National Aeronautics and Space Administration

The Sun as a star: exploring stellar activity with NASA's flagship Doppler RV instrument

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Program: FY21 R&TD Topics **Strategic Focus Area: Extra-solar planets and star and planetary formation**

Objectives

We aim to **improve our understanding of the effects of stellar magnetic activity on high precision radial velocity (RV) measurements** by studying 'Sun-as-a-star' observations from both ground and space-based facilities. In doing so, we seek to develop tools and techniques for modeling and removing activity signatures from solar RV measurements

Our approach is two-pronged: we 1) **use state-of-the-art, high resolution solar spectra to derive reliable magnetic activity indicators and identify magnetically-insensitive lines**, and 2) use space-based **data products from SDO/HMI to independently quantify the magnetic activity** and improve the precision of the ground-based RVs.

Background

RV measurements play a central role in exoplanet discovery. By measuring the minute spectral Doppler shifts in stellar spectra induced by orbiting planets, the RV technique had led to hundreds of planet detections in the past 30 years. **Critically, RVs provide precise planetary mass estimates** that are otherwise unattainable with other detection techniques (e.g. transit photometry). While highly successful, the RV field has **hit a precision floor of ~1 m/s** in recent years. This precision **prohibits the detection of Earth-like planets** orbiting Sun-like stars, **which imprint a mere ~10 cm/s Doppler signature** on their host stars.

With instrumentation continually improving, **the dominant source of noise is now the stars** themselves. Magnetic activity, such as star spots and plages, add structured noise to stellar RVs, and must be modelled and removed to reliably push below the ~1 m/s barrier.

Approach

We used a combination of data from the recently-commissioned NEID RV spectrometer and a suite of images from SDO/HMI to better understand the relationship between magnetic activity and disc-integrated stellar radial velocity in the Sun. **We developed a variety of tools and techniques to characterize the spectral signatures of activity** and tie observed variations in the NEID spectra to measured solar variability derived from SDO/HMI images. Together, these tools represent a major step towards enhancing our understanding of activity in Sun-like stars. Our developed analysis packages include:

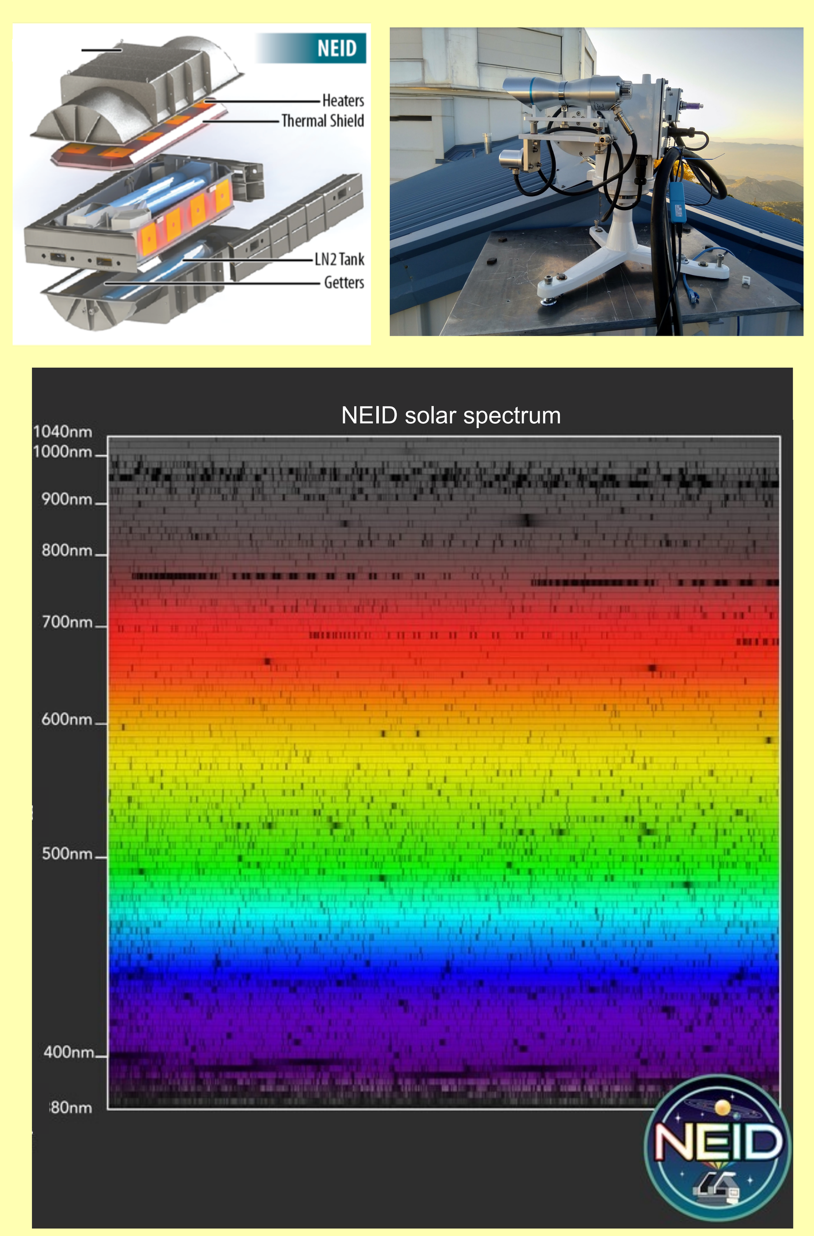
- **Algorithms to improve activity measurements using canonical indicators**, and identify new spectral features that could be tracers for magnetic activity.
- **An independent RV pipeline that derives color-by-color and line-by-line RVs**, enabling a deep study of magnetic sensitivity at the in individual line level.
- A robust pipeline to automatically **calculate solar radial velocities, magnetic field strength, and identify spots and active regions using SDO/HMI data.**

