The impact of P-T profile on exoplanet transmission spectroscopy

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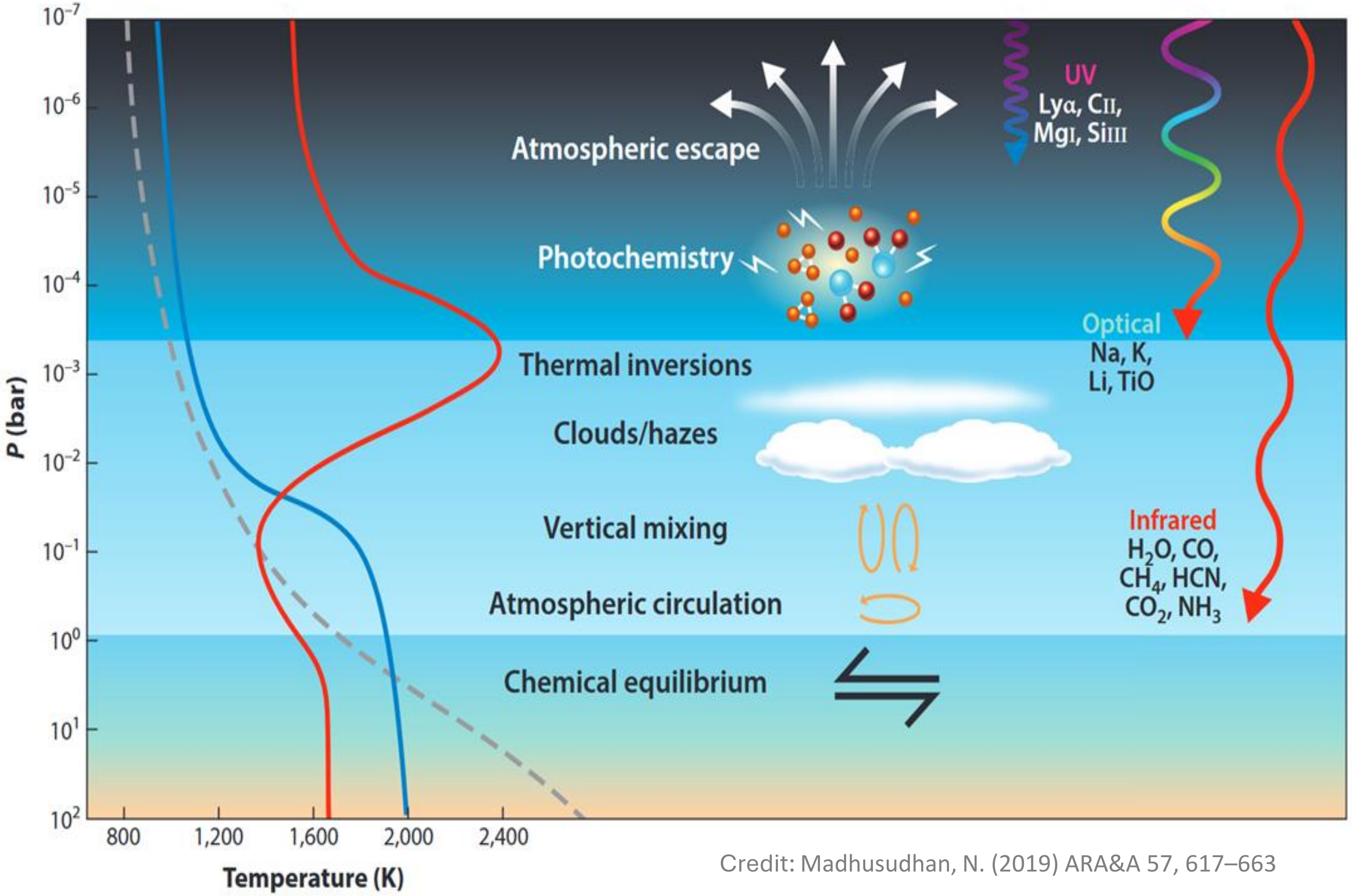
Exoplanet Atmospheres

Primarily **molecular composition**

Deep in the atmosphere – chemical equilibrium

Higher in the atmosphere thermal inversions, anisotropic radiation, kinetic processes and clouds – deviation from chemical equilibrium



Credit: Madhusudhan, N. (2019) ARA&A 57, 617–663

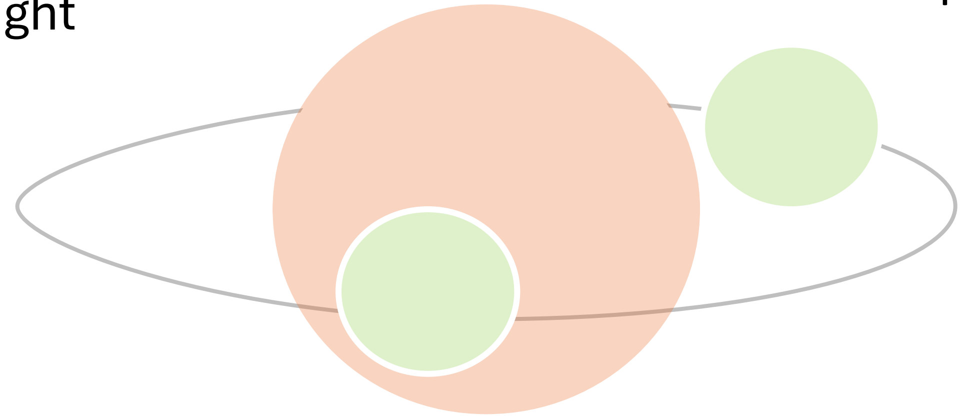
Exoplanet Spectra

Primary transit spectra

- Transmission spectra
- Light from the star passes through the exoplanet atmosphere
- Less sensitive to the temperature structure, but it can be extracted
- Extremely sensitive to atmospheric scale height

Secondary transit spectra

- Thermal emission spectra
- Difference between spectra of planet and the star when looking at planet dayside and spectra of the star when the planet lies behind the star
- Used for deriving the pressure-temperature profiles



Exoplanet Spectra

Giant planets

H_2 He with traces of H_2O CO CH_4 NH_3 PH_3 H_2S Na K

Terrestrial planets

H_2O CO CH_4 NH_3 PH_3 H_2S Na K CO_2 O_2 O_3 N_2O HNO_3

Spectrum - apparent radius of the planet at certain wavelength

$$\left(\frac{R_{\mathrm{p}}}{R_{\mathrm{s}}}\right)^2 = \delta$$

Initial elemental composition is the same as the composition of the host star, because both were formed from the collapse of one molecular cloud

The ratio of C/O tells us, where in the protoplanetary disk the planet was formed

Model Setup

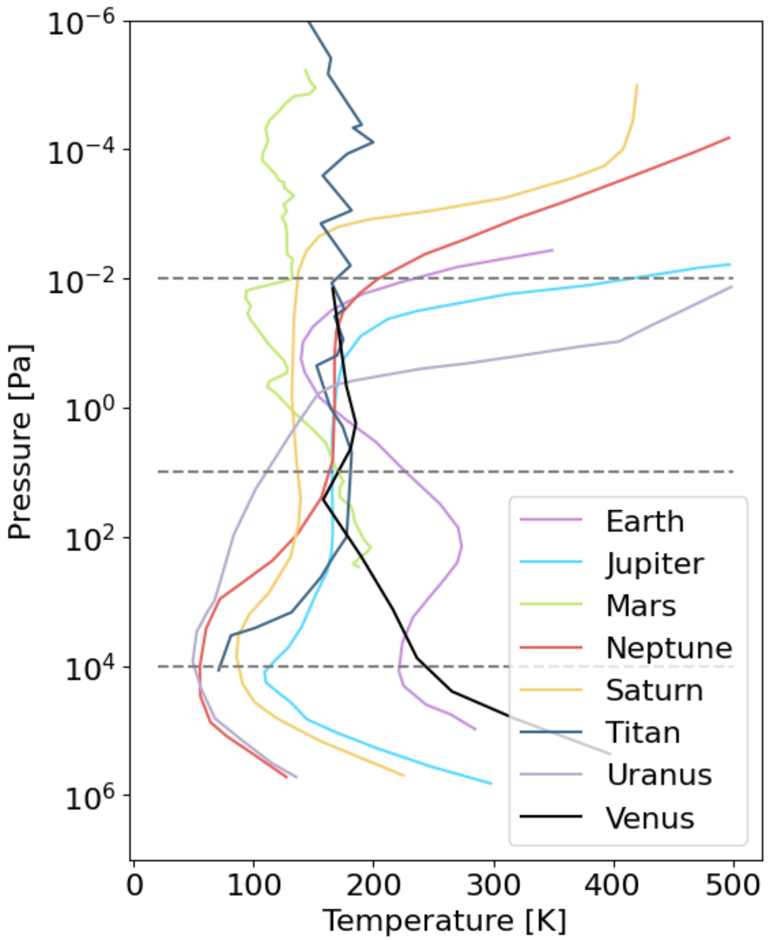
	Hot Jupiter WASP 43b	Sub-Neptune K2-18b
R_p [R_J]	1.036	0.211
M_p [M_J]	2.052	0.028
Z [$Z_\odot$]	1	100
R_{star} [$R_\odot$]	0.667	0.411
T_{star} [K]	4520	3457
C/O	0.3 and 1.3	0.3 and 1.3

