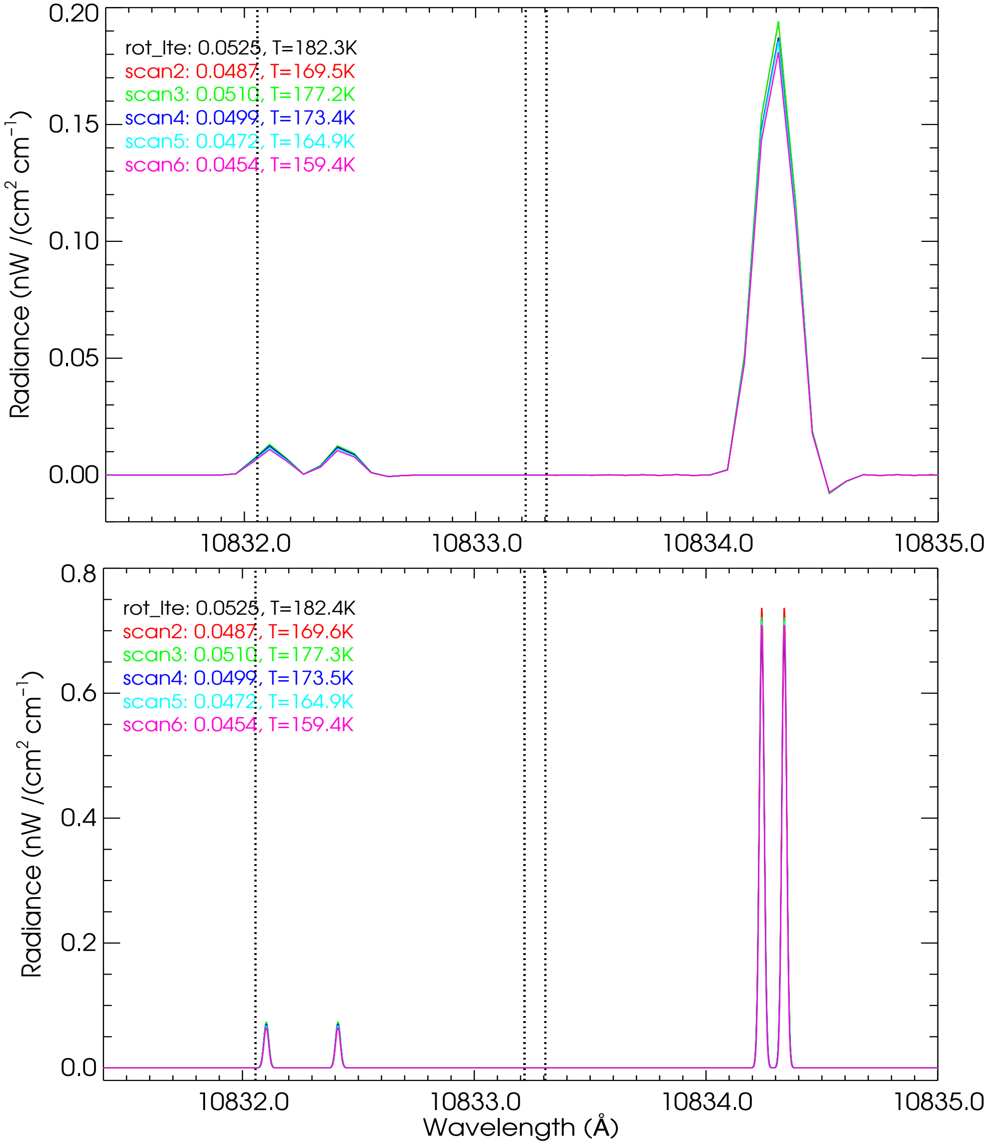
Relation between Q_1 and Q_2 components



$$\frac{\partial Q_{2,\mathrm{blue}}}{\partial Q_1} = 0.0531 +/- 0.0003 \Rightarrow T = 184\ \mathrm{K}$$

