Disentangling Planetary and Stellar Signals in Barnard's Star

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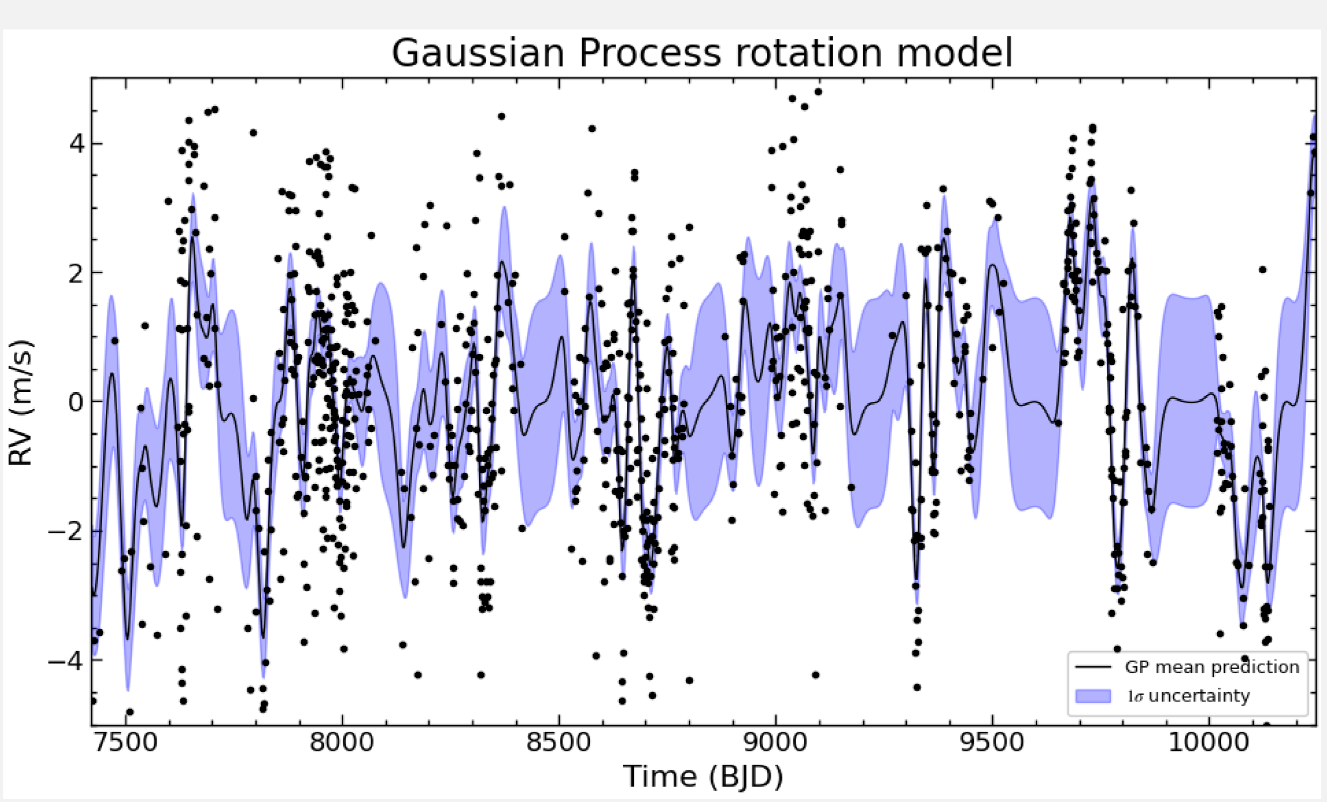
Introduction

