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Precision modeling of telluric absorption features through the retrieval of atmospheric trace gases and spectroscopy update toward Extreme Precision Radial Velocity (EPRV) measurements

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Strategic Focus Area: Extra-solar planets and star and planetary formation

Objectives: We have demonstrated a proof of concept on breaking through the barrier caused by near infrared telluric interference in Extreme Precision Radial Velocity (PRV) measurements by leveraging JPL's state-of-the-art expertise in atmospheric remote sensing, precision laboratory spectroscopy, and diffraction-limited stellar spectroscopic observations. Three independent precision spectrographs were employed as testbeds, which are PARVI at the Palomar Observatory, iSHELL on the IRTF, and NEID at the Kitt Peak Obs. Our main goal was to fit the telluric features in the very broad spectral regions (0.66 – 5.3 µm) towards a goal of < 1 m/s of RV measurements required for detecting small planets around low mass stars.

Background: Near-IR telluric contamination is primarily due to atmospheric H_2O, CH_4, CO_2, and O_2. Among them, H_2O features are problematic because of the temporal and geographical variability of atmospheric water content. Therefore, the telluric features can be fit to the noise level in the spectra only when adjusting their atmospheric concentrations rigorously to a best value at the time of observation. Also contributions from other trace gases cannot be neglected. Therefore, all of the trace gases should be adjusted independently and simultaneously in the telluric feature modeling to be able to achieve ~1% fit residuals. As far as we are aware of, this level of a rigorous approach was not used in any existing telluric-modelling packages such as TelFit [1], TAPAS [2], and Molecfit [3].

Approach and Results from the three spectrographs at three different observation sites

First of all, we adapted the existing state-of-the-art atmospheric spectrum fitting package (GFIT) [4] to develop Stellar-GFIT for modeling of the telluric features captured in stellar spectra. For atmospheric models (i.e. P and T) and the initial volume mixing ratio profiles of the atmospheric trace gases, we used meteorological data (e.g., GEOS-FPIT [5]) and trace gas profile climatology provided by the Total Carbon Column Observing Network (TCCON) [6], http://www.tccon.caltech.edu/). Next, we characterized and implemented the instrumental line shape (ILS) of the three spectrographs (*i.e.*, PARVI, iSHELL, and NEID), by employing Gaussian function. Actual spectrum fitting was performed echelle order by order of the spectrographs, for which we also developed the individual spectral fitting intervals (called microwindows) tailored to each spectrograph. Finally, we used the Stellar-GFIT to analyze (1) iSHELL spectra of Vega and GJ699 obtained at the IRTF, Mauna Kea, HI, (2) PARVI spectra of multiple target stars (e.g., 93 CET, AD Leo, GJ699, GJ9520, etc) observed at the Palomar Obs., CA, and (3) NEID solar spectra (for which the Sun is regarded as a star) obtained at the Kitt Peak Observatory, AZ. The performance of the Stellar-GFIT was found excellent and robust. We were able to model any telluric features captured in the three different spectrographs, having achieved the fitting residuals down to 1 % or their spectral noise levels. The spectrum fitting results are presented for each of the spectrographs.

iSHELL spectra from the IRTF, HI

We have analyzed sample spectra of GJ699 (M4) observed by iSHELL at the IRTF, Mauna Kea, HI, in 2016 – 2017. As shown in **Fig. 1**, all the telluric absorption features were very well fit down to the spectral noise level, where $^{12}CH_4$ and H_2O are the primary absorption contributors. Their abundances were simultaneously adjusted as part of the spectrum fitting.