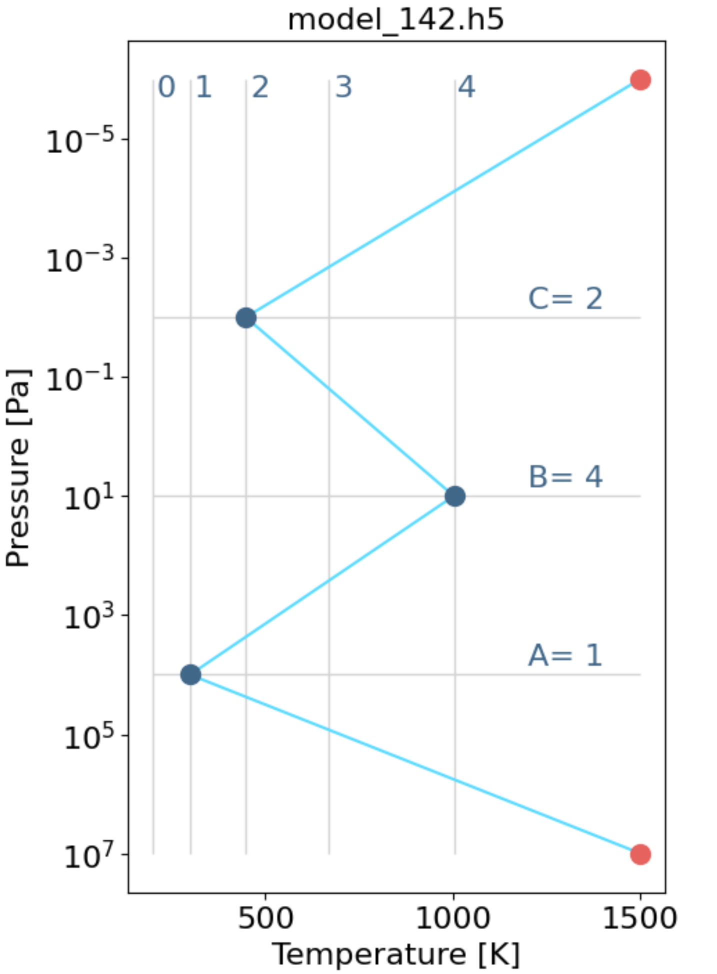
Chemistry setup

Chemistry model: FastChem

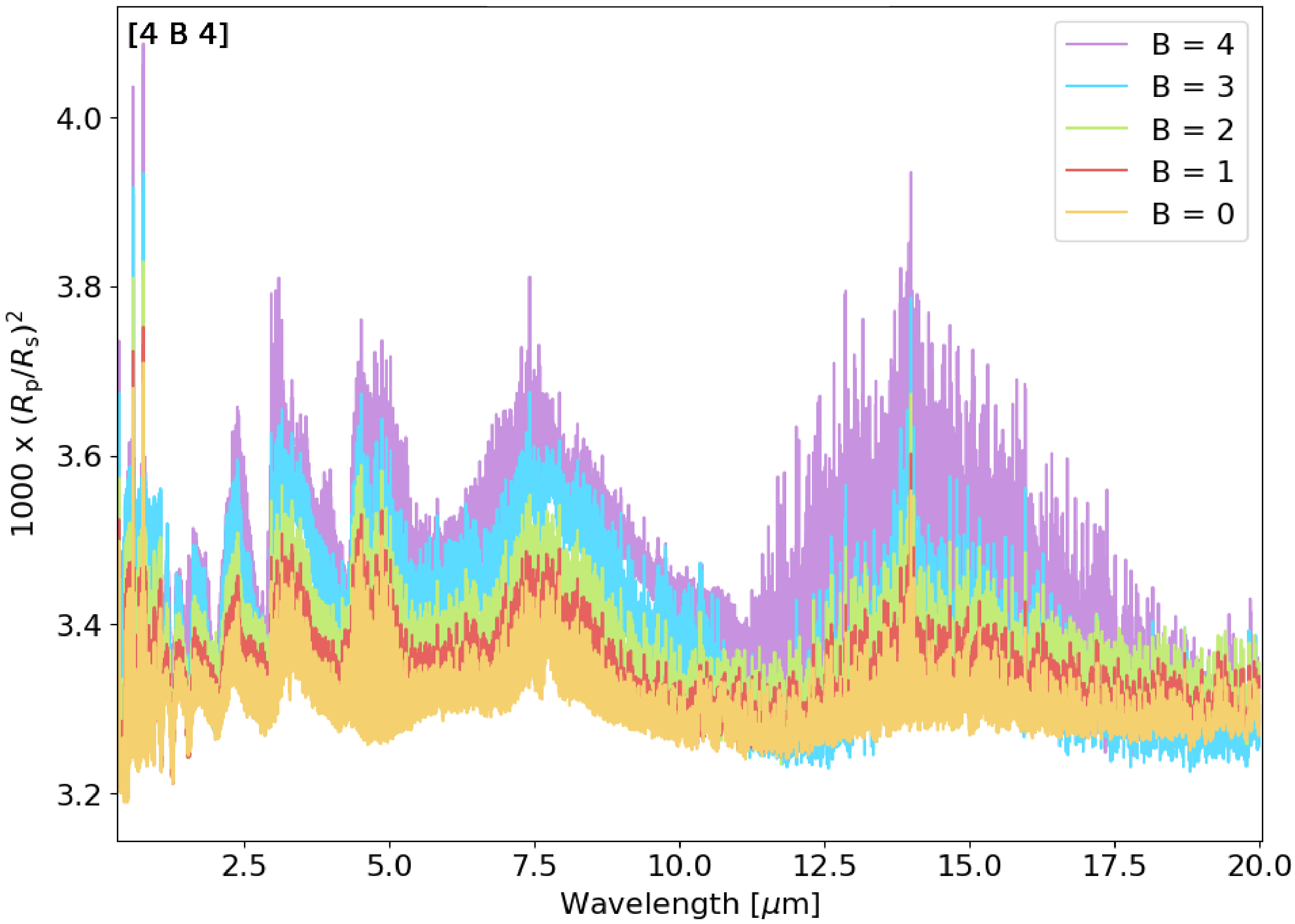
Molecules: CH_4 CO CO_2 H_2O H_2S HCN K Na NH_3 SO_2 TiO VO

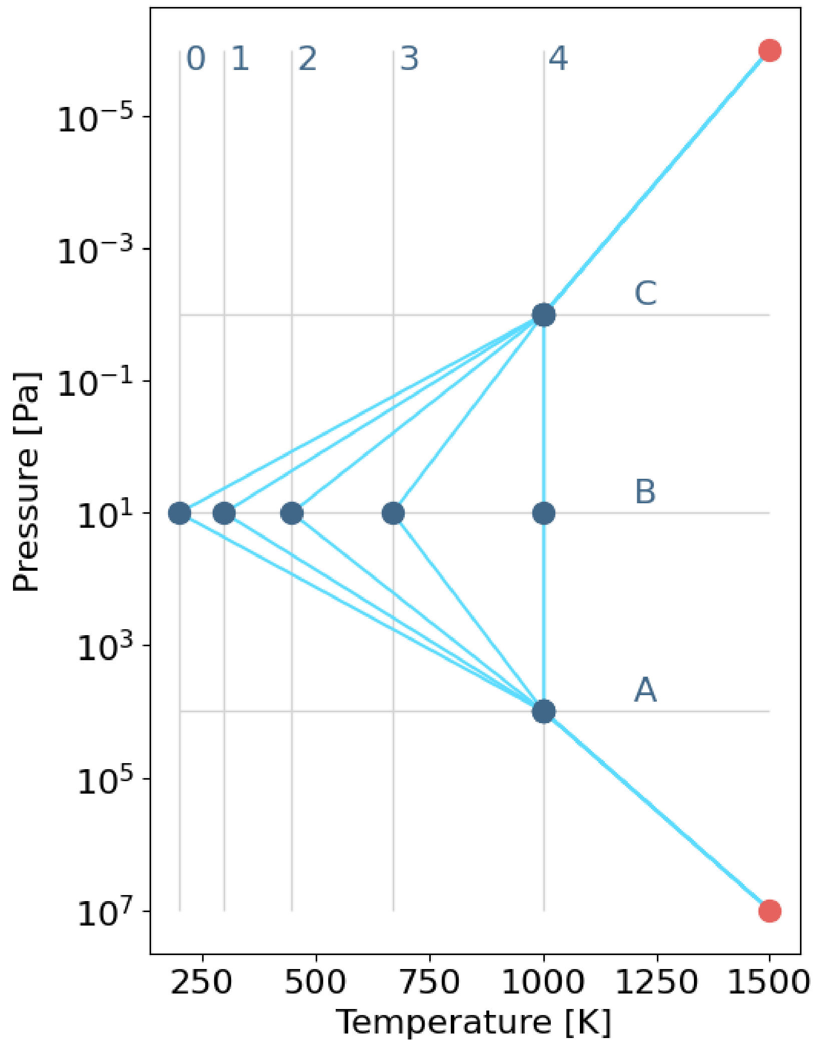
p-T profile grid





Transmission Spectra





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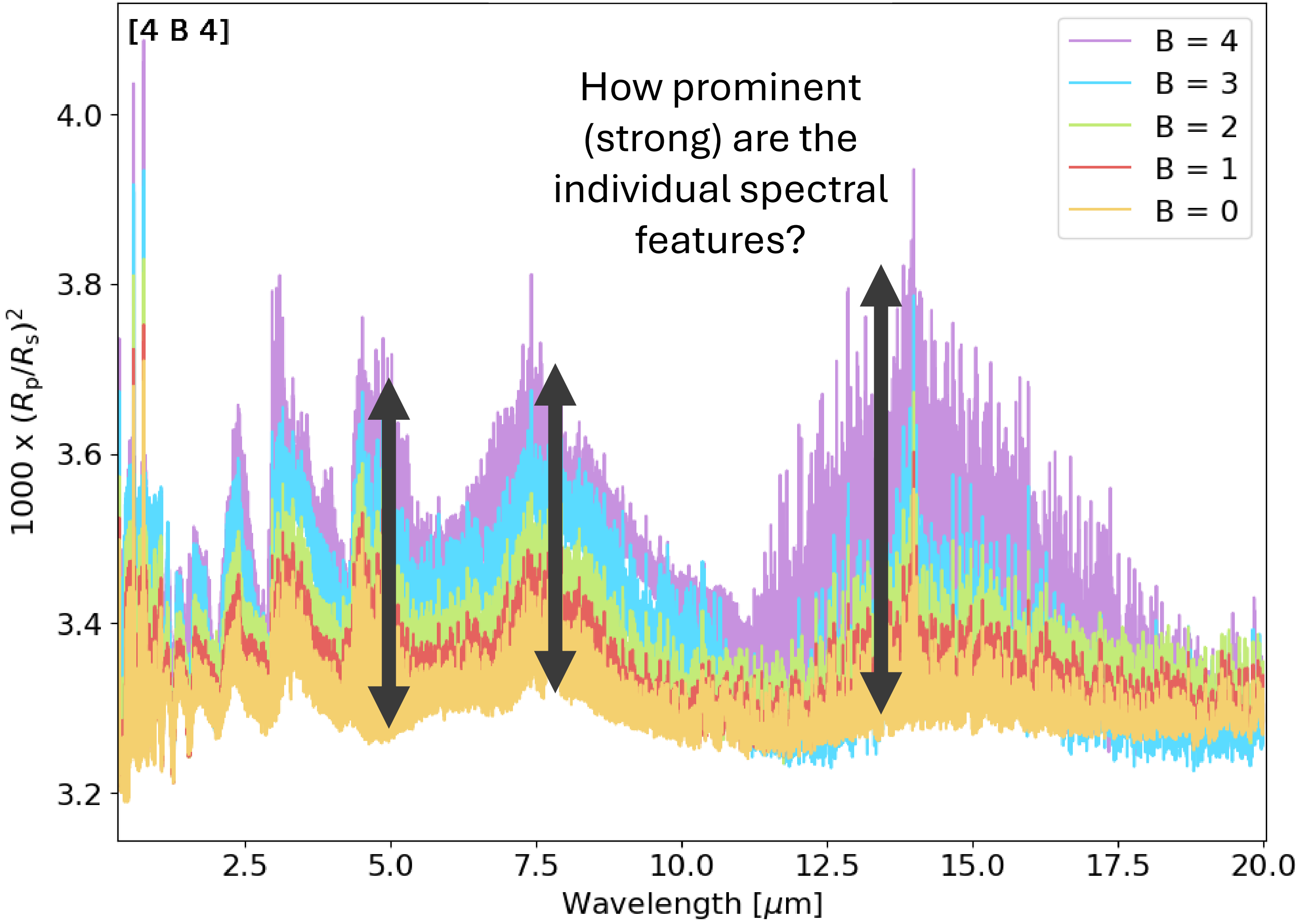

