Astroclimes - a synthetic transmission spectra code for removing telluric lines and measuring atmospheric CO_2

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Key message

We present Astroclimes, a synthetic transmission fitting algorithm that can be used for measuring the abundance of greenhouse gases in the Earth's atmosphere and for removing telluric lines from stellar spectra. Our goals are to:

Complement global measurement networks and climate models with CO_2 column abundances measured at night

Provide an improved mechanism to remove telluric lines using a Bayesian approach which could be incorporated into existing models

1 - Compute model spectra

- Calculate molecular cross sections.
- Obtain atmospheric profile.
- Model transmission spectra, including effects:
  - Line-by-line absorption
  - Rayleigh and aerosol scattering
  - Collision-induced absorption (CIA)
  - Instrumental broadening

2 - Fit model to observational data

- Observational sample was compiled from public data from the CARMENES spectrograph. Sample included O, B and A stars, known as telluric standard stars.
- Best fit model is obtained by running an MCMC, with abundances of CO_2, H_2O, CH_4 and O_2 chosen as free parameters. The log likelihood equation comes from Brogi & Line (2019) [1]. Best fit models and residuals are shown in Figure 1.
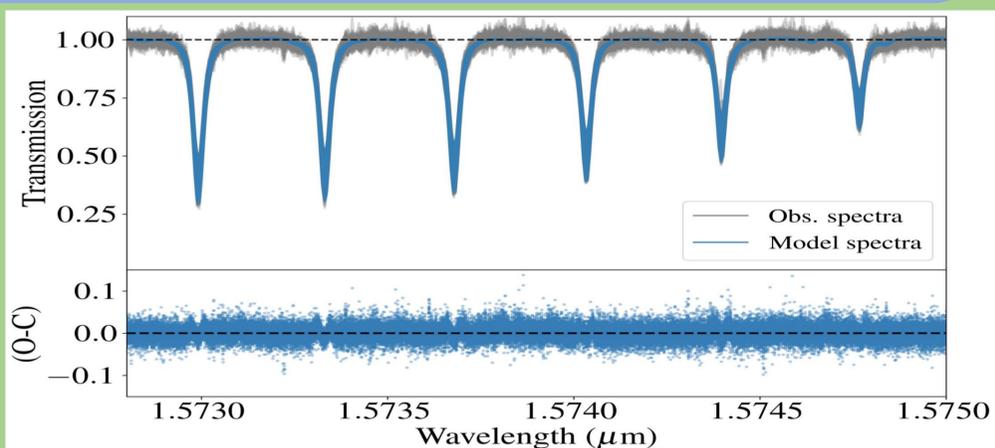

Figure 1: Comparison between the CARMENES spectra (gray) and the fitted models obtained with Astroclimes (blue), zoomed in on CO_2 lines. Bottom plot shows residuals.

Atmospheric CO_2 monitoring

3 - Compare results to literature

- There is no direct comparison between our results and those from current measurement networks, so instead we compare our results to the latest CAMS reanalysis model, EGG4 [2]. These are shown in Figures 2 and 3.
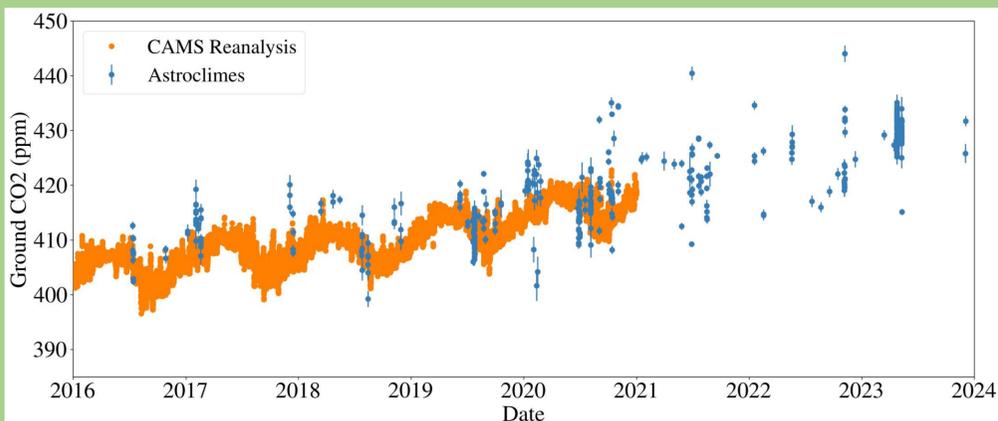

