The Search for an Earth Analog

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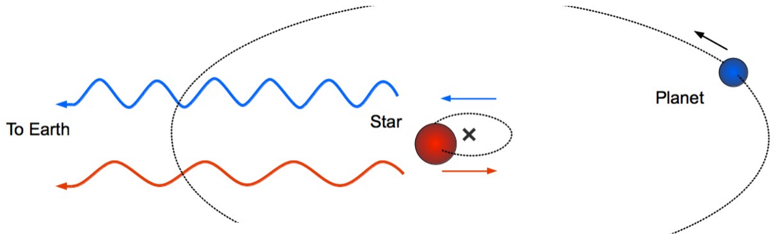
Editors: Jessi Cisewski-Kehe, David Hogg, Vinay Kashyap, Aneta Siemiginowska

Overview

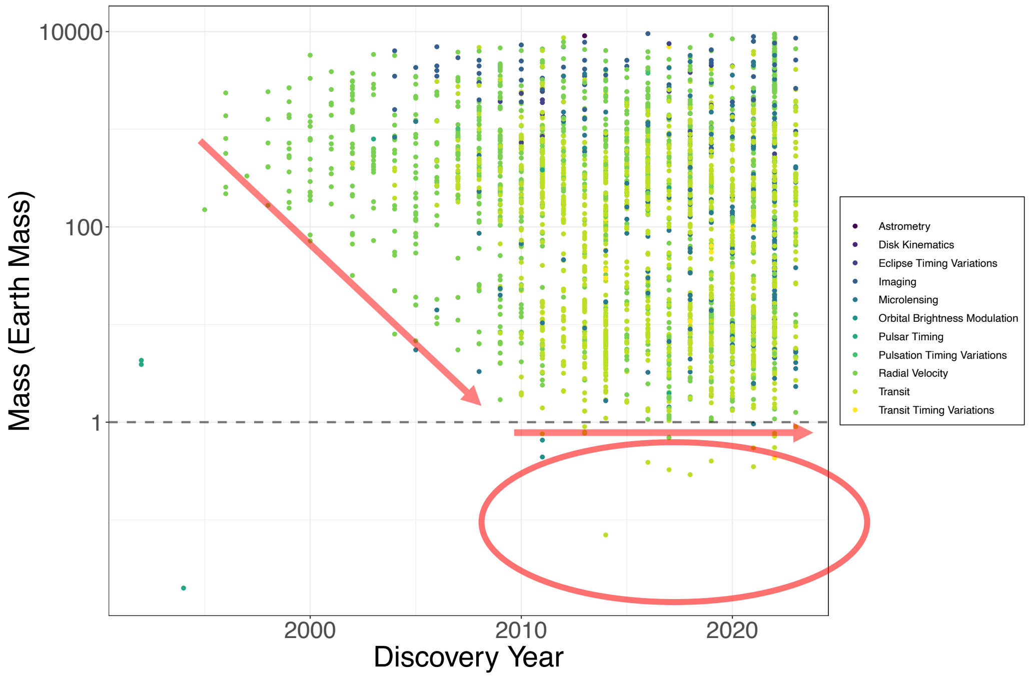
- Our goal is to find low-mass exoplanets such as Earth analogs
- I focus here on the radial velocity (RV) method used to detect exoplanets
  - The RV Method looks for the wobble of a star due to orbiting exoplanet(s)



Issues:

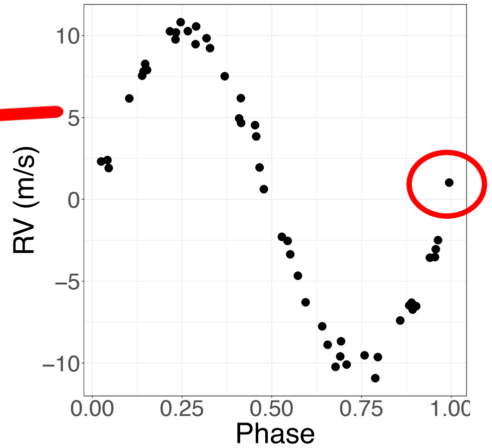
- Low-mass exoplanet signals are hard to detect because they are small
- Stellar activity can cause problems (such as false detections)

