Chromospheric Semi-empirical Model of Proxima Centauri at Activity Cycle Extremes:

Reconstructing the Radiative Environment of Proxima b

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Stellar activity plays a fundamental role in determining the radiation environment and habitability of orbiting planets. Variations in stellar output, ranging from transient flares to long-term magnetic cycles, directly influence atmospheric chemistry, circulation, and potential biosignatures. Among cool stars, M dwarfs are especially active, showing strong magnetic fields and intense chromospheric emission in lines such as Ca II H&K (393 nm), Na I D1&D2 (580 nm), and the Balmer series (Hα, Hβ, Hϵ).

Proxima Centauri (M5.5Ve) is a key benchmark for understanding magnetic activity in active M dwarfs and its impact on the habitability of terrestrial exoplanets. Long-term studies report magnetic variability in Proxima Cen, but the proposed period depends on the dataset, diagnostic, and temporal baseline (Wargelin et al. 2017, 2024, Ibañez Bustos et al. 2025, Suárez Mascareño et al. 2025).

While long-term magnetic variability is well documented, the physical changes in its atmosphere remain poorly constrained.

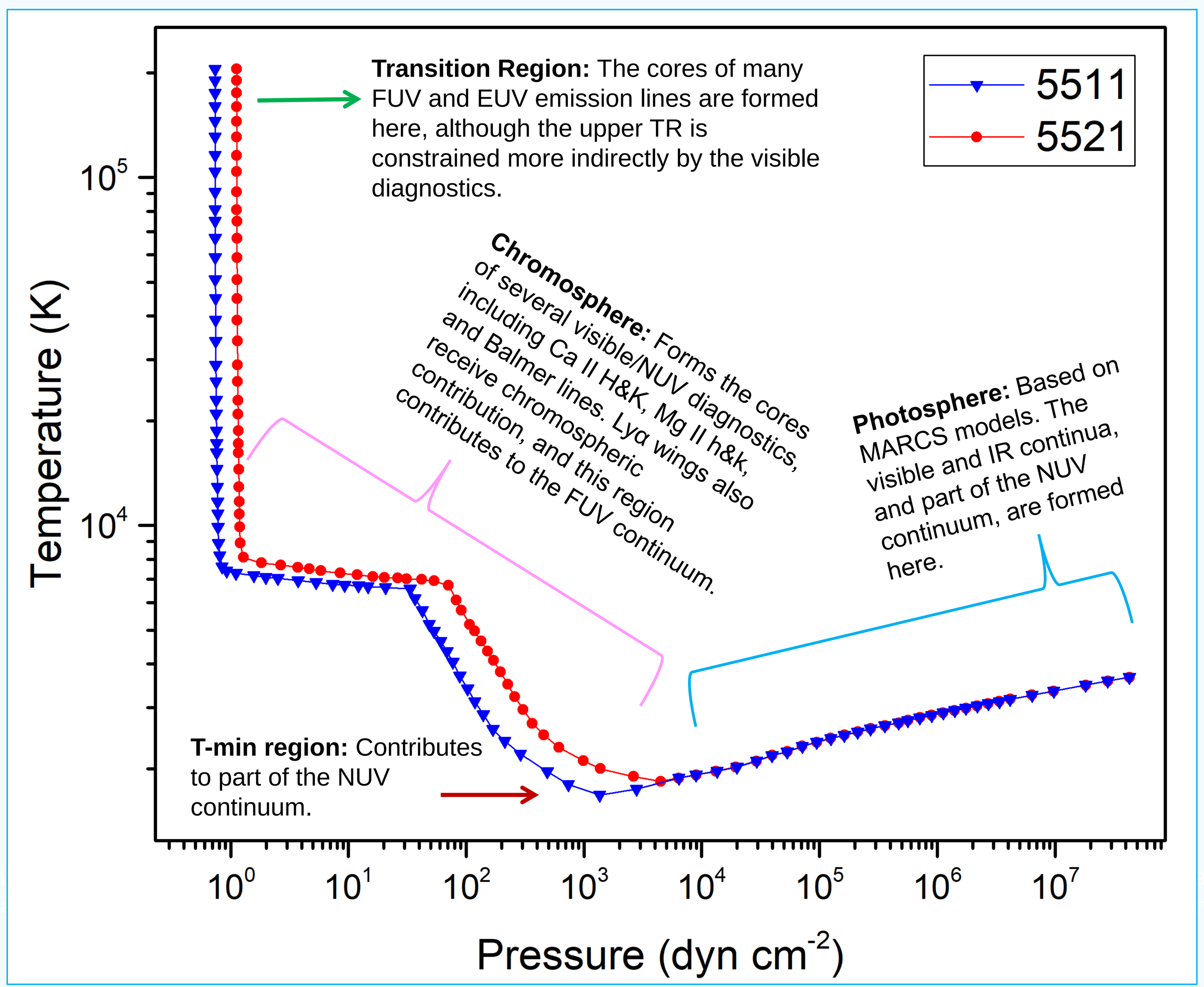
In this work, we present the NLTE semi-empirical modeling of Proxima Centauri's atmosphere at the minimum and maximum of its activity cycle to investigate the evolution of its chromospheric thermal structure. The ultimate goal of this research is to reconstruct the full spectral irradiance at the orbit of Proxima b to provide physically-grounded stellar forcing for future planetary climate and photochemical models.