From Stefan Czesla

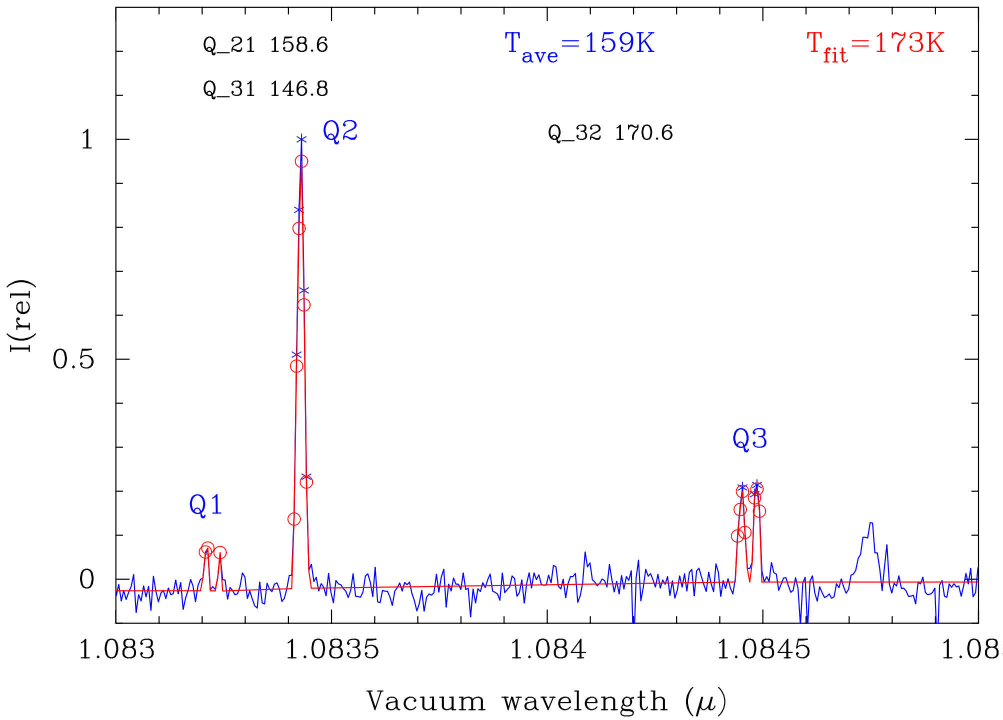
KOPRA simul. of OH emission



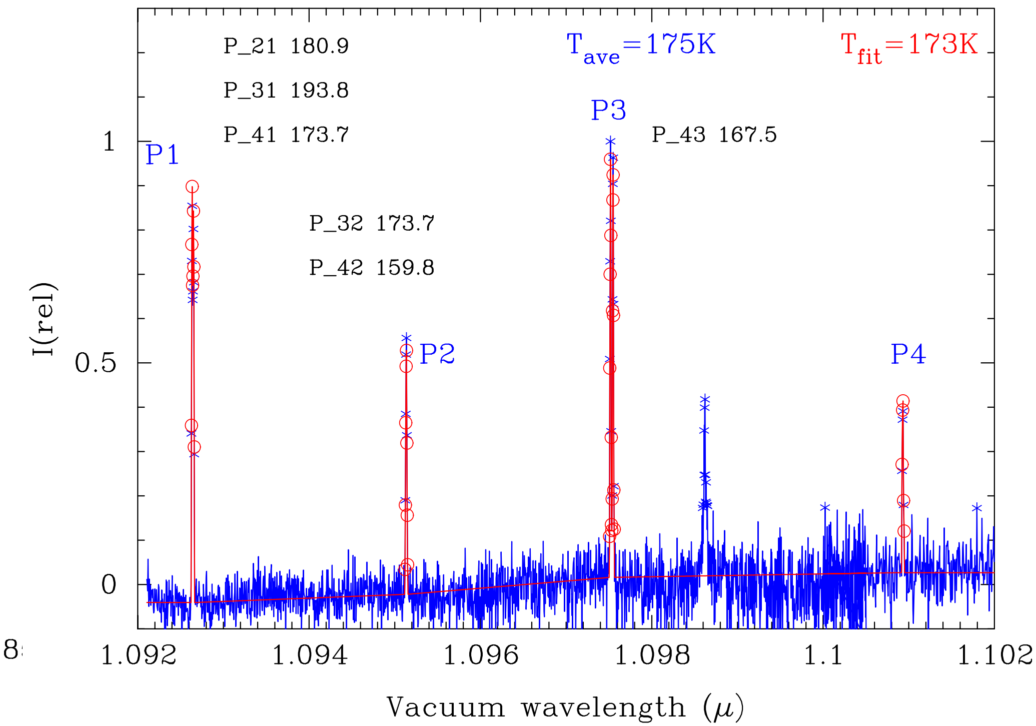
$$T = -\frac{k_B(E_1 - E_2)}{ln\left[\frac{A_2(2J_2+1)}{A_1(2J_1+1)}\frac{I_1}{I_2}\right]}$$