Data source (2023-05-23): https://exoplanetarchive.ipac.caltech.edu/

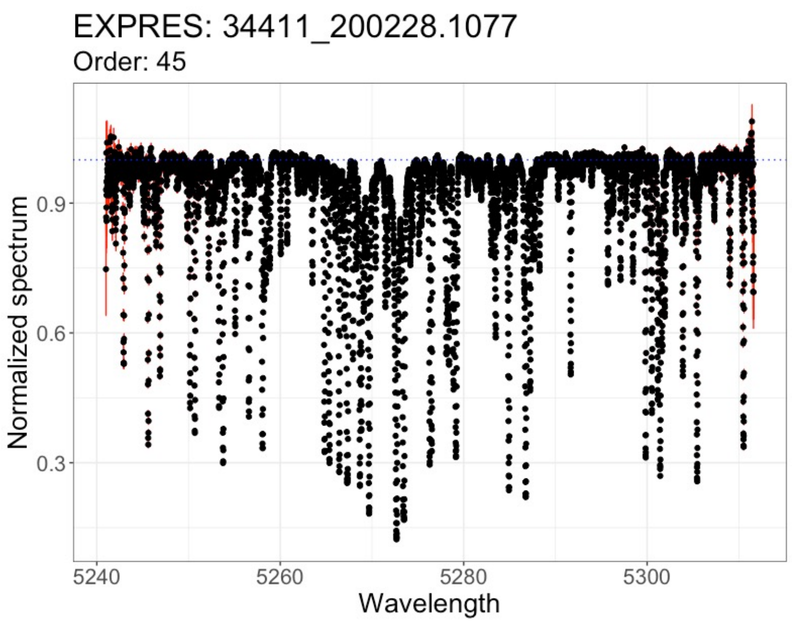


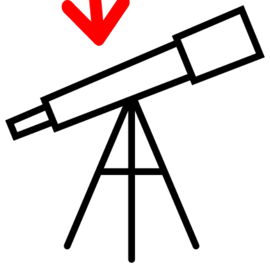
RV Pipeline

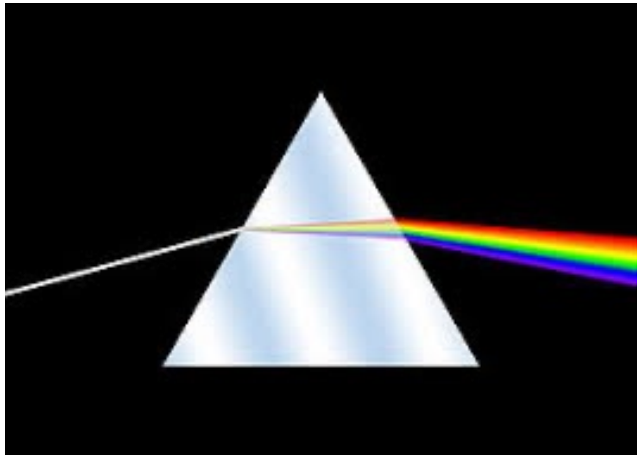
$$v_r(t) = K\left(e\cos\omega + \cos(\omega + \phi(t))\right) + \gamma$$