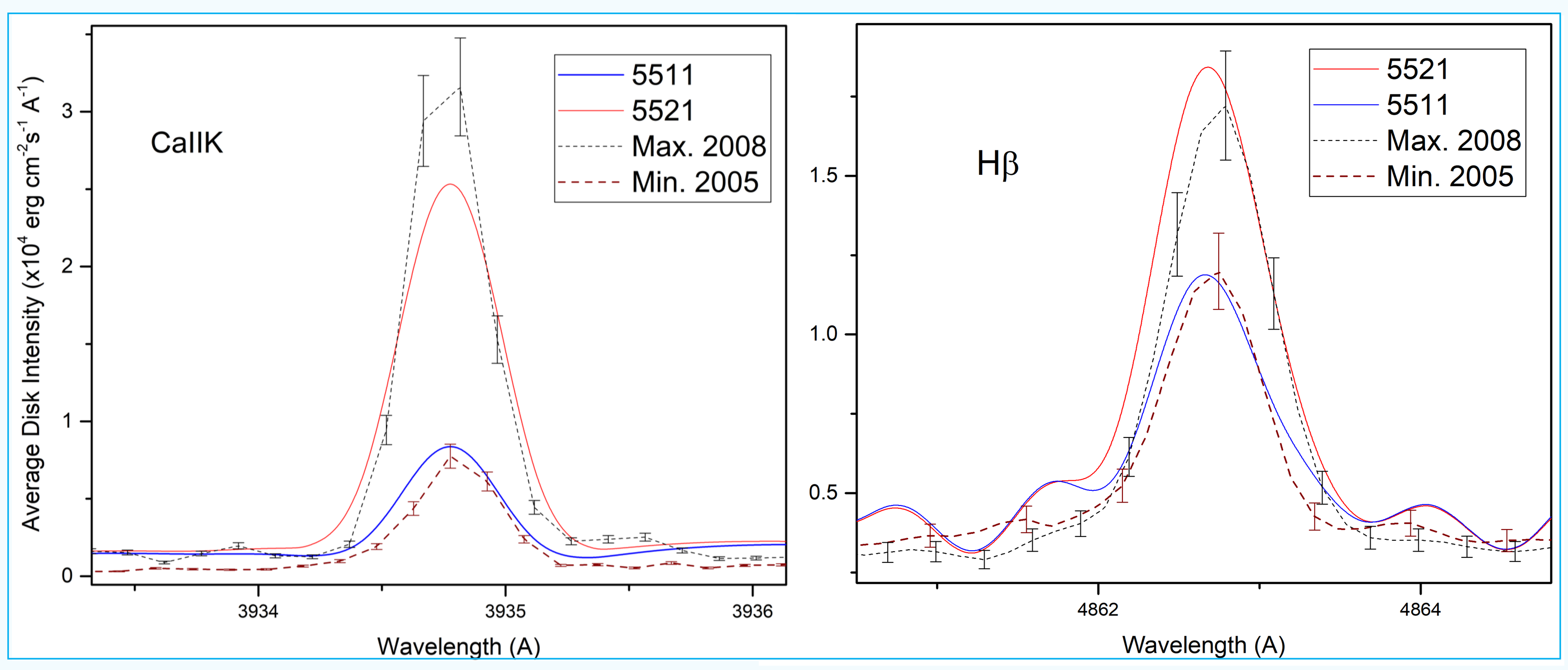
NLTE Atmospheric Models of Proxima Cen

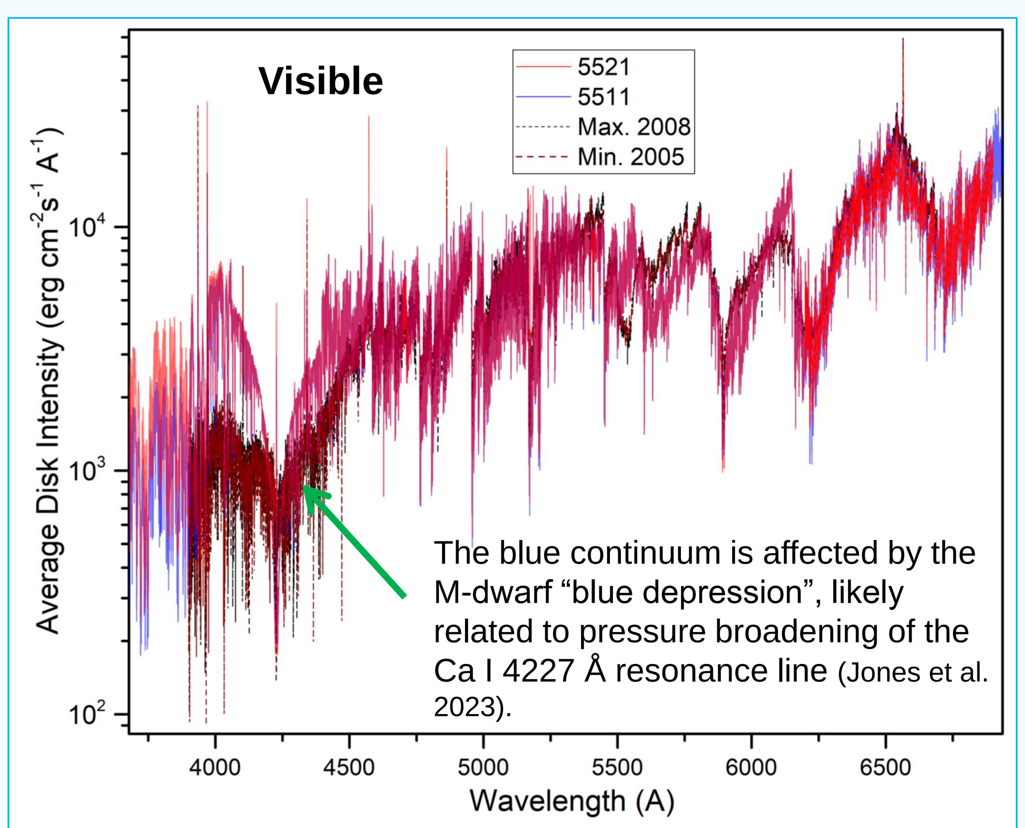
We use the **SSRPM code suite** to construct 1D semi-empirical models from the photosphere through the chromosphere and transition region (Fontenla et al. 2016, Tilipman et al. 2021). The thermal structure is adjusted until synthetic spectra reproduce the observed diagnostics.

- ✓ Full non-LTE treatment for key atoms and ions
- ✓ Extensive atomic + molecular opacity database
- ✓ Visible, UV, and X-ray constraints when available
- ✓ Contribution functions used to identify where lines form
- ✓ Computes unobservable FUV/EUV/Lyα spectra from a physical atmosphere

