Use strong words for proposals: don't say 'we plan to', say 'we will'. don't say 'it will help', say 'it will do…'. don't say 'constrain'. In general, USE MORE ACTION WORDS.

Finding the Lowest Mass Exoplanets with Improved Radial Velocimetry

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1 Overview

The excellent synergy between NASA's *Kepler* mission and the ground-based radial velocity (RV) surveys has made numerous ground-breaking discoveries of exoplanets, including many interesting low-mass and rocky planets (e.g., Howard et al. 2013; Pepe et al. 2013; Marcy et al. 2014). This has brought the field of exoplanets into an exciting era with an inceasing sample of small and potentially rocky planets (Weiss & Marcy 2013) with the great promise towards the discovery of Earth analogs in the near future.

In the post-*Kepler* era, radial velocimetry will undoubtedly continue to play a key role in validating *Kepler* candidates and measuring their masses, as well as discovering exoplanets independently. However, the current precision of radial velocimetry (0.5–1 m/s) acts as one of the major limiting factors in detecting exoplanets with even lower masses or rocky planets further out in the orbit, especially in or near the Habitable Zone. Breaking this limit is critical for pushing the lower mass boundary of the exoplanet ensemble. It is also an absolutely necessary step towards finding Earth-mass ($M_\oplus$) exoplanets in the Habitable Zone around Sun-like stars, which requires an RV precision of ~0.1 m/s.

We propose to improve the RV precision of several leading RV instruments exoplanets **[illegible] correction of systematic errors, with the aim to find the lowest mass exoplanet.** Improved radial velocimetry will also enable better characterization of the current known low RV amplitude planetary systems. Moreover, eliminating instrumental systematic errors will help in isolating the RV signals induced by stellar activities and promote a better understanding of the stellar RV jitter, which is also crucial for finding lower mass exoplanets.

2 Expected Scientific Outcome and Impact

Our work will directly improve the RV precision of the two leading RV instruments on two 10-meter-class telescopes: Keck and the Hobby-Eberly Telescope (HET). The large collecting areas of these telescopes make them the ideal facilities for carrying out large and deep surveys around bright or faint stars, as well as for extensive follow-up observations on *Kepler* planet candidate systems. Our work will also improve ~~help~~ improving the RV precision of two instruments on smaller telescopes: CHIRON and the upcoming MINiature Exoplanet RV Array (MINERVA). Designed for carrying out dedicated surveys with extremely high RV precision, these two instruments will provide valuable high cadence data on nearby and bright stars, which are the best targets for planetary atmosphere characterization studies.

Science with Keck/HIRES: The primary instrument we work with is the High Resolution Echelle Spectrometer (HIRES) on Keck I (current RV precision ~1 m/s). Among the RV discovered exoplanets, Keck/HIRES has contributed to a majority of these discoveries. It has also contributed to a great number of mass measurements of confirmed *Kepler* planets — in particular, *most* of the low mass ones (e.g., Gautier et al. 2012; Gilliland et al. 2013;

Howard et al. 2013; Marcy et al. 2014). However, its current RV precision is limiting its ability to detect lower mass planets or planets with the same mass but further out in orbit (e.g., Marcy et al. 2014).

Our work will improve the RV precision of Keck/HIRES, and thus extend the lower mass limit of the current exoplanet sample. This is especially promising when considering the large candidate pool that *Kepler* provides: among the 1600 KOIs with transit signals suggesting a planet radius smaller than 2 Earth radii, there are 260 whose host stars have *Kepler* magnitude < 13 and are thus bright enough for Keck to follow to up (compared with fewer than 10 such targets with *Kepler* mag < 9 and thus accessible by HARPS-N).

Meanwhile, better RV precision will improve the characterization of multiple-planet systems, especially the ones that host challenging low RV amplitude planets/candidates and with potentially very active dynamic interactions. We plan will to reanalyze the RV data and perform dynamic analysis on such systems, including the GJ 876 system, which is the closest multi-planet systems to the Sun (Marcy et al. 2001; Rivera et al. 2005, 2010), the υ Andromedae system, the first multi-planet system discovered around main-sequence star (Butler et al. 1999; Wright et al. 2009; Curiel et al. 2011), as well as the GJ 581 system, which hosts the first claimed terrestrial-mass exoplanet in the Habitable Zone (Vogt et al. 2010~~)~~, these are though under debate (e.g., Gregory 2011; Vogt et al. 2012; Robertson et al. 2013).)