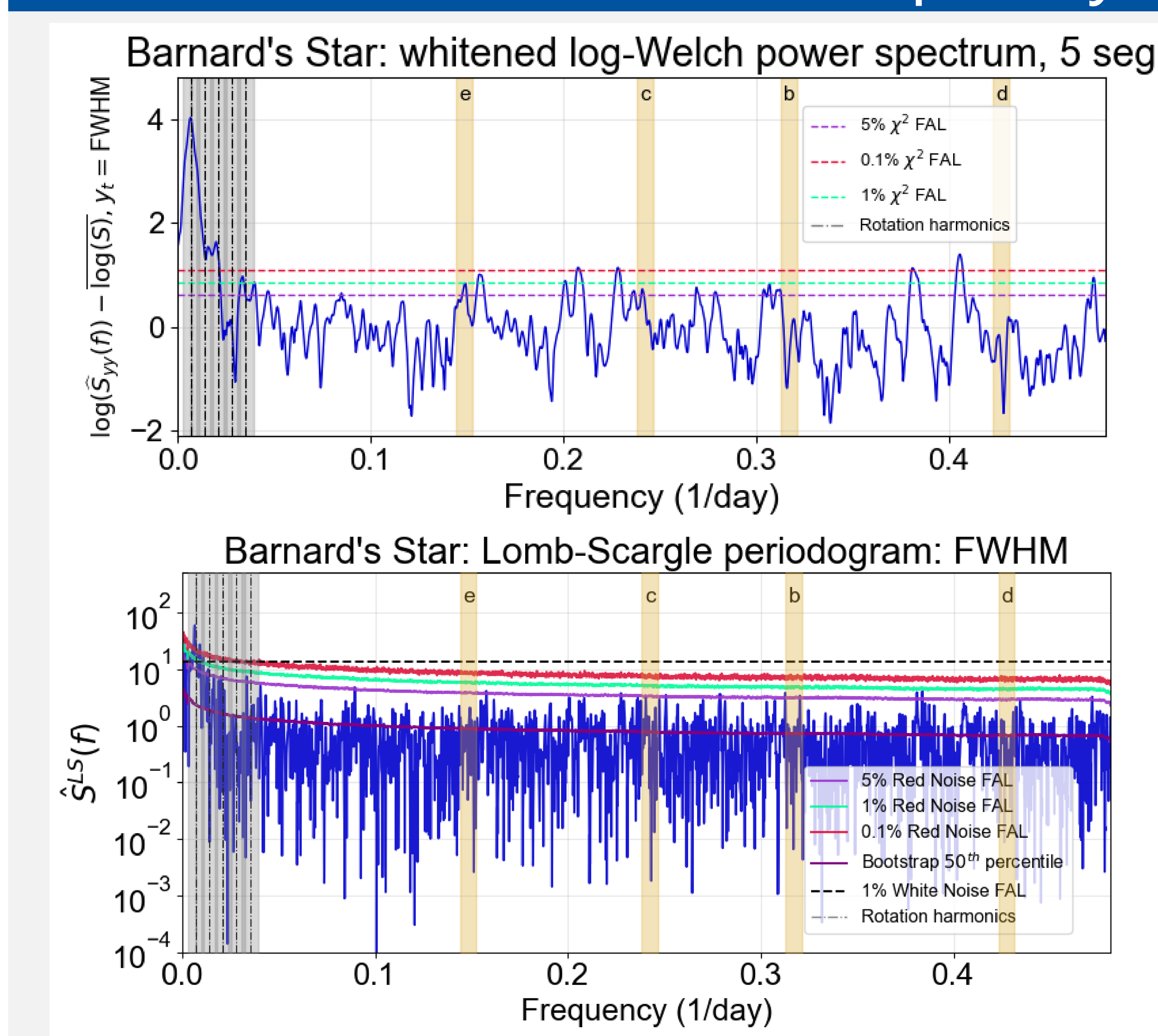
- Barnard's Star (GJ 699) is the second closest stellar system and the closest halo and single star to the Sun.
  - 2018: Ribas et al. reported the discovery of a super-Earth candidate ($3.2 M_{\oplus}, P = 233$ days).
  - 2021: Lubin et al. proved the planet to be an alias of the stellar rotation period.
  - 2024: González Hernández et al. reported the discovery of Barnard b, a short-period sub-Earth planet ($0.37 M_{\oplus}, P = 3.15$ days) and three additional candidates at orbital periods of 4.12, 2.34 and 6.74 d.
  - 2025: Basant et al. confirmed the existence of previous candidates Barnard c, d and e.
- Stellar activity creates velocity signals with high enough amplitude to either mimic or mask low-mass planet signals (Vanderburg et al. 2016).
- We analyze the stellar and planetary signals of Barnard's Star using multi-instrument RV and FWHM data to follow up on the planetary signals confirmed by Basant et al. (2025).
  - Data: ESPRESSO (2019-2023), CARMENES (2016-2020), HARPS (2016-2023), HARPS-N (2017) and MAROON-X (2021-2023).
  - Methods: Gaussian Process (GP), Markov-Chain Monte Carlo (MCMC), Magnitude-squared Coherence (MSC).
- High RV-FWHM coherence at the frequency of Barnard d and close to the frequency of Barnard e **indicate that more follow up is needed to establish that the signals are Keplerian.**