5511 and 5521 correspond to the minimum and maximum states, respectively





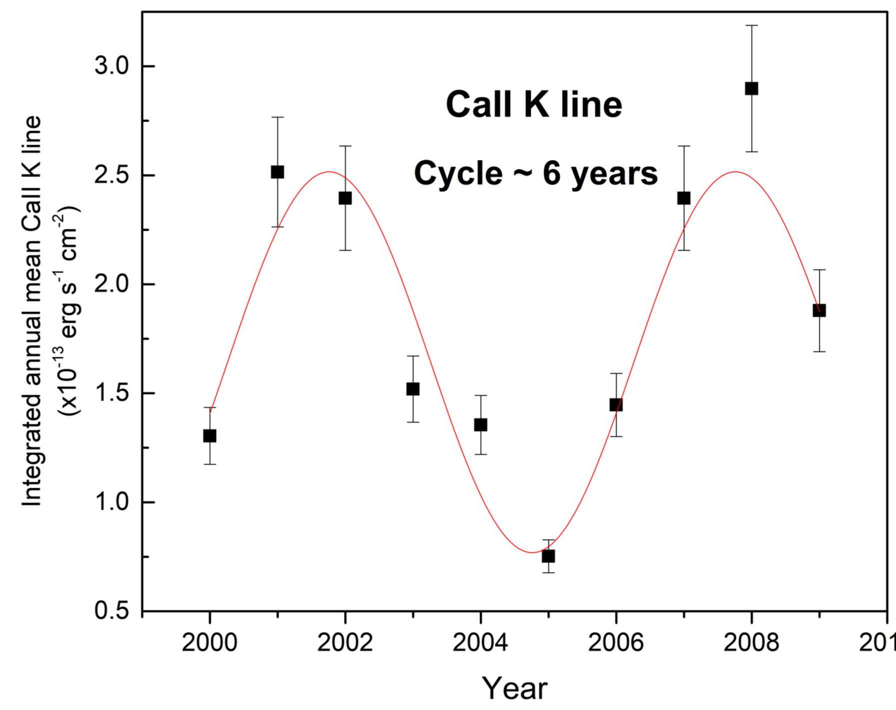


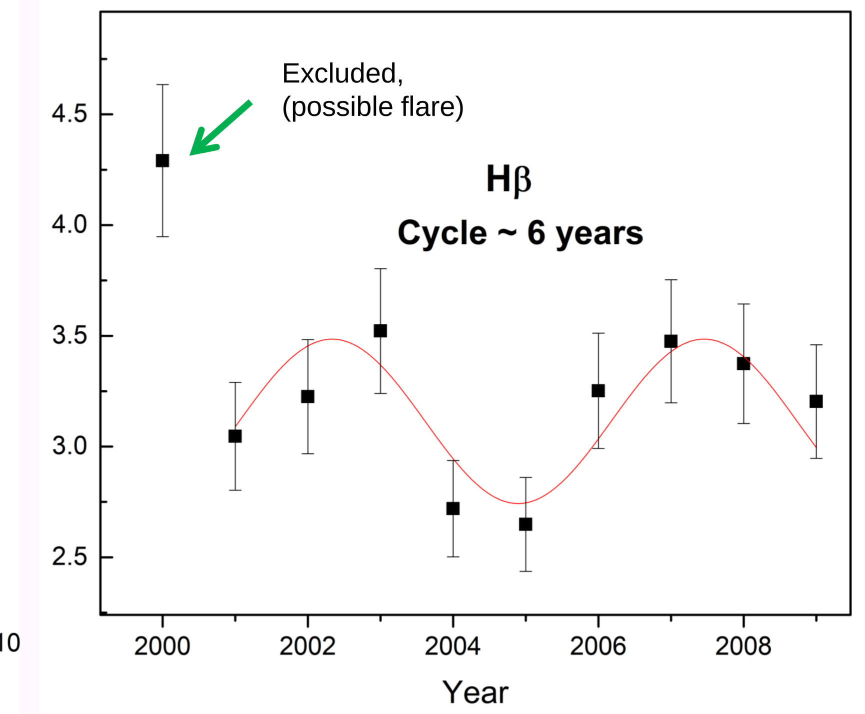
The minimum (5511) and maximum (5521) models differ mainly above the temperature-minimum region, where the chromosphere and transition region control Ca II K, Hβ, and the FUV/NUV emission. This structural change, rather than a uniform flux scaling, drives the wavelength-dependent SED response.

The model 5511 is already well constrained by Ca II K and Hβ.
The model 5521 is still under development: it captures the increase in Hβ but does not yet reproduce the full Ca II K peak.
Even at this stage, the model pair provides a preliminary estimate of how the flare-filtered SED changes between activity-cycle extremes.

Chromospheric Variability of Proxima Cen

We use annual-mean, **flux-calibrated visible spectra** of Proxima Centauri from the **HKα Project** (Buccino et al. 2024) obtained with the 2.15 m Jorge Sahade telescope **at CASLEO** (San Juan, **Argentina**) (R~13000). We model the observed flare-filtered chromospheric extremes in the spectra: the **minimum around 2005 and the maximum around 2008**.