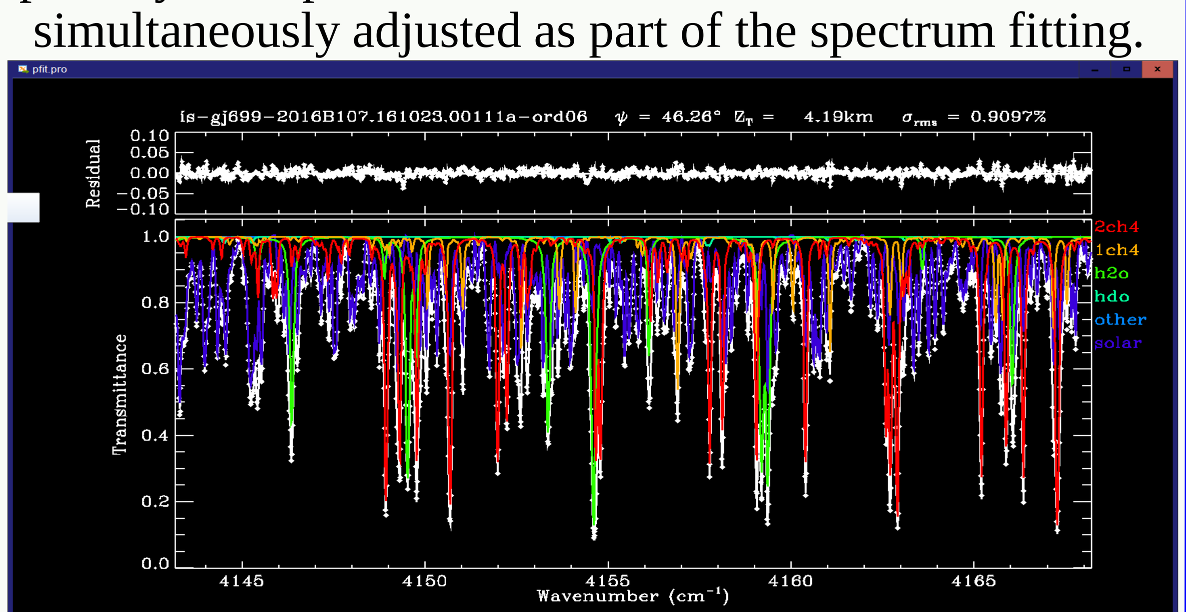

Fig. 1 Fitting residuals of iSHELL GJ699 spectra in the 2.4 µm region.

Note that the $^{13}CH_4$ features (in red) from a gas cell placed in the beam were also simultaneously fitted by Stellar-GFIT, which would facilitate utilizing any additional frequency calibration references.

After the successful modeling of the telluric features, we were able to pull out the residuals from individual observations, as presented in Fig. 2. It clearly shows the Doppler shifted component of the target stellar features in the time interval of several months.

