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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Program: FY21 R&TD Topics **Strategic Focus Area: Extra-solar planets and star and planetary formation**

Objectives:

The objective is to provide a proof of concept on breaking through the barrier caused by near infrared telluric interference in stellar radial velocity measurements. For this, we have experimented a new methodology to model and remove the telluric interferences by leveraging JPL's state-of-the-art expertise in atmospheric remote sensing, precision laboratory spectroscopy, and diffraction-limited stellar spectroscopic observations. Two independent precision spectrographs have been employed as testbeds; one is JPL's frequency-comb based Palomar Radial Velocity Instrument (PARVI) deployed on the Palomar Observatory, CA, and the other is deuterated-methane ($^{13}CH_4$) gas-cell based iSHELL on IRTF at Mauna Kia, HI. Our main goal is to fit the telluric features in target spectral regions (1.1 – 2.4 micron), towards a goal of < 1 m/s of radial velocity measurements which is required for detecting small planets around low mass stars.

Background:

As presented in a model spectrum (See Fig. 1) for a typical atmospheric condition at the Palomar Observatory, near-IR telluric features are enormous, which are primarily due to atmospheric H_2O, CH_4, CO_2, and O_2. Among them, H_2O features are particularly problematic because of the temporal and geographical variability of atmospheric water content. Therefore, stellar features cannot be used to determine the star's radial velocity until the telluric features are properly modeled and removed, which in turn cannot be achieved without having their atmospheric concentrations rigorously adjusted to a best value at the time of observations. Contributions from other trace gases cannot be neglected, either. Therefore, all of the atmospheric trace gases need to be adjusted independently and simultaneously in the telluric feature modeling and spectrum fitting to be able to achieve sub-1 % level of the fitting residuals of the telluric features. We have investigated the new approach and tried to provide a proof-of concept of it. As far as we are aware of, this rigorous approach of telluric feature fitting through atmospheric trace gas retrieval hasn't been used in any existing telluric-modelling packages such as TelFit [1], TAPAS [2], and Molecfit [3].

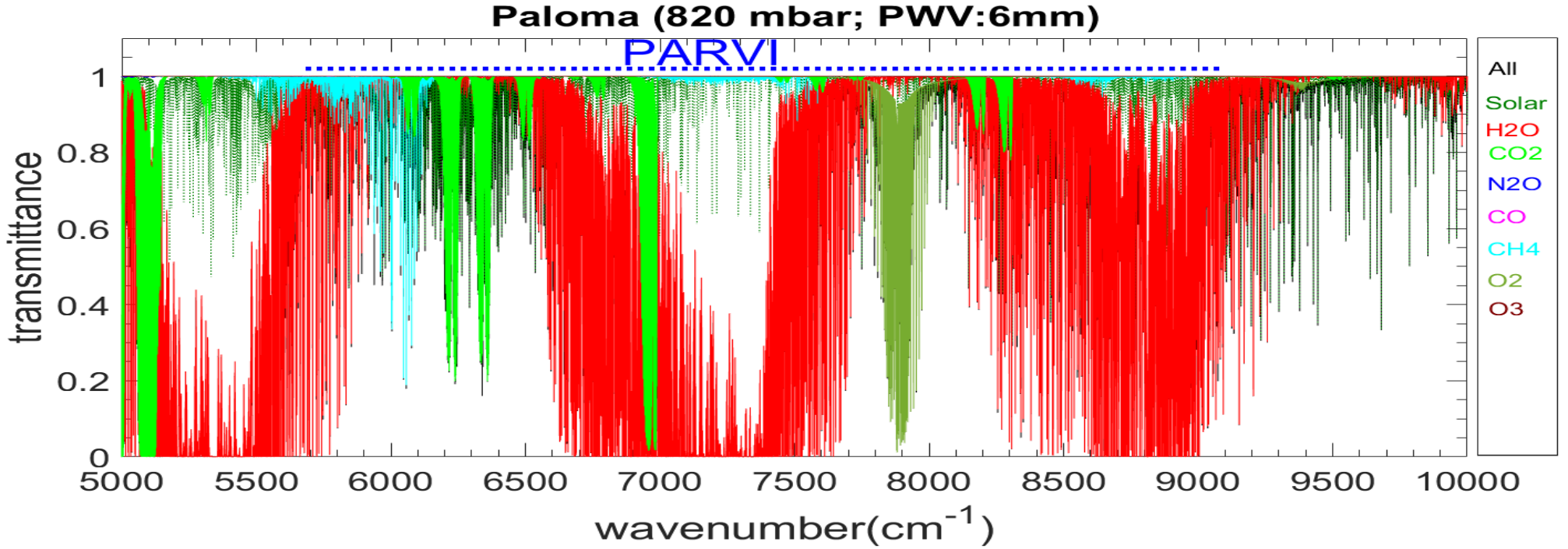

Fig.1. A model atmospheric spectrum simulated by GFIT for the Palomar Obs. site with PVW of 6 mm, showing that the telluric features are dominated by H_2O, CH_4, CO_2, and O_2. This synthetic model spectrum gives a good overview of the telluric absorption features.