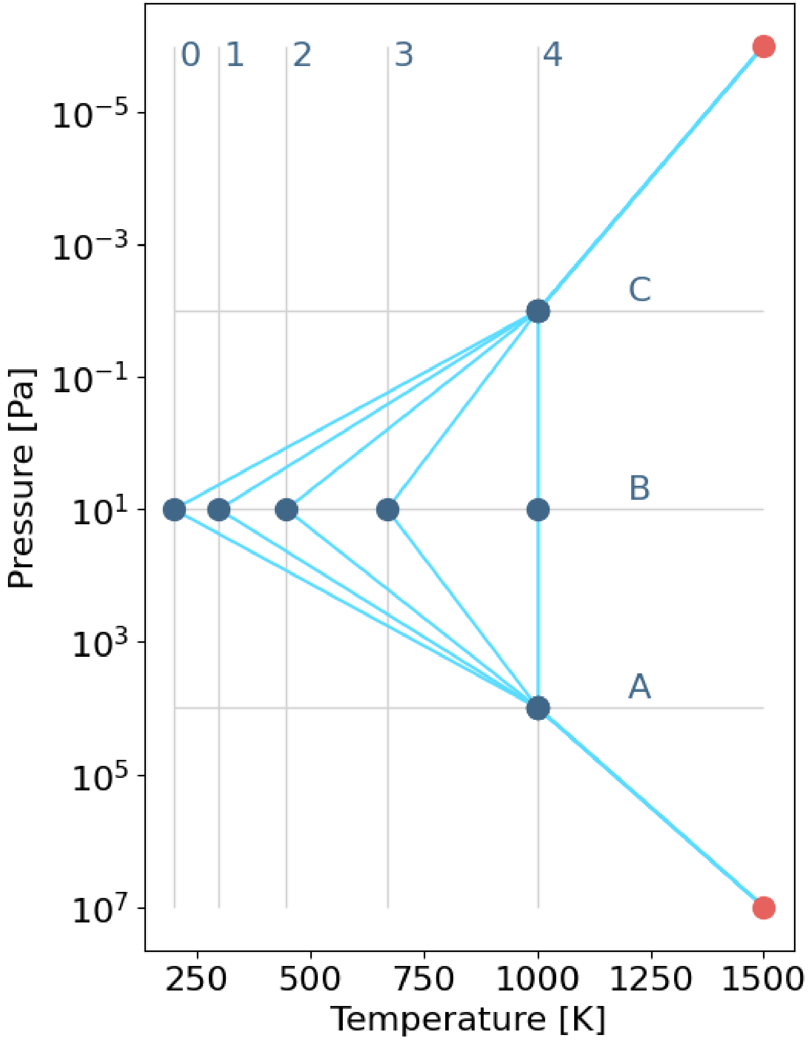

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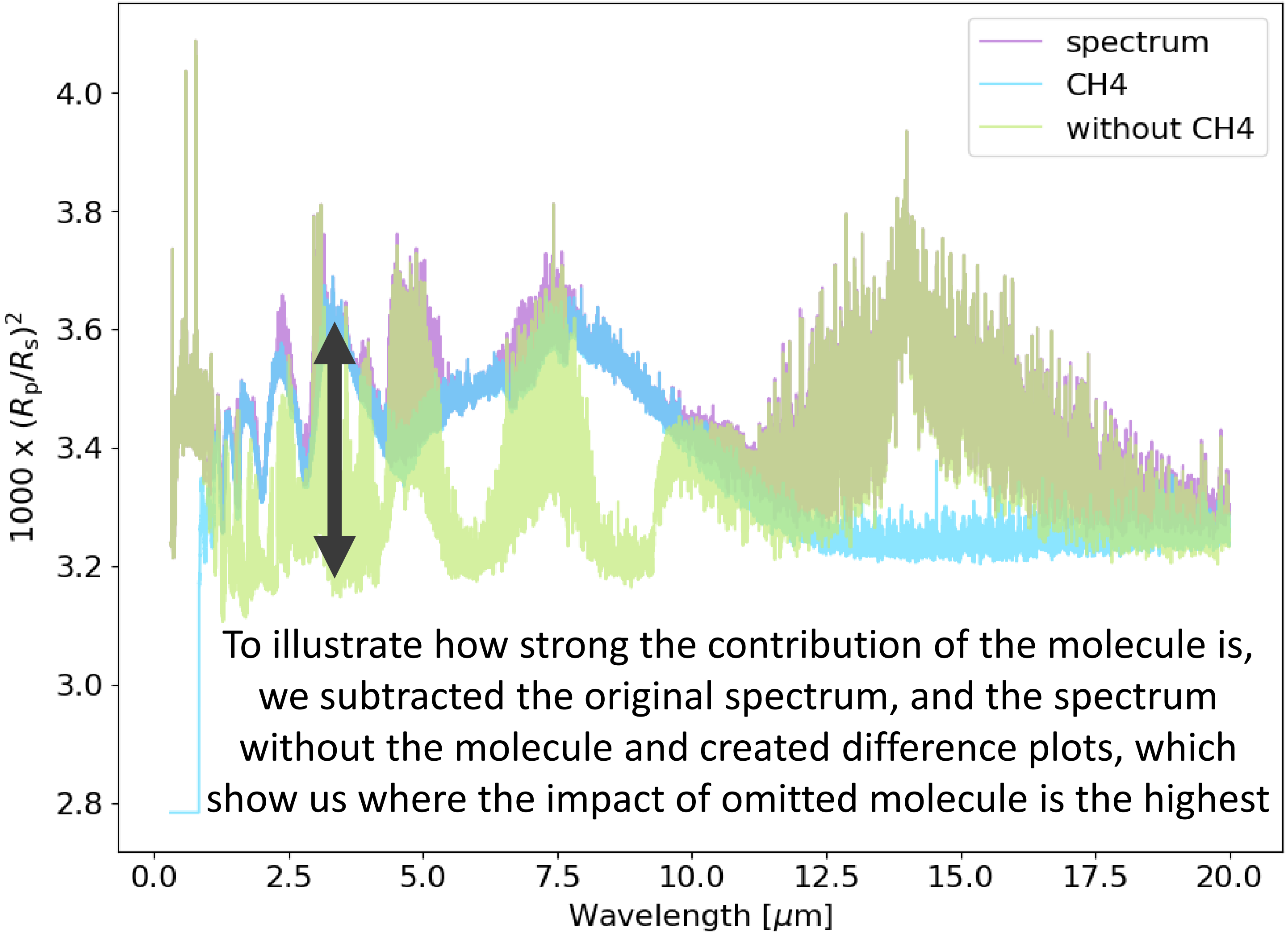
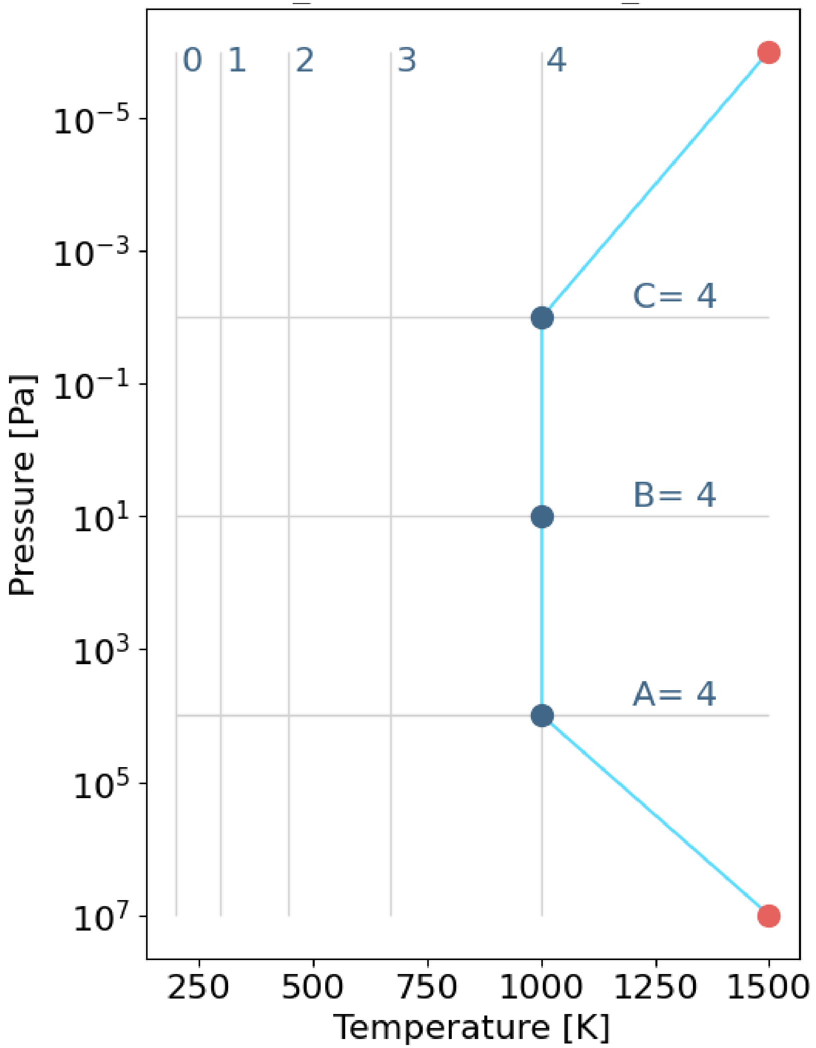


To illustrate how strong the contribution of the molecule is, we subtracted the original spectrum, and the spectrum without the molecule and created difference plots, which show us where the impact of omitted molecule is the highest