Science with HET/HRS: We will also ~~work with~~ improve another leading RV instrument on a 10-meter-class telescope: the High Resolution Spectrograph (HRS) on HET (current RV precision ∼3–5 m/s). With multiple ongoing upgrades on HET/HRS (expected to finish in summer 2014), its throughput will be improved by a factor of ∼5, also with the promise of ~~a~~ higher RV precision of the new HRS. HET will become the second telescope, besides Keck, ~~that is suitable for~~ capable of RV follow-up on ~~the stars hosting~~ planet candidates discovered by *Kepler*. This ~~will make the *Kepler* follow-up programs more efficient. It~~ will also benefit other planet search programs on HET/HRS such as surveys on long-period planets and multiple-planet systems.

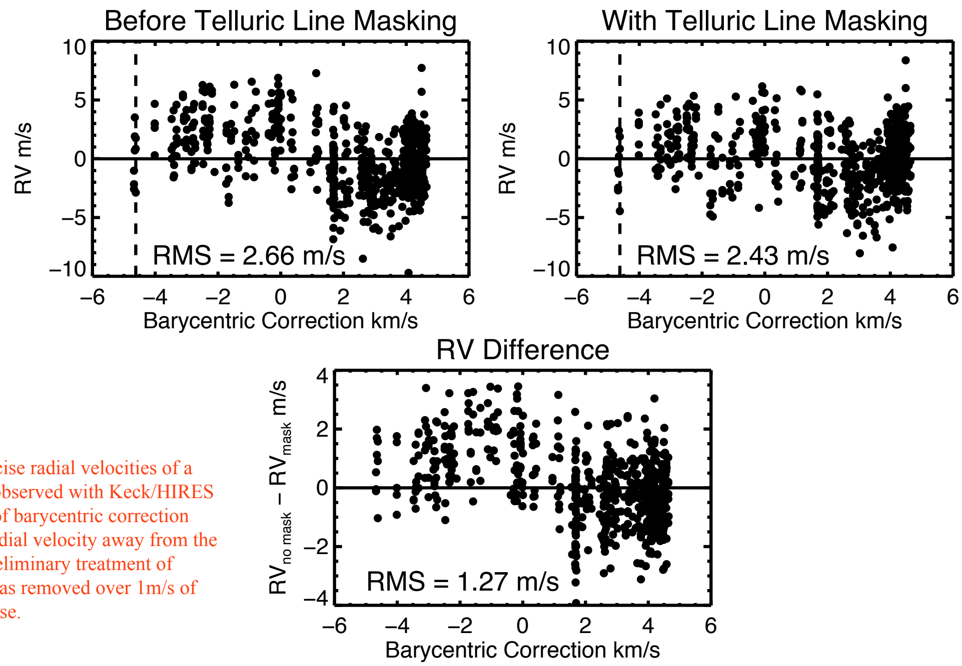
MINERVA and CHIRON: Our work also has great synergy with two very high RV precision instruments on smaller telescopes: the upcoming MINERVA and CHIRON on the 1.5m SMARTS telescope at CTIO.

MINERVA ~~consists~~ will consist of will comprise an array of four 0.7m telescopes and a vacuum-sealed highly-stable spectrograph that will perform dedicated RV monitoring on a carefully-selected ensemble of nearby stars. It is expected to discover $\gtrsim 10$ Earth- to super-Earth-size planets with orbital period of 1–100 days around nearby stars, with 3–5 expected to be in the Habitable Zones of their host stars (Bottom et al. 2013; Hogstrom et al. 2013). The proposed work here will help prepare the project to meet its targeted long-term RV precision of ~ 0.8 m/s.

CHIRON has demonstrated short-term RV stability of ~ 0.5 m/son space τ Ceti (Tokovinin et al. 2013). The improvement we propose will help CHIRON achieve long-term RV stability below 1 m/s and help validate or characterize the potential planetary systems around τ Ceti (Tuomi et al. 2013) and α Centauri B (Dumusque et al. 2012; Hatzes 2013), which both have exoplanets with RV amplitudes on the order of ~ 1 m/s or even smaller.

3 Methodology

Our approach for improving the RV precision is to eliminate the RV systematic errors, ~~known as~~ one of the two major contributors to the ‘RV jitter~~s~~’ (the other ~~one~~ being ~~the~~ stellar jitter). ~~Through o~~ur pilot study, has ~~we have~~ identified several contributing factors to RV systematic errors, some of which are being recognized and studied in detail *for the very first time*. Some of these factors contribute to the RV error budget at $\sim$ 1 m/s level, and thus they set the floor of long-term RV precision at 1 m/s if not carefully studied and corrected for.



Measured precise radial velocities of a standard star observed with Keck/HIRES as a function of barycentric correction (i.e. Earth’s radial velocity away from the target) Our preliminary treatment of telluric lines has removed over 1m/s of systematic noise.

Figure 1: Before and after making telluric lines.