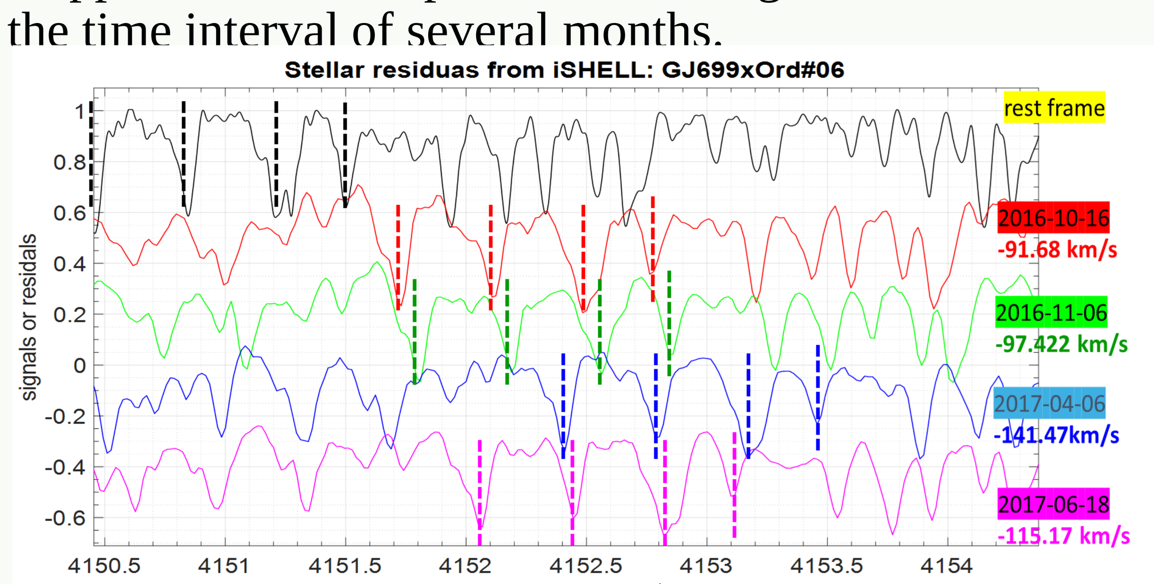

Fig. 2 A time series of spectrum fitting residuals, which are predominantly due to GJ699 stellar features, clearly shows the progression of their Doppler shifts over a 10 month period.

PARVI spectra from the Palomar Obs.,CA

We also analyzed a series of spectra observed by PARVI (JPL's frequency-comb based Palomar Radial Velocity Instrument) in 2021, which include multiple target stars (e.g., 93 CET, AD Leo, GJ699, GJ9520, etc). For all of them, we were able to achieve the spectrum fitting residuals down to their spectral noise level, as shown in Figs. 3 – 4 for different spectral regions, respectively.

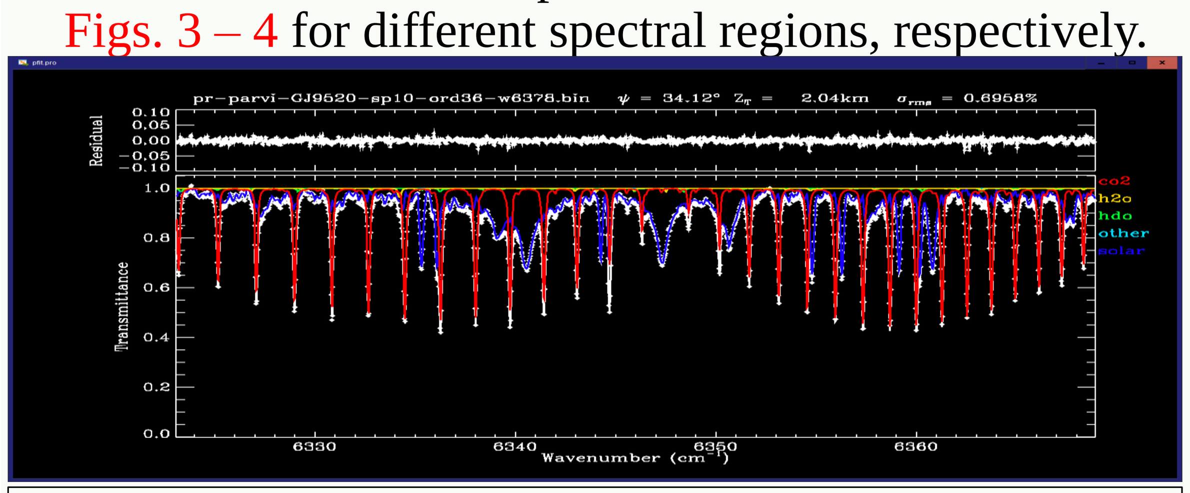

Fig. 3 PARVI observation of GJ9520, showing atmospheric CO_2 (in red) and the stellar features (in purple)