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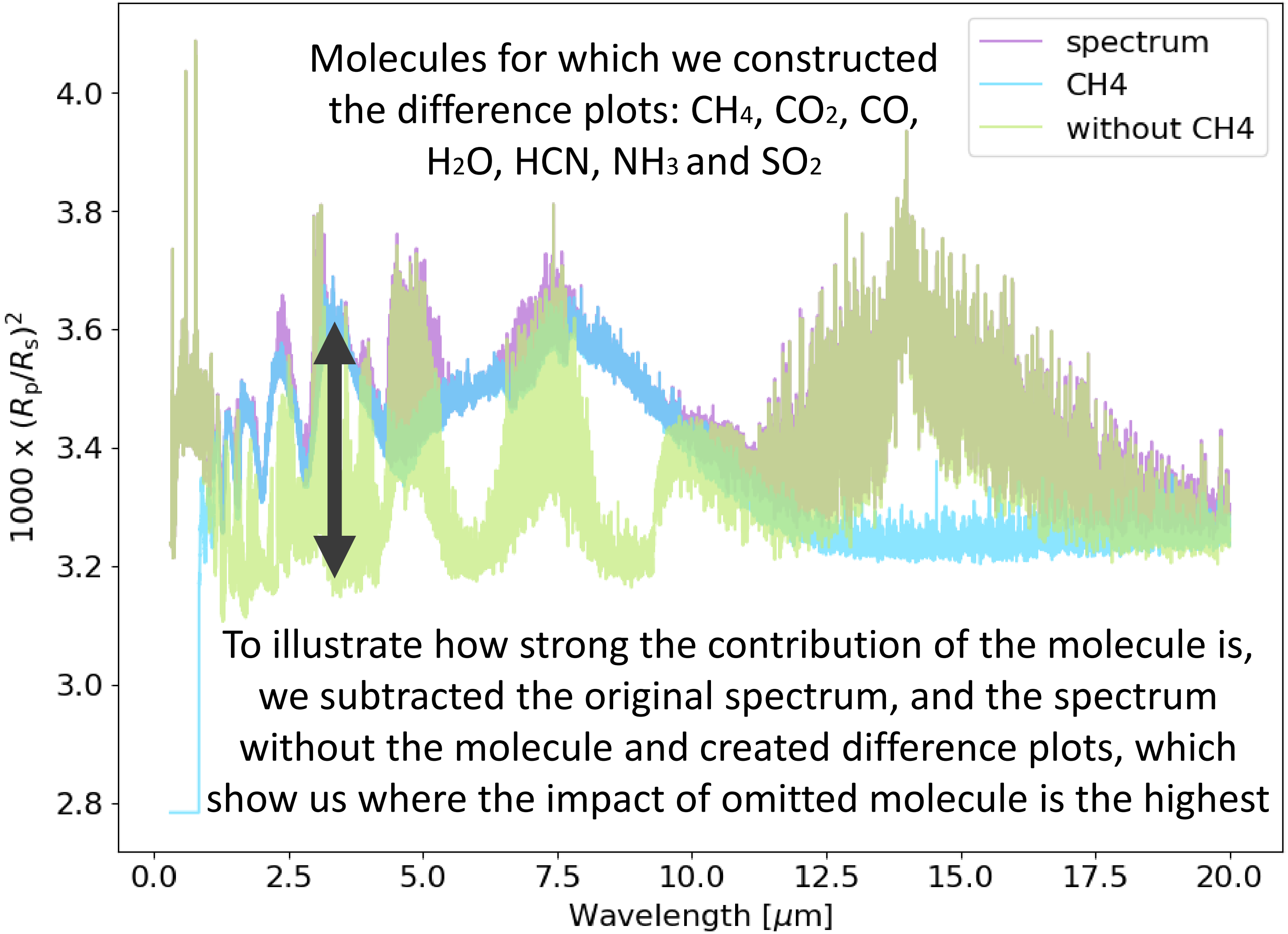
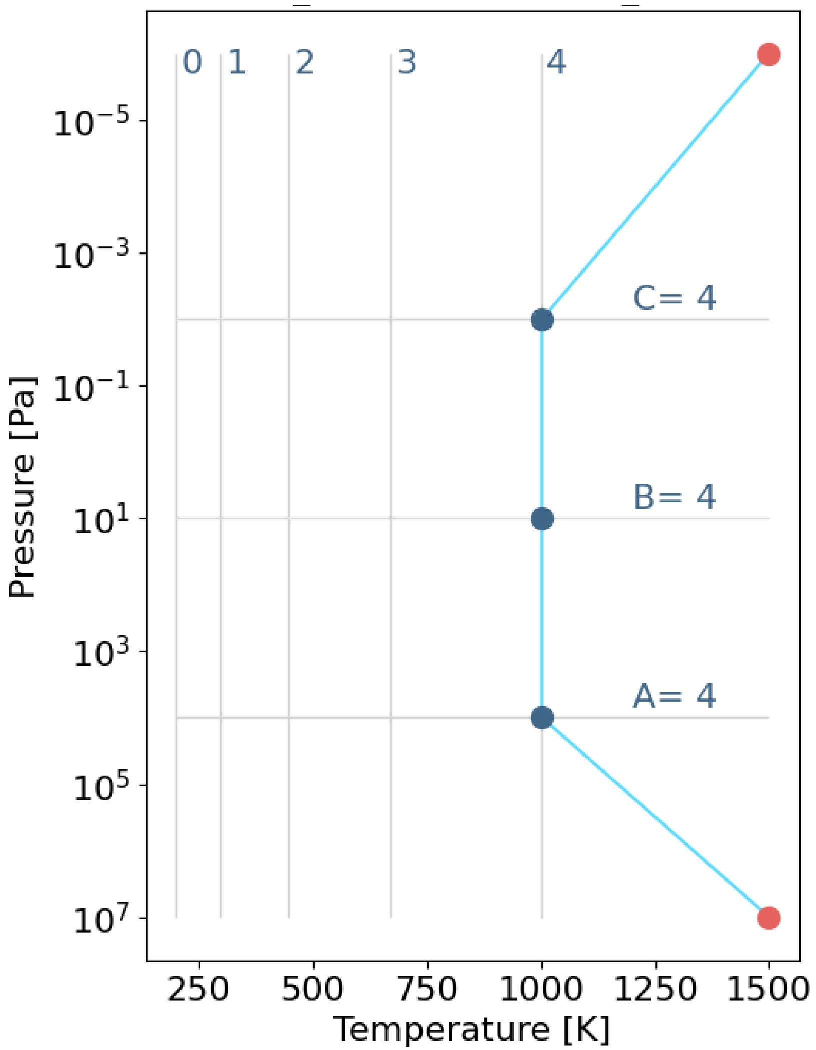
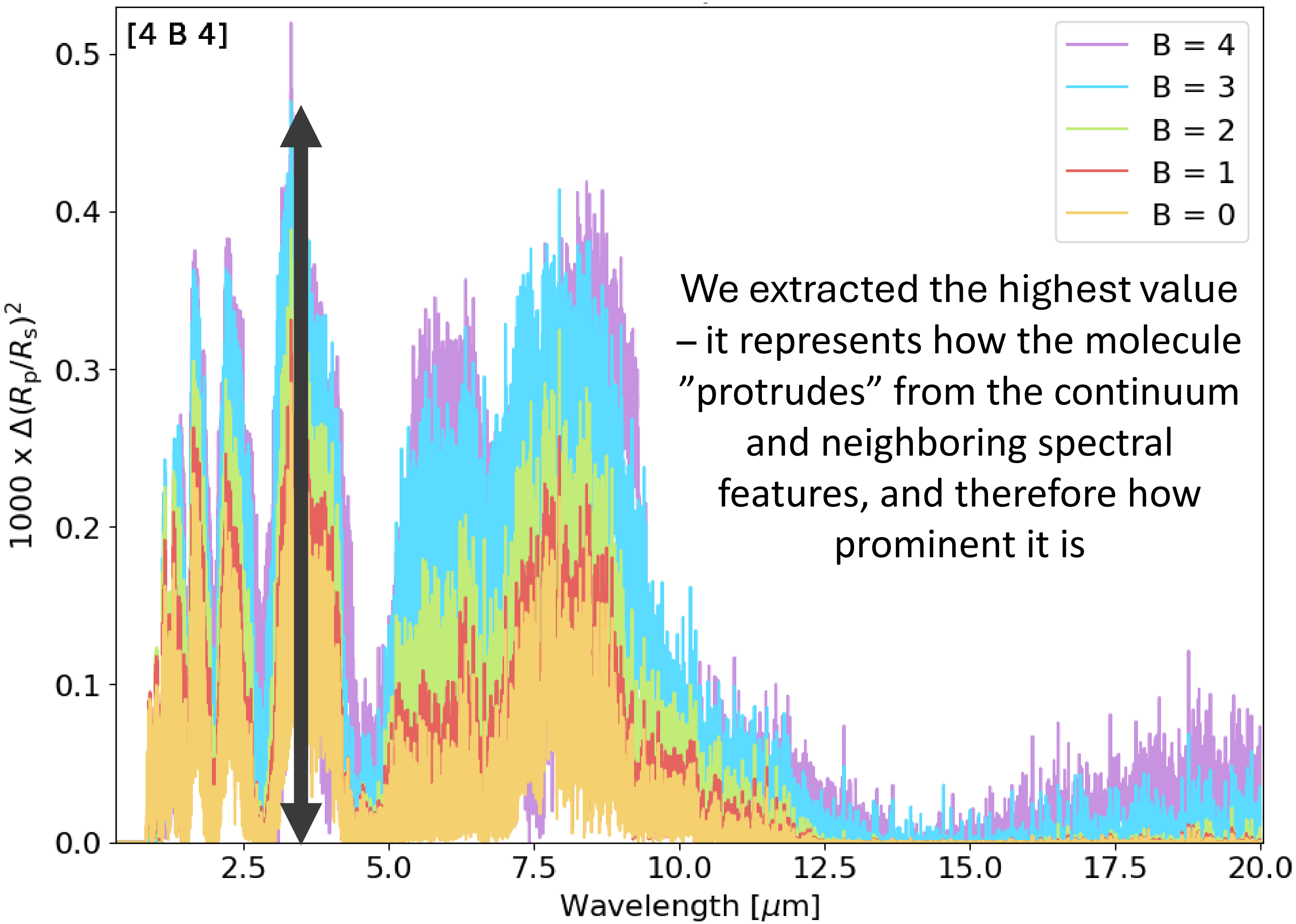
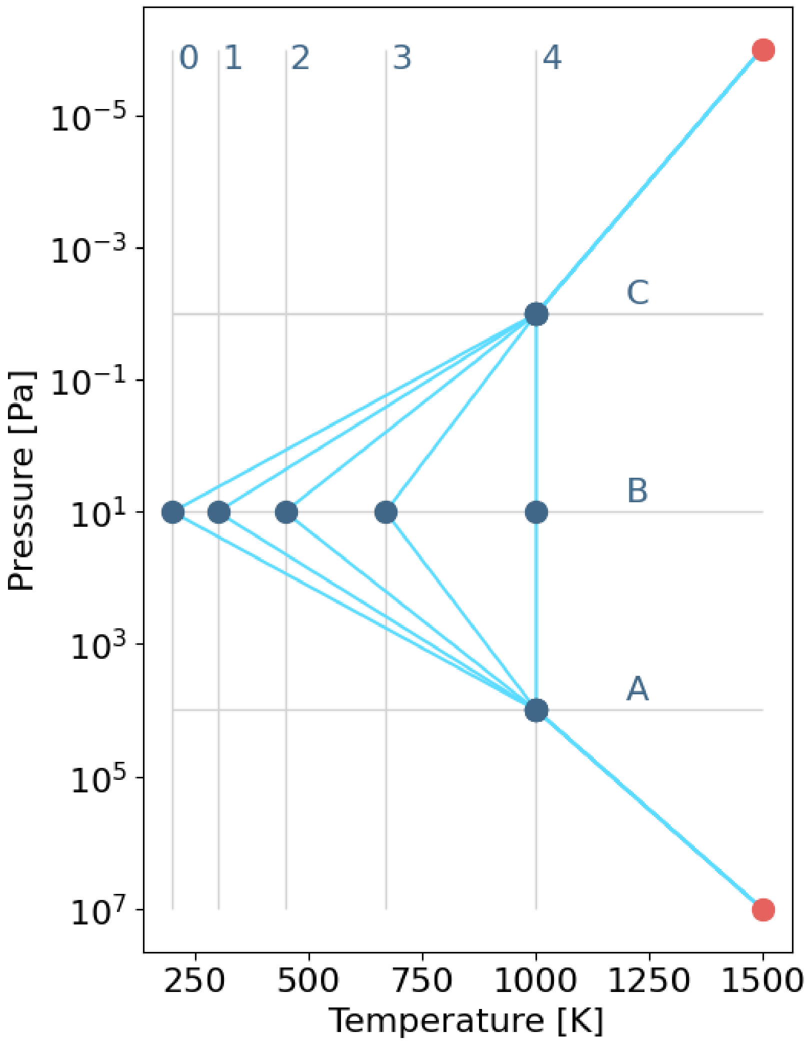




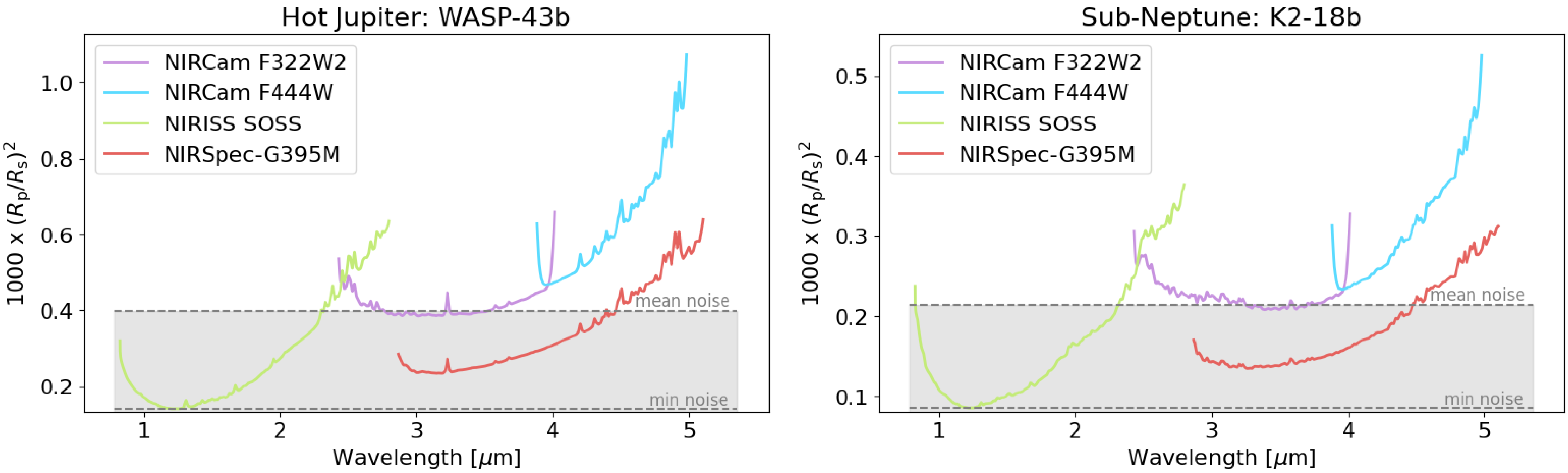
Difference Plots



We extracted the highest value – it represents how the molecule ”protrudes” from the continuum and neighboring spectral features, and therefore how prominent it is

