

# 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 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 enriching the diversity of the current exoplanet ensemble towards the lower mass end, and it is a necessary step towards finding Earth-mass exoplanets in the Habitable Zone around Sun-like stars, which requires an RV precision of  $\sim 0.1$  m/s.

**We propose to improve the RV precision of several leading RV instruments through correction of systematic errors, with the aim to find the lowest mass exoplanets.** 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 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  $\sim 1$  m/s). Among the 432 RV discovered exoplanets, Keck/HIRES has contributed the most ( $\sim 200$ ). 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 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  $\sim 1600$  KOIs with transit signals suggesting a planet radius smaller than 2 Earth radii, there are  $\sim 260$  whose host stars have *Kepler* magnitude  $< 13$  and are thus bright enough for Keck to follow up (compared with fewer than 10 such targets with *Kepler* mag  $< 9$  and thus accessible to HARPS-N; data from 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. We will 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  $\nu$  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 these are under debate, e.g. Gregory 2011; Vogt et al. 2012; Robertson et al. 2013).

**Science with HET/HRS:** We will also improve another leading RV instrument on a 10-meter-class telescope: the High Resolution Spectrograph (HRS) on HET (current RV precision  $\sim 3\text{--}5$  m/s). With multiple ongoing upgrades on HET/HRS (expected to finish in summer 2014), its throughput will be improved by a factor of  $\sim 5$ , also with the promise of higher RV precision of the new HRS. HET will become the second telescope, besides Keck, capable of 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:** 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 will consist of 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). Our work will prepare MINERVA to meet its targeted long-term RV precision of  $\sim 0.8$  m/s.

CHIRON has demonstrated short-term RV stability of  $\sim 0.5$  m/s on  $\tau$  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  $\tau$  Ceti (Tuomi et al. 2013) and  $\alpha$  Centauri B (Dumusque et al. 2012; Hatzes 2013), whose planets (candidates) have RV amplitudes on the order of  $\sim 1$  m/s or even smaller.

### 3 Methodology

Our approach for improving the RV precision is to eliminate the RV systematic errors, one of the two major contributors to the ‘RV jitter’ (the other being stellar jitter). Our pilot study has 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.

#### 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 planets. 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  $\sim 1$  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 in telluric line masking, we were able to eliminate a visible amount of the systematic RV errors**, which is illustrated in Figure 1.

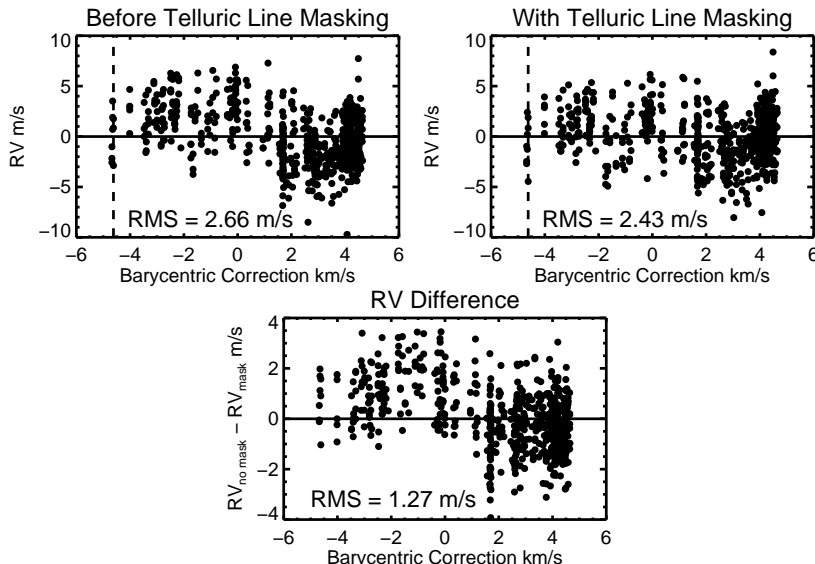


Figure 1: Measured precise radial velocities of a standard star observed with Keck/HIRES as a function of barycentric correction (i.e. Earth’s radial velocity away from the target). Our preliminary treatment of telluric lines has removed over 1 m/s systematic noise.

Figure 1 shows that the long-term ( $> 5$  years) RV RMS of an RV standard star observed

by Keck/HIRES, HD 185144 ( $\sigma$  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 bottom 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  $\chi^2$  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 RV.

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 equally as other clean chunks.

**We propose to improve the statistical weighting by incorporating prior knowledge on the intrinsic quality of different wavelength regions.** Our work will actually go beyond 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,

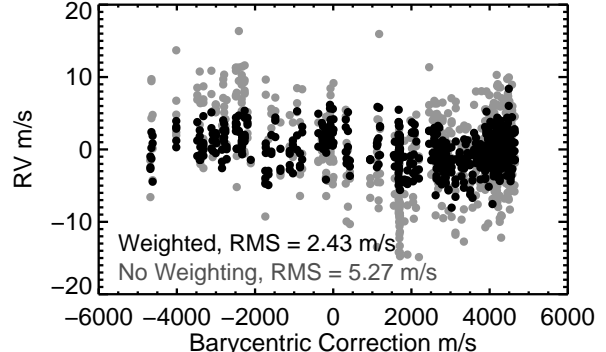


Figure 2: RV RMS of HD 185144 before (gray) and after (black) weighting.

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  $\sim 5$  m/s when we use the new FTS atlas vs.  $\sim 4$  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, whose 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  $2\text{\AA}$  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. 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.

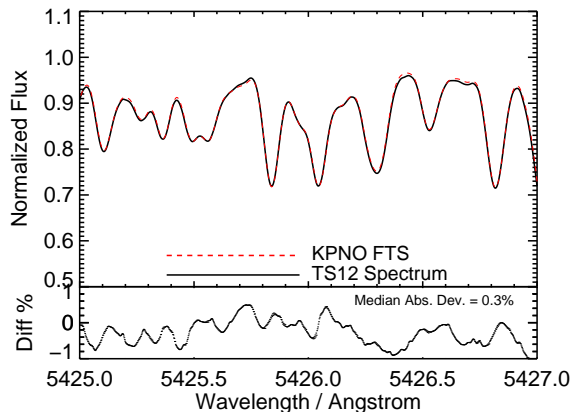


Figure 3: FTS iodine atlas compared with echelle spectrum, both at  $R = 60,000$ .

## 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 also support current and future NASA missions and enhance their scientific outcome: **(1) the *Kepler* mission**: Our work directly supports the *Kepler* mission through candidate validation/confirmation, planetary mass measurements, TTV target follow-up, and outer planet discovery using Keck/HIRES and HET/HRS. **(2) TESS**: Keck/HIRES, HET/HRS, and MINERVA can all contribute significantly to the follow-up programs of TESS. **(3) JWST**: Finding more lower mass exoplanets means more super Earths and Earth analogs, which are the primary targets for JWST for planetary atmosphere characterization.

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