National Aeronautics and Space Administration

Mapping the Evolution of Exoplanets with Precision NIR Radial Velocities

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Program: FY21 SURP **Strategic Focus Area: Extra-solar planets and star and planetary formation**

Objectives

Science: The objective of this SURP is to characterize the effect of stellar activity on radial velocity observations of young and low-mass stars, and lay the groundwork for measuring the masses of terrestrial planets around these types of stars. We are using three high resolution spectrographs that span a full octave of wavelength space from the optical to the near infrared (500nm - 1800nm), including JPL's PARVI spectrograph on Palomar 5-m telescope and UT Austin's Habitable-zone Planet Finder spectrograph on the 11-m Hobby-Eberly Telescope, to monitor variable stars and and model/mitigate their activity and its deleterious effects on the mass measurements of exoplanets. **Technical**: Simultaneous HPF & PARVI observations across the instruments' complementary wavelength ranges (810 - 1280nm for HPF and 1250 - 1800nm for PARVI, Figure 1) will distinguish the wavelength dependent false positive signals from starspots and stellar flares from the achromatic signals caused by an orbiting planet. New methods to detrend these signals and measure their limits are crucial to future science programs, including the measurement of planet masses for the temperate, terrestrial planets orbiting Sun-like stars that will be discovered by future direct imaging mission concepts such as Habex or LUVOIR.

Background

Planetary systems around young stars and M-dwarfs offer unique tests of formation, evolution, and habitability models. M-dwarfs provide the best opportunity to find habitable-zone (HZ) planets, due to their low mass, small size, and close-in HZ [1]. Young planets directly test formation and evolution theories, before they transition to their final compositions, radii, and orbits [2]. Measuring the masses of small planets to the precision necessary for atmospheric characterization is difficult [3], particularly for active young stars and M-dwarfs. Stellar activity introduces correlated noise (jitter) that can mask, or masquerade as, a planetary signal. In general, jitter is smaller at longer wavelengths [4, **Figure 1**]. This chromatic property of stellar activity is regarded as the key to disentangling stellar and planetary signals, but there does not exist a robust understanding of jitter's dependence on wavelength or stellar properties. To effectively mitigate jitter, we must characterize stellar activity signals across wavelength simultaneously and model the underlying physical mechanisms responsible for the multiple manifestations of jitter. With methods to mitigate jitter, it is possible to precisely measure the masses of young exoplanets, directly determine their formation pathways, and turn them into competitive targets for future atmospheric characterization.

Approach and Results

We have begun a long-term observing campaign monitoring three active stars to assess the dependence of stellar variability (jitter) on wavelength and host star properties, such as mass and age, and build the activity-mitigation infrastructure to measure the masses of planets around young stars. It is crucial to have contemporaneous observations across the entire spectrum, from the optical to the near infrared (NIR), to carry out this campaign. We are observing with two state-of-the-art precision NIR spectrographs that we have institutional access to, HPF at McDonald Observatory and PARVI at Palomar Observatory, and one precision optical spectrograph, the Levy, on the Automated Planet Finder (APF) telescope. By observing with these instruments, whose spectral ranges are shown in **Figure 1**, we will map the jitter-wavelength dependence from the optical to the NIR. As we observe more targets, we will also determine how this dependence changes for stars of varying masses and ages, in which activity will manifest differently. When we begin observing planet hosts, these three instruments will work in tandem to distinguish achromatic planetary signals from chromatic activity signals, enabling mass measurements of small planets that are currently at the threshold of our capabilities. As an observation-based project, our timeline was significantly disrupted by the COVID-19 pandemic which shut down observatories worldwide and stalled the commissioning of the PARVI spectrograph for much of 2020 and 2021. Despite this, our team proposed for and acquired time to monitor a variety of active stars with HPF, the APF, and PARVI. Due to these delays, we have only observed one object in-depth: the young, active star AD Leo. However, we have recently begun observations of additional targets. With complete time series observations, we will combine data from each instrument and characterize the stellar variability as a function of time (including comparisons to previously published data when possible) and wavelength (as our data will stretch further into the NIR than previous work). **Figure 2** shows the in-progress results of our observing campaign for AD Leo. We detect significant stellar activity signals in our data, with a smaller variability amplitude in the NIR than the optical. We find a comparable optical activity signal to previously published studies, but a larger NIR amplitude than previously reported. AD Leo's activity is known to vary on long timescales, however, and we have perhaps captured long-term spot coverage or temperature evolution in the NIR amplitude. We have observed AD Leo with PARVI, but those data are not yet fully reduced due to the pandemic-induced delay of PARVI's commissioning. We plan to publish these activity studies once observing campaigns are wrapped up in the next year. In the future, we will observe young planet-hosting stars identified by the TESS mission as the main focus for the remainder of our SURP program. These observations will capitalize on the NIR advantage of RV variability falling off as a function of wavelength provided by HPF and PARVI, and our improved understanding of jitter from the previously described activity studies.