Stellar Activity/GP

- The most significant signals identified on the RVs and FWHM are the rotation, rotation harmonics and yearly aliases.
- We modeled the stellar rotation in the RV and FWHM data with an SHO kernel GP using `celerite2` (Foreman-Mackey, 2018). We implement Markov-Chain Monte Carlo (MCMC) to find the best-fit parameters.
- We find a best-fit rotation period $P = 133 \pm 8$ days, consistent with the reported results in the literature of 142 ± 9 days (González Hernández et al. 2024).
- We subtract the mean GP prediction and analyze the residuals.



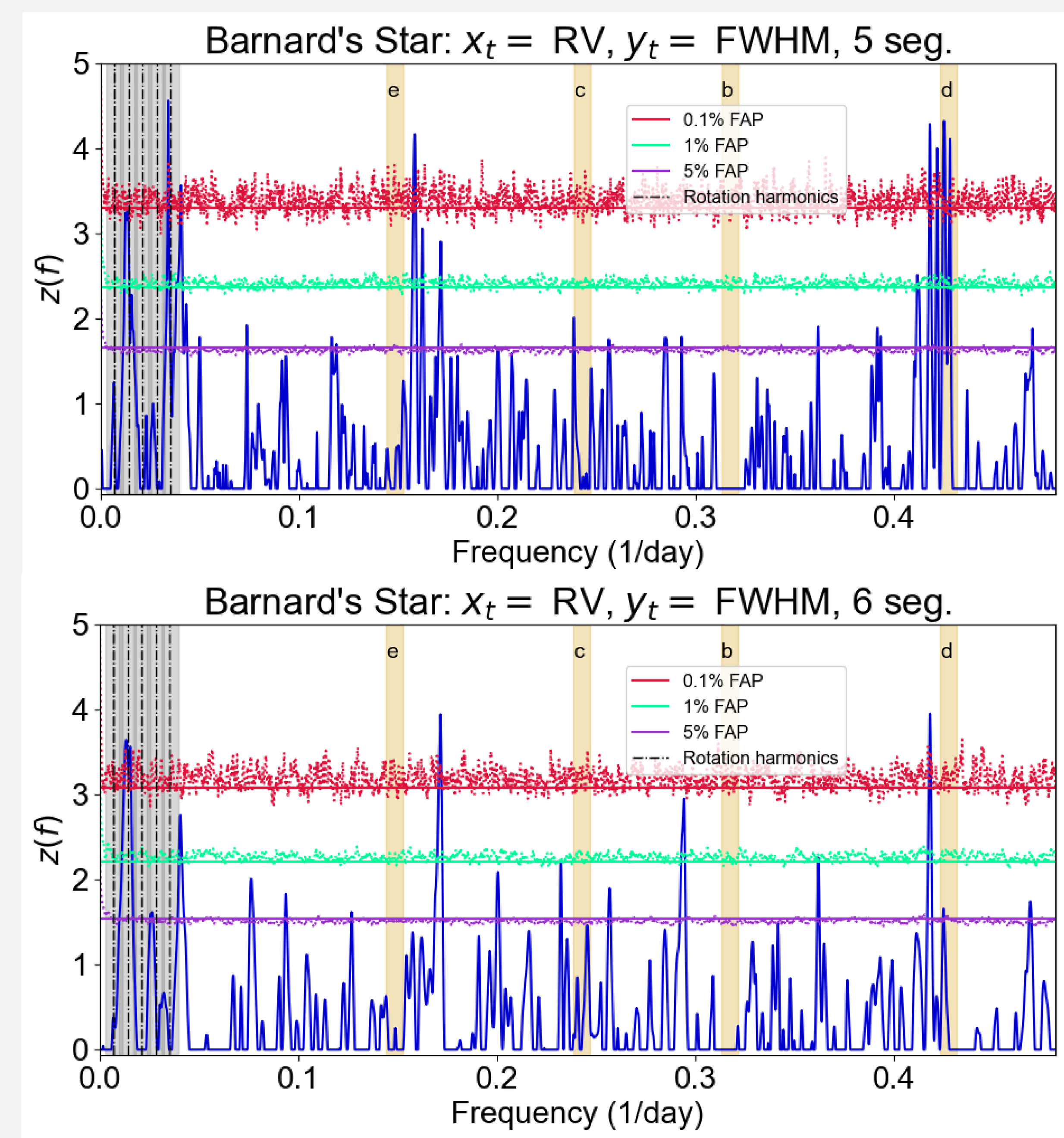
Frequency Domain Analysis



- We performed a preliminary analysis using `NWelch` (Dodson-Robinson et al. 2022). We computed Lomb-Scargle periodograms and Welch's power spectrum estimates to identify significant periodic signals in RV and FWHM data.
- Using χ^2 quantiles we detect a peak near planet e above the 1% FAL in the FWHM, and additional signals are found above the 0.1% FAL corresponding to 2.46, 2.62, 4.37 and 4.81d.
- Using red-noise based FALs (Ejaz et al. 2025), the peak near planet e and signals of planets c and b appear exceed the 5% FAL, and the signal at 2.62d peaks above the 1% FAL.

Magnitude-squared Coherence

- The magnitude-squared coherence $\hat{C}^2_{xy}(f)$is a frequency-dependent correlation coefficient that is sensitive to oscillations that are jointly traced by two time series (Dodson-Robinson et al. 2022).
- We calculate the magnitude-squared coherence between an activity-indicator and RV to look for shared signals between FWHM and RV using `NWelch`.
- We use Welch's method with a Kaiser-Bessel window varying the numbers of segments and combining data from different instruments.
- For 5 segments, we detected a peak above the 0.1% FAL at the frequency of planet d; another peak appears near planet e.
