SEPARATING STELLAR ACTIVITY FROM DOPPLER SHIFTS

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Sun in calcium K/hydrogen alpha by Alan Friedman
PRELIMINARY STATEMENT OF PROBLEM

• The mechanical problem of detecting exoplanets has improved dramatically.

• This improvement has plunged us into a new noise regime, where astrophysical noise from the stars themselves obscures exoplanets.

• Unlike measurement uncertainty, this noise may be ameliorated after the fact to reveal interesting signals.
OUTLINE

1. Science applications of Doppler/Radial Velocity (RV)
2. Introduction to cutting-edge Doppler technology
3. Description of stellar activity problem
4. Identification of questions for you!
INTRODUCTION: RADIAL VELOCITY
THE OTHER OPTION: TRANSIT PHOTOMETRY
FROM DISCOVERY TO CHARACTERIZATION

Density $\rightarrow$ Bulk Composition!

Predicted sizes of different kinds of planets

$M_p \sin(i) = 1 M_{\text{Jup}}$
$M_p \sin(i) = 4 M_{\text{Jup}}$

RV: Mass

Transit: Radius

David et al. 2016

$b R_\ast = a \cos i$

$R_\ast$
• Complement transit surveys

• Mass $\rightarrow$ density to understand planet composition, formation

• Dynamics to understand planetary system migration, evolution

Dressing et al. 2016
RADIAL VELOCITY: SCIENCE CASES

The diagram illustrates the relationship between temperature and period for various exoplanets. The lines represent different observational campaigns:

- **NEID (all-sky)**: 5 nights/year
- **NEID (ecliptic poles)**: 30 nights/year
- **TESS**: 50 nights/year

The diagram shows the temperature range and period for each campaign, with specific exoplanets labeled, such as **Venus**, **Earth**, and **Mars**. The positions of these planets are marked on the graph, providing insights into the radial velocity science cases.
• Equivalent shifts on detector:
  • 100 cm/s: diameter of DNA helix
  • 10 cm/s: diameter of carbon atom
THE STATE OF THE ART
PUSHING THE ENVELOPE: NEW RV INSTRUMENTATION

ESPRESSO
ESO, VLT Telescope (Chile)
Precision goal: 10 cm/s
PUSHING THE ENVELOPE: NEW RV INSTRUMENTATION

NEID
NASA/NSF, 3.5m WIYN Telescope (Arizona)
“Out-of-the-box” precision: 27 cm/s
Goal precision: 10 cm/s

neid.psu.edu
@NEID_at_WIYN
UNDER THE HOOD: ENVIRONMENTAL STABILITY

Stefansson et al. 2016

14 Control Channels: Per-channel RMS=0.102-0.168 mK

Optical Bench: 15-day RMS=0.63 mK

1-day RMS: 0.14 mK
UNDER THE HOOD: ULTRA-PRECISE WAVELENGTH STANDARD

Schibli 2008

Ycas et al. 2012
UNDER THE HOOD: FIBER OPTIC TELESCOPE/INSTRUMENT COUPLING

Before After

Telescope focus
Spectrograph input

Halverson & Roy+ 2015
BREAKING THE 1 M/S BARRIER

- Upcoming instruments aim to exceed current measurement precision by an order of magnitude.

- This should be sufficient to detect True Earth Analogs™!

- So what’s the problem?
THE STELLAR ACTIVITY PROBLEM
THE STELLAR ACTIVITY PROBLEM
STARSPOTS

RV amplitudes: typically 1-5 m/s

Timescales: 1-100+ days

Animation via Svetlana Berdyugina
STELLAR PULSATON

Especially important for evolved stars

RV amplitudes: 1-10+ m/s

Timescales: minutes-days
STELLAR GRANULATION

RV amplitudes: 10+ cm/s
Timescales: minutes

Big Bear Solar Observatory
MAGNETIC ACTIVITY CYCLES

RV amplitudes: up to 10+ m/s
Timescales: 1-25+ years

The 11-year solar cycle (NASA/SOHO)
MANIFESTATIONS OF ACTIVITY: NOISE

- Activity adds red noise to Doppler measurements.
- Worst for young, active stars.

Kepler-78, Howard et al. 2013
MANIFESTATIONS OF ACTIVITY: NOISE

• Quietest stars: activity “jitter” floor of 3 m/s!

• Solar RV measurements: jitter > 50 cm/s

• Reminder: Earth analogs have amplitude ~ 8 cm/s.

Bastien et al. 2014
MANIFESTATIONS OF ACTIVITY: FALSE POSITIVE PLANETS

• Periodic activity phenomena mimic exoplanets

• Most troublesome at the stellar rotation period and its harmonics/aliases.

RV (blue) and activity (red) for Gliese 581 (Robertson et al. 2014)
STELLAR ACTIVITY: RECAP

• RV noise/signal from stellar activity occurs in every star, with amplitudes at least as large as those from Earthlike planets.

• These signals occur on every timescale of interest to exoplanet science.
I am not a statistician! And I don’t know the answer.

I have identified 4 questions that I think statisticians can help provide valuable answers to.

Earth analog!

False positives?

Stellar activity
QUESTION 1: WHAT DATA ARE NEEDED?

Velocity
Spectral Line Index
Brightness
Color

HD 166435 (Queloz et al. 2001)
QUESTION 1: WHAT DATA ARE NEEDED?

Example of a stellar line bisector (Brown et al. 2008)
QUESTION 2: WHAT OBSERVING CADENCE IS NEEDED?

The 143-day rotation period of Kapteyn’s star (Robertson et al. 2015)

Is it necessary to resolve activity signals/periods?

What strategies yield planets with fewest number of observations?
QUESTION 3: WHAT MODELING TECHNIQUE(S)?

Gaussian Process models to Doppler measurements of Alpha Centauri B (Rajpaul et al. 2015)
QUESTION 3: WHAT MODELING TECHNIQUE(S)?

\[ y(t_i) = V + \sum_{j=1}^{m} \left[ K_j \exp \left( -\frac{(t_i - t_{ja})^2}{2\tau_j^2} \right) \times (\cos(\theta(t_i + \chi P_j) + \omega_j) + e_j \cos \omega_j) \right] + \beta \, rhk(t_i), \]

Apodized Kepler periodogram of a simulated RV time series (Gregory 2016)
QUESTION 4: WHAT IS THE LIMITING PRECISION?

Plavchan et al. 2015

"Instrument-limited" regime

"Activity-limited" regime

Plavchan et al. 2015
REMINDER: THE REWARD FOR SUCCESS
Simulated image of the solar system as viewed by a future space-based LUVOIR imager.
*(Webster Cash, Univ. Colorado)*

Simulated E-ELT images of a habitable super-Earth around Proxima *(Snellen et al. 2015)*
CONCLUSIONS

• Upcoming Doppler instruments promise precision sufficient to discover Earth twins and characterize exoplanet taxonomy and composition.

• This leaves stellar activity as the limiting factor in the detection of low-amplitude exoplanet signals.

• Sophisticated statistical analyses are required to maximize the scientific yield of these instruments!
QUESTIONS?

WE NEED YOU!