Figure 2: Retrieved ground level CO_2 abundance from Astroclimes (blue) and CAMS EGG4 (orange) as a function of time. Astroclimes values were shifted down by 14 ppm.
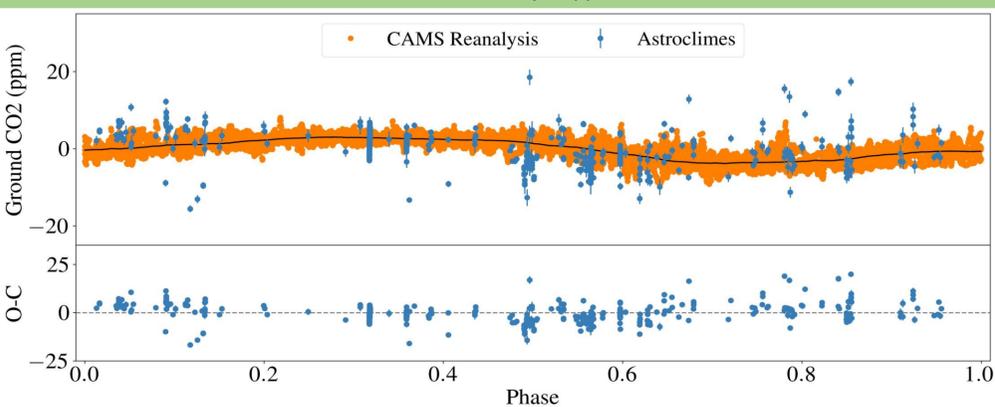

Figure 3: Top: phase-folded retrieved ground CO_2 distribution from Astroclimes (blue) and CAMS (orange). The solid black line is a rolling median of the CAMS values with a window size of 10% the number of points. The y-axis shown as the y-axis correspond to the seasonal variation of the abundances with the long-term trend removed based on a fitted exponential function. Bottom: residuals between the retrieved Astroclimes values and the interpolated rolling median of the CAMS values.

- Astroclimes was able to recover both the seasonal variation (Figure 3) and the long-term increasing trend (Figure 2).
- However, our results exhibit an overall vertical shift and larger scatter when compared to the CAMS values. Presumably, this is due to uncorrected systematic biases, which will be tackled in future work.
- The uncertainties in our individual measurements were typically around 0.3-0.7%, which would correspond to 1-2 ppm in CO_2, but the scatter in our retrievals compared to the CAMS values yields a standard deviation closer to 5 ppm.

Future work

- Identify and quantify systematic biases in our CO_2 retrieval and crosscheck Astroclimes retrievals against retrievals from the TCCON GGG2020 pipeline [3].
- Run more robust retrieval of planetary signal to determine the quality of our telluric line removal compared to other techniques.
- Extend analysis to different stellar types and different spectrographs.

References

[1] Brogi, M., & Line, M. R. 2019, AJ, 157, 114.
[2] Inness, A., et al. 2019. ACP, 19(6), 3515–3556.
[3] Laughner, J. L., et al. 2023. AMT, 16(5), 1121-1146.
[4] Webb, R., et al. 2022, MNRAS, 514, 4160-4172.

Telluric line removal – Tau Bootis

3 - Organise data in "cubes"

