Analysis of NIR activity indices for exoplanet detection and characterization

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Introduction

Stellar variability can impact planetary signals detected via the RV method. This is often addressed by tracking spectral lines sensitive to magnetic or/and temperature changes in the stellar atmosphere. With the growing use of NIR instruments like NIRPS [1], understanding NIR activity indicators is crucial, as their sensitivity may vary with stellar properties. We analyzed 18 new and already studied NIR lines in 20 M and K stars to identify the best ones for tracking stellar variability across different stellar characteristics, using simultaneous observations with HARPS and NIRPS spectrographs.

Observations, data and methods

We compiled effective temperature, metallicity, pEW(Hα) and rotation periods for all stars, either from the literature or using ODUSSEAS [2]. ACTIN [3, 4] was used to extract activity indices based on the Hα and Na I D lines in the visual range. These, along with the FWHM of NIRPS CCF, served as reference indicators for activity level and variability.

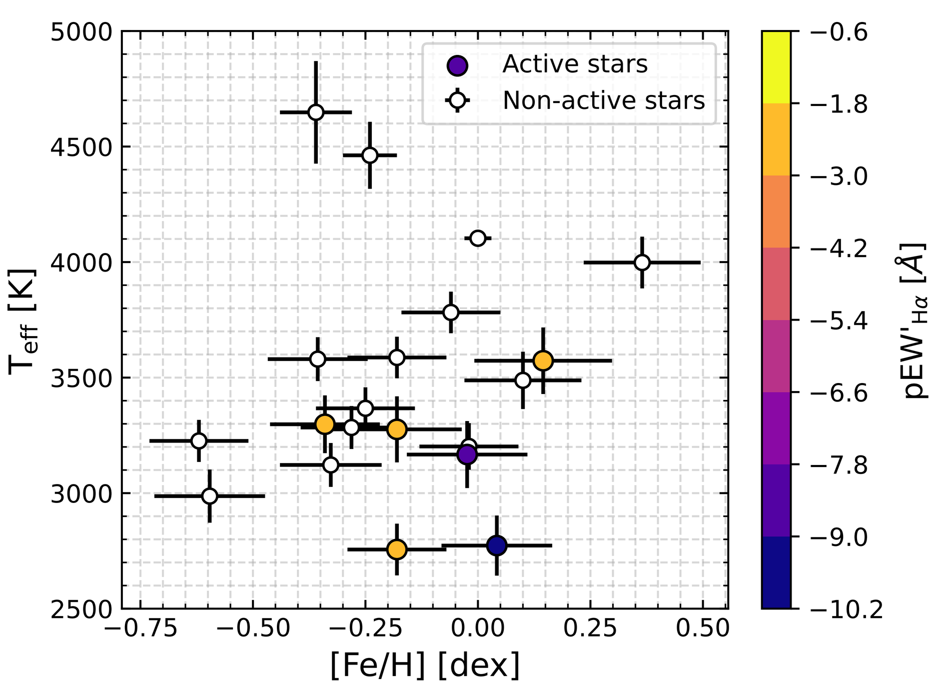

Figure 1. $T_{\rm eff}$ in function of [Fe/H]. Active stars were colored by the pEW(Hα) for visualization.

Table 1. NIR spectral lines used. Wavelengths are in vacuum. The ones in bold are new possible activity indices from [5].

Line center [Å]	Species	ID
10 498.989	Ti I	Ti I (a)
10 831.866	He I	He I (a)
10 833.347	He I	He I (bc)
11 693.408	Fe I	Fe I (a)
11 772.862	K I	K I (a)
11 786.493	Fe I	Fe I (b)
11 831.409	Mg I	-
11 887.328	Fe I	Fe I (c)
12 435.647	K I	K I (b)
12 525.544	K I	K I (c)
12 821.57	Paβ	-
12 825.181	Ti I	Ti I (b)
12 903.289	Mn I	Mn I (a)
13 127.011	Al I	Al I (a)
13 154.345	Al I	Al I (b)
13 322.609	Mn I	Mn I (b)
15 061.205	Ca I	-
17 701.335	Unidentified	Unid.

The activity indices based on the 18 NIR lines were also computed with ACTIN. The reference bands, $R_{1,2}$, used as continuum were defined as to minimize the correlation between I and R_1/R_2. We used different central bandpasses from 0.1 Å up to a defined maximum. We computed Spearman correlation coefficients between the NIR indices and the reference indicators and GLS periodograms, to recover the stellar rotation period [6].