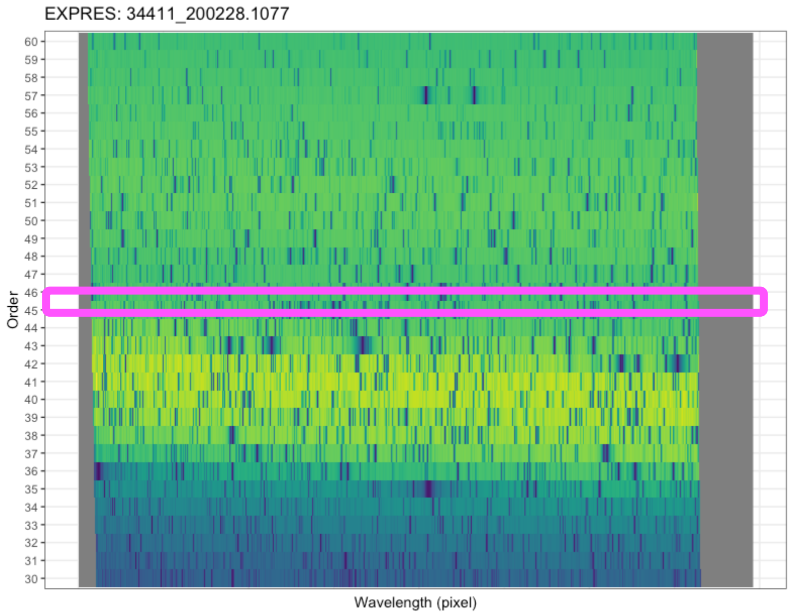


$$\frac{\lambda - \lambda_0}{\lambda_0} \approx \frac{v_r}{c}$$





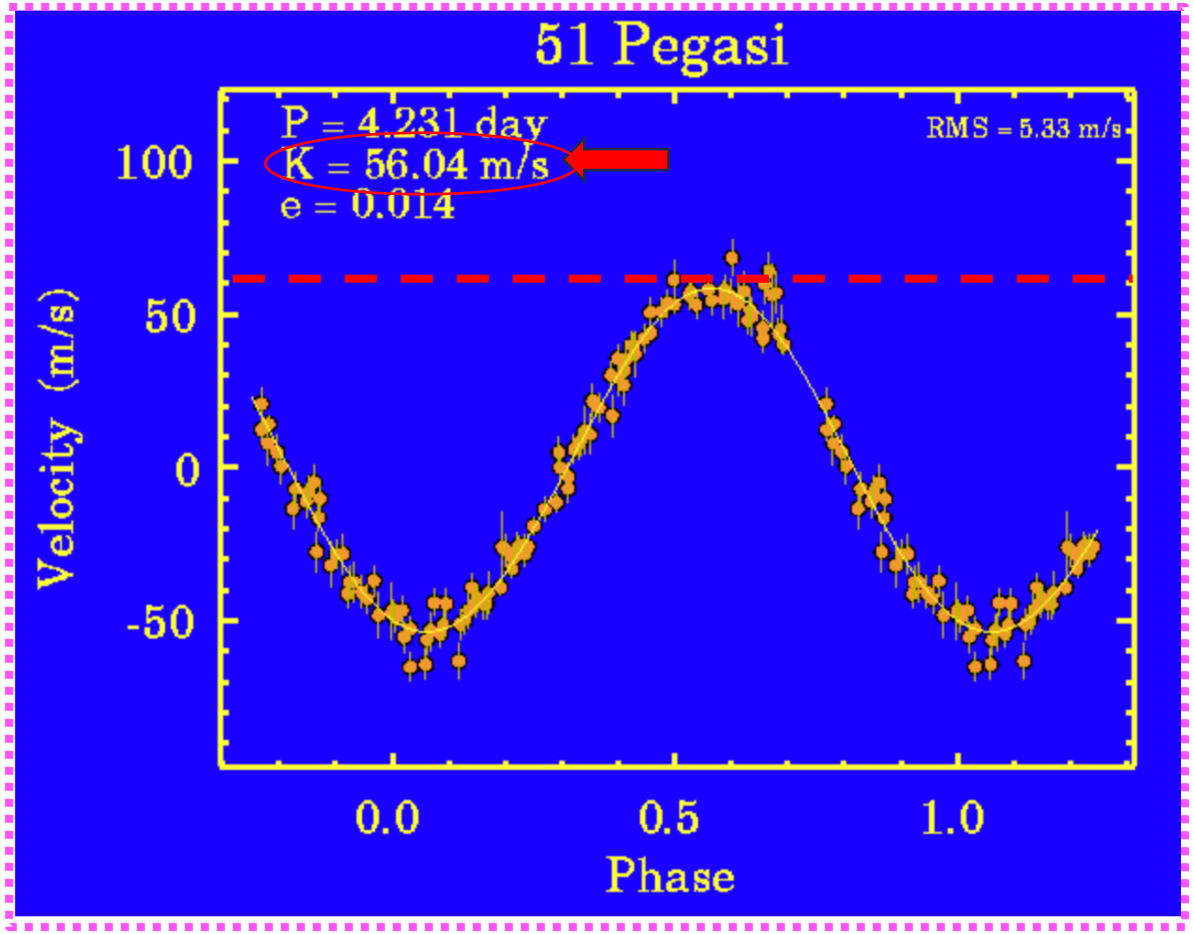




Data reduction pipeline