- Data is stacked in "cubes" of shape (n_{orders}, $n_{observations}$, $n_{wavelength}$), as shown in Figure 4.
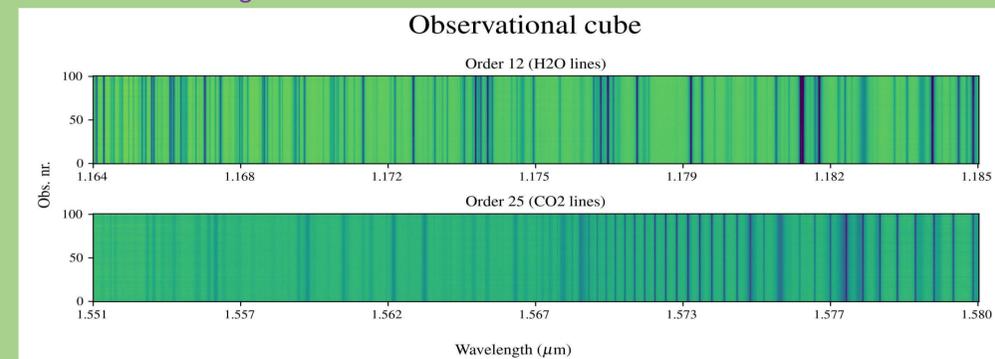

Figure 4: CARMENES observations of Tau Bootis stacked over the y-axis, with wavelength on the x-axis, for two selected CARMENES orders with H_2O and CO_2 lines.

4 - Remove telluric and stellar lines

- Data is divided by the telluric line model, and stellar lines are removed by dividing each observation by the time average telluric line removed spectra (Figure 5). This is done to uncover possible planetary signals, which Tau Bootis is known to have [4].
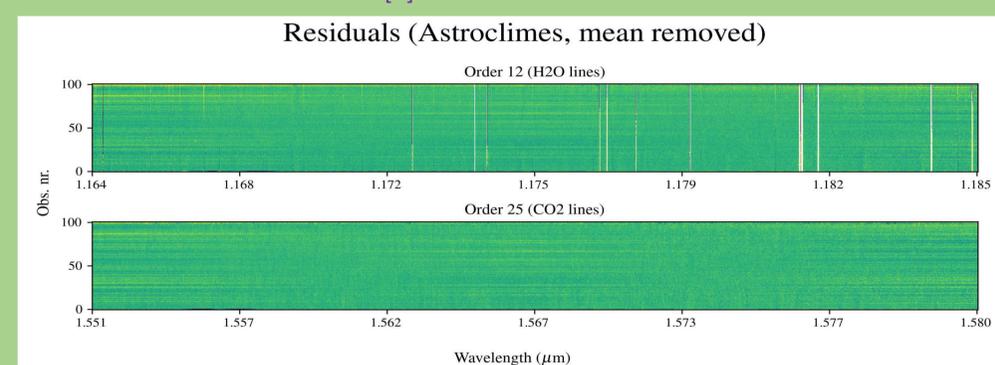

Figure 5: Data shown in Figure 4 divided by the telluric line model and further divided by the time average telluric line removed spectra. The white lines correspond to deep lines that had to be masked out.

5 - Recover planetary signal

- A planetary signal is injected in the observational cube, and we check to see if this signal is recovered after removing the telluric and stellar lines (Figure 6).
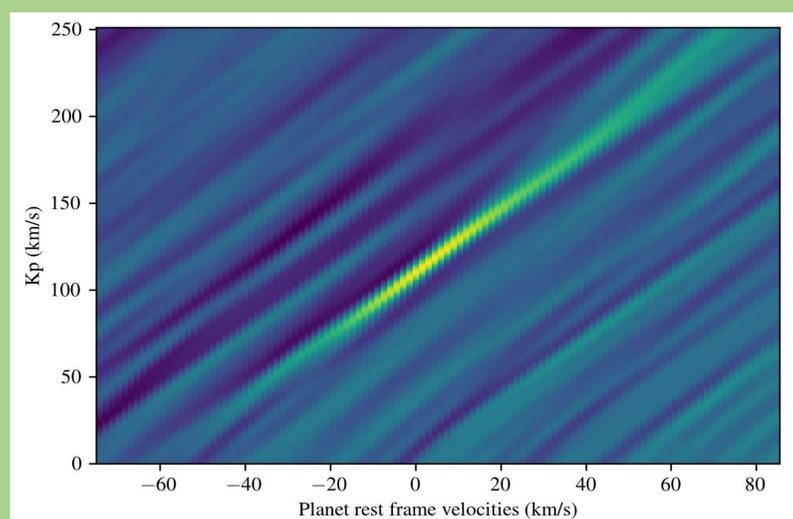

Figure 6: Velocity map of the recovered planetary signal. The injected signal is 10 times stronger than the original signal.