- For 6 segments, only the signal near planet d remains above the 0.1% FAL; there is no longer a peak near the frequency of planet e.
- No significant coherence is found at the frequencies of planets b and c.
- These results suggest that planets d and e might have a stellar origin but further follow up is required for validation.



Future Work

To further investigate the nature of the signals from planet d and e we will:

- Perform joint Keplerian + GP modelling.
- Incorporate additional activity indicators to assess coherences across more diagnostics.
- Conduct complementary photometric analysis for independent validation.

Conclusions

- High RV-FWHM coherence at the frequencies of Barnard d and near Barnard e suggest that the system requires further follow up. If coherence between RV and other activity indicators persist, that would indicate that the planets are stellar signals.
- Power spectrum analysis reveals statistically significant signals at the periods of all the planets, but red-noise diagnostics and FWHM raise doubts about the nature of signals from planets d and e.
- No significant coherence was found near planets b or c, suggesting they are not related to stellar activity.
- GP model with an SHO kernel estimates a stellar rotation period of ~133 days.

References: **[1] Dodson-Robinson S. E., Delgado V. R., Harrell J., Haley C. L., 2022,AJ, 163, 169.** **[2]** *Ribas I., Tuomi M., Reiners A., et al., 2018, Nature, 563, 365-368.* **[3]** *Lubin J., Robertson P., Stefánsson G., et al., 2021, AJ, 162, 61.* **[4]** *González Hernández J. I., Suárez Mascareño A., Silva A.M., et al., 2024, A&A, 690, A79.* **[5]** *Basant R., Luque R., Bean J. L., et al., 2025, ApJL, 982, L1.* **[6]** *Foreman-Mackey D., 2018, RNAAS, 2, 1.* **[7]** *Vanderburg, A., Plavchan, P., Johnson, J. A., et al. 2016, MNRAS, 459, 3565-3573.* **[8]** *Ejaz, A., Dodson-Robinson, S.E., 2025. In prep.*