Significance to JPL and NASA

Improving RV precision is critical for future flagship direct imaging missions, such as HabEx and LUVOIR. These missions will require a well-vetted (RV-discovered) target list of exo-Earths prior to beginning any direct-imaging survey. **Any spectra of these planets will also require precise, RV-derived masses** to constrain atmospheric retrieval models.

NEID solar data

NEID is a stabilized, fiber-fed radial velocity spectrometer with a precision goal of ~30 cm/s, a factor of 2-3 above the current state-of-the-art (Halverson et al. 2016). Commissioned on the 3.5m WIYN telescope in 2019, NEID also includes a dedicated solar telescope, which records ultra-high SNR, disc-integrated solar spectra continuously throughout the day.

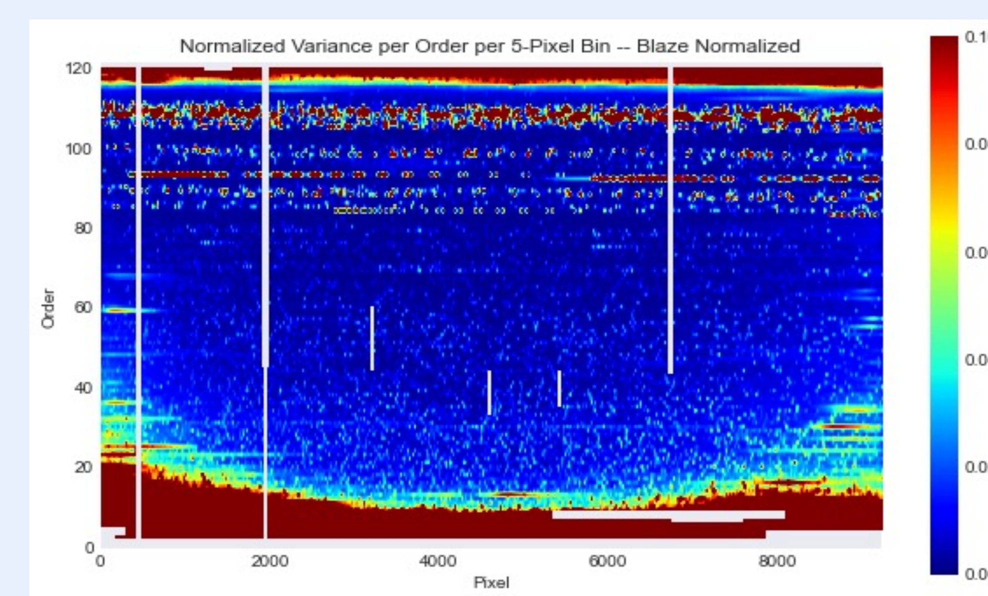


Top left: NEID spectrometer overview. The high resolution spectrometer is encased in a stabilized vacuum chamber. Top right: the 3" NEID Solar telescope next to the 3.5m WIYN. The solar feed autonomously tracks the Sun and delivers disc-integrated sunlight to the spectrometer. Bottom: Full NEID spectrum of the Sun, spanning 380 – 1030 nm with a a resolving power of 110,000.