New OH lines

Current



New Lines



- The stronger OH lines of the P-branch seem to give a better estimate of the temperature (and hence of the OH correction) than from the Q1 & Q2.
- Extent the study to more spectra

Temp. Variability of the OH layer over OSN

2386 M.J. López-González et al. / Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 2379–2390

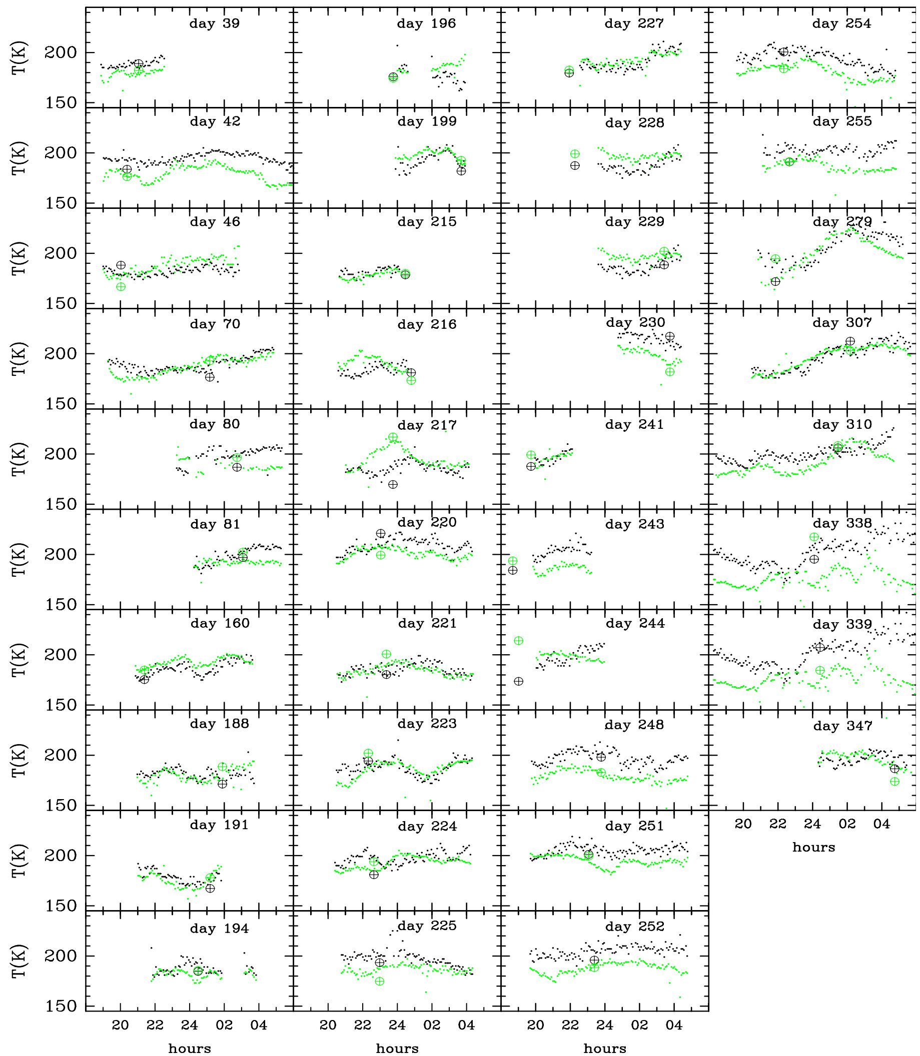


Fig. 6. SATI (dots) and SABER 1.06 (circles) night temperatures during 2002. Black: from OH; grey: from O_2; black: at 87 km; grey: at 95 km.

López-González et al., 2007

OH rot and vibrational NLTE

Table 13
Collisional processes included in the OH model.

No.	Process	Rate ($cm^3\ s^{-1}$)	Ref.
1	$H+O_3 \rightarrow OH(\nu,J,\Omega,A)+O_2$[a]	$1.4\times10^{-10}\exp(-470/T)$; $\Phi(\nu=0-10)(\%)=4, 0.5, 0.5, 1, 1, 2, 4, 19, 28, 38, 2$	[123,124]