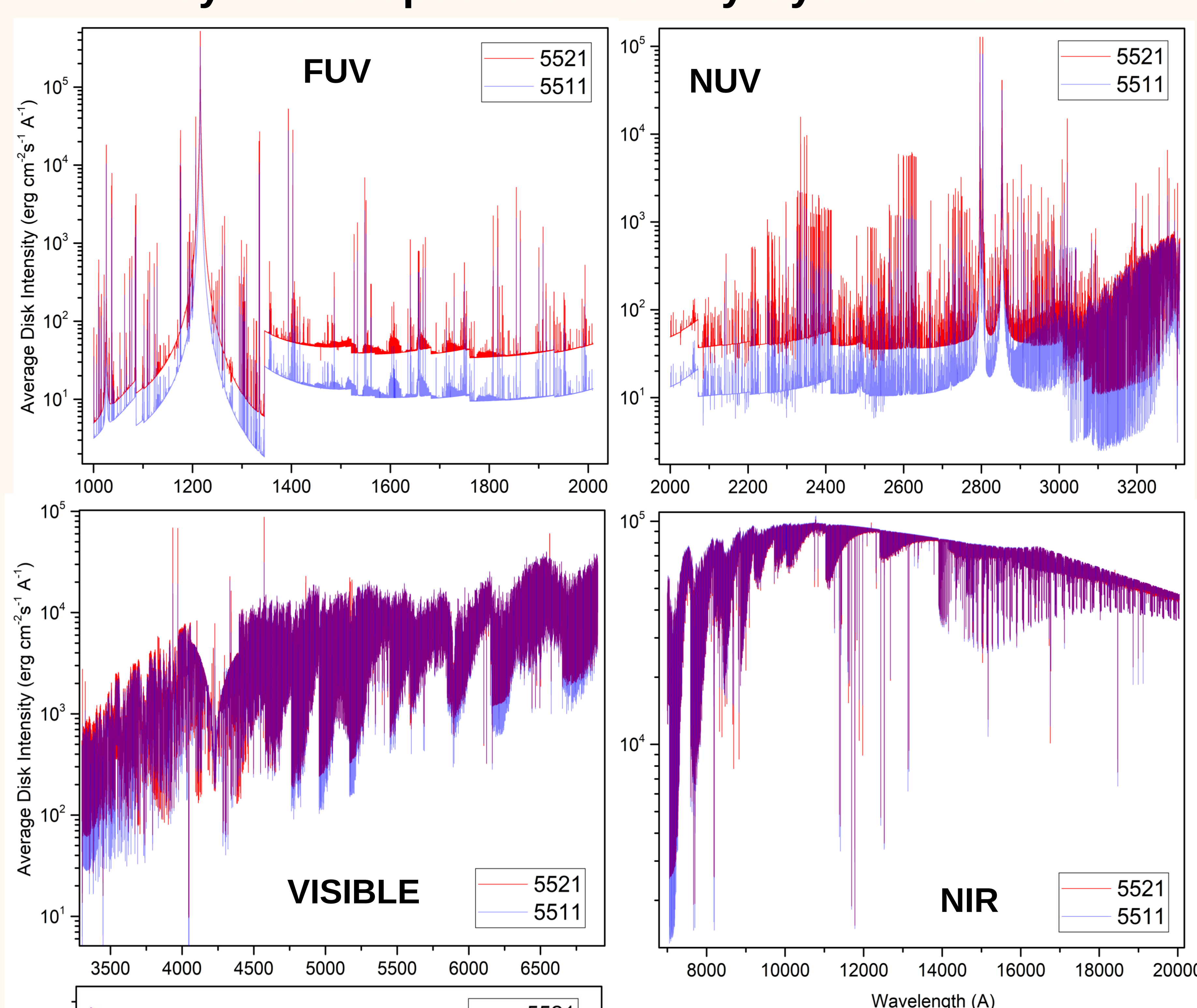


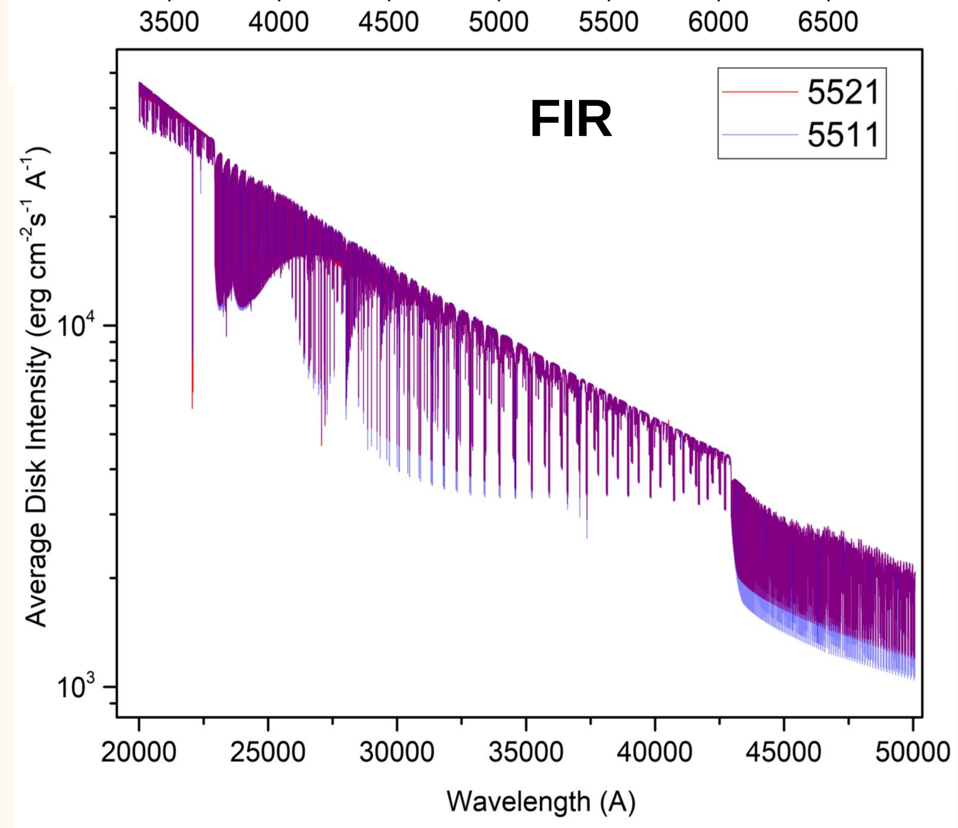


The Ca II K integrated flux shows a clear long-term modulation. The variation between these selected flare-filtered cycle extremes is 114%, making Ca II K the strongest observational constraint on the upper chromosphere in our dataset.

Hβ also varies across the cycle, but more moderately than Ca II K. Excluding the anomalous 2000 point, likely affected by residual flare contamination, Hβ varies by 58% between the selected cycle extremes. Hα shows a smaller variation than Hβ, suggesting saturation effects.

Synthetic Spectra at Activity-Cycle Extremes





The **5511–5521 comparison** shows a strongly wavelength-dependent response to activity. Atomic lines formed in the chromosphere and transition region change the most, especially in the FUV/NUV and in visible diagnostics such as Ca II K and Hβ, while molecular-band dominated red optical/IR regions are less affected. FUV predictions are more indirect, anchored by the visible diagnostics and guided by the nearly constant-pressure TR structure.

