iSHELL PRV Follow-up of TESS Candidates

Mohammed El Mufti, Peter Plavchan, Bryson Cale, Michael Reefe, Angelle Tanner, Eric Gaidos, Rena Lee, Claire Geneser, Farzaneh Zohrabi, Ahmad Sohani, Kingsley Kim, Kevin Isaac Collins, David James Vermilion, Caitlin Stibbards, Shreyas Banaji, Jonathan Gagne, Peter Gao, Sharon Xuesong Wang, Johanna Teske

Main affiliation: Department of Physics & Astronomy, George Mason University, 4400 University Drive MS 3F3, Fairfax, VA 22030, USA

Motivation

The NASA Transiting Exoplanet Survey Satellite (TESS) mission launched in the spring of 2018 with the first data release coming in early 2019. TESS has the Level 1 mission requirement to measure the masses of 50 planets smaller than 4 $R_\oplus$. PRVs provide essential NASA mission support for target identification and mission yield optimization, follow-up validation, characterization of low-mass transiting exoplanets, measuring exoplanet masses, and constraining orbits. We observe at near infrared [NIR] wavelengths because stellar activity induced RVs from star spots and plages are diminished at [NIR] wavelengths. iSHELL is the only instrument capable of NIR PRVs with <5 m/s single measurement precision with open public access to US PIs [1]. Moreover, many of the new red and NIR PRV spectrometers surveying nearby M dwarfs do not go out to K-band, thus creating a unique wavelength range niche for using iSHELL for PRVs calibrated by our methane isotopologue gas cell.

pychell Data Pipeline

When star light passes through our gas cell and iSHELL cross-dispersed echelle spectrograph, we obtain high-resolution (R=80k) multi-order spectra. For each of the 29 orders, we do optimal spectral extraction (weighted summation) in the vertical direction so that in each column eventually we get a single value, which gives us a 1D spectrum for each order. We then forward model the spectrum to measure the radial velocity for each order, and then co-add the RVs from each order.

We analyze our extracted spectral data using the following standard forward model where each term is a function of wavelength:

Intensity = Blaze Function × (Star × Gas Cell × Tellurics) ⊛ Line Spread Function.

The blaze function ultimately sets the continuum of our spectrum. The line spread function effectively blurs the spectrum down to resolution of the iSHELL spectrograph. The star has a Doppler shift, and the gas cell also has a Doppler shift which enables us to calibrate for instrumental drift in the wavelength solution and to constrain the line spread function. The tellurics, parameterized by a scaling factor optical depth related to airmass, are the remaining lines that causes by the greenhouse gases in the Earth's atmosphere.

Our RV pipeline is adapted from the CSHELL RV code described in (Gao et al. 2016). We have rewritten the CSHELL code in a Python script *pychell* to adapt to iSHELL's larger spectral grasp with multiple orders [2].

Results

We were able to observe many of TESS Objects of Interest (TOIs) using iSHELL and analyze the data through *pychell*, leading to new discoveries and confirmation of new planets.

A subset of the most frequently observed TOIs from our current target list is presented in Table 1. TOI-442 is one of our detections with 10 iSHELL data points. The data we gathered with iSHELL was able to pick out a period consistent with the known orbit and ephemerides at a semi-amplitude of 15 m/s. These results are widely consistent with the results obtained from full data sets from many other spectrographs, such as HIRES and SPIRou. Another successful detection is the TOI-836 system with 7 data points. It's a two-planets system, and their semi-amplitudes were 3 ms^{-1} and 6 ms^{-1} respectively. The phased RVs for TOI-442 and TOI-836 are shown in Figure [1] and Figure [2].