Significance/Benefits to JPL and NASA:

This task is an exemplary cross-collaboration between Earth atmosphere observers and astronomers that leverages Earth atmosphere expertise to address a problem that the atmosphere poses for precision astronomical measurement. This work will help establishing JPL as the leader in the advanced modeling and removal of telluric contaminants to improve PRV data, and in turn help JPL further cement leadership in PRV and exoplanet science. This methodology that we have tested is not confined to particular facilities or spectrographs or locations, thus we expect further funding opportunities from NASA SMD when the on-going task is completed and evaluated in due time. Furthermore, since the ground-based EPRV measurements will be a vital complement to the space missions such as TESS[8], CHEOPS[9] PLATO[10], and future direct imaging missions, the results from this study will facilitate JPL exoplanet astronomers planning follow-up observations to measure the masses of detect transiting planets with small radii in the short term. Thus, the impact of this task is expected to be huge and broad, not only improving the EPRV measurements from the existing dataset but also maximizing the scientific return from all the high-resolution spectrograph data to come.

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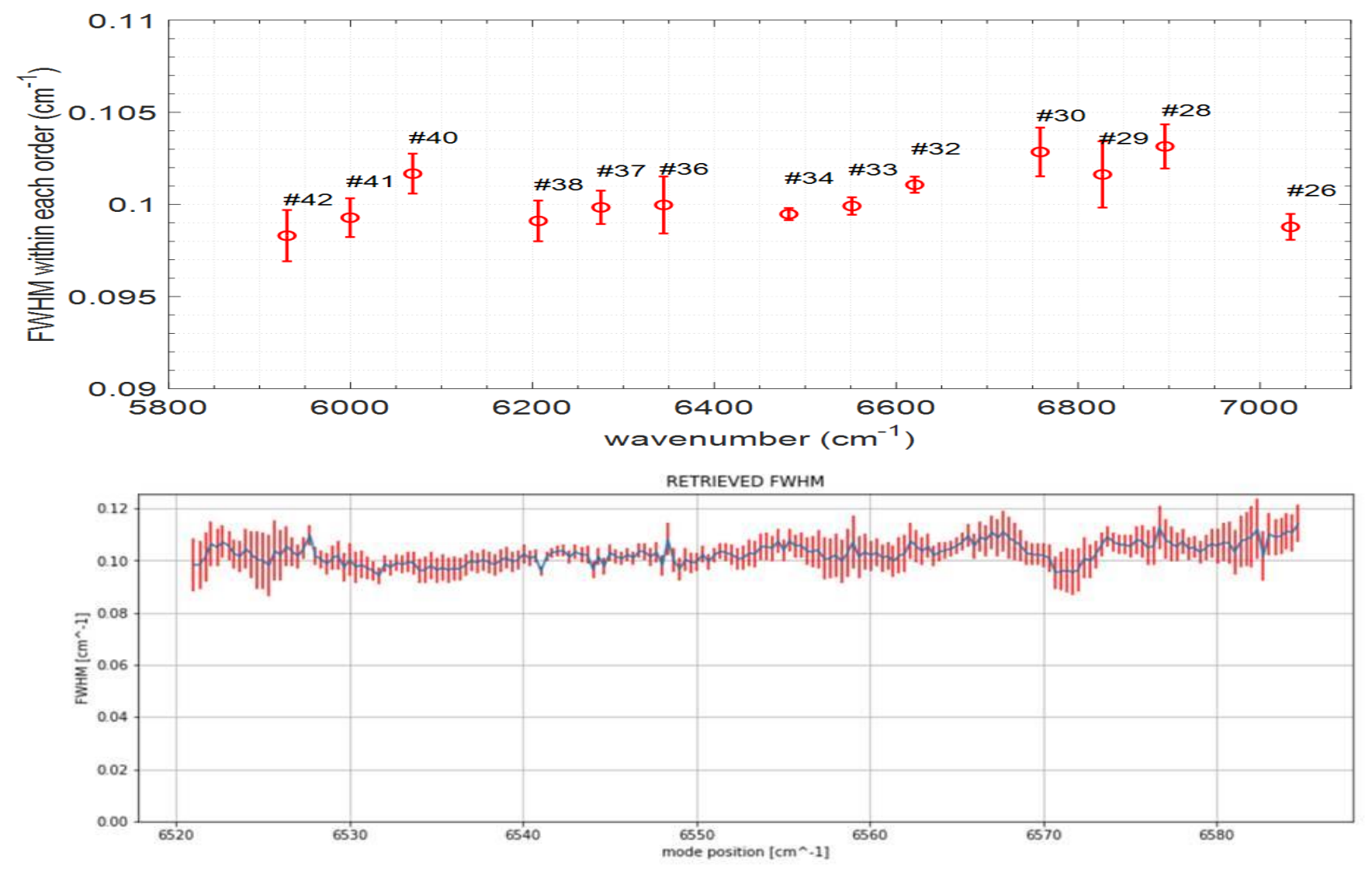

Fig. 2 (top) The PARVI ILS width is constant w.r.t. wavenumber from the 25th to the 42nd orders (from ~ 5900 to ~ 7100 wavenumbers) (bottom) The width is also constant within an order, e.g., for the 33rd order (6520 – 6585 wavenumbers), showing retrieved FWHM for every comb mode across the order (with 1-sigma error bars). Variations across the order are found not statistically significant.