This is consistent with **Vieytes et al. (2025),** who found a non-uniform response of visible atomic lines to chromospheric heating in a dG2 star, with stronger effects toward the blue/violet optical range. These results highlight the need for activity-state-specific SEDs, rather than a single quiet or composite spectrum built from data obtained at different activity levels.

Take-away & Future Work

The activity cycle of Proxima Cen produces wavelength-dependent spectral changes, with the strongest response in chromospheric and transition-region lines. Our preliminary minimum/maximum models show that activity-state-specific SEDs are needed to describe the radiation environment of Proxima b.

Next steps are to refine the maximum model to better reproduce the Ca II K peak, compute the final flare-filtered FUV/NUV/EUV irradiance at Proxima b, and use these spectra as input for planetary climate and photochemical models.

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References

Buccino et al. 2024 BAAA , 65, 87 ; Fontenla et al. 2016 ApJ, 830, 154; Ibañez Bustos et al. 2025 A&A, 696, A230; Jones et al. 2023 MNRAS, 523, 1297; Suárez Mascareño et al. 2025 A&A, 700, A11; Tilipman et al. 2021 ApJ, 909, 61; Vieytes et al. 2025 ApJ, 981, 4; Wargelin et al. 2017 MNRAS, 464, 3281; Wargelin et al. 2024 ApJ, 977, 144.

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