Astro2020 Science White Paper

Advanced Statistical Modeling of Ground-Based Radial Velocity Surveys as Critical Support for Future NASA Earth-Finding Missions

Thematic Area: Planetary Systems

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White Paper Description:
Realizing the potential of the upcoming generation of Doppler exoplanet surveys will require considerable investment in advanced stellar modeling, statistical and machine-learning methodologies, and Doppler pipelines.

Abstract:
The complex convective and granular photosphere of stars, their oscillations and their myriad manifestations of magnetic activity (e.g., star spots) present a barrier to measurement of stellar line-of-sight velocities at ~1 m/s, an order of magnitude larger than the instrumental precision and the amplitude of the Doppler shift due to Earth-mass planets in the habitable zone of sun-like stars. Indeed, the observed dispersion of radial velocity (RV) measurements significantly exceeds the internal instrumental capabilities for most target stars (Fischer et al. 2016). Already, the primary barrier to Doppler discovery of low-mass planets is not instrumental precision, but rather the astrophysical variability of the target stars. Recent research suggests that future Doppler surveys can overcome these barriers through a combination of next-generation instrumentation, high-cadence observations, advanced statistical methods, high-performance computing, and machine learning and astrophysical insights (e.g., Rajpaul et al. 2016, Jones et al. 2017, Bedell et al. 2019). **Realizing the potential of the upcoming generation of Doppler exoplanet surveys to support NASA missions targeting low-mass planets in the habitable zone of sun-like stars will require considerable investment in advanced stellar modeling, statistical and machine-learning methodologies, and Doppler pipelines,** in addition to observatories and instruments.

Increasing Importance of Stellar Variability:

In the early days of Doppler planet surveys, observers would quickly discard target stars that showed early signs of stellar activity, so as to focus their limited observation time on "quiet" stars more amenable to precise Doppler measurements. As we begin the search for Earth-like planets around Sun-like stars, however, it is likely that even the quietest stars will have stellar noise at amplitudes above the desired signal. Additionally, stars traditionally considered too active for Doppler searches are being prioritized for other reasons: RV observations of transiting planets discovered by TESS (and other surveys of nearby stars, e.g., APF, TRAPPIST, MINERVA) will be critical to the success of future missions, even though some of these host stars may have significant astrophysical variability. Similarly, astronomers want to characterize the **closest** planetary systems in preparation for direct imaging missions, even if the target star has significant astrophysical variability. These scientific drivers demonstrate the critical need for a strategy to enable the Doppler detection and characterization of exoplanets that induce a Doppler shift smaller than the apparent RV variations due to stellar astrophysics.

Characterizing low-mass planets requires a plan for addressing each of the confounding sources of spectroscopic variability: pulsations, granulation, rotationally-linked variability and long-term magnetic cycles. Pulsations of solar-like stars can be mitigated through appropriate choice of exposure times (Kjeldsen et al. 2005; Dumusque et al. 2011, Chaplin et al. 2019). Stellar magnetic activity has historically been the dominant source of confusion for Doppler exoplanet surveys (Borgniet et al. 2015). Rotationally-linked stellar activity such as spots and faculae are particularly problematic since the stellar rotation period (or an associated alias) is often comparable to plausible orbital periods of putative planet candidates. Long-term stellar magnetic cycles (e.g., the 11 year sunspot cycle) can complicate the interpretation of apparent Doppler variations for planets with orbital period of multiple years.

Advances in Instrumentation:
The exoplanet community is advancing the state-of-the-art in detection capabilities and investing in a new generation of complementary precision Doppler spectrographs (e.g., ESPRESSO, EXPRES, HPF, NEID, KPF; González Hernández et al. 2017, Jurgenson et al. 2016, Mahadevan et al. 2014, Robertson et al. 2019). Translating the improved precision and stability of these upcoming instruments into low-mass planet discoveries will require overcoming the barrier of intrinsic stellar variability. Early spectrograph specifications were optimized to maximize RV information content from stellar absorption lines and measure a common line shift, assuming that the intrinsic stellar spectrum was stable. Now, instrument teams treat strategies to mitigate stellar variability as a first-order design challenge. They incorporate increased spectroscopic resolution, increased spectral coverage, and highly stabilized line spread functions, so as to enable these instruments to measure subtle spectral signatures that are potentially useful for untangling activity from bulk motion, such as minute changes in the shapes of spectral lines and small differences in the temporal variability of different spectral lines. A recent study demonstrated that upcoming Doppler surveys using the new generation of spectrographs can measure 1-3 distinct spectral indicators of magnetic activity (i.e., sunspots or faculae) for solar-like stars (Davis et al. 2017).

Advances in Characterizing Stellar Spectroscopic Variability:
Traditionally, Doppler surveys have been reduced to a list of times and measured radial velocities, before performing statistical inference on this univariate time series (and associated measurement uncertainties). With new instruments capable of measuring additional changes in the stellar spectrum (i.e., changes orthogonal to an apparent Doppler shift), we need to develop a more general statistical framework for simultaneously modeling the apparent stellar velocity and the changes to the stellar spectrum. Pulsations, convective motions, rotationally-linked magnetic activity (e.g., spots, faculae) and long-term stellar cycles each contribute with timescales and relative amplitudes that depend on stellar properties. Different lines form at different heights (and thus different temperatures) and often multiple nearby lines are blended. Therefore, spectral features respond in many different ways to stellar activity. Multiple research groups have begun exploring algorithms to distinguish real planet-induced Doppler shifts from spurious Doppler signals due to stellar activity. Some groups are choosing a relatively small set of spectral lines to use (Wise et al. 2018) or measuring apparent radial velocities using different subsets of lines that are intentionally chosen to be more or less sensitive to magnetic activity than average (Dumusque et al. 2018). The choice of stellar activity indicators in published works is largely

historically motivated and does not harness the potential of large data sets and machine learning to create improved spectroscopic indicators for recognizing spurious Doppler signals. Jones et al. (2018)—an interdisciplinary team—developed a machine learning approach to develop stellar variability indicators that were orthogonal to planetary Doppler shifts and more powerful for disentangling planets from intrinsic stellar variability. **Without substantial further innovation in statistical and computational methods, the current or next-generation spectrographs will not realize their potential to detect Earth-mass planets in the habitable zone of sun-like stars.**