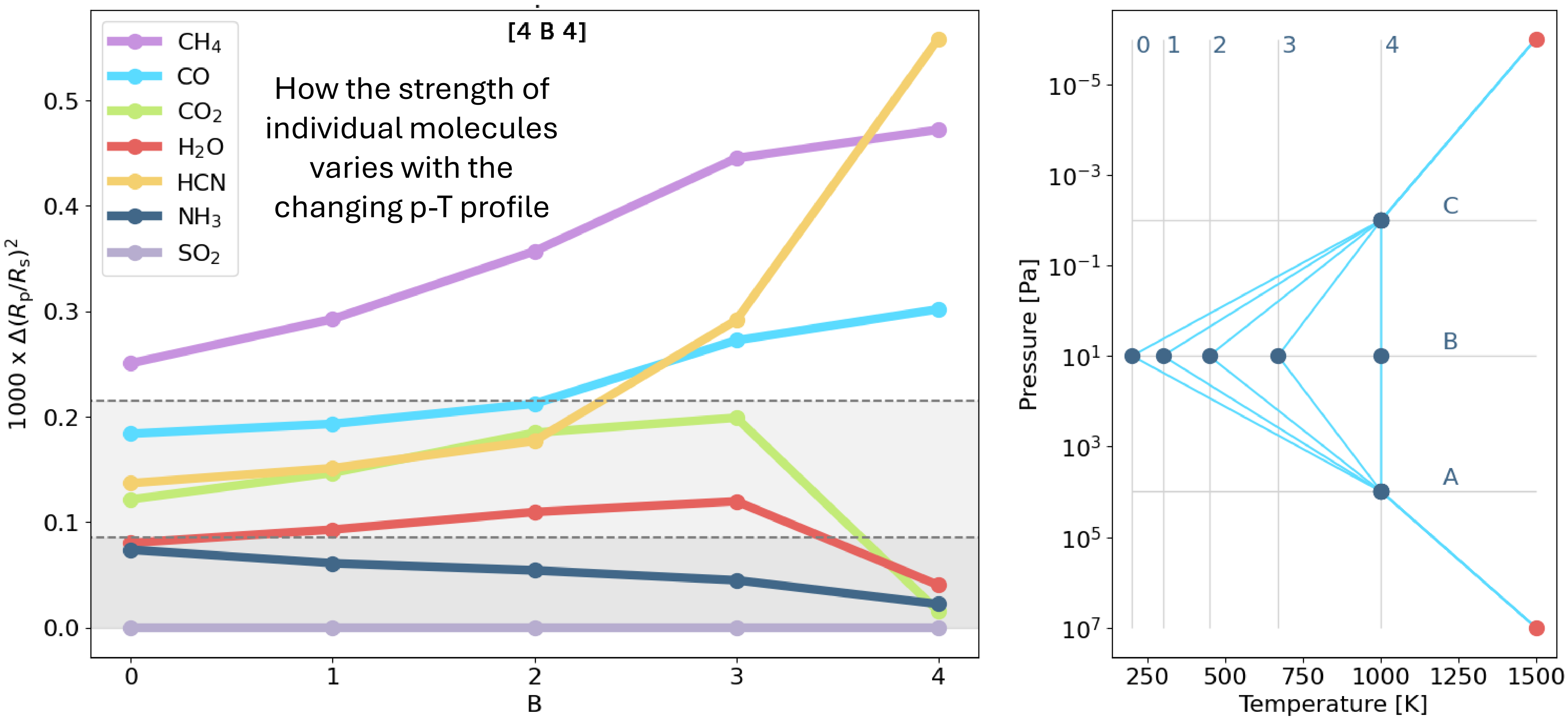


Noise Determination



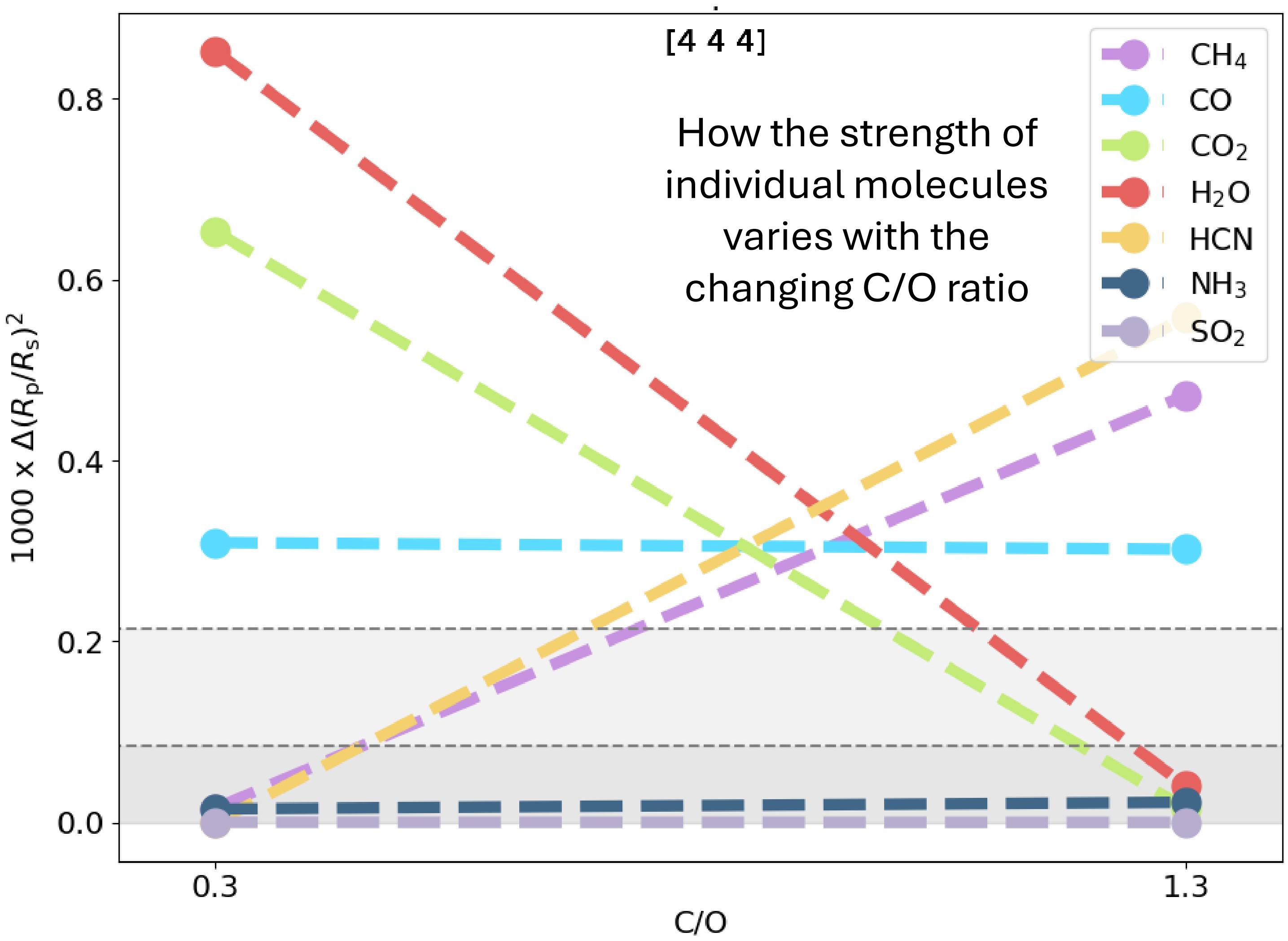
- **Mean noise**: the feature may or may not be visible, depending on certain wavelength
- **Minimum noise**: the feature will not be visible independent of wavelength

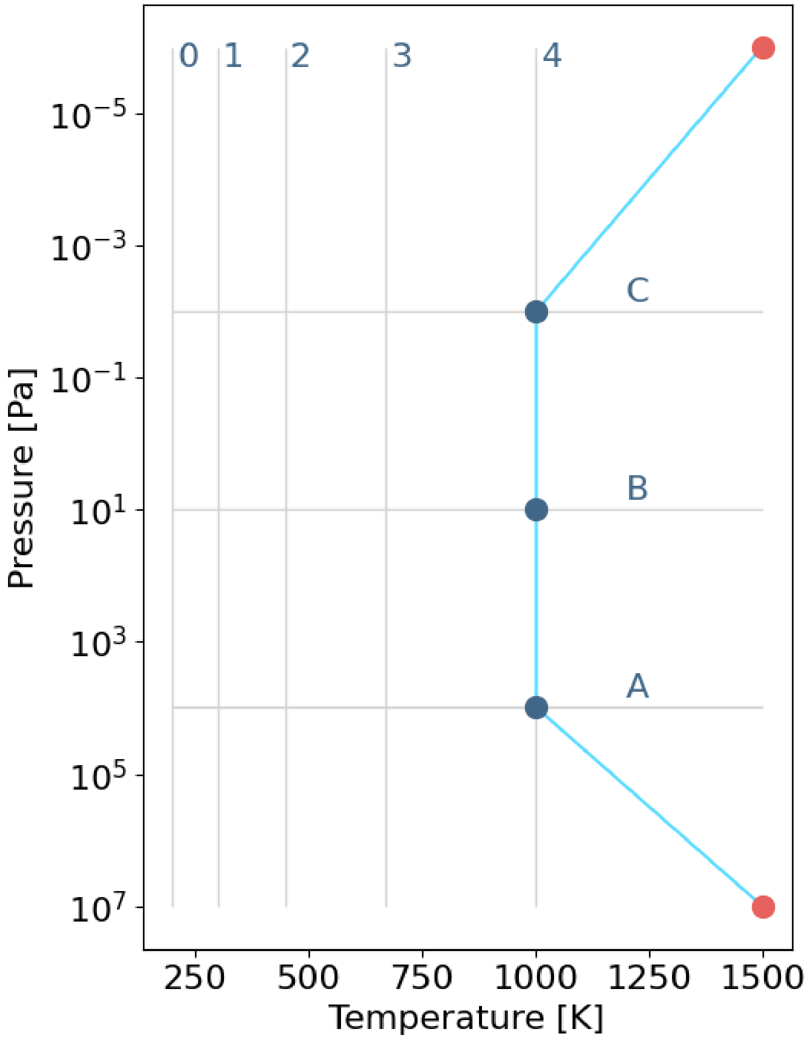
Line Plots



[4 B 4]
CH4
CO
CO2
H2O
HCN
NH3
SO2
How the strength of individual molecules varies with the changing p-T profile
1000 x Δ(Rp/Rs)^2
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
B
0
1
2
3
4
C
B
A
Pressure [Pa]
10^-5
10^-3
10^-1
10^1
10^3
10^5
10^7
250
500
750
1000
1250
1500
Temperature [K]