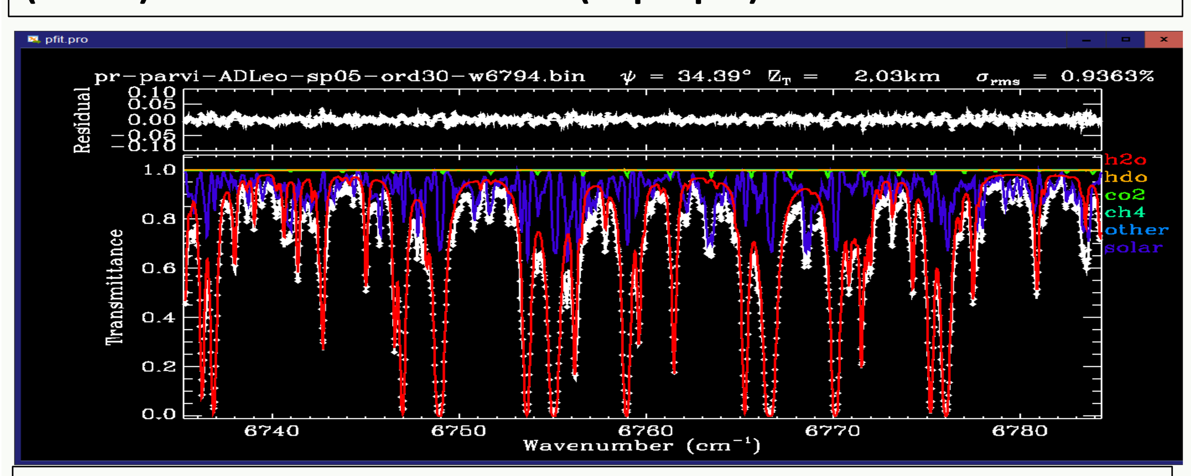

Fig. 4 PARVI observation of AD Leo, showing atmospheric H_2O (in red) and the stellar features (in purple)

We also analyzed 14 spectra of GJ699 observed in Aug. 2021, from which we tried to extract the RV components each order. It was possible by including monochromatic model stellar templates provided by the PARVI team (PI: Gautam Vasisht) in the spectrum fitting.

- **Order#38 at 1.613 µm region: δRV = 23.9 m/s**
- **Order#33 at 1.527 µm region: δRV = 0.5 m/s**
- **Order#18 at 1.319 µm region: δRV = 33.2 m/s**

We note that the δRV retrievals vary with orders, which is attributed to the spectral characteristics of the stellar features for the given order. The result from Order#33 is exceptionally good (i.e. < 1 m/s), which is associated with the presence of relatively well-isolated stellar features in the region. For other orders, the RV retrievals are expected to be improved when many observations and orders are combined.

NEID spectra at he Kitt Peak Obs., AZ

Finally we analyzed 11 NEID solar spectra, for which the Sun was regarded as a star. The NEID spectrograph has more than 120 orders, among which we found useful spectrum data from ~30 orders covering 0.66 – 1.031µm region. Even for this region, we found that the Stellar-GFIT performs spectrum fitting excellent. As shown in Fig. 5, better than 1 % of spectrum fitting residuals were achieved even for atmospheric water, the challenging species to model because of temporal and spatial variability of the atmospheric water content.