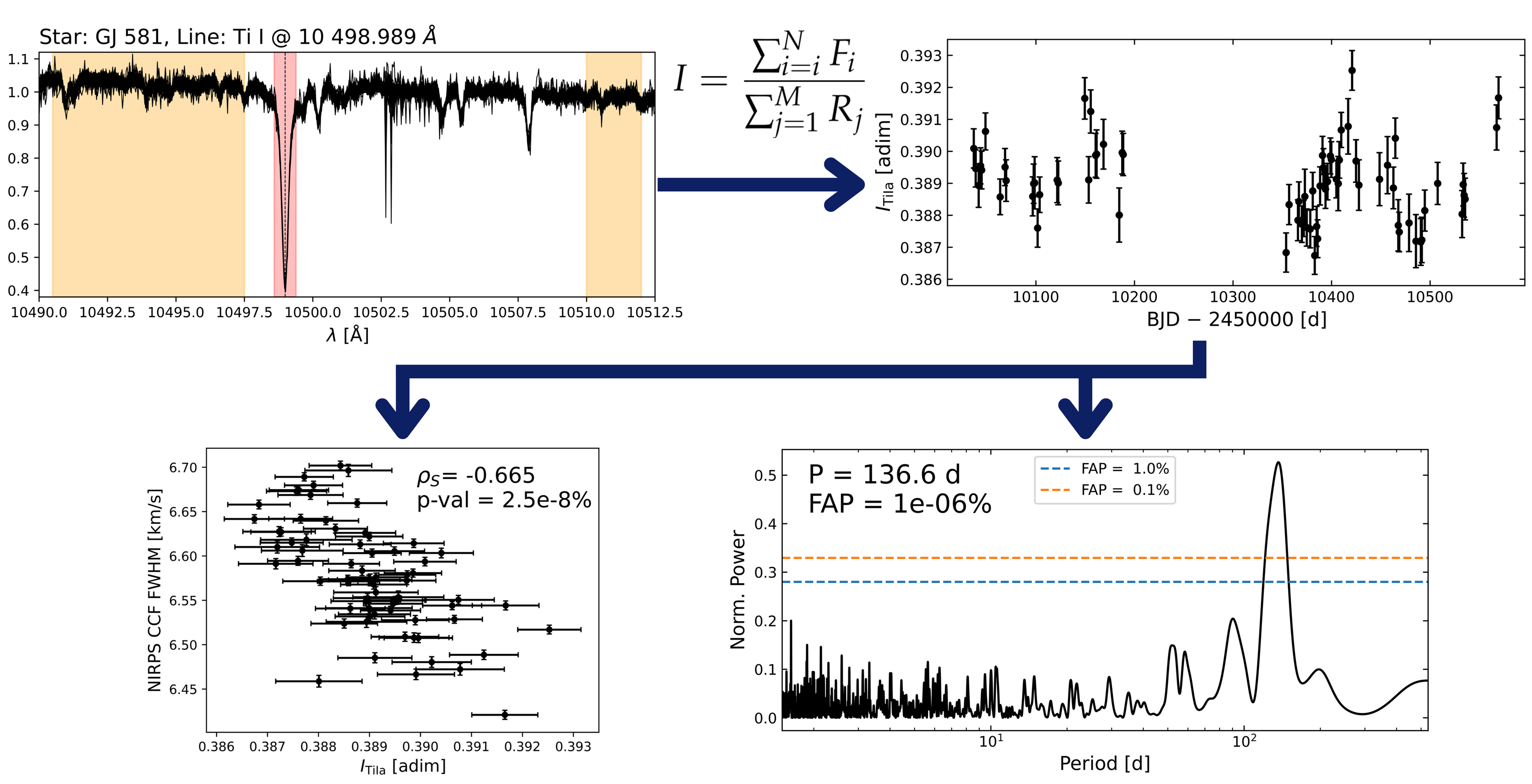

Figure 2. Methodology schematic, applied to Ti I (a) observations of GJ 581, using a central bandpass of 0.8 Å. After obtaining a time-series, we compute ρ_S with reference indicators and the GLS periodogram.