C/O Comparison Plots





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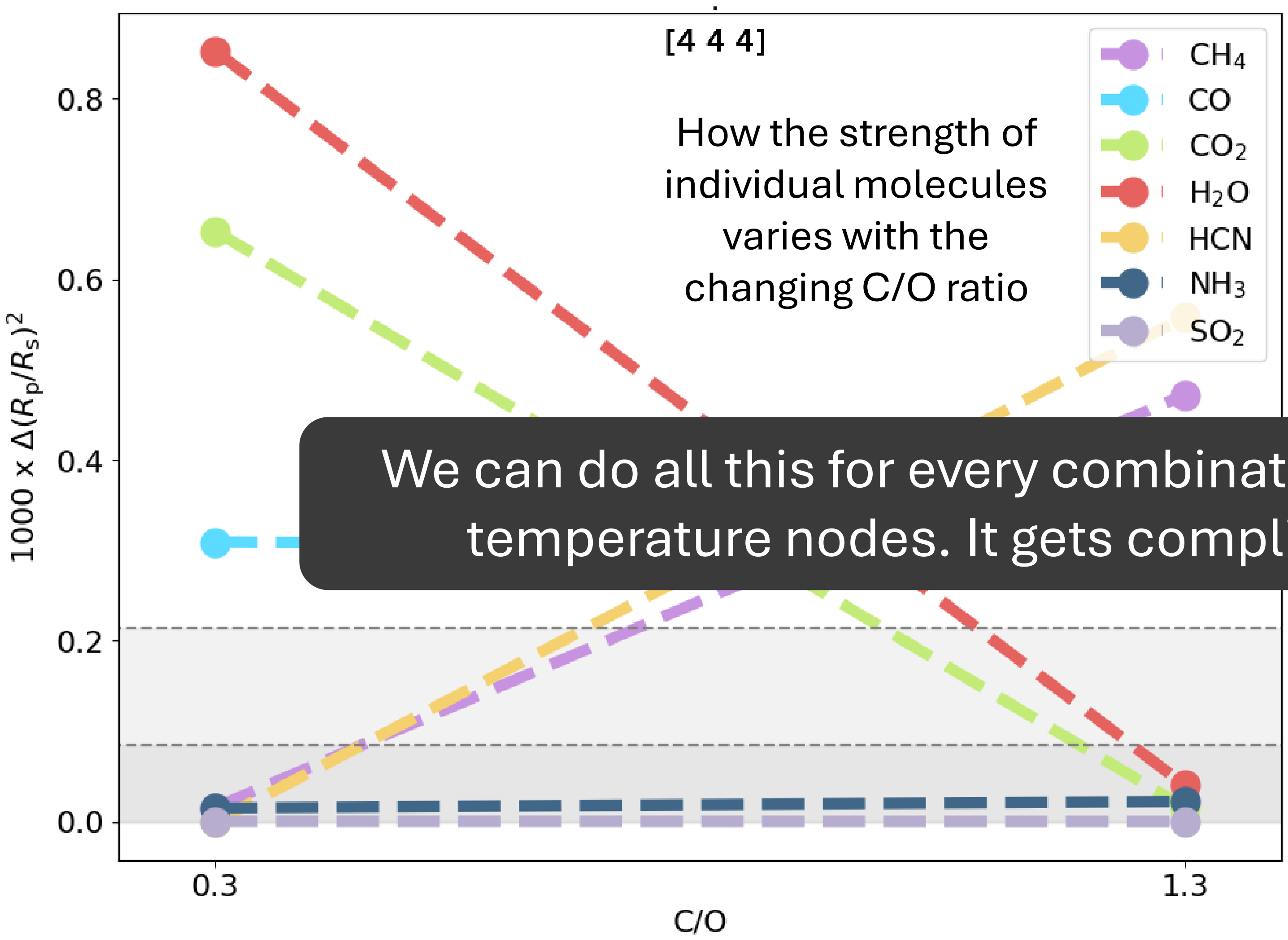
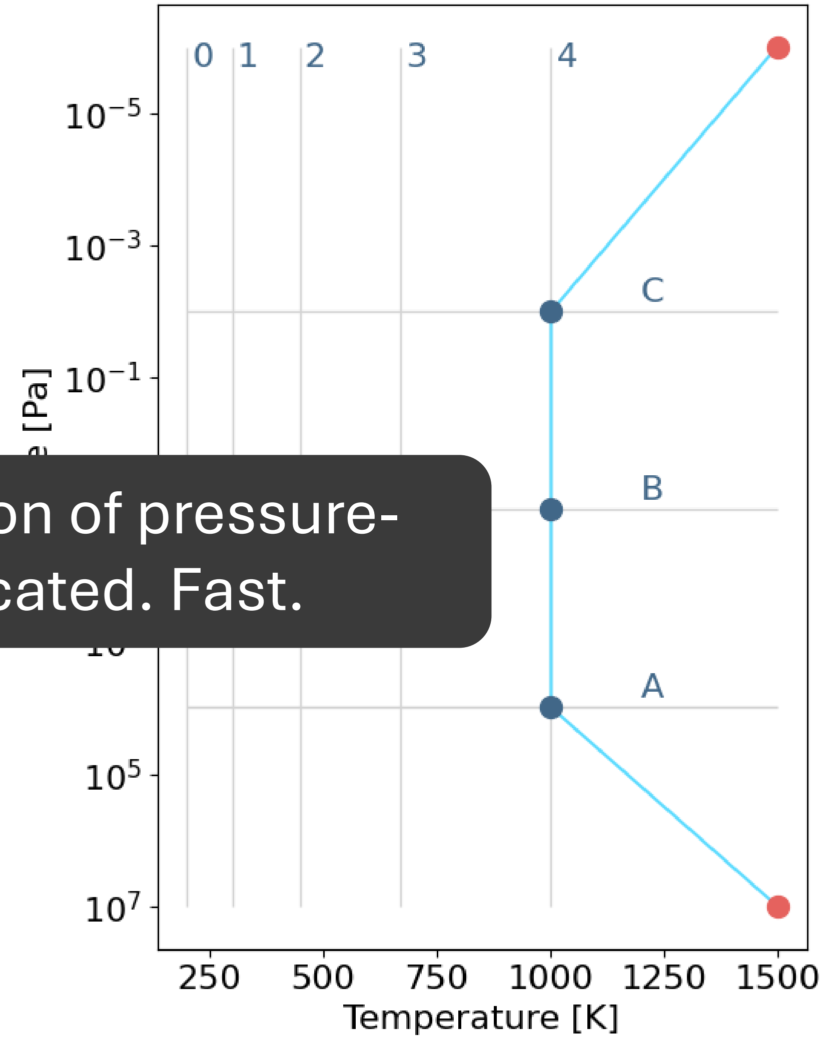
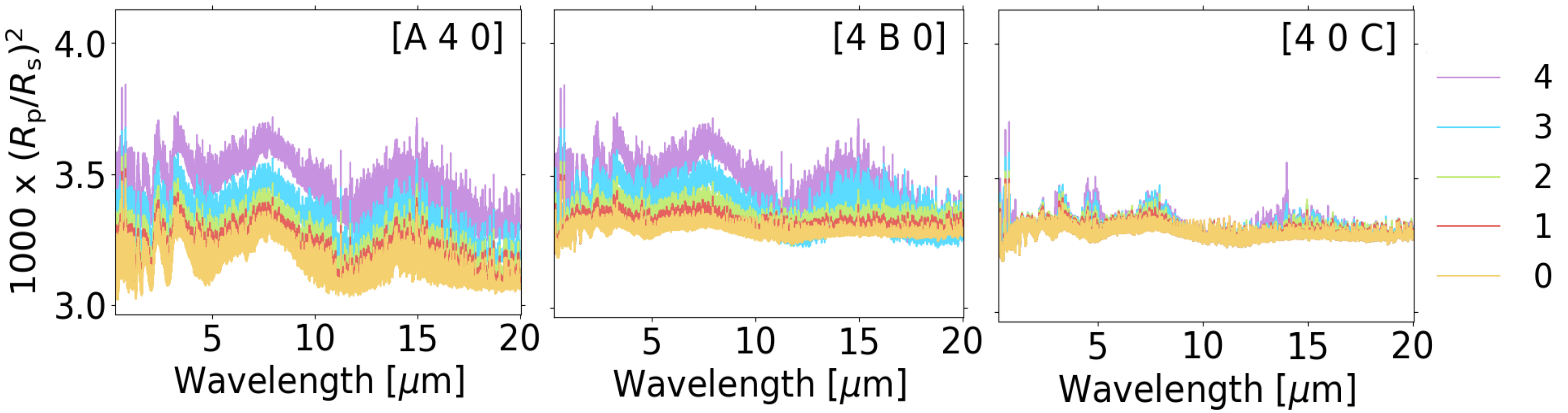




We can do all this for every combination of pressure-temperature nodes. It gets complicated. Fast.

Transmission Spectra - Again



Variations in A

Change the height of continuum, not shape

Variations in B

Change the shape of the spectra

Variations in C

Amplify some features, not significant

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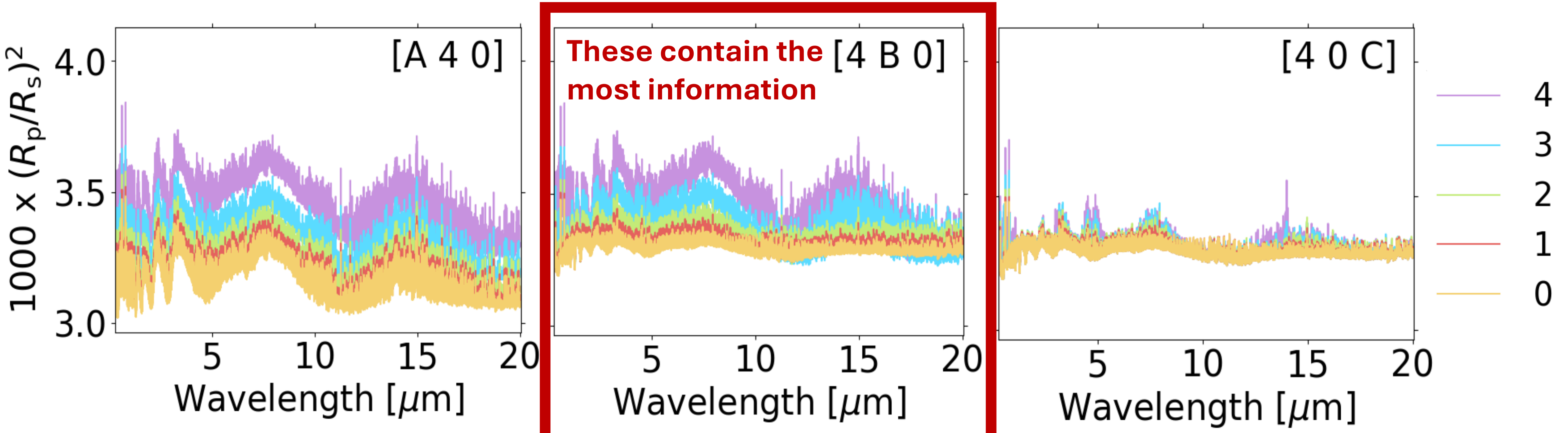

