Finding the Lowest Mass Exoplanets with Improved Radial Velocimetry: 2015 Progress Report

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1 Summary of Project and Orignal Plans

Our project is on improving the radial velocity precision...

In our original proposal, our plans include:

(1) removing the RV systematics caused by telluric lines;

(2) validating the calibrator: the iodine atlas;

(3) improving the wavelength-dependent statistical weighting;

(4) improving data reduction and instrument modeling.

We have made significant progress on all fronts, essentially finished all proposed work in the original proposal, and carried out advanced studies and next-stage work for all items above, as detailed in the next section. We plan to finish the on-going work described in Section 2 before the end of this funding cycle, and we lay out our plans for the next one, starting September 1 2015, in Section 3.

2 Progress and Achievements

We describe our progress on item (1) in Section 2.1, item (2) in Section 2.2 and item (3) in Section 2.3. Our new work described in Section 2.4 address both (3) and (4).

We plan to publish the work described in Section 2.1 through 2.3 in two papers (in prep.), and the work of Section 1.3 is in the form of a new code, written in *Python*, that is made available to the public and will also be presented and documented in peer-reviewed literature. Most of the work described here was presented in a Solar, Stellar, and Planetary Seminar talk at Harvard/CfA in October 2014, and will be presented in future meetings such as the Extreme Precise Radial Velocity Workshop in July 2015 at Yale and a couple of more other future meetings in 2015–2016.

2.1 Telluric-Free Stellar Templates and Forward Modeling of Telluric Lines

Earth's atmosphere creates absorption lines (telluric lines) in the observed spectra based on which we derive the RVs of the stars. These telluric lines impersonate stellar lines but do not exhibit Doppler shifts, and thus they creates a bias to the measured RV, at a level of at least ~ 1 m/s. Our original plan was to improve the mask for flagging the telluric-contaminated pixels as bad ones, and also to tune the fitter in our modeling code to adjust to this change.

However, during the past year, we have found that more elaborate solutions rather than simply 'ignoring' the telluric pixels would be more efficient in correcting the biases. As a result, we have made two major progresses:

(a) We have created, for the first time, stellar spectral templates that are free of telluric contamination fro Keck observations.

(b) We are incorporating a full forward-modeling module into the existing RV code to model the telluric lines in the epoch observations (work in final step).

Figure 1 illustrates the improvements made by these two new efforts. Similarly to Figure 1 shown in our original proposal, this is the RMS of RVs of a standard star observed by Keck. Different from the old Figure 1, this set of RVs were derived from a particular stellar template observation which had large amount of telluric contamination (i.e. deep water lines caused by humid observing condition). Our old approach of masking telluric pixels would bring only marginal improvement on these RVs. However, with our telluric-free stellar template and preliminary modeling implementation, a significant portion of the aliasing signal caused by the telluric lines is successfully removed (the trend shown in the third panel). We also see reduction of powers in the periodogram at harmonics of a sidereal year, which means that for future planet detection, successful removal of telluric-induced aliasing signal would boost detection confidence level or even reveal planet signals that otherwise would not be able emerge in the periodogram.

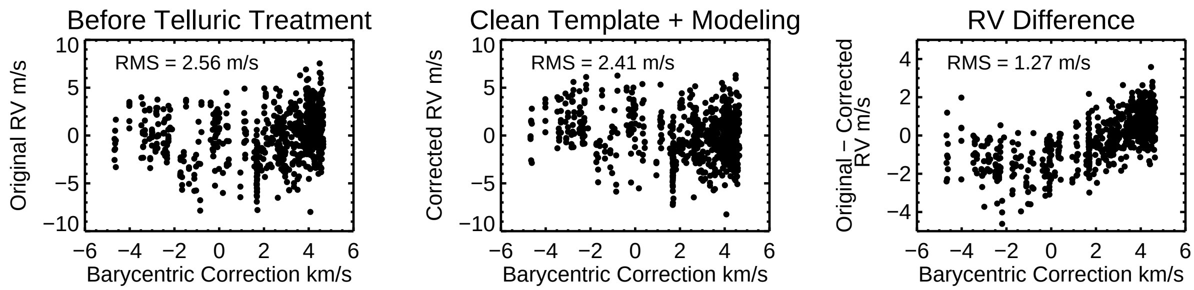

Figure 1: Measured precise radial velocities of a standard star observed with Keck/HIRES as a function of barycentric correction (i.e. Earth's radial velocity away from the target). Our preliminary treatment of telluric lines has removed over 1 m/s systematic noise (panel 3; note the change in scale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

We have also applied our code to a couple more test targets at Keck, and we are confident that, with telluric-free templates and full incorporation of telluric lines in the forward-modeling process, we will be able improve the RV precision and accuracy for many targets at Keck, especially the stars which have low-mass, low-RV amplitude planets, such as some of the *Kepler* targets.

