Finding the Lowest Mass Exoplanets with Improved Radial Velocimetry

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1 Overview

The great synergy between NASA's *Kepler* mission and the ground-based radial velocity (RV) surveys has made ground-breaking discoveries of exoplanets, including many interesting low-mass (Marcy et al. 2014) and likely rocky planets (Weiss & Marcy 2013) such as Kepler-78b, the first exoplanet known to have radius and mass very close to Earth's (Howard et al. 2013; Pepe et al. 2013). In the post-Kepler era, radial velocimetry will continue to play a key role in validating Kepler candidates and measuring their masses, as well as discovering exoplanets independently.

However, the current RV precision ($\gtrsim$ 0.5–1 m/s)[1] is limiting our ability to detect exoplanets with even lower masses or rocky planets orbiting farther out, especially in or near the Habitable Zone. Breaking this limit is critical for enriching the diversity of the exoplanet ensemble towards lower masses, and it is a necessary step for finding Earth analogs 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 by eliminating > 1 m/s of systematic errors, with the aim to find the lowest mass exoplanets. We will improve the RV precision of Keck and the 9.2m Hobby-Eberly Telescope (HET), which are the leading facilities for extensive *Kepler* follow-up observations as well as independent large and deep RV surveys. Our work will also improve the RV precision of two instruments on small telescopes: CHIRON and the upcoming MINiature Exoplanet RV Array (MINERVA). Designed for carrying out dedicated surveys with extremely high RV precision, CHIRON and MINERVA will provide valuable high cadence data on nearby and bright stars, which are the best targets for planetary atmosphere characterization studies.

With improved RV precision, we will revisit and perform dynamic analysis on systems with multiple planets, especially the ones with small RV amplitudes, such as 55 Cancri, GJ 876, upsilon Andromedae, and GJ 581.

2 Expected Scientific Outcome and Impact

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 432 RV discovered exoplanets, Keck/HIRES has contributed the most (~200). 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 even lower mass planets or planets with the same mass but orbiting farther out (see, e.g., the marginal or null detections of the confirmed *Kepler* planets in Marcy et al. 2014).

[1] The photon-limited precision of the leading RV instruments (HARPS and Keck) is ~0.5–1 m/s for bright stars, while in reality, there is almost always some extra error, i.e. the "RV jitter", comprised of systematic errors and unaccounted stellar-activity signals. For example, the RMS of RV residuals against best-fit model for the Kepler-78b system is ~ 2.5 m/s, with an RV jitter of ~ 2.1 m/s, while the photon-limited error for the star is < 2 m/s (Howard et al. 2013; Pepe et al. 2013).

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 pool of low mass planet candidates that *Kepler* provides: among the ∼1600 KOIs with transit signals suggesting a planet radius < 2 Earth radii, there are ∼260 whose host stars have *Kepler* magnitude < 13 — bright enough for Keck to follow up (vs. fewer than 10 such targets with *Kepler* mag < 9 and thus accessible to HARPS-N; exoplanets.org).

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. Such systems are valuable samples for studying the architecture of exoplanet systems and planet formation. We will reanalyze the RV data and perform dynamic analyses on several of these systems, including the GJ 876 system, which is the closest multi-planet systems to the Sun and the only known exoplanet system with a triple conjunction (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, though it is under debate, e.g. Gregory 2011; Vogt et al. 2012; Robertson et al. 2013).

Science with HET/HRS: We will also improve the RV precision of 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 higher RV precision of the new HRS. HET will become the second telescope, besides Keck, capable of extensive RV follow-up on planet candidates discovered by *Kepler*. This will also benefit other planet search programs on HET/HRS such as surveys on long-period planets and multiple-planet systems.

MINERVA and CHIRON: The upcoming MINERVA will consist of an array of four 0.7m telescopes and a vacuum-sealed, highly-stable spectrograph (schedule to be online in 2015). It 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). Our work will prepare MINERVA to meet its targeted long-term RV precision of ∼ 0.8 m/s.

CHIRON (on the 1.5m SMARTS telescope at CTIO) has demonstrated short-term RV stability of ∼ 0.5 m/s on 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), whose planets (candidates) have RV amplitudes on the order of ∼ 1 m/s or even smaller.

3 Methodology

We have identified several underlying causes for RV systematic errors through our pilot study. Some of these errors are being recognized and studied in detail *for the very first time*. A few of them enter the RV error budget at a ∼ 1 m/s or even larger level, and thus they set the floor for long-term RV precision at 1 m/s if not carefully studied and corrected for. We will determine the first comprehensive error budget of iodine radial velocimetry.