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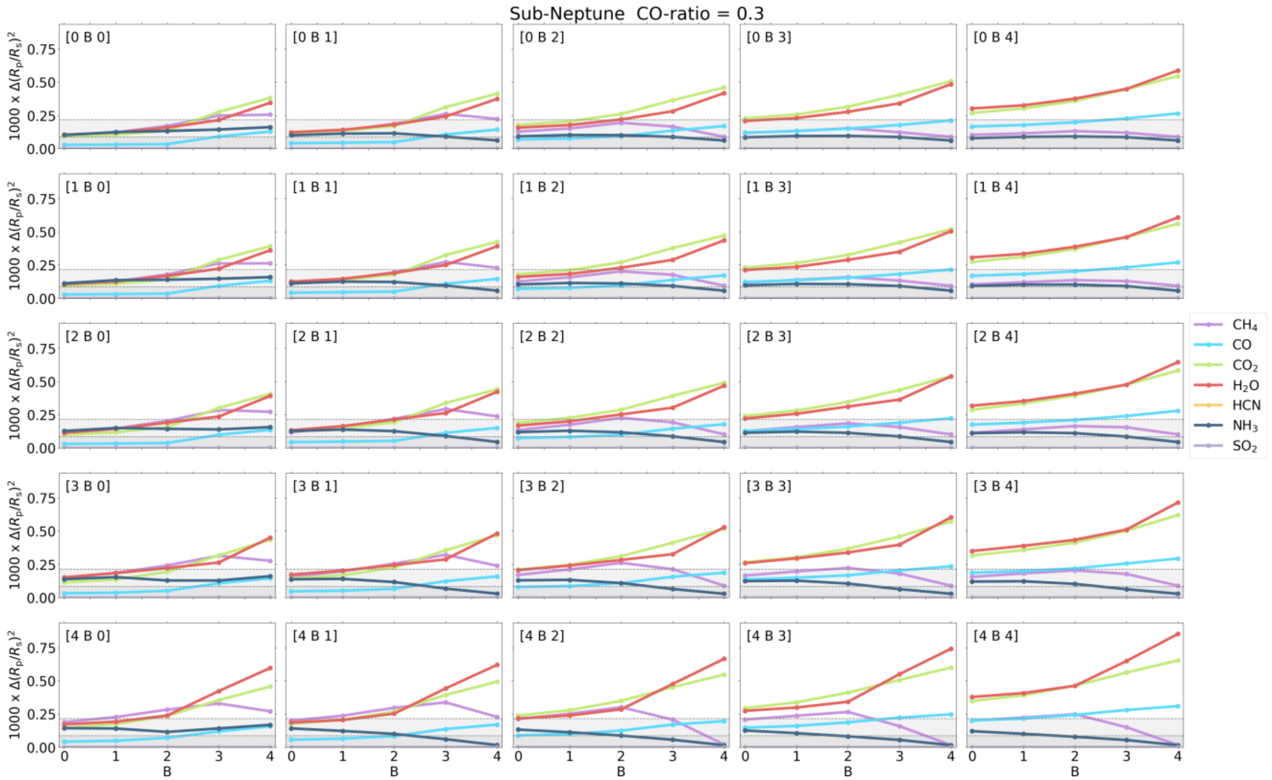
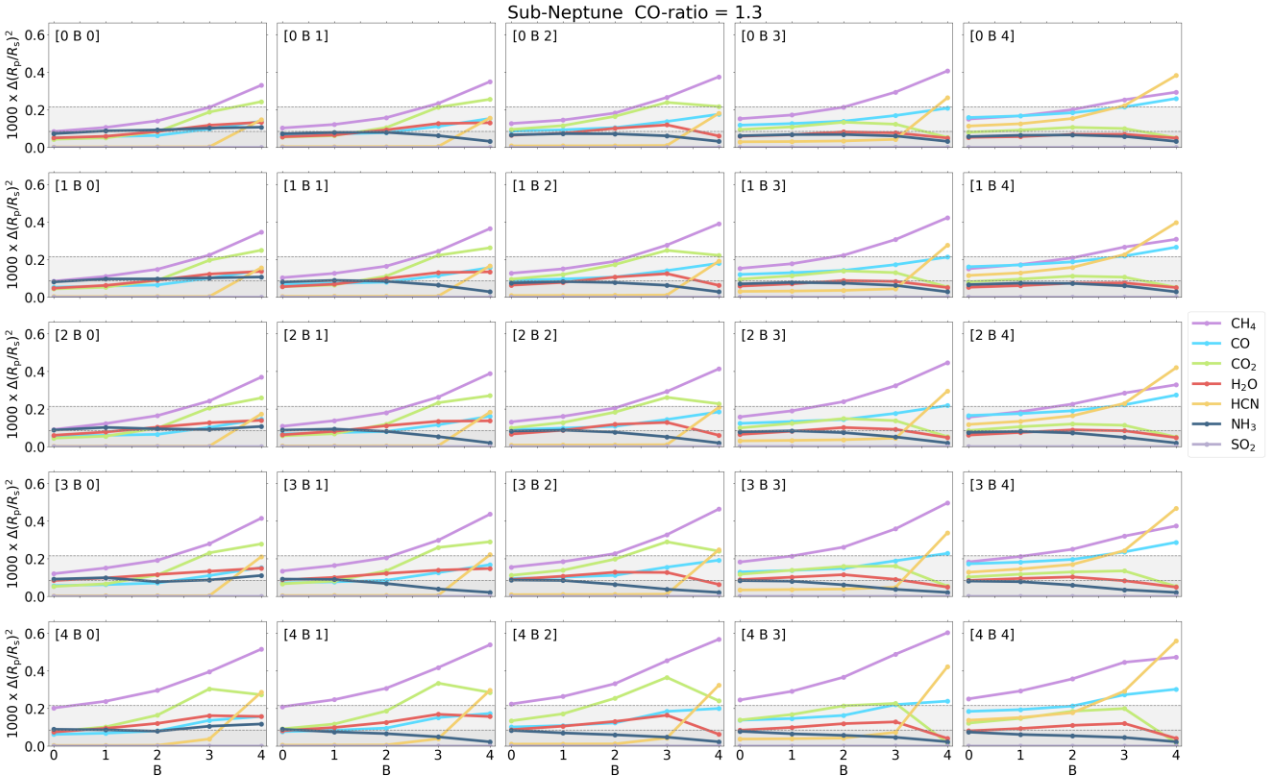
Sub-Neptune



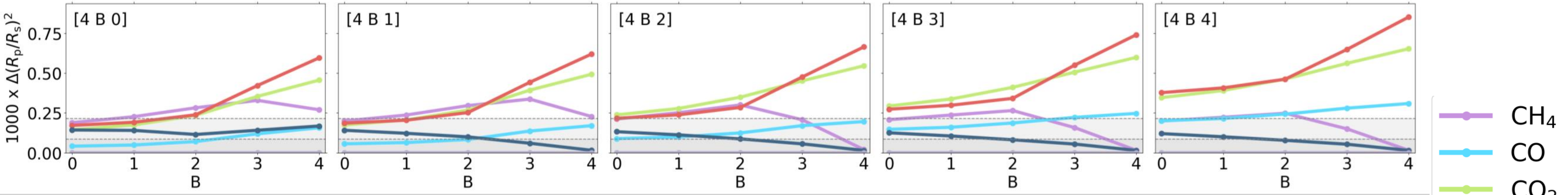


Yes, these are the “simpler” plots. Let’s zoom in.

Sub-Neptune

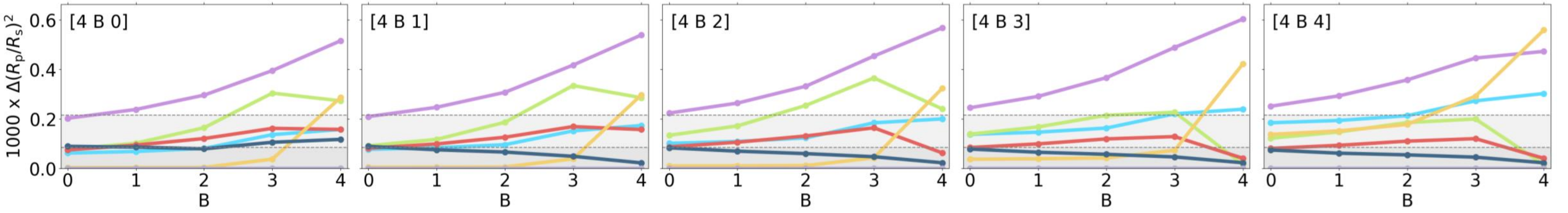
CO_2, CO, H_2O

C/O = 0.3 => **Oxygen-rich atmosphere**



CO, CH_4, HCN

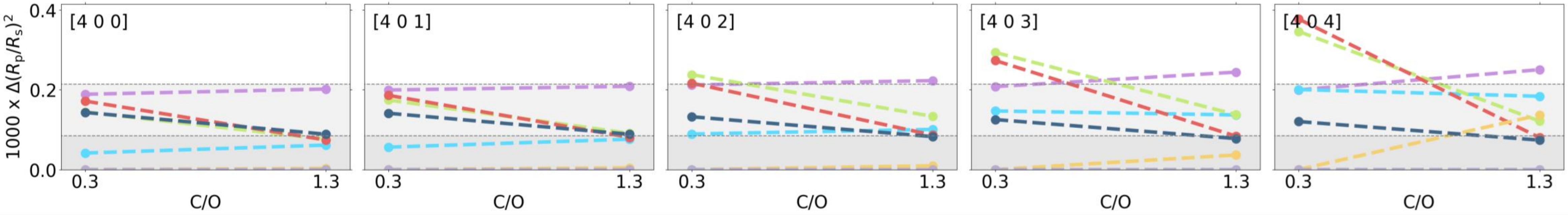
C/O = 1.3 => **Carbon-rich atmosphere**



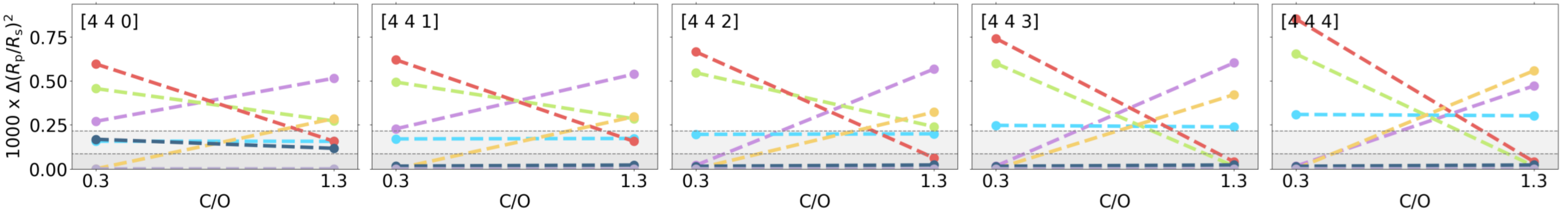
There seems to be a trade-off between oxygen-bearing and carbon-bearing molecules

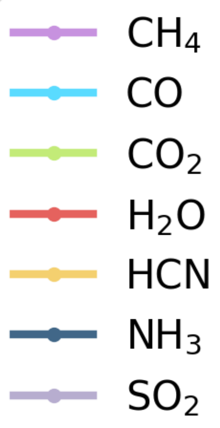
Sub-Neptune

B = 0 => **Colder atmosphere**



B = 4 => **Hotter atmosphere**



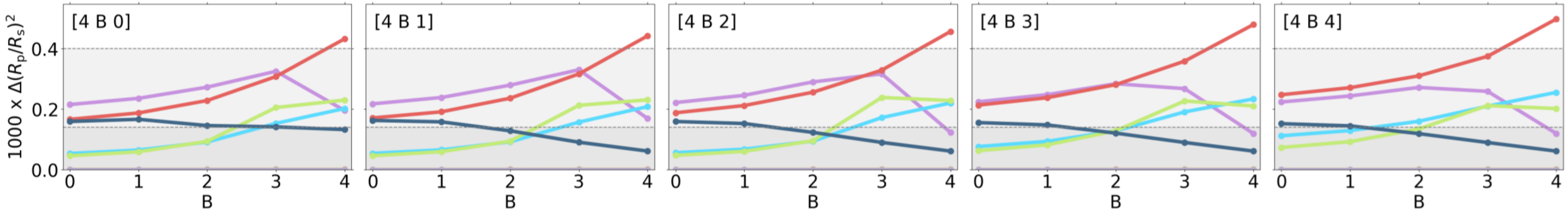


The colder atmospheres are not so sensitive to C/O value. The trade-off becomes visible in hot atmospheres