2	$OH(\nu,J,\Omega,A)+N_2 \rightleftharpoons OH(\nu-1,J',\Omega',A')+N_2$[b]	$(0.058, 0.10, 0.17, 0.30, 0.52, 0.91, 1.6, 11, 4.8, 6)\times10^{-13}$ for $\nu=1$–10	[124]
3	$OH(\nu,J,\Omega,A)+O_2 \rightleftharpoons OH(\nu-1,J',\Omega',A')+O_2$[b]	$(0.13, 2.7, 5.2, 8.8, 17, 30, 54, 98, 170, 300)\times10^{-13}$ for $\nu=1$–10	[124]
4	$OH(\nu,J,\Omega,A)+O(^3P) \rightarrow H+O_2$	2.2×10^{-10} (for all ν's; 10% larger than in [124])	[124]
5	$OH(\nu,J,\Omega,A)+M \rightleftharpoons OH(\nu,J',\Omega',A')+M$	$a_0=6.6\times10^{-10}$, $a_3=2.7$, $\beta=1$, $B_0=46.71$; $a_1=a_2=c(0)=c(1)=d=0$	[123]

[a] $T_{nsc}(J)(\nu=0-10)=$ 22 000, 17 000, 12 000, 11 000, 9000, 7000, 3000, 1940, 1230, 760, 200 K. $T_{nsc}(\Omega)(\nu=0-10)=$ 14 000, 13 000, 12 000, 11 000, 9000, 7000, 3000, 1940, 1230, 760, 200 K. $T_{nsc}(A)(\nu=0-10)=60$ K.
[b] $T_{nsc}(J)=T_{nsc}(\Omega)=T_{nsc}(A)=T_k$ for all ν's.