Significance/Benefits to JPL and NASA

Stellar activity and its effects on radial velocity measurements present the largest roadblock to precision mass measurements of small exoplanets. Our investigation will determine new methods to model and mitigate stellar activity signals, which has been marked as a top priority for RV science by NASA and NSF's recently commissioned Extreme Precision Radial Velocities working group. Precise mass measurements are necessary for the atmospheric characterization of exoplanets planned with current and future NASA missions (HST, JWST, HabEx, LUVOIR, Origins), and our stellar activity mitigation methods will be key in achieving the precision necessary for small, terrestrial planets. Additionally, we will directly measure the masses of young exoplanets, providing high-quality targets to probe the early evolution of exoplanet atmospheres with these current and future observatories. This research directly benefits the new JPL spectrograph PARVI by combining its data products with those from the established near-IR HPF spectrograph, which has been in successful operation for three years. The UT Austin collaborators' expertise in extracting and analyzing radial velocities from near-IR spectroscopic data will be crucial in maximizing the efficiency, accuracy, and scientific impact of PARVI in its early years of science operations.

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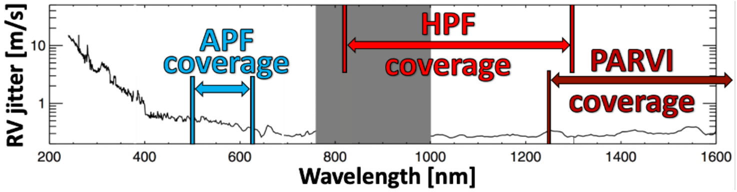

Figure 1. RV jitter in the sun [black curve, 5], caused by phenomena such as spots and plages, decreases with wavelength. HPF and PARVI operate in the least active wavelength regime, which is substantially redder than traditional RV instruments like the APF. This makes them especially well-suited to measuring RV masses of planets orbiting active young stars and M-dwarfs. This RV jitter curve is not well-defined for stars other than the sun, and our understanding of activity is crucial in planning follow-up observations for interesting planets that are discovered around cool stars by TESS. The evolutionary timescale of jitter is also unknown, which is needed to plan efficient and effective observing campaigns depending on the planet's orbital period and the host star's properties. We use contemporaneous observations from HPF, PARVI, and the APF to study jitter properties in active stars, to measure the RV jitter semi-amplitude as a function of wavelength and study jitter trends across stellar parameters such as spectral type and age.

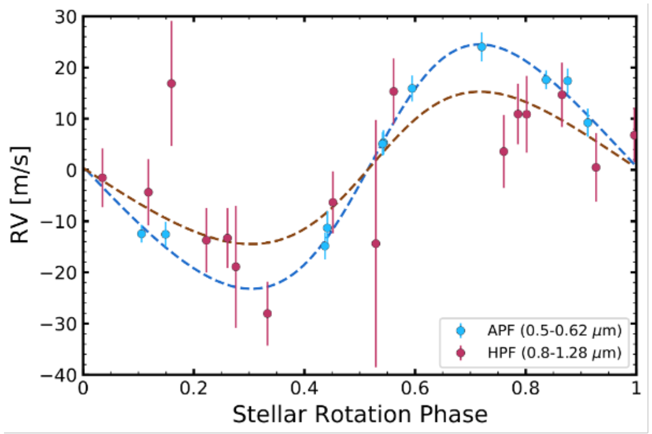

Figure 2. RV time series of the young, active star AD Leo from our pilot study with HPF and the APF. The optical APF RV time series was fit with a periodic stellar activity signal, and we find significant, coherent variability at the rotation period of the star. This is likely the result of starspots rotating in and out of view. The near infrared signal in the HPF data has a smaller variability amplitude than the optical signal, which is expected due to the decrease in spot contrast at longer wavelengths. While we have observed AD Leo with PARVI, which operates even further in the NIR, those data have not yet been reduced and analyzed. With these data, we can search for the wavelength region that is least affected by jitter. Our program of contemporaneous and high-precision optical and NIR RVs will be key to characterizing the synchronous jitter amplitude of AD Leo as a function of wavelength, and a similar analysis will be conducted on the remaining active stars we are currently observing.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronaturics and Space Administration (80NM0018D0004).

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Clearance Number: URS303400
RPC/JPL Task Number: SP21019