3.1 Removing the Systematics Caused by Telluric Lines

In precise iodine radial velocimetry, the measured RV is derived from the differential shift of stellar lines between two stellar spectral observations. Since all current RV instruments are ground-based, the stellar spectra inevitably contain telluric absorption lines ~~as stellar~~ from the light‘s travel~~s~~ through Earth’s atmosphere. These telluric lines ~~are impostors of the true~~ impersonate stellar lines~~, as they exist in every observation and are hard to identify. However, unlike the stellar lines, telluric lines~~ but do not ~~have~~ exhibit Doppler doppler shifts~~. This creates problems when one tries to measure the amount of differential line shift between two stellar spectra, since the ‘impostor stellar lines’ do not shift between two observations while the true stellar lines do. As the dominant doppler shift of stellar lines is~~ caused by the Earth’s barycentric motion ($\sim$a few to ten~~th~~s of km/s), ~~the effect of telluric lines will manifest~~ The resulting “peak-puling” effect in the iodine analysis (see, e.g. Wright et al. (2013)) then manifests as an annual systematic signal.

For years, such problems caused by telluric lines ~~are~~ were thought to have been suppressed to ~~be at~~ a negligible level, because there are only few telluric bands within the working wavelength region of iodine radial velocimetry (5000Å–6000Å), ~~and~~ most of the telluric lines in this region are shallow. However, as the RV precision ~~improves~~ improved over time and ~~approaching~~ has approached $\sim$ 1 m/s and better, the adverse effects of telluric lines have emerged and become one of the current bottlenecks of precise radial velocimetry. **This is demonstrated *for the first time* through our preliminary study, and with some initial effort, we were able to eliminate at least some of the systematic RV errors caused by telluric lines**, which is illustrated in Figure 1.

Figure 1 shows that the long-term (> 5 years) RV RMS of an RV standard star observed by Keck/HIRES, HD 185144 (σ Draconis), is reduced from 2.66 m/s to 2.43 m/s — an RMS of 1.08 m/s is removed from the RV jitter of the star ($\sqrt{2.66^2 - 2.43^2}$). The bottom panel of Figure 1 illustrates the systematic errors that are being removed, which ~~is~~ have a clear annual ~~trend~~ signal. The rest of the RV jitter may be due to residual telluric line effects not removed completely, intrinsic stellar jitter, other unknown systematic errors, or even low RV amplitude planets. ~~Note that HD 185144 is the most stable RV standard star (with the least RV RMS) observed by Keck.~~

We will ~~In our preliminary work, we simply ‘ignored’ the telluric lines by masking them out. We gave zero statistical weights to the pixels associated with telluric lines when modeling the observations and extracting RVs. This is only the very first step, and there are many future improvements that will~~ in several ways further reduce the systematics caused by telluric lines. For example, the mask we used was derived from naive atmospheric models based on the elevation of Mauna Kea with nominal atmospheric compositions and conditions. In the future we will employ empirical masks derived from B star observations. Another example is that the RV extraction code is not yet optimized to consistently produce a ~~robust~~ good fit when some of the pixels are being masked out due to telluric lines, especially ~~when the~~ for cases with large barycentric velocity shifts ~~velocities differ a lot for the two stellar spectra whose RVs are being differentially measured. We think this might be the cause for the residual trend seen at large barycentric velocity (∼ 2–4 km/s).~~ A more carefully-tuned \chi^2 minimization algorithm will allow us to recover reliable RVs from _all_ segments of the iodine-laced stellar spectrum, including those with signifiant telluric contamination.

This work will naturally improve the RV precision of HET/HRS and MINERVA, as they share essentially the same RV extraction code inherited from the Keck/HIRES pipeline. with Keck at its core. We will also work with the CHIRON team to implement the treatment for telluric lines to help CHIRON achieve higher long-term RV precision.

3.2 Validating the Calibrator: the Iodine Atlas

One key element in precise RV work with iodine is the ‘ground truth’ of the absorption spectrum of the iodine cell, which is normally a wavelength-calibrated, very high-resolution spectrum taken by a Fourier Transform Spectrometer (FTS). This FTS iodine atlas is treated as the ‘true and perfect iodine spectrum’ and is used for modeling the iodine lines in the observed stellar+iodine spectrum to anchor the absolute wavelength solution and ~~the ‘spectral PSF’ (formally known as the~~ spectrograph response function~~)~~. Therefore, an accurate and precise iodine atlas is crucial for achieving high RV precision. **We propose to validate the quality of the FTS iodine atlases for the new HET/HRSand MINERVA, and also for CHIRON and other RV instruments if necessary.**

~~Over the years, the FTS iodine atlases are considered of very high quality and thus are regarded as the ‘ground truth’ of the iodine absorption spectra.~~ However, recently ~~we have discovered that the quality of an FTS spectrum is not always close to ‘perfect’ and that it can affect the RV precision at a visible level. For test purposes,~~ we took a newer FTS spectrum of the iodine cell of HET/HRS at NIST. Comparison between this new FTS spectrum and the old one (taken at KPNO in 1993) reveals significant differences between the two in terms of wavelength solution, wavelength dispersion scale, as well as iodine line depths and line depth ratios. Two Doppler reductions on the RV standard star HD 185144 using these two FTS spectra respectively yield different RV jitter: the new FTS spectrum reports an RV RMS of ~ 5 m/s while the old FTS spectrum reports ~ 4 m/s. This calls into question~~s of~~ how 'true' any existing FTS iodine atlas really is, and demands for an independent method to validate the FTS spectra.