We will publish the work described in this section to share our methods and findings with the broader community, and moreover, as a result of this work, I am invited to host a discussion session on treating the telluric contamination in precise RV work at the upcoming Extreme Precise Radial Velocity Workshop in July 2015 at Yale.

Here is a more detailed description of the progress, including on-going work:

For (a): Stellar spectral templates are derived based on observations of the target star (without an iodine cell) and thus is also subject to telluric contamination. We have created a pipeline for producing telluric-free stellar template for Keck (also adaptable for other instruments). Using the telluric simulation package TERRASPEC (written by Chad Bender, Penn State, based on the HITRAN molecular line database; Rothman et al. 2013), we are able to determine the oxygen and water column densities based on the red portion of the spectra near 7000Å and construct telluric line model for the iodine region of the spectra. Then for each step of spectral modeling in the process of template creation, we are able to model the telluric lines and therefore remove it form the end product.

We are now collaborating with the CHIRON group at Yale (Debra Fischer and Matt Giguere) to provide them with a telluric-free τ Ceti template, to enhance the RV accuracy and precision on this important RV standard star for better understanding of stellar activity induced RV signal.

For (b): For the epoch observation (with the iodine cell), we have a implemented basic function of telluric line modeling in our RV code as a first step, where the water column density would be a fixed value for all observations. We are constructing the module which would fit for the water column density for each night and construct different telluric models. This would be the final step to fully modeling the telluric lines in RV observations, and thus provide the maximal capability of removing the biases within the frame of our current RV code (for work beyond this, see Section 2.4).

2.2 Evidence for Changes of Iodine Calibration Cells and Solutions

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). Our previous work has revealed potential problems with FTS atlases, and in our original proposal, we promised to use the TS12 arm of the Tull spectrograph at McDonald Observatory to validate the qualities of the FTS iodine atlases for HET/HRS, MINERVA, and the McDonald 2.7m (all three are important current or future RV instruments in the northern hemisphere).

In October 2014, the TS12 observations were successfully carried out. All data are reduced and we have made comparisons between the TS12 spectra and FTS scans. For the 2.7m cell, its TS12 spectrum matches very well to its FTS atlas, again (together with the 2.1m cell data from 2013) proving that TS12 is an appropriate tool for validating FTS atlases. The TS12 spectra for the MINERVA cell is also ready, and right now we are waiting for the FTS expert on our team to reduce the MINERVA FTS data for comparison, which is expected to be done before June (first light of the proto-type MINERVA spectrograph).

Finally, for the HET/HRS iodine cell, we have taken its TS12 spectra at three different temperatures (50, 60, and 70°C; the RV working temperature for the cell is 70°C). Our main findings (both are first-time discoveries for iodine RV work) are as follows:

(a) Temperature change (5–10°C) in iodine cell matters: The long suspected temperature-induced iodine spectrum change was finally confirmed, which is seen very visibly among the TS12 spectra taken at three different temperatures. Based on our NIST FTS atlases taken at two different temperatures, temperature change on the order of 10°C should not induce visible line changes. However, we suspected issues with temperature control and data calibration with the NIST atlases, and the TS12 spectra confirmed our suspicion and proved that temperature on the order of even 5°C would have manifested as significant line changes (for precise RV purposes).

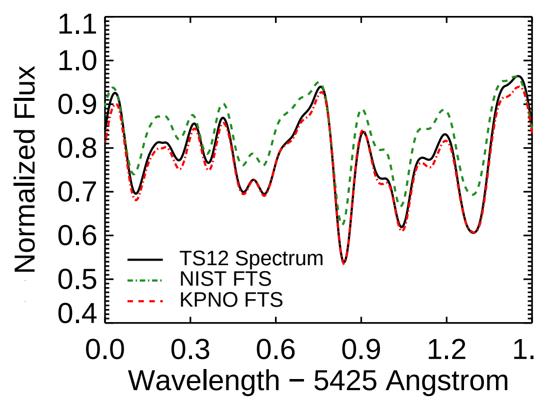

Figure 2: TS12 spectrum vs. NIST FTS vs. KPNO FTS for the HET/HRS iodine cell at 70°C, all convolved down to a resolution of $R = 60,000$ (typical RV observation resolution) for comparison purposes.

(b) The HET/HRS cell very likely has changed over time: The TS12 spectra match better with the more recent but potentially problematic NIST FTS atlas, which had worse χ^2_ν fit than the old KPNO atlas. This is completely unexpected and suggests that: the NIST atlas was perhaps taken at the correct temperature (i.e. the KPNO atlas was at a lower and wrong temperature) but the worse fit was caused by calibration errors in the atlas; and/or the temperature or optical depth of the cell changes over the course of 20 years, and hence the differences between these three spectra (Figure 2); and further more, it is possible that the temperature/optical depth of the cell changes on a much shorter scale during the observing seasons, and most of the time it stays at a temperature/optical depth that is similar to the one when the KPNO atlas was taken (e.g. actually at a lower temperature though thought to be at 70°C).