3.1 Removing the Systematics Caused by Telluric Lines

In precise iodine radial velocimetry, RVs are measured from the differential shift of stellar lines between two stellar spectra. Since all current RV instruments are ground-based, the stellar spectra inevitably contain telluric absorption lines as from the light's travel through Earth's atmosphere. These telluric lines impersonate stellar lines but do not exhibit Doppler shifts caused by the Earth's barycentric motion ($\sim$a few to tens of km/s) and the exoplanets. The resulting "peak-pulling" 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 were thought to have been suppressed to a negligible level, because there are only few telluric bands mostly with shallow lines within the working wavelength region of iodine radial velocimetry (5000Å–6000Å). However, as the RV precision improved over time and has approached ~ 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 in telluric line masking, we were able to eliminate a visible amount of the systematic RV errors**, which is illustrated in Figure 1.

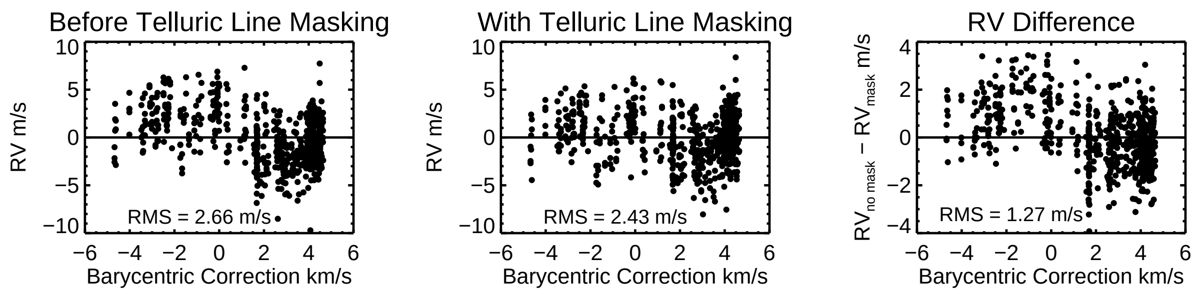

Figure 1: Measured precise radial velocities of a standard star observed with Keck/HIRES as a function of barycentric correction (i.e. Earth's radial velocity away from the target). Our preliminary treatment of telluric lines has removed over 1 m/s systematic noise (panel 3; note the change in scale on y-axis).

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** ($\sqrt{2.66^2 - 2.43^2}$). The last panel of Figure 1 illustrates the removed systematic errors, which has a clear annual signal. The rest of the RV jitter may be due to residual telluric line effects, intrinsic stellar jitter, other unknown systematic errors, or even low RV amplitude planets.

We will further reduce the systematics caused by telluric lines in several ways. For example, currently we are masking out the telluric lines by using a naive simulated telluric spectrum 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 good fit in regions where some of the pixels are being masked out due to telluric lines, especially for the cases with large barycentric velocity shifts. A more carefully-tuned χ^2 minimization algorithm will allow us to recover reliable RVs from *all* segments of the iodine-laced stellar spectrum, including those with significant 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. Moreover, the sites of HET/HRS and MINERVA are at much lower elevations than Mauna Kea, which means that the telluric line contamination probably causes more severe systematic errors. 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 Improving the Wavelength-Dependent Statistical Weighting

The application of wavelength-dependent statistical weights is the "secret sauce" of precise iodine radial velocimetry. It evaluates the RV performance of each wavelength region (an "RV chunk") across observations and assigns them statistical weights before computing the final mean RV. It also adjusts for the wavelength-dependent systematic offsets and rejects outlier chunks with poor RV RMS performance. Figure 2 illustrates the crucial role of this weighting scheme in precise radial velocimetry.

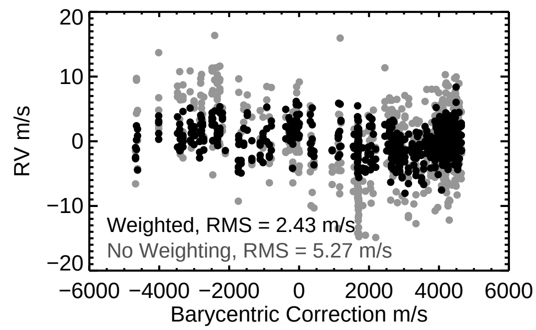

Figure 2: RV RMS of HD 185144 before (gray) and after (black) weighting.

Through our preliminary work with telluric lines, we discovered that the weighting procedure does not give proper treatment to the telluric-contaminated chunks. It does not incorporate any prior knowledge on the intrinsic quality of chunks, and consequently, the telluric-contaminated ones tend to be either brutally rejected or taken in almost equally as the clean chunks.

We propose to improve the statistical weighting by incorporating prior knowledge on the intrinsic quality of different wavelength regions. Our work will extend beyond implementing proper treatment for the telluric regions: the current weighting procedure is purely a post-RV-reduction outlier rejection process, and we will increase its power by exploiting more prior knowledge on each chunk, such as the amount of Doppler information content, the signal-to-noise ratio, and instrumental effects.