Through our pilot study, we have found a method to independently validate the quality of FTS iodine atlas, which is to take an high-resolution iodine absorption spectrum in the 'real wavelength space' (as opposed to in Fourier space with FTS) using an echelle spectrograph. The echelle spectrograph we used that has the matching spectral resolution to an FTS (at $R \sim 500,000$) is the TS12 arm of the Tull Spectrograph at the 2.7m Harlan J. Smith telescope of McDonald Observatory. ~~As the HET/HRS iodine cell was not available,~~ we took a 30Å chunk of echelle absorption spectrum of the iodine cell at the McDonald 2.1m telescope and compared it with its FTS iodine atlas, which was also taken at KPNO in 1993 and thus can represent the quality of the KPNO FTS spectra.

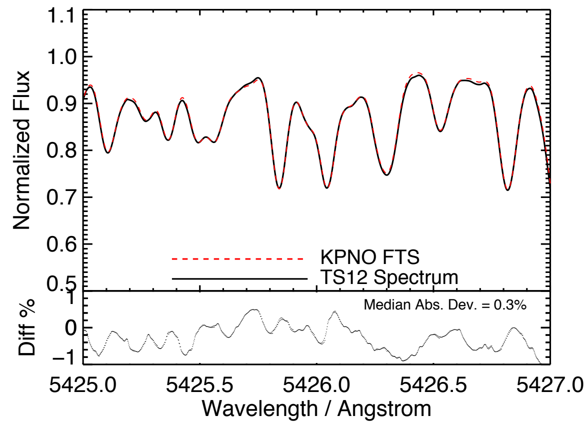


Figure 2: FTS compared with echelle spectrum.

Figure 2 illustrates this comparison zoomed into a 2Å chunk. It shows that, when convolved down to resolution $R = 60,000$ (typical resolution of an star+iodine RV observation), the difference between the KPNO scan and the echelle spectrum is very small considering photon-limited errors and potential errors in flat fielding and scattered light removal. This demonstrates that we have found an independent and reliable method to validate any FTS iodine atlas in the future.

~~Though the KPNO FTS spectrum has proven its quality, the FTS facility is no longer available.~~ Recent and upcoming RV instruments such as the new HET/HRS, CHIRON, and MINERVA will need validation for their FTS iodine atlases to eliminate one risk factor that could potentially compromise the RV precision, which is our proposed work here.

4 Relevance to NASA's Objectives and Missions

Broadly, our investigation addresses one of the science objectives of NASA SMD, "Discover the origin, structure, evolution and destiny of the universe and search for Earth-like planets".

More specifically, this proposal is directly and closely relevant to the Astrophysics Research Program, theme (iii) Exoplanet Exploration, in the solicitation:

- "to search for planets and planetary systems about nearby stars in our Galaxy": This is the direct science goal of our work.
- "to determine the properties of those stars that harbor planetary systems": We will acquire high resolution spectra on planet host stars with Keck/HIRES and HET/HRS

for, e.g. the *Kepler* stars, as required by the RV technique. Improved RV precision will also help better understanding stellar activities and stellar RV jitter.

- "to determine the percentage of planets that are in or near the Habitable Zone of a wide variety of stars and to measure their orbits": Improved RV precision of Keck/HIRES and HET/HRS will enable more detections of potentially rocky exoplanets in the Habitable Zone of their host stars — through both *Kepler* follow-up programs and independent RV surveys. Project MINERVA will find more Earths and super-Earths in or near the Habitable Zone of nearby stars.

Our work will also support current and future NASA missions and enhance their scientific outcome: (1) **the *Kepler* mission**: Keck/HIRES and HET/HRS will directly support *Kepler* through follow-up programs, including candidate validation/confirmation, planetary mass measurements, TTV follow-up, and outer planet discovery. **(2) TESS:** Keck/HIRES, HET/HRS, and MINERVAcan all contribute significantly in follow-up programs on TESS targets. **(3) JWST:** Finding more lower mass exoplanets means more Earth- or super-Earth-like exoplanets, which are the primary targets for JWST for planetary atmosphere characterization.

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