Wavelength solution
Blaze function
Barycentric correction
Telluric corrections
Etc.

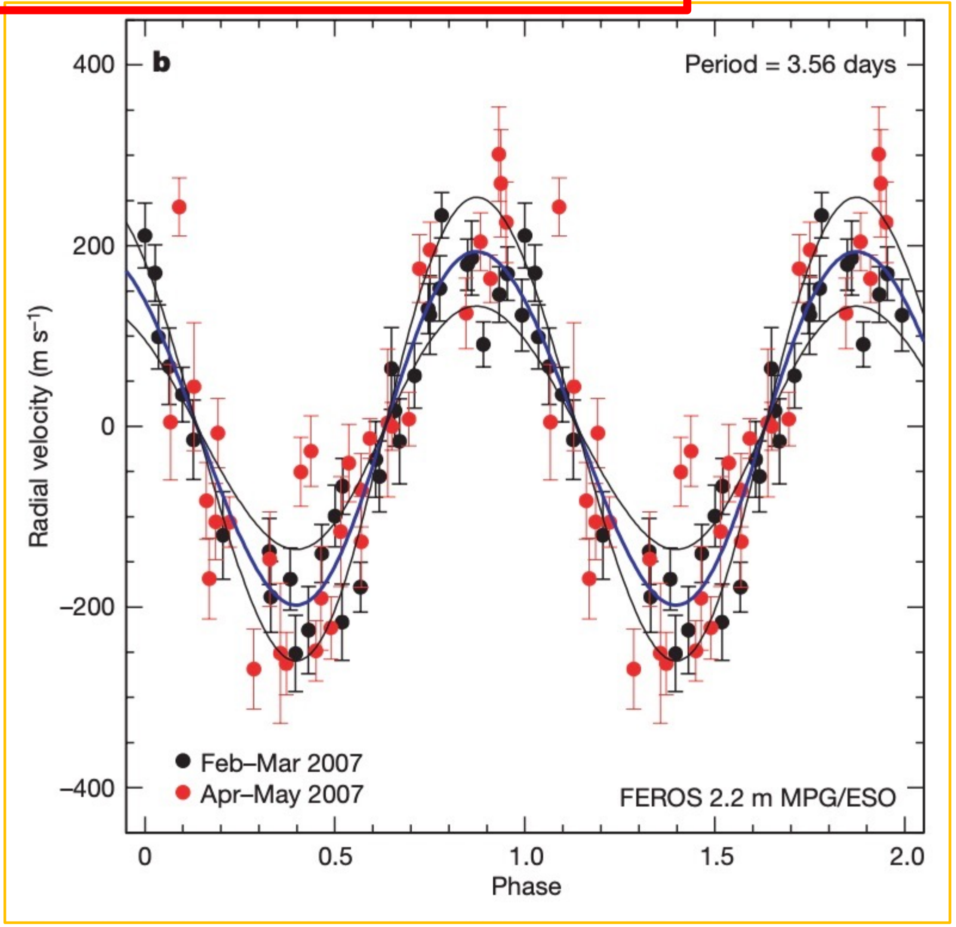
Slide design inspired by slide by Megan Bedell (Flatiron/CCA)