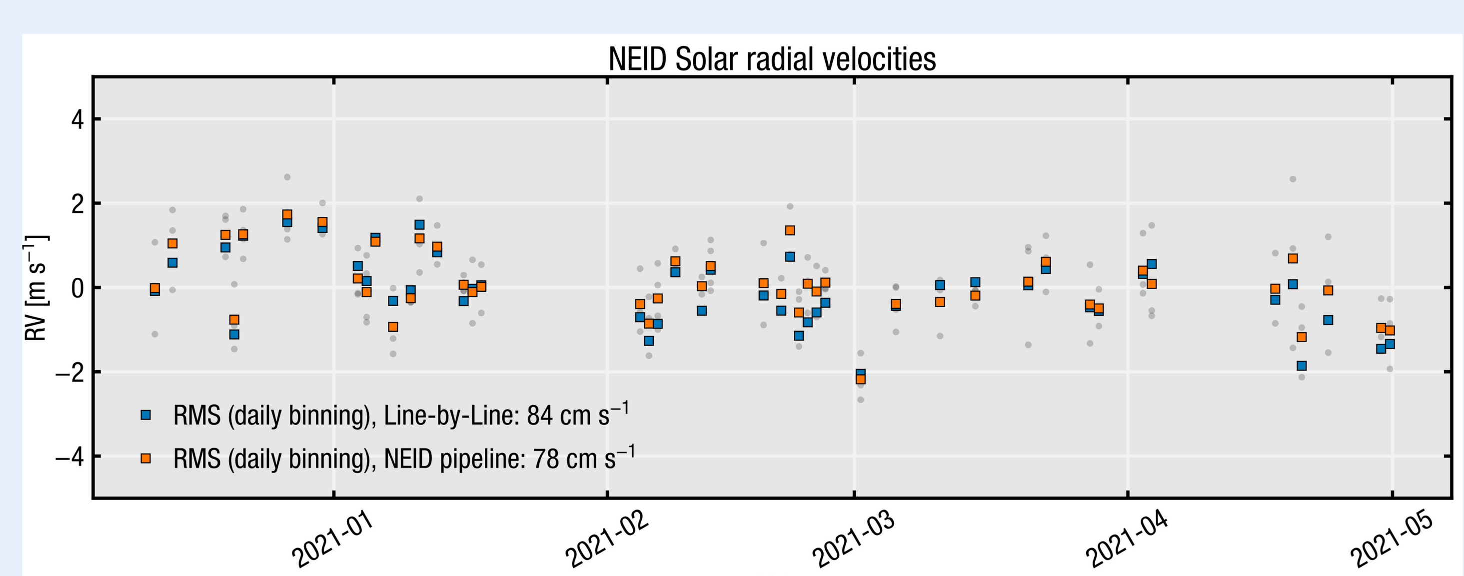
Exploration of NEID spectra

We leveraged the **unparalleled sampling and SNR of the NEID solar telescope** to systematically search for activity-sensitive lines across the solar spectrum. We developed a custom software package to continuum normalize and flux calibrate the NEID spectra. Using these 'cleaned' spectra, we measured the intrinsic variability of >10,000 individual lines (see figure below).

Right: ***Line-by-line variability map for the full NEID solar spectrum****. We use this variability map to identify the most 'quiet' (blue) and 'active' (cyan) regions of the solar spectrum that could be used to model activity signals. Regions with ultra-high variability (red) are low SNR or telluric features. A large number of features show significant (>photon noise) variability, which may indicate magnetic sensitivity.*



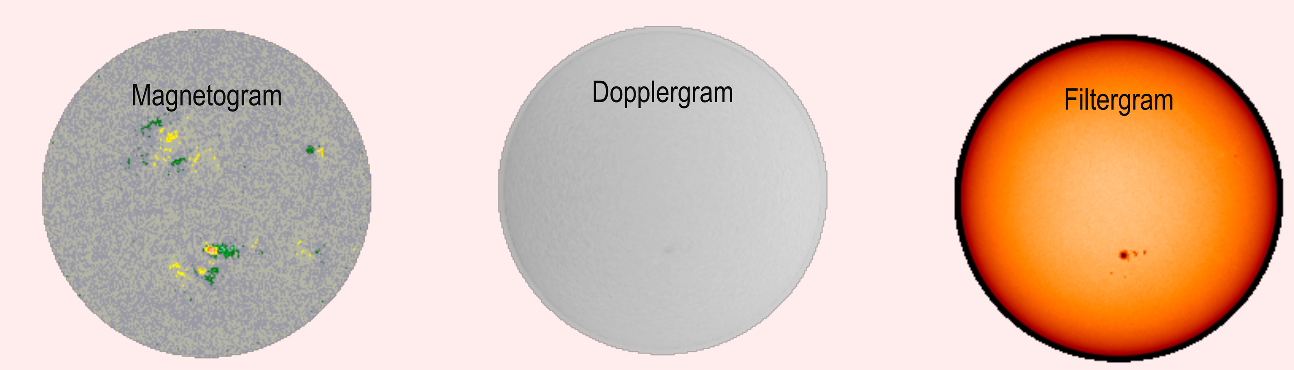
We also developed an RV pipeline that calculates individual line velocities, which contains significantly more information than standard RV pipelines that measure averaged velocity of thousands of lines**. Moving forward, our pipeline will allow for a deep, granular study of the effects of solar activity on individual features**, and allow us to identify inactive lines (used to improve RV performance) as well as active ones (used to model residual activity signals)