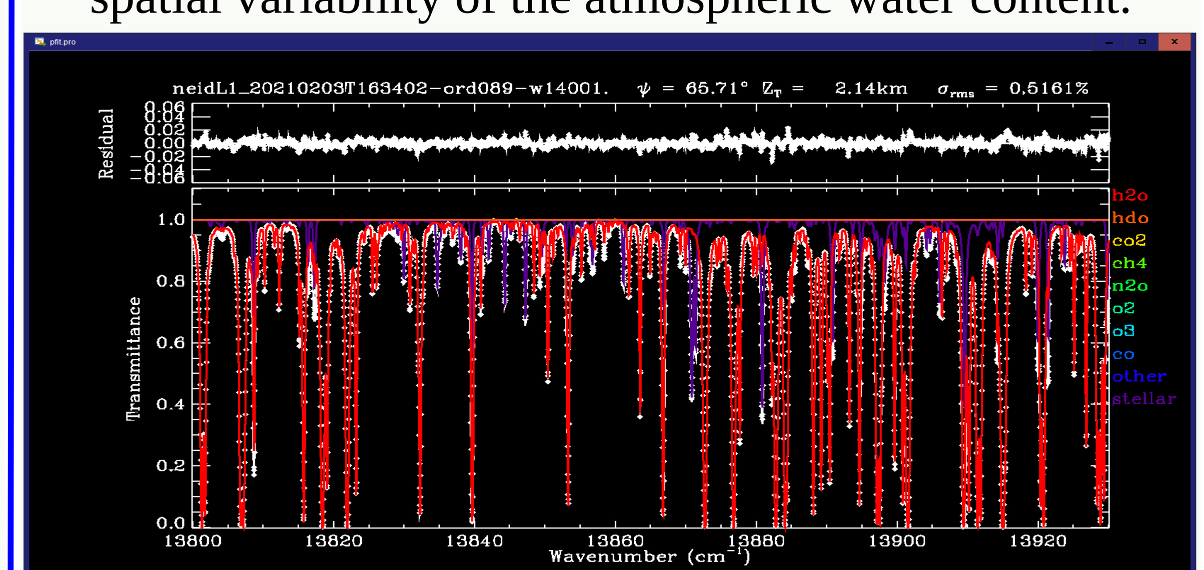

Fig. 5 Spectral fitting residuals from a NEID solar atmospheric spectrum , showing atmospheric H_2O (in red) and the Solar features (in purple)., all of which were fitted to the noise level.

However, we note that there were numerous hot or dead pixels in the spectrum data, which were repaired or avoided during the spectrum fitting. We have run the Stellar-GFIT for multiple orders and derived the δRV values to be ~8 m/s across the orders of the NEID echelles, as presented in Fig 6.

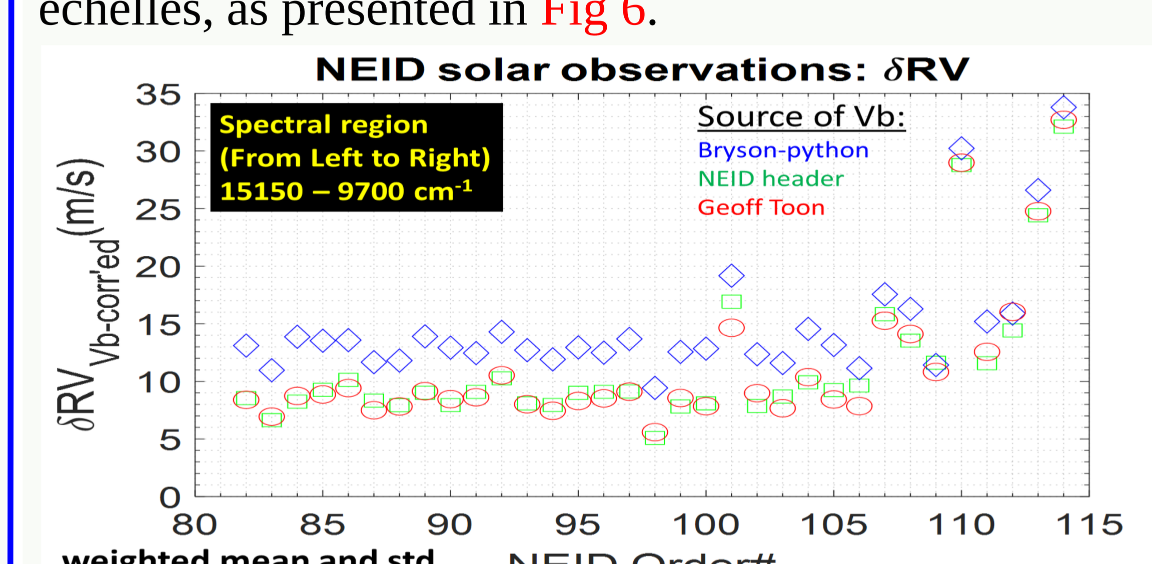

Fig. 6 Retrieved δRV values across the orders. Note that the δRV retrievals are substantially influenced by three different barycenteric velocity correction sets.

Significance/Benefits to JPL and NASA: The application of the stellar spectrum fitting package, Stellar-GFIT, that we tested in this project is universal by nature, not confined to particular facilities or spectrographs or observation sites. Since the ground-based EPRV measurements will be a vital complement to the space missions such as TESS[7], CHEOPS[8], PLATO[9], and future direct imaging missions, the novel methodology and software pipelines established from this study will facilitate JPL exoplanet astronomers planning follow-up observations. The impact of this task is expected to be substantial and broad, not only improving the EPRV measurements from the existing datasets but also maximizing the scientific return from all the high-resolution spectrograph data to come.

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