Planet Signal



- 51 Pegasi b was first exoplanet discovered orbiting a Sun-like star (Mayor+Queloz, 1995)
- Semi-amplitude of RV curve ~56 m/s; Estimated mass ~150 Earth masses

False Detection



- Original: Setiawan+2008. A young massive planet in a star–disk system. *Nature*, *451*(7174), pp.38-41.
- Follow up: Huélamo+2008. TW Hydrae: evidence of stellar spots instead of a Hot Jupiter. Astronomy & Astrophysics, 489(2), pp.L9-L13.

9 cm/sec

Small Signal

Planet	Mass (M_{Earth})	Radius (AU)	Period	RV (m/s)
Mercury	0.06	0.4	88 days	<0.01
Venus	0.82	0.7	225 days	0.08
Earth	**1**	**1**	**365 days**	**0.09**
Mars	0.1	1.5	687 days	<0.01
Jupiter	318	5.2	11.9 years	12
Saturn	95	9.5	29.45 years	2.75
Uranus	14.5	19.2	84 years	0.3
Neptune	17.2	30.1	165 years	0.28
(Pluto)	0.002	39.5	248 years	0.00003

The RV of the Sun due to the Earth is approximately 9 cm/sec

The width of one (high-resolution) spectrum pixel spans about 500 m/s

- Jupiter would shift the solar spectrum by 0.024 pixels
- Earth would shift the solar spectrum by 0.00018 pixels

Extreme Precision Radial Velocity (EPRV)

ELODIE (spectrograph used in the 51-Pegasi b discovery) had a precision around 15 m/s and resolution of 42,000

→ sufficient for discovery of large exoplanets, but not exo-Earths (Mayor and Queloz, 1995; Baranne+1996)

Next-generation spectrographs are more stable instruments with higher resolution and higher signal-to-noise ratios (SNR)

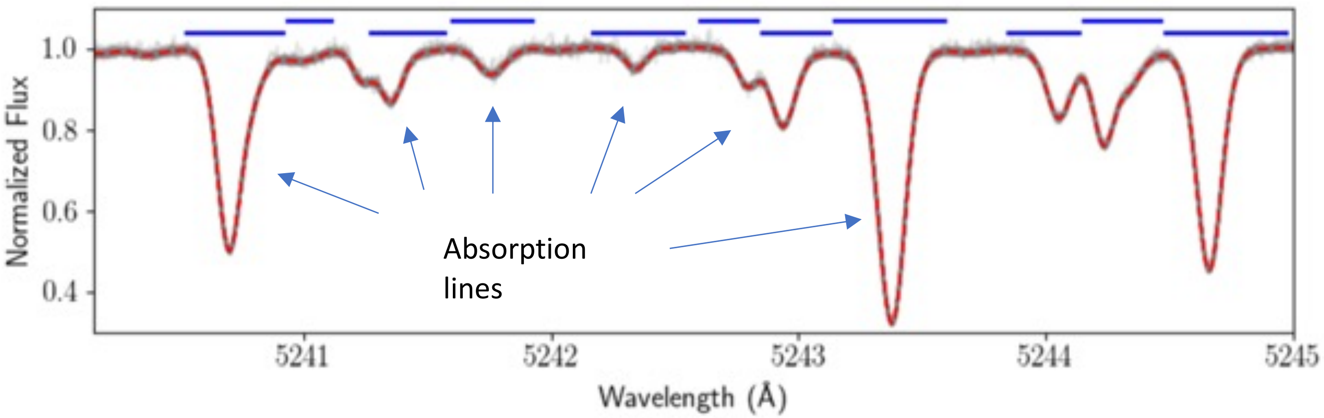
→ initiated field of EPRV research (e.g., EXPRES, NEID)

