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THE EFFECTS OF TELLURIC LINES IN RADIAL VELOCITY SEARCHES FOR PLANETS WITH IODINE CELLS AS CALIBRATORS[1]

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ABSTRACT

Tellurics are bad and you really don't want them. Here's why and how to get rid of them.

Subject headings: instrumentation

1. INTRODUCTION

The first exoplanets around main-sequence stars were discovered by the radial velocity (RV) method, where precise Doppler spectroscopy measures the wavelength shift of the host stars induced by the gravitational pull of the planets (Campbell et al. 1988; Latham et al. 1989; Hatzes & Cochran 1993; Mayor & Queloz 1995; Butler & Marcy 1996). Since then, the RV method has discovered hundreds of planetary systems (see exoplanets.org; Han et al. 2014) and contributed to numerous confirmation and characterization of exoplanets discovered by the transit method (e.g., for *Kepler* follow-up observations; Marcy et al. 2014).

The current best RV precision is around 1 m/s (Fischer et al. 2016), attainable via two wavelength calibration methods in the optical band: ThAr lamp emission line calibration (e.g., ELODIE and HARPS; Baranne et al. 1996; Mayor et al. 2003; ∼400-690 nm) and iodine cell absorption line calibration (e.g., Keck/HIRES and Magellan/PFS; Butler et al. 1996; Crane et al. 2010; ∼500-620 nm). The major obstacles for achieving a higher RV precision are: stellar activity induced RV signals, instrumental effects, telluric contamination, and limitation in data analysis (Fischer et al. 2016).

Traditionally, telluric contamination is not considered as problematic for precise RV in the optical. It is certainly a sever source of spectral contamination and a bottleneck for achieving higher RV precision in the near infra-red region (e.g., Bean et al. 2010), where a large number of deep water and methane lines reside. However, there is only a small wavelength range in the optical that has deep telluric lines, and typically such regions are simply thrown out for the purpose of precise RV analysis, either by giving them zero weights in the cross correlation masks (for ThAr calibrated spectra, e.g., Pepe et al. 2002) or flagging them as bad pixels (for iodine calibrated spectra, e.g., for Keck/HIRES).

Recently, the works by Artigau et al. (2014) and Cunha et al. (2014) have characterized and mitigated the effects of telluric contamination in the precise RV data taken by the ThAr-calibrated HARPS-S. Cunha et al. (2014) focuses on the issues with "micro-telluric" lines (shallow telluric absorption lines with < 1-3% depths), which are recognized for the first time. Cunha et al. (2014) fit and then divide out the telluric lines in the observed spectra using synthetic telluric spectra generated by the LBLRTM package (Line-By-Line Radiative Transfer Model, Clough et al. 1992; with line lists from HIgh-resolution TRANsmission molecular absorption database, or HITRAN, Rothman et al. 2013) and also TAPAS (Bertaux et al. 2014), which is a more user-friendly but less flexible package wrapper using LBLRTM. They concluded that the micro-tellurics have an impact (defined as RMS of difference between RVs before and after micro-telluric removal) of ∼10-20 cm/s for G stars observed with low to moderate air masses, but the impact can be substantial in some cases to up to ∼0.5-1 m/s. Artigau et al. (2014) uses principal component analysis (PCA) to empirically correct for telluric lines in HARPS-S data (both micro-tellurics and the deep lines in the ∼630 nm region), and combined PCA with rejection masking, they reduced the RV RMS by ∼20 cm/s (and more significantly for the ∼630 nm region).

This paper focuses on the adverse effects of telluric contamination and its remedies under the context of iodine-calibrated precise RV, especially for "micro-telluric" lines (shallow telluric absorption lines with < 1-3% depths; Cunha et al. 2014). As for spectral region contaminated with deep telluric lines, typical precise RV analysis usually gives

Previously, Cunha et al. (2014) have characterized the effects of micro-telluric contamination and proposed solution for the ThAr-calibrated HARPS-S data.

Modeling telluric lines itself is a challeging task. ZZZ Cite the paper TERRASPEC and simular softwares and their 2% modeling precision. Cite Lockwood, Bender et al. for 1% in L band. ZZZ

In this paper, we characterize and discuss the remedies for micro-telluric lines in the context of iodine-calibarted precise RVs. We first quantify the effects of micro-telluric contamination on RV precision through simulation. Then we discuss possible remedies and their effectiveness. Finally we discuss implementation on real data and future work.