Testing NIR activity indices

A correlation with any reference indicator is considered strong if $|\rho_S| \geq 0.4$ and p-value < 0.1%. The $P_{\rm rot}$ is considered detected if FAP < 0.1% and within an interval defined taking into account periods in the literature and in the reference indicators periodograms. For each NIR indice, we defined two types of central bandpass:

- "Overall": same bandpass applied to all stars, defined through a voting system with the counts of stars with strong correlations with reference indicators or $P_{\rm rot}$ detected;
- "Optimal": one bandpass that shows the strongest significant correlation witn any reference indicator and another that detects $P_{\rm rot}$ with the lowest FAP.

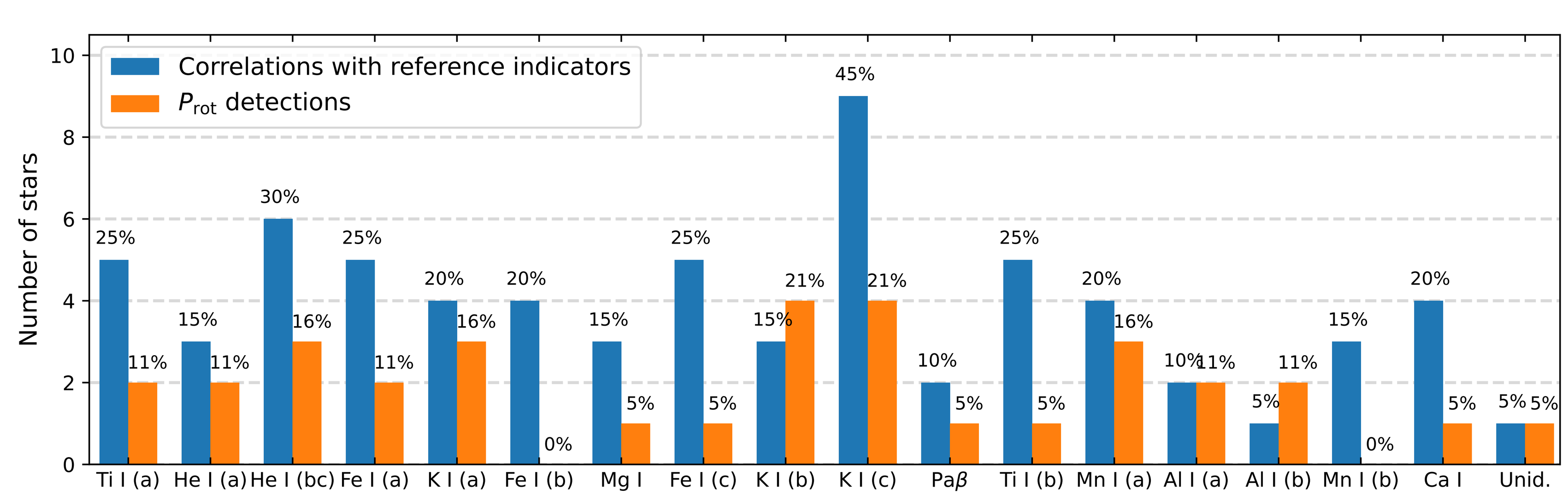

Figure 3. Number of stars where the NIR indice has strong correlation with at least one reference indicator or detects $P_{\rm rot}$. One star was not considered in $P_{\rm rot}$ detections. Central bandpass: "overall".

Optimizing the central bandpass increased correlations and $P_{\rm rot}$ detections.