EXtreme PREcision Spectrometer (EXPRES) built by Debra Fischer (Yale) and her team (Jurgenson+2016)

→ EXPRES has demonstrated instrumental RV precision <10 cm/s (Blackman+2020)

→ On-sky, on-star measurement precision of at least 30 cm/s (Petersburg+2020) in spectra with per pixel SNR of 250

New instruments have potential to uncover small signals.



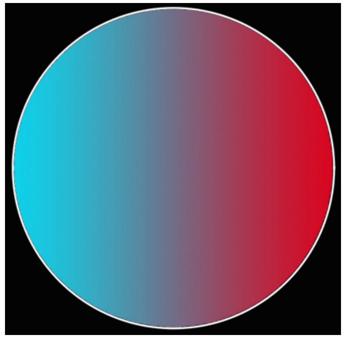
indicate absorption lines detected by an algorithm proposed in Holzer+ (2021).
Note: The full spectrum goes from 4470–6800 Å.
Image credit: Holzer+2021

What is the problem?

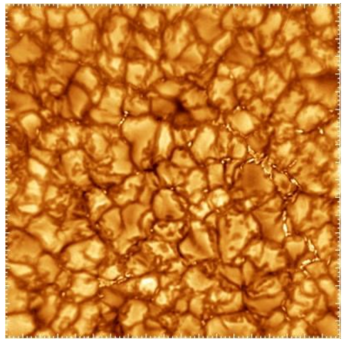
EPRV instruments can measure small RV planetary signals, but the high precision also picks up other astrophysical effects (e.g., photospheric activity like spots)

These can obscure any true planetary signal or even mimic planetary signals leading to false detections (Queloz+2001; Desidera+2004; Desort+2007; Robertson+2014)