2. IMPACTS OF MICRO-TELLURICS ON RV PRECISION

[1] Based on observations observations obtained at the Keck Observatory, which is operated by the University of California. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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We performed end-to-end simulation of Keck data and analysis process to access the impacts of micro-tellurics on RV precision. We use Keck to demonstrate this because Keck has the highest precision. We chose sig Dra and tau Ceti as our stars because they are RV standards which have been observed hundreds of times with Keck/HIRES, and are also favorite RV standards at other precise RV facilities. I really want to add an M dwarf standard here as well!

2.1. *Methodology*

We simulated Keck observations on sig Dra and tau Ceti by using synthetic stellar spectra of their respective spectral types (?) using SME (ZZZ cite Valenti and Fischer). We simulated one spectrum for each actual observed spectrum taken at Keck through the CPS programs. The synthetic stellar spectra is multiplied with the iodine atlas to create the standard iodine+ star RV observations. The multiplied spectrum is then multiplied with the blaze function and convolved with the observed spectral PSF, both derived from real observations for each night. Poisson noise is added.

We then forward model the simulated spectra to extract RVs using the CPS Keck code (ZZZ cite Johnson and Howard). We used the synthetic stellar spectrum as the input stellar template. In reality, stellar templates are derived from observed stellar spectra via deconvolution, which would introduce additional errors. Using the same synthetic stellar spectrum would eliminate such errors and isolate the problem to telluric lines only.

We ran two sets of simulations: control and contaminated. In the control, we only had stellar spectrum and iodine spectrum. In the contaminated, we added in simulated telluric lines in the simulated observed spectrum. The telluric lines were generated using TERRASPEC (ZZZ cite Bender). We adopted the typical Mauna Kea atmospheric condition (temperature and pressure profiles) and typical oxygen column density (which in realiaty flucturate very little anyway). For simplicity, we assumed the same water column density for every observation, which is pwv= 1mm, a little bit humid than a typical Mauna Kea night (true? I think this is actually pretty typical). The pair of simulated control and contaminated spectra have the same added Poisson noise, and therefore any RV differences derived from these two sets of simulation would reveal the net effect of telluric contamination.

2.2. *Results*

Plots: RV difference vs. BC for sig Dra and tau Ceti. And M stars.

Micro-tellurics in the iodine region introduces RMS= 0.6 m/s scatter for GK stars (RV systematic error added in quadrature). Leaving untreated, this would define the precision floor.

Additionally, it manifests as spurious signal at periods of a sidereal year and harmonics, with an amplitude of 20 cm/s. This would affect our ability to detect super-Earth in the habitable zone of GK stars (Earth's signal is 8 cm/s). We have seen such spurious signal in Keck data on many stars, and telluric contamination is one of the contributing factors (see discussion for other factors).

For M stars... (probably worse)

3. REMEDIES AND EFFECTIVENESS

Plots: effects of full forward modeling (RV difference between modeled and contaminated, modeled and control).

We demonstrate the effectiveness of several remedies. First, double masking: probably a terrible idea. Throwing away the pixels will make the fitter harder to converge, and introduce additional errors on the scales larger than the effects of telluric lines themselves. Additionally, it is hard to choose a flux cut-off level. Throwing away too much would mean unstable solution and lower RV precision, but masking too little would mean insufficient removal of tellurics.

Second, full forward modeling plus some sort of masking for deep lines. This is the most effective way. Modeling precision of $\sim$90% basically bring the adverse effects of tellurics down to $<$10 cm/s. 90% is very easy to achieve – remember the state-of-the-art is 1-2%, and even consider errors induced by modeling residuals caused by atmospheric wind or lack of knowledge on linelist or broadening parameters or inaccurate knowledge on atmospheric temperature/pressure profiles. The deep lines may not be modeled very well. However, the statistical weighting procedure at the very end will empirically quantify which chunks behave badly due to ineffective modeling of telluric lines and thus throw out or de-weigh the chunks.

4. DISCUSSION AND FUTURE WORK

In terms of application to real observations, this brings marginal improvements to existing Keck data. We tested on sig Dra, tau Ceti, and M stars, the differences are...

Important for MINERVA, HRS2, HPF2. Crucial for CARMENES, HPF, EPDS, SHREK, ESPRESSO, SPiRou etc. White paper has suggested improvement on line lists in HITRAN. EPRV2 has a lot of recommendations. That is the future direction.

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