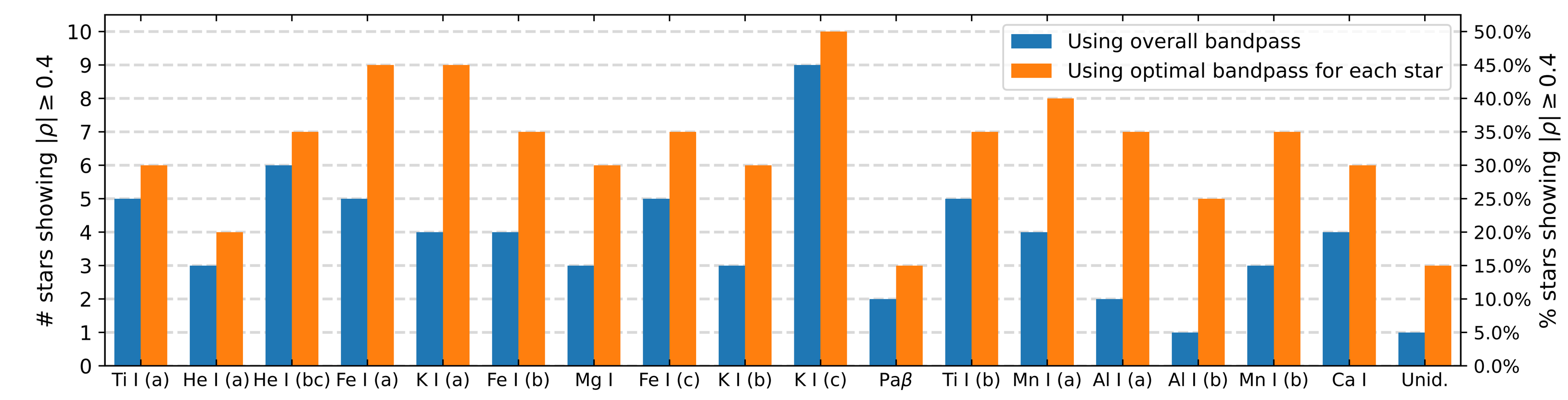

Figure 4. Comparison of number of stars showing a strong correlation with any of the reference indicators, using the overall bandpass or the optimal for each star.

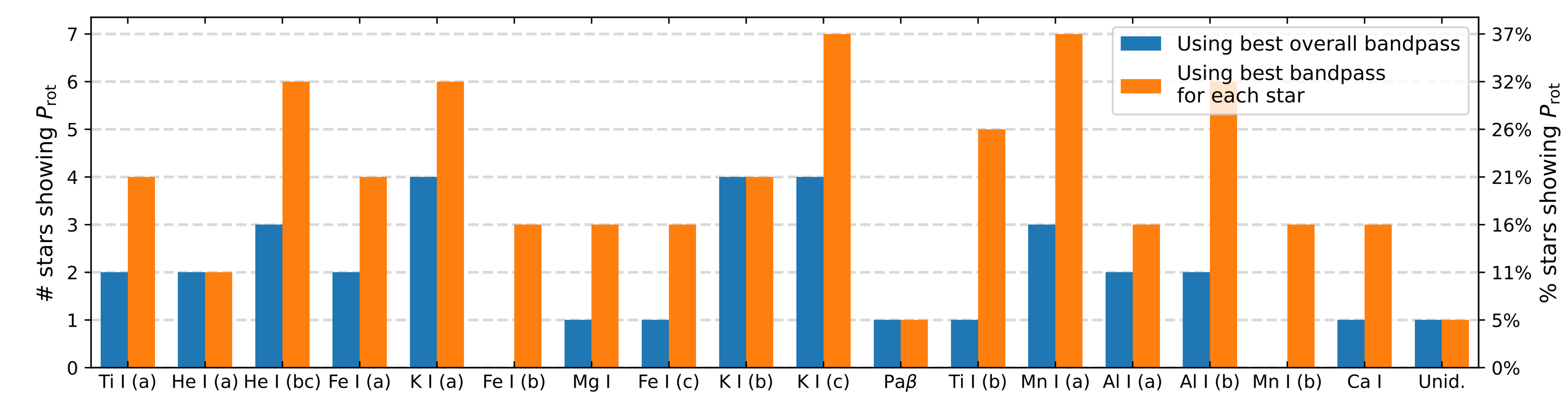

Figure 5. Comparison of number of stars where $P_{\rm rot}$ was detected with each NIR indice, using the overall bandpass or the optimal for each star.

We divided the sample in 8 sub-samples. Factors that highly increase $P_{\rm rot}$ detection rates include higher Hα activity, lower $T_{\rm eff}$, high number of observations and detecting $P_{\rm rot}$ in the reference indicators.