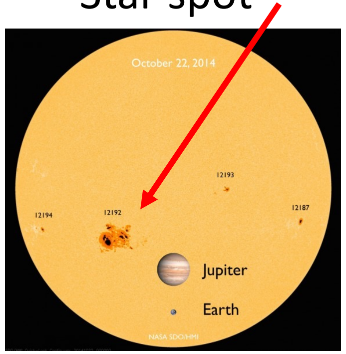
Rotation

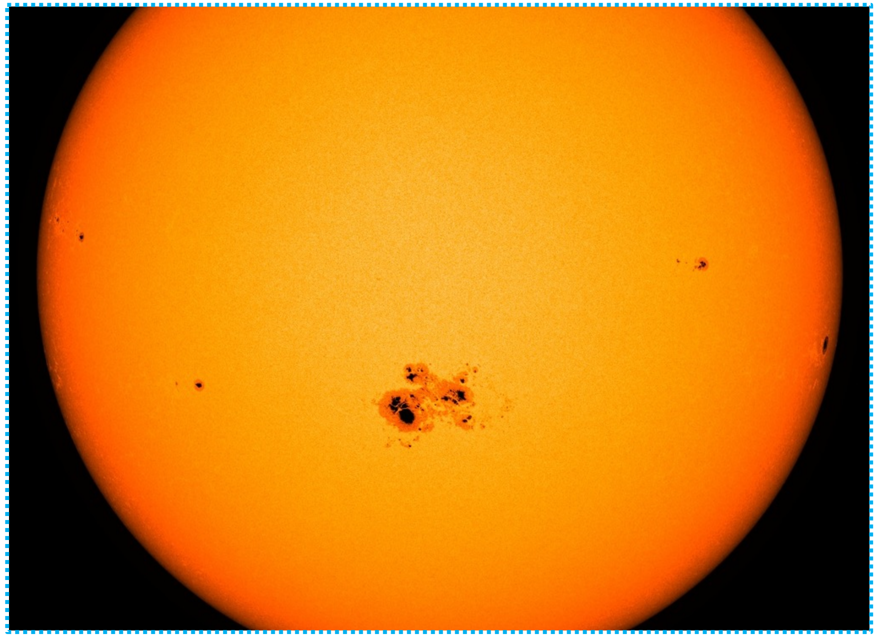


Granulation



Star spot





Activity image credit (L to R): Xavier Dumusque (Geneva); BBSO/NJIT, http://phys.org; SDO/HMI/Alex Young, universetoday.com

Some different approaches for addressing activity…

- Line-level modeling and robust methods for RV estimation
  - Dumusque, X. (2018), "Measuring precise radial velocities on individual spectral lines-I. Validation of the method and application to mitigate stellar activity," Astronomy & Astrophysics, 620, A47.
  - Bedell, M., Hogg, D. W., Foreman-Mackey, D., Montet, B. T., and Luger, R. (2019), "WOBBLE: a data-driven analysis technique for time-series stellar spectra," The Astronomical Journal, 158, 164.
  - Simola, U., Dumusque, X., and Cisewski-Kehe, J. (2019), "Measuring precise radial velocities and cross-correlation function line-profile variations using a Skew Normal density," Astronomy & Astrophysics, 622, A131.
  - Holzer, P., Cisewski-Kehe, J., Fischer, D., and Zhao, L. "A Hermite–Gaussian based exoplanet radial velocity estimation method." The Annals of Applied Statistics 15, no. 2 (2021): 527-555.
  - Holzer, P., Cisewski-Kehe, J., Zhao, L., Ford, E.B., Gilbertson, C., and Fischer, D.A. "A Stellar Activity F-statistic for Exoplanet Surveys (SAFE)." The Astronomical Journal 161, no. 6 (2021): 272.
  - …
- Identification of Activity-sensitive lines
  - Wise, A., Dodson-Robinson, S., Bevenour, K., and Provini, A. (2018), "New Methods for Finding Activity-sensitive Spectral Lines: Combined Visual Identification and an Automated Pipeline Find a Set of 40 Activity Indicators," The Astronomical Journal, 156, 180.
  - Ning, B., Wise, A., Cisewski-Kehe, J., Dodson-Robinson, S., and Fischer, D. (2019), "Identifying Activity-sensitive Spectral Lines: A Bayesian Variable Selection Approach," The Astronomical Journal, 158, 210.
  - …
- Gaussian process-based methods
  - Rajpaul, V., Aigrain, S., Osborne, M. A., Reece, S., and Roberts, S. (2015), "A Gaussian process framework for modelling stellar activity signals in radial velocity data," Monthly Notices of the Royal Astronomical Society, 452, 2269–2291.
  - Jones, D. E., Stenning, D. C., Ford, E. B., Wolpert, R. L., Loredo, T. J., and Dumusque, X. (2017), "Improving Exoplanet Detection Power: Multivariate Gaussian Process Models for Stellar Activity," arXiv preprint arXiv:1711.01318.
  - Cabot, S. H., Roettenbacher, R. M., Henry, G. W., Zhao, L., Harmon, R. O., Fischer, D. A., Brewer, J. M., Llama, J., Petersburg, R. R., and Szymkowiak, A. E. (2020), "EXPRES. II. Searching for Planets around Active Stars: A Case Study of HD 101501," The Astronomical Journal, 161, 26.
  - …
- EPRV Data Challenge
  - Zhao, L.L., Fischer, D.A., Ford, E.B, et al. (2022), "The EXPRES stellar signals project II. State of the field in disentangling photospheric velocities," The Astronomical Journal, 163(4), p.171.

Perhaps you have other ideas?

Thank you!