Hot Jupiter

C/O = 0.3 => **Oxygen-rich atmosphere**

CO_2, CO, H_2O



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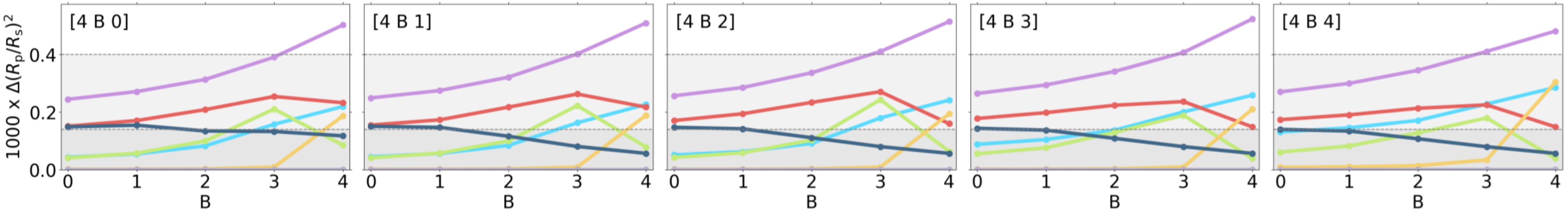

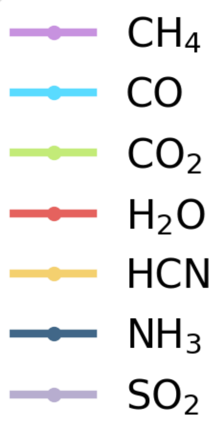

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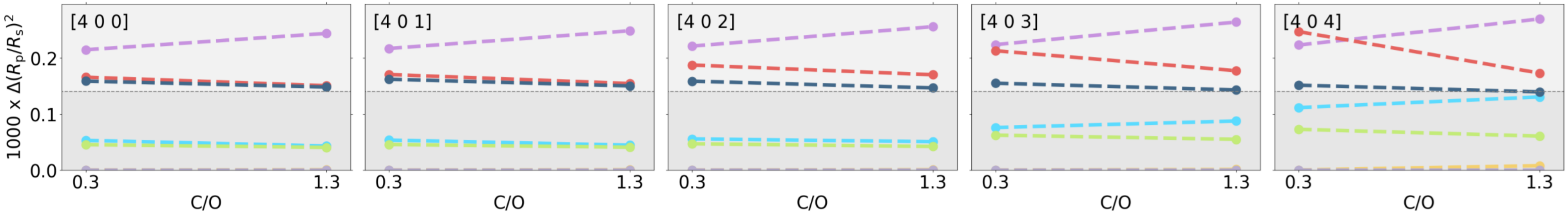

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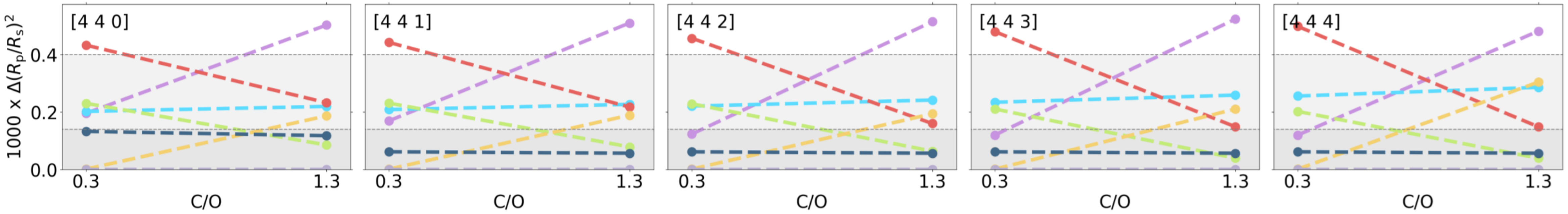

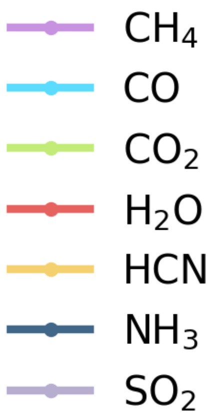

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Hot Jupiter

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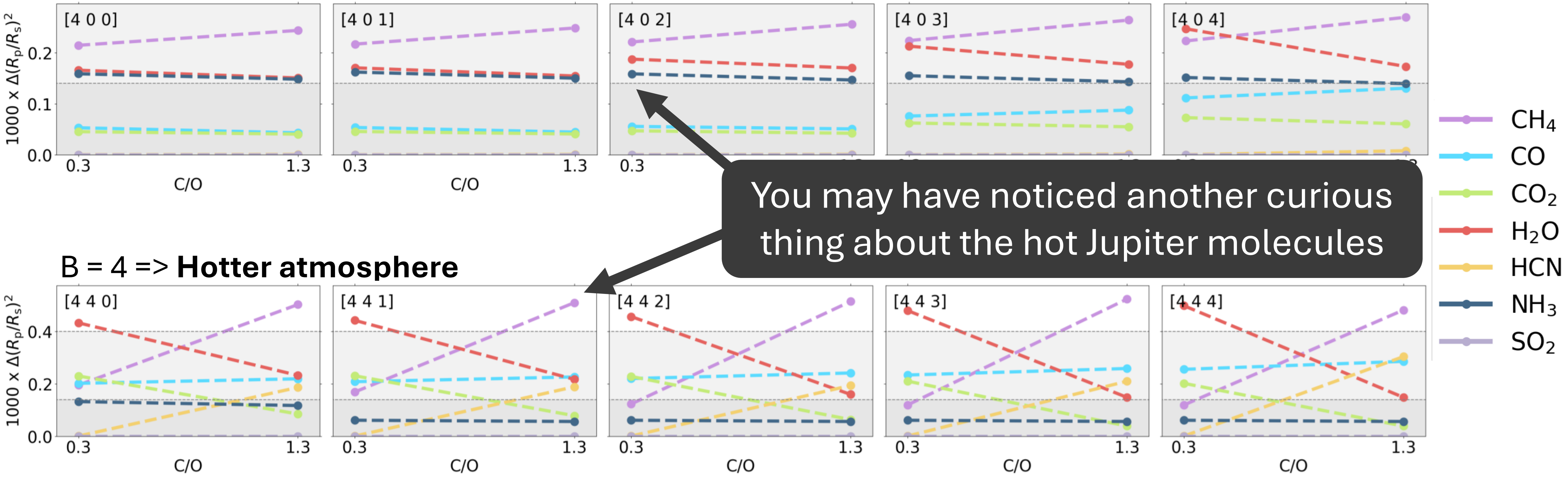


You may have noticed another curious thing about the hot Jupiter molecules

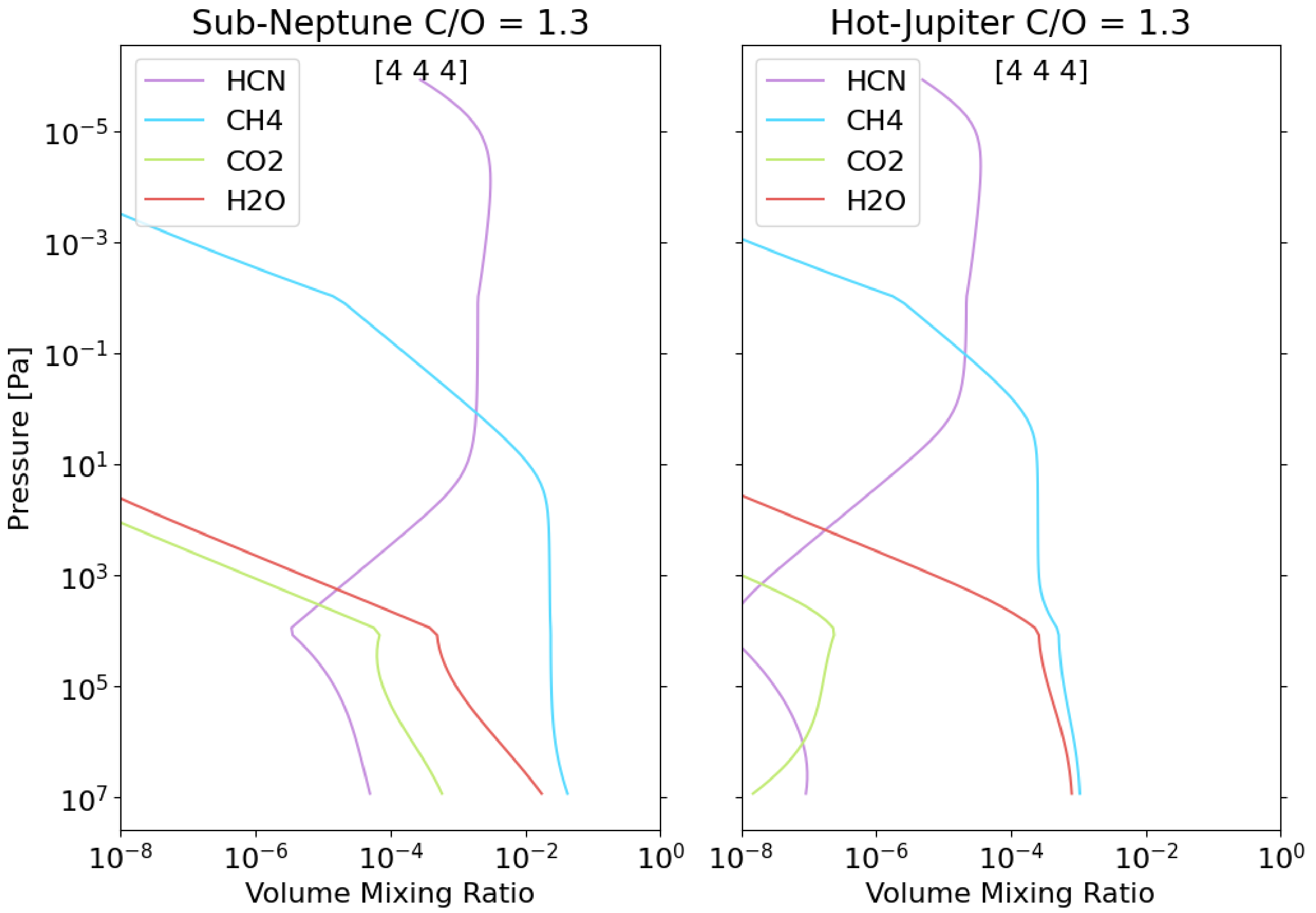
Barely visible, even for the hottest cases

Hot Jupiter Paradox

Overall transit depth good and very easy to observe (compared to other exoplanets)

Low metallicity – they are dominated by H and He, there are not enough metals to cause change with the changing p-T profile

P-T profile of hot jupiter cannot be sufficiently constrained using transmission spectra – we need to use other methods (secondary transit spectra)



Conclusions

Shape of spectra

Shape of the spectra changes with the change of the middle node (B). Changing the A inflates the atmosphere and only shifts the continuum, and changing C does not produce significant change, because density of molecules is too low

C-O trade-off

In carbon-rich atmospheres, the carbon-bearing molecules (HCN, CH_4) dominate, while oxygen-bearing molecules (H_2O, CO_2) are not visible. In oxygen-rich atmospheres, it is exactly reversed. In colder atmospheres, their molecular compositions are very similar.

Hot Jupiter paradox

Detecting metals in sub-neptunes and determining the p-T profile from them should be easier than in hot jupiters. Hot Jupiter transmission spectra cannot constrain the p-T profiles.

Thank you for your attention!