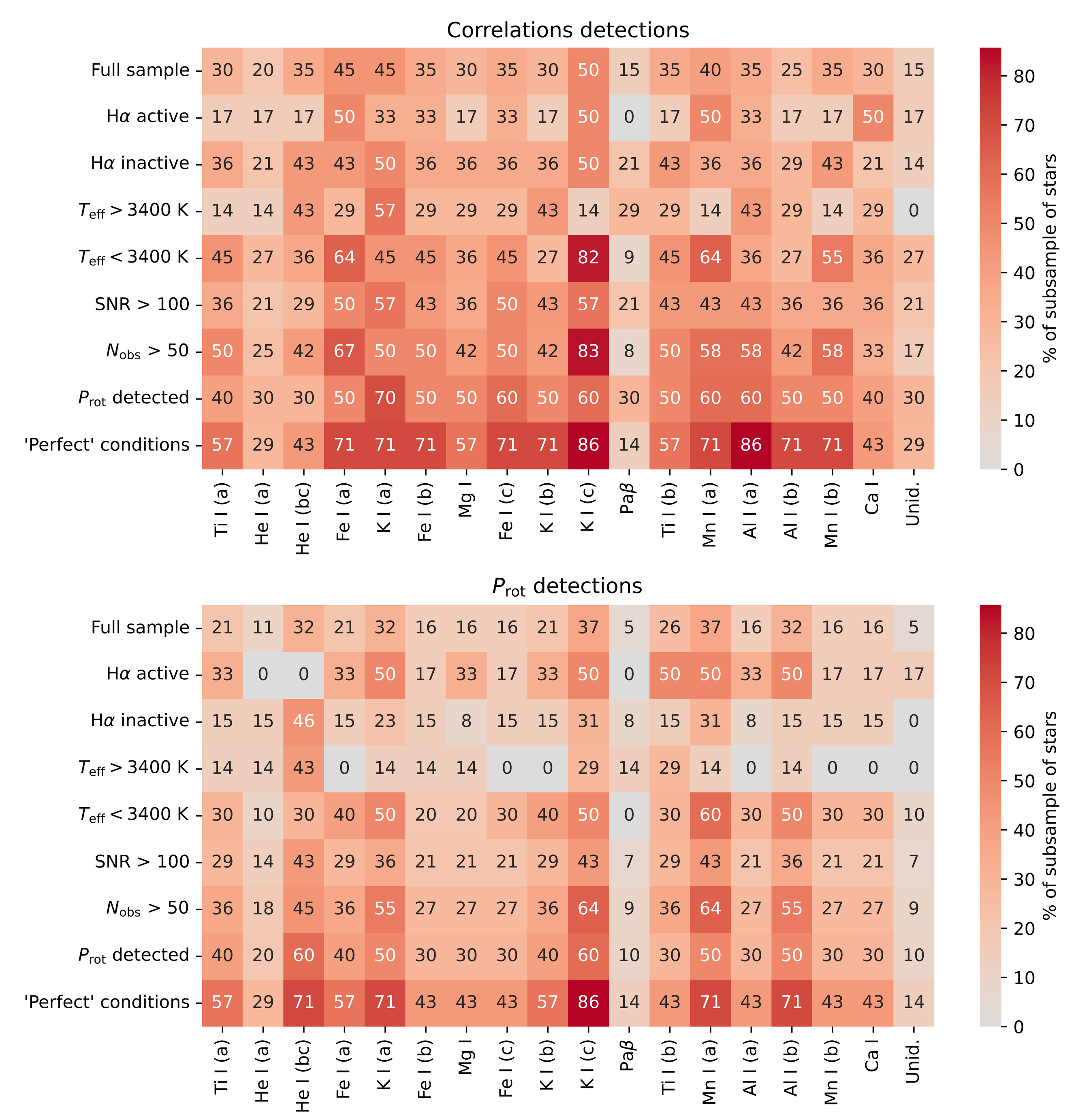

Figure 6. Fraction of stars showing strong correlations with any reference indicators or $P_{\rm rot}$ detections with each NIR indice for all subsamples tested. "$P_{\rm rot}$ detected" refers to reference indicators and "Perfect conditions" is the combination of the previous three conditions.

AMATERASU

Open source Python tool to identify potential activity-related periodic signals.

- Given a user-defined input period, the tool computes the pEW of spectral lines in a normalization-independent way, using different central bandpasses.
- Cleans data and runs GLS periodograms, following a process similar to shown in fig. 2;
- Spearman correlation analysis is also integrated.

Although developed with NIR absorption lines in mind, AMATERASU is flexible and can be applied to visual spectra. It offers a fast, user-friendly and low-input method to explore whether observed periods, such as those detected in RV, may be related to stellar activity.

Conclusions

- A 0.6 Å central bandpass for Hα is optimal for both M and FGK stars [7].
- No single NIR indicator consistently traced activity across all stars, but several were effective for specific stellar parameter and observational ranges.
- Selecting the optimal indicator case by case, with individual central bandpass optimization, improves results, but limits generalization.
- We developed AMATERASU, a tool for easy extraction and analysis of pEW-based activity indices with varying central bandpasses, with performance similar to ACTIN.

References

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