Performance of our line-by-line RV pipeline *(orange) relative to the standard NEID RV pipeline (which averages over all lines at once, losing all chromatic information),* ***highlighting nearly identical performance*** *over the full range of NEID data. Our next steps are to compare individual line velocities to known activity indicators (e.g. Ca H&K.)*

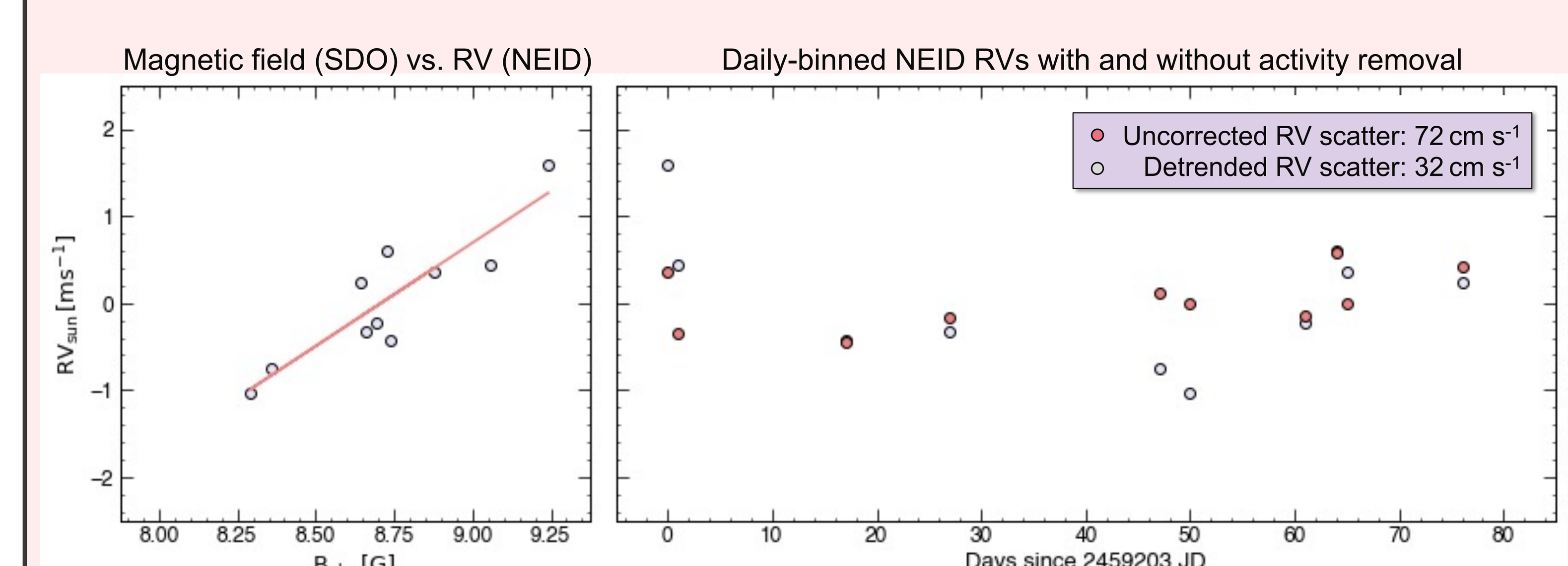
SDO/HMI analysis

Beyond the ground-based spectra we also **developed an independent analysis pipeline** to measure **unsigned magnetic flux**, disc-integrated **solar radial velocity, and spot coverage** using SDO/HMI images.



Example SDO images used in our analysis. Our automated pipeline uses these images to calculate sunspot coverage, identify magnetically active regions, and measure integrated magnetic field strength and RV, following methods described in Haywood et al. 2020

Using this comprehensive set of measurables from SDO, **we computed an independent model of the activity-correlated RV signal** in the NEID data (see figure below). Even during this 'quiet' period in solar activity, the bulk of the RV signal measured by NEID is driven by magnetic variability. Once **removing the activity-induced signal, the residual RV scatter drops to 30 cm/s** over a ~90 day span. In the future, we will improve this activity-driven RV model by including time-dependent scaling factors (e.g. Gaussian processes).



Ground-based NEID RV measurements before and after correction for correlation with unsigned flux (SDO). ***With a simple linear detrending, the resultant RV scatter (red) is 2x improved*** *relative to the raw time series (grey).* ***We aim to expand our parametrization to include time-dependent models that are likely to improve the RVs even further.***

Publications: Ervin et al. in prep (SDO/HMI analysis), Burrows et al. in prep. (Line-by-line analysis)

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