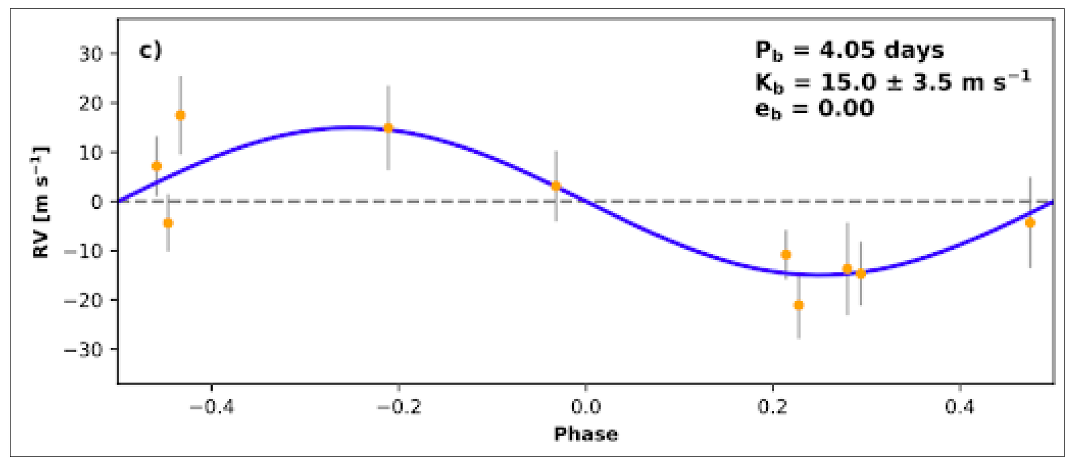

Figure 1:The phased RVs for TOI-442.

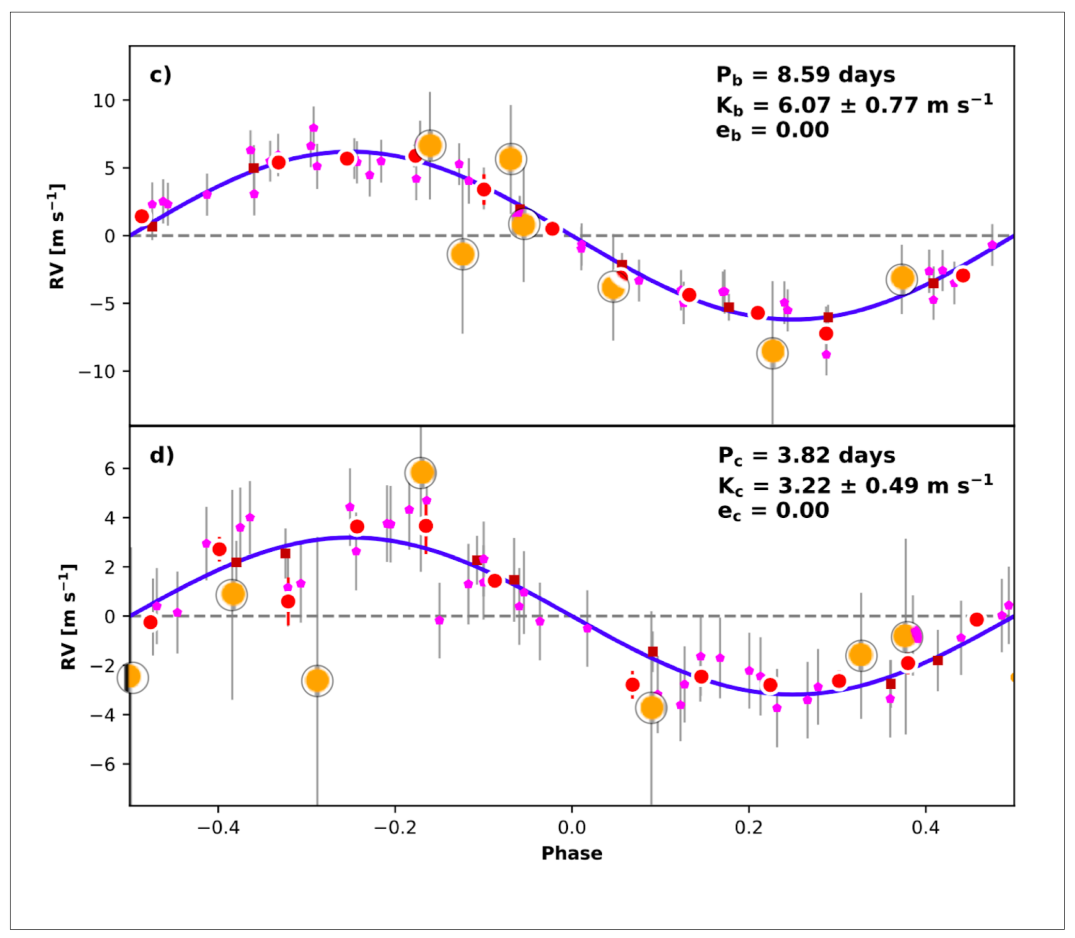

Figure 2:The phased RVs for TOI-836 system.

Target	Decl.	Spec. Type	K_{mag}	N_{nights}
TOI-2221.01	-31:20:27	M1Ve	4.53	50
TOI-1411	+47:03:24.61	K6	7.25	39
TOI-461	-10:21:08	K2	7.459	35
TOI-560	-13:15:24.09	K4	6.95	30
TOI-620	-12:09:55.75	M2	7.95	27
TOI-1801	+23:01:36.678	K5	7.8	25
GJ-699	+4:41:36.2	M4V	4.52	19
Eps-Eri	-09:27:29.731	K2Vk	1.78	15

Table 1:Sample list of our observed targets.

Challenges of Stellar Activity

Stars are not perfect blackbodies; they exhibit RV variations from rotationally-modulated activity (e.g., star spots and plages on the surface of the star). Depending on the temperature differences between that spot and the surrounding photosphere of the star, it will induce apparent RV shift. We first model the stellar activity as a Gaussian Process (GP). We construct a covariance matrix a square symmetric matrix 'K', each entry in it defines the covariance between any two observations. We build upon what's called quasi-periodic Kernel composed of a decay and periodic term [2]:

$$K_{J2}(t,t') = \eta_{\sigma^2} \overbrace{\exp\left[-\frac{\Delta t^2}{2\eta_{\tau^2}}\right]}^{Decay} \overbrace{\exp\left[-\frac{1}{2\eta_{l^2}}\sin^2\left(\pi\frac{\Delta t}{\eta_p}\right)\right]}^{Periodic}$$

where: $\Delta t = |t - t'|$, η_{σ^2} is the amplitude, η_{τ^2} is the mean activity timescale, η_{l^2} is the period length scale, and η_p is the rotation period.

We applied this kernel to our most observed target, AU Mic, which has been observed by multiple PRV spectrographs. Using the quasi-periodic kernel with different data sets from a set of spectrographs, each with their own uncorrelated GP (disjoint GPs), gave us over-fitted results, indicating that our model is too flexible.

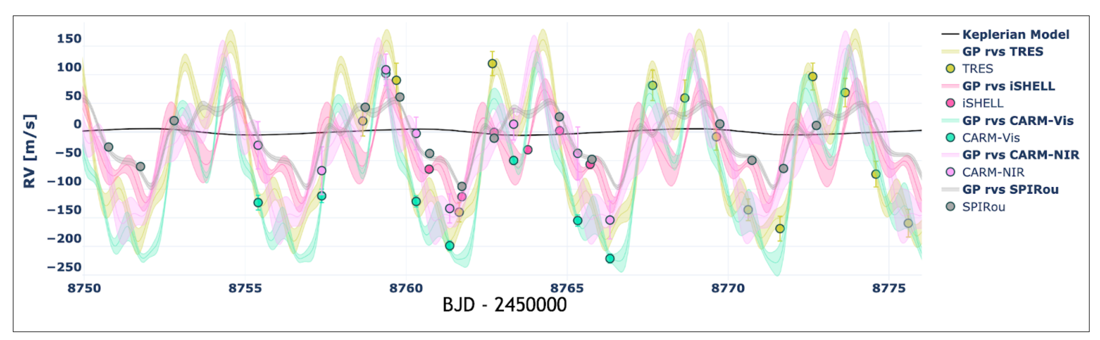

Figure 3:The RV series of AU Mic. The curves are the GP models. The black curve is the signal from two planets orbiting AU Mic.

Afterwards, we decided to combine all of our data points across multiple spectrographs into a single, joint covariance matrix. Starting with quasi-periodic Kernel, we modified the amplitude parameter to account for different effective spectrograph wavelengths and thus GP amplitudes between spectrographs. [3]. This new Chromatic Kernel not only takes the time of the observation, but also the wavelength of any pair of observations. The Chromatic Kernel then gives us better results, indicating that our model is less flexible and more robust.

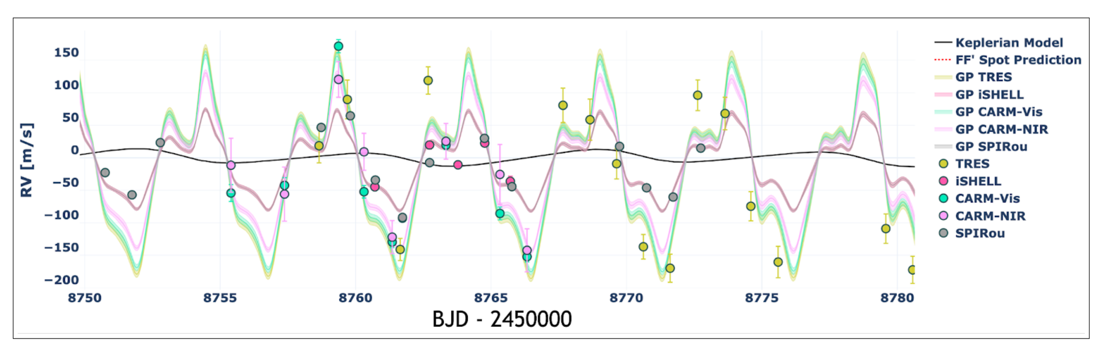

Figure 4:Using Chromatic GP, the width of each curve is much thinner (less uncertainty).

AU Mic

AU Microscopii (AU Mic) is the second closest pre-main-sequence star, at a distance of 9.79 parsecs and with an age of 22 million years [4]. Therefore, it's a very young M dwarf. Since AU Mic is so young, it has a large stellar activity amplitude of ∼150 m/s in the visible, so this gave us incentive to create the chromatic RV kernel. We break up the model for the radial velocity measurements into a Keplerian component (the radial velocities induced from planets), and a stellar activity component. While the planetary signals are achromatic and only functions of time, the stellar activity is a function of time and wavelength.

We define the RV-color to be the difference between two observations taken at the same time but with different wavelengths. When we obtain quasi-simultaneous measurements at two different wavelengths, then the Keplerian components will completely cancel out since they are only functions of time, leaving us with the chromatic activity signal. When we were able to coordinate these observations across multiple spectrographs and telescope facilities, we find that our chromatic GP model is able to accurately reproduce the observed RV color (Figure 5). We do not yet use the RV color to further constrain our chromatic GP model, which will be the subject of future work, but this figure validates our chromatic kernel approach. It also demonstrates that the highest SNR measurements of RV color come from the pairs of spectrographs spanning the largest wavelength range (e.g. HIRES and iSHELL).

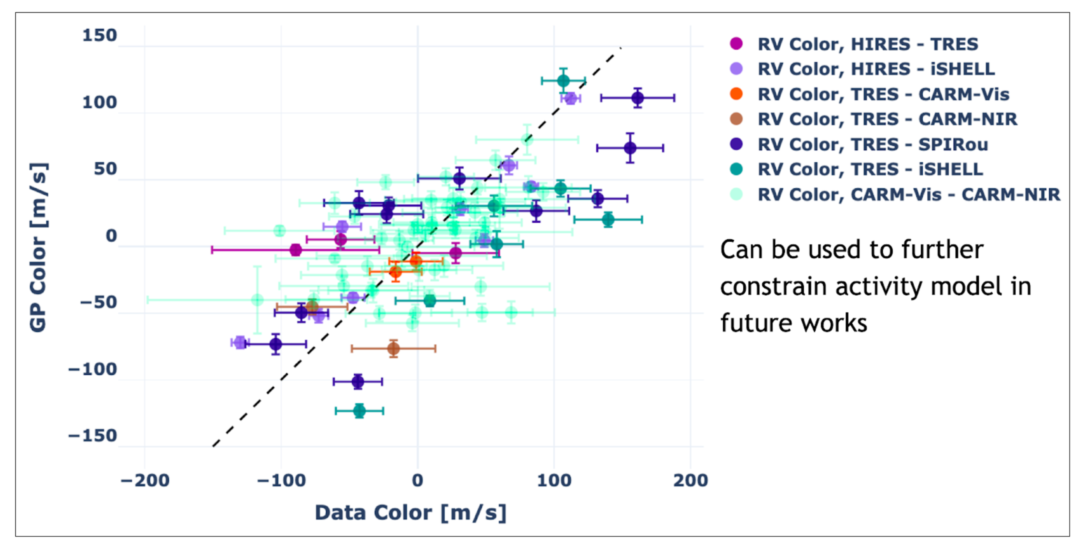

Figure 5:Example of pairs of wavelengths (the RV-color).

References

[1] John Rayner et al.
ishell: a construction, assembly and testing.
SPIE, 9908, 2016.

[2] Bryson Cale et al.
Precise radial velocities of cool low mass stars with ishell.
Astronomical Journal, 158 170, 2019.

[3] Bryson Cale et al.
Diving beneath the sea of stellar activity: Chromatic radial velocities of the young au mic planetary system.
paper submitted to AAS Journals, 2021.

[4] Peter Plavchan et al.
A planet within the debris disk around the pre-main-sequence star au microscopii.
Nature, 582, 2020.