3.3 Validating the Calibrator: the Iodine Atlas

A "ground truth" iodine atlas is crucial for the precise iodine radial velocimetry. It is used for modeling the observed iodine lines in the stellar+iodine RV observation to anchor the absolute wavelengths and the spectrograph response function. Such a "ground truth" atlas is normally obtained through a Fourier Transform Spectrometer (FTS). However, our recent work has revealed potential problems with the quality of FTS iodine atlases.

We took a new FTS atlas of the HET/HRS iodine cell at NIST and compared it with the old one (taken at KPNO in 1993), which showed that they differ significantly in terms of wavelength scales and line shapes. The RV jitter of the RV standard star HD 185144 (observed with HET/HRS) is ~ 5 m/s when we use the new FTS atlas vs. ~ 4 m/s with the old one. This calls into questions of how "true" any existing FTS iodine atlas really is, and demands for an independent method to validate them. **We propose to validate the quality of the FTS iodine atlases for the new HET/HRS and MINERVA, and also for CHIRON and other RV instruments if necessary.**

We have found a method to independently validate the quality of FTS iodine atlas, which is to take a high-resolution echelle spectrum of the iodine cell in the "real wavelength space" (as opposed to in Fourier space with FTS). We used the TS12 arm of the Tull Spectrograph at the McDonald Observatory 2.7m telescope, which has the matching spectral resolution to an FTS ($R \sim 500,000$). For our pilot study, we used the iodine cell at the McDonald 2.1m telescope, whoese FTS atlas was also taken at KPNO in 1993 and thus can represent the quality of the KPNO FTS atlases.

Figure 3 illustrates the comparison between the FTS iodine atlas and the echelle spectrum (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 consistent with photon-limited errors and potential errors in flat fielding and scattered light removal.

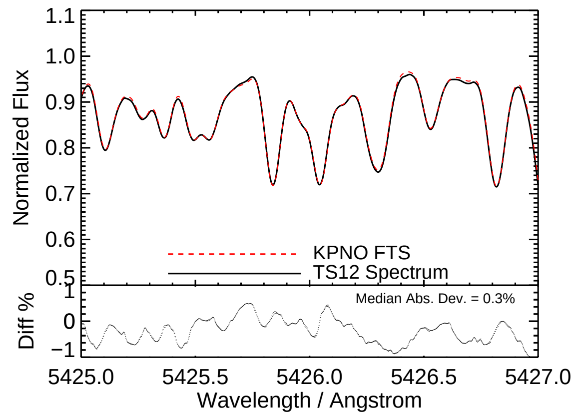

Figure 3: FTS iodine atlas compared with echelle spectrum, both at $R = 60,000$.

This demonstrates that we have found an independent and reliable method to validate any FTS iodine atlas. Current and upcoming RV instruments such as the new HET/HRS, MINERVA, and CHIRON 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.

3.4 Improving Data Reduction and Instrument Modeling

We propose to improve the data reduction pipeline of HET/HRS in preparation for its upgrade (schedule to finish in Summer 2014) and also for the upcoming project MINERVA. The new HET/HRS will have a new spectral format that is similar to CHIRON and MINERVA. This new format will have five parallel images for each echelle order due to the implementation of an image slicer, and this poses a challenge to data reduction, especially for flat fielding. With our experience of setting up data reduction pipeline for the current HET/HRS (Wang et al. 2012) and our close collaboration with the CHIRON group, we will produce a pipeline for the new HET/HRS and MINERVA to ensure the delivery of high RV precision.

Another factor that is limiting the current precision of HET/HRS is the modeling of the spectrograph response function (SRF). This is probably not a dominant issue for Keck/HIRES, since the SRF of HIRES has been studied in detail and modeled successfully. However, for the fiber-fed HET/HRS and MINERVA, the SRF will be significantly different and require more careful study on fiber spectroscopy. We have acquired on-sky and engineering test data with HET/HRS designed to address this issue, as well as the issue of modal noise, which is also unique to fiber-fed spectrographs.

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: **(1) "to search for planets and planetary systems about nearby stars in our Galaxy":** This is the direct science goal of our work. **(2) "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. **(3) "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, which is also the immediate goal of project MINERVA.

Our work will support current and future NASA missions: We will enhance the scientific outcome of the ***Kepler* mission** through follow-up programs such as candidate validation, planetary mass measurements, and TTV target follow-up. In the future, Keck/HIRES, HET/HRS, and MINERVA can all contribute significantly to the follow-up programs of **TESS**. Improved radial velocimetry will find more super Earths and Earth analogs, which are the primary targets for **JWST** for planetary atmosphere characterization.

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