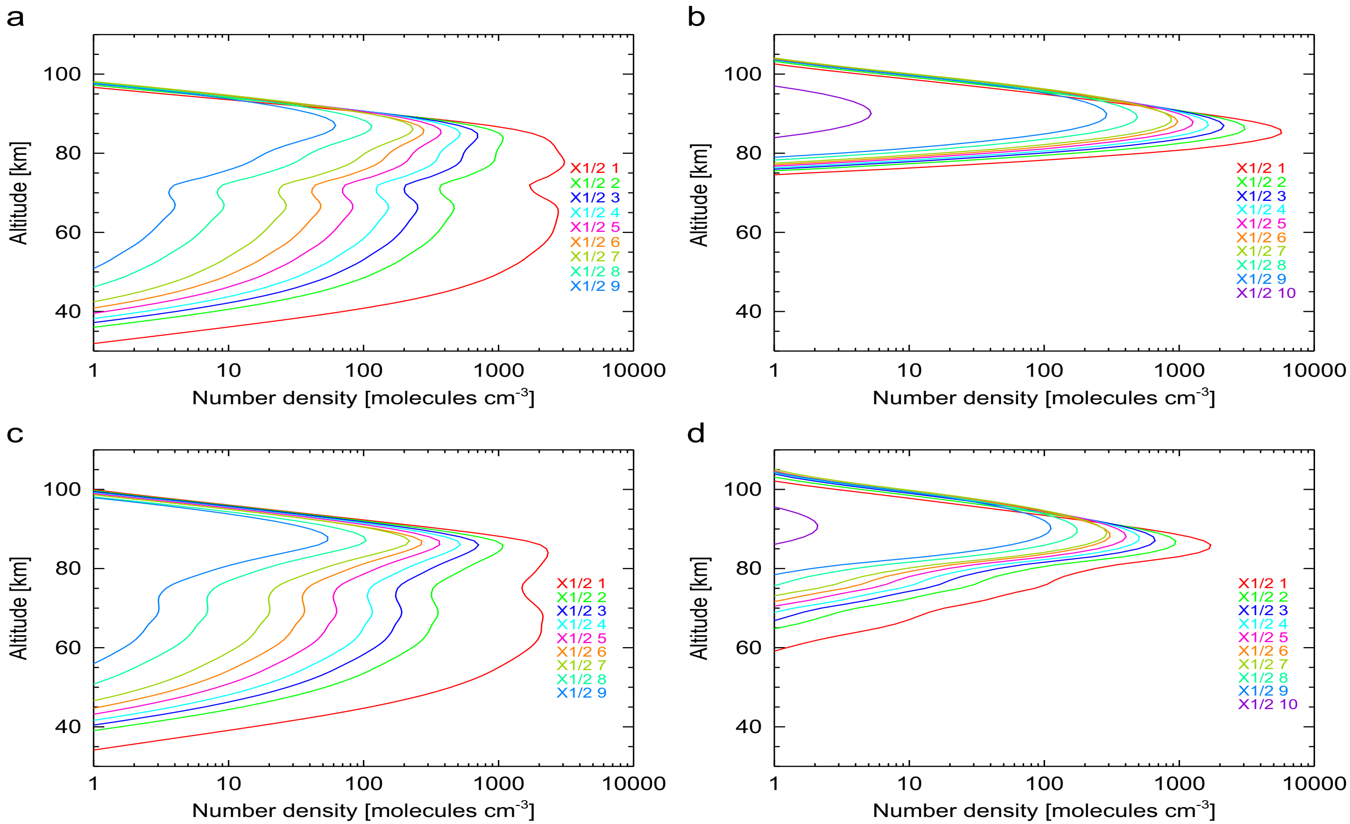


Fig. 40. Number densities for the OH levels for the four reference atmospheres: (a) `day`, (b) `ngt`, (c) `sum` and (d) `win`.

Funke et al., 2012

Future work/science

- Molecules detections with HDS
  - ➢ Water detection in the VIS channel
  - ➢ Molecular features (TiO, VO, H2O+other) of planets in red giant stars.
  - ➢ Molecules detection in other (fainter) target?
  - ➢ New potential targets (TESS)?
- He triplet
  - ➢ 1D analysis of other targets
  - ➢ He triplet 3D model.
  - ➢ Adapt the RT model to cope with 3D T and 2D winds along LOS
- Atmospheric OH lines:
  - ➢ Study the OH emission variability => to derive a better correction for He absorp.
  - ➢ Atmospheric temperature studies (waves?) + OH rotational non-LTE