Seeing Double:

RVs Lagging Behind Magnetic Activity Indicators in HD 26965

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The Need for Extreme Precision Radial Velocities (EPRV)

A vetted list of well-characterized planets will be critical for HWO success:

1. Improved efficiency over a blind direct imaging search

2. Precise masses are essential for distinguishing between atmospheric models (<20%) & determining planet composition (<10%)

Batalha et al. (2019), Valencia et al. (2007)
Radial Velocity Detections

Adapted from Anna John et al. (2023)
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RV discoveries at the sub-m/s level remain elusive
RV discoveries at the sub-m/s level remain elusive...even in the EPRV era

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Radial Velocity Detections

RV discoveries at the sub-m/s level remain elusive...even in the EPRV era

Diagram adapted from Anna John et al. (2023)
Earth-analog detections are no longer limited by instrumental precision, but instead by intrinsic stellar variability.

A finding of the EPRV Working Group Report (Crass et al. 2021), echoed in Luhn et al. (2023)
The Challenge of Stellar Variability

**Magnetic activity**
- https://www.physics.uu.se
- days/months/years
  - 1–10+ m/s

**Granulation**
- DKIST, NSO/NSF/AURA
- minutes–hours
  - 0.3–1+ m/s

**Oscillations**
- Victoria Antoci, asteroSTEP
- minutes
  - < 1 m/s
Overcoming Stellar Variability

**Magnetic activity**

- Activity indicators
  - Bonfils+ (2007), Robertson+ (2014)

- Gaussian processes

- Line morphology
  - Collier Cameron+ (2021), Gilbertson+ (2023)

**Granulation**

- Binning observations
  - Dumusque+ (2011)

- Line morphology
  - Collier Cameron+ (2021), Gilbertson+ (2023)

**Oscillations**

- Exposure time averaging
  - Chaplin+ (2019)

see de Beurs+ (2023) for a good summary
The EXPRES Stellar Signals Project

A community data challenge to assess techniques for mitigating stellar variability

4 EXPRES targets

20+ mitigation techniques
Methods disagree on amplitude/timescales associated with variability for each star.

Performance of methods is inconsistent from star to star.
The Case for High-fidelity Variability Data Sets

In the EPRV era, we have:

Requisite precision & stability to resolve sub-m/s variability

New probes of stellar variability (CCF morphology, LBL diagnostics)

Ultimately allow unprecedented views of how stellar variability affect spectra
The Case for High-fidelity Variability Data Sets

...beyond the Sun

Solar data have set the stage for these detailed analyses

We will want similar data sets for testing on other stars

Zhao et al. (2023)
MAGNETIC ACTIVITY ON ROTATION TIMESCALES IN HD 26965
NEID observations show clean activity signal…
NEID observations show clean activity signal… also seen in the RVs…
NEID observations show clean activity signal...also seen in the RVs...and matched by EXPRES!

A very active time series
A very active time series

NEID observations show clean activity signal...also seen in the RVs...and matched by EXPRES!
A correlated signal

RVs are correlated, but indicate a several day time lag
A simple spot model

Traditional activity indicators trace global magnetic fields
A simple spot model

Magnetic fields inhibit local convection & reduce the net convective blue-shift
A simple spot model

Spots perturb rotational symmetry of disk, à la Rossiter-McLaughlin for transiting planets.
A simple spot model

$RV_c$ is proportional to activity, and $RV_{rot}$ proportional to its derivative.
A simple spot model — multiple spots

More complex spot geometries lead to quasi-periodic behavior
A simple spot model — A GP approach

e.g., Rajpaul et al. (2015)

\[ H\alpha = a_{10}G(t) \]

\[ RV = a_{00}G(t) + a_{01}G'(t) \]

RV<sub>c</sub>, RV<sub>rot</sub>

G(t) often chosen as a quasi-periodic GP kernel
A simple spot model — multiple spots

The relative contributions of $RV_c$ and $RV_{rot}$ introduce apparent time lags
A simple spot model — apparent time lags

The relative contributions of $RV_c$ and $RV_{rot}$ introduce apparent time lags.
Fitting apparent time lags

$H\alpha = a_{10}G(t)$

$RV = a_{00}G(t + \Delta t)$

Lagged GP model includes a time lag hyperparameter, as well as “jitter” terms for RV and activity.

GP time lag:

$\Delta t = 4.44$ days

see Burrows et al. (submitted)
Fitting apparent time lags

The lagged GP model appears to not capture the full story
A simple spot model — A GP approach

e.g., Rajpaul et al. (2015)

\[ H\alpha = a_{10} G(t) \]

\[ RV = a_{00} G(t) + a_{01} G'(t) \]

RV \_c \quad RV \_rot
A simple spot model — A GP approach

\[ H\alpha = a_{10}G(t) \]

\[ RV = a_{00}G(t) + a_{01}G'(t) \]

The simple spot model performs similar to lag model, leaving 85 cm/s of stellar “jitter”
Can the RVs be explained by a lagged derivative model?
A time-lagged derivative?

Can the RVs be explained by a lagged derivative model?
\[ \Delta t = -6.4 \text{ days} \]
What are the implications?

Instantaneous derivative of activity time series predicts RV behavior 6.5 days later!

An opportunity for PRV instruments?

Can complex spot geometries/configurations be at play?

Possibly, we are *spinning up* STARRY, SOAP2.0

An astrophysical lag?

Simple spot model assumes flux effect, magnetic effect, and RV are coupled

Magnetically bright (but photometrically quiet) features that precede dark spots?
Summary

Activity–RV connections highlight need for high cadence & tricks beyond simple correlation metrics

Time lags between activity and RVs suggest a more complex spot configuration or an astrophysical lag not accounted for in current models