To answer these questions, and also to go beyond diagnosis and actually resolve the issue of a changing cell, we have found a possible third venue that might provide reliable, ultra-high resolution, and wavelength calibrated iodine atlas – a theoretical code that computes iodine transmission spectrum (at any specified temperature) based on both physics and empirical calibrations (IodineSpec5; Knöckel et al. 2004). We have successfully installed and learned the code, and properly translated the code output into practical astrophysical units and to account for optical depth differences. We are now using the code to diagnose the HET/HRS cell to study whether the cell temperature or optical depth changes (as reflected by actual HET/HRS observations instead of FTS/TS12 atlas observations), and to explore the possibility of using the theoretical output as the new "ground-truth" atlas.

We will publish these results and any iodine atlases or spectra we derive for any instrument in this work in the near future.

2.3 A Better Instrumental Profile Model for Fiber-Fed Spectrographs

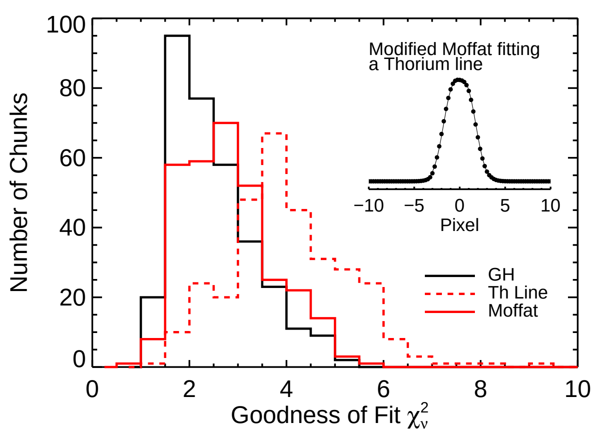

Figure 3: Histogram of goodness of fit, χ^2_ν, values for spectral chunks of a calibration frame. The modified Moffat function (red) performs almost equally well while having only 3 parameters, compared with the complicated 11-parameter GH function (black solid).

One limiting factor for the current precision of HET/HRS is the modeling of its intrumental profile (IP, or the spectrograph response function or spectral PSF). In our original proposal, we promised to look for a better IP for HET/HRS, as a test case for future fiber-fed precise RV spectrographs, such as the upcoming MINERVA and the future fiber-fed Keck/HIRES.

The old IP model for HET/HRS is the very versatile, orthogonal, 11-parameter Gauss-Hermite polynomials (GH). However, through our study during the past year, we have found that although GH is probably sufficient to describe the HET/HRS IP, because of its ultra flexibility and multi-parameters, it deeply complicates the χ^2 space and very often hinders the fitter from finding the true minimal (to address the issue with the fitter, see next section and future plans). A simpler IP is therefore in great desire.

By analyzing iodine calibration spectra and IP function possibilities in Fourier space, we have found a better IP function for HET/HRS: the modified Moffat function:

$$[1 + (x/\theta)^2]^{-\beta\cdot(x/\delta)^2} \tag{1}$$

It is called the "modified" Moffat function because the original Moffat function does not have the $(x/\delta)^2$ term. We added this term to add flexibility at the wings to enable change of characteristic IP width while preserving wing profile. Figure 3 illustrates the results: black line is the χ^2_ν distribution for fitting spectral chunks in an observation with GH IP; red line is for modified Moffat IP; and dashed red is for fixing the IP in the shape of a thorium line (proving that thorium line is a good proxy for IP). This 3-parameter function fits the HET/HRS data almost equally well, and it fits very well to the observed thorium line (Figure 3 inset).

This modified Moffat function can also be potentially used for other fiber-fed instruments, since these instruments tend to have IPs with the same characteristic flat top and sharp wings.

Our on-going work includes: adding small perturbation term to the modified Moffat IP to account for IP assymetry and subtle wings due to scattered light etc.; disentangling the effects of a bad IP model and bad iodine atlas (as described in previous sectio); and other tests with the aim to bring χ^2_ν for fitting HET/HRS data to ~ 1, which is what is achieved at Keck and enabled $\sim$ 1m/s RV precision.

2.4 Building the Next-Generation Data Analysis Tools for Future RV Surveys

3 Future Plans

References

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Rothman, L. S., Gordon, I. E., Babikov, Y., et al. 2013, J. Quant. Spec. Radiat. Transf., 130, 4