Principled Statistical Frameworks for Doppler Planet Detection:
In several cases, follow-up studies have cast serious doubt on premature planet claims, primarily by noticing that the apparent Doppler signal happens to coincide with the stellar rotational period and/or changes of indicators of magnetic activity (e.g., GJ 581, Gl 667C, GJ 176; Robertson et al. 2014, Robertson & Mahadevan 2014, Johnson et al. 2016). This approach, while useful to understand activity in M dwarfs, doesn't necessarily provide a general path towards detecting and characterizing planets in cases where both planets and activity contribute at significant levels.

Through collaborations of astronomers, statisticians, applied mathematicians and experts in high-performance computing, the RV community is starting to envision a path towards disentangling stellar variability and planet-induced Doppler shifts on similar timescales through joint modeling. For example, the claim for an Earth-mass planet orbiting α Centauri B (Dumusque et al. 2012) was contradicted by Rajpaul et al. (2016). Modern follow-up analysis combines traditional stellar activity indicators and a multivariate Gaussian process (GP) model for stellar activity (e.g., Rajpaul el al. 2015). Increasingly, exoplanet observing teams are adopting this GP as a model for the "noise" introduced by intrinsic stellar variability.

These above successes represent early steps towards the development of a rigorous statistical framework for simultaneously analyzing Doppler motion and intrinsic stellar variability, and much more research is needed. Recently, Jones et al. (2018) described how to combine multiple machine learning methods in the wavelength and temporal domains with domain-specific constraints. Idealized tests on simulated solar observations demonstrated that modeling solar activity could explicitly improve sensitivity to planetary signals by >30x compared to treating the variability as unmodeled noise for a realistic number and timespan of observations. While promising, much more research and testing will be necessary before these methods can be applied to real-world Doppler surveys. For example, a related data-driven approach offers a promising path towards modeling variable telluric absorption (Bedell et al. 2019), an additional challenge that is particularly concerning for near-infrared Doppler spectrographs that are now beginning to approach the 1m/s level (eg. Metcalf et al. 2019). **The results of early studies such as these demonstrate the potential and necessity of further research in machine**

learning and data-driven modeling to advance the state-of-the-art in statistical and computational methodology for interpreting the exquisite high-resolution spectroscopic time series data sets to be delivered by next-generation radial velocities.

Advances in stellar modeling:
The RV community is well on its way to developing tools to model spectral variability due to stellar activity (e.g., SOAP 2.0; Dumusque et al. 2014) and granulation (Meunier et al. 2015, Cegla et al. 2018). As astronomers become more adept at modeling stellar activity, complex convective patterns of rising hot gas and cooler falling gas (known as "granulation") could become the limiting factor for characterizing low-mass planets around stars similar to or hotter than the sun (Bastien et al. 2014). Based on detailed observations of the Sun, granulation patterns can remain coherent over one night (or longer), making it impractical for observational strategies to average over granulation patterns. Fortunately, granulation causes changes in the stellar spectrum that can be used to distinguish stellar variability from the Doppler signature of planets (Meunier et al. 2015, 2017). Early attempts to to model the complex hydrodynamics and radiative transfer that is responsible for granulation led to qualitative discrepancies with observations (Cegla et al. 2013). Only recently have astrophysicists reached a level of sophistication to reproduce key spectroscopic diagnostics of granulation (Cegla et al. 2018). **Further research is needed to to improve both physical and mathematical models for stellar spectroscopic variability on multiple timescales.**

Solar observations provide valuable insights into sources of variability that will need to break the 1m/s barrier (e.g., Borgniet et al. 2015). Detailed comparisons of models to observations of the sun as a star with be important for validating advanced statistical models for stellar variability (Dumusque et al. 2015, Phillips et al. 2016, Milbourne et al. 2019). Together these will play an important role in exploring how well recent methods can be generalized to model the effects of granulation or whether new methods are necessary.

Conclusions:
Future NASA missions will benefit enormously from intensive Doppler campaigns to detect and characterize planets around nearby stars (e.g., Astro 2020 white papers by D. Ciardi & C. Dressing). Critically, major mission concepts currently under study are likely to focus their attention on the closest stars, even if they have significant intrinsic astrophysical variability. Therefore, there is a crucial need for Doppler detection and characterization of exoplanets that induce a Doppler signature an order of magnitude smaller than the apparent Doppler variations caused by stellar astrophysics. Overcoming this challenge will require substantial investment in: (1) research on advanced statistical and computational methods for modeling high-resolution spectroscopic time series, (2) integrating the latest development in statistical modeling with real-world pipelines, (3) detailed modeling of effects of stellar activity, granulation and

pulsations, and (4) solar observations with multiple instruments to help test and validate these approaches on the nearest star, in addition to the widely recognized need for investments in next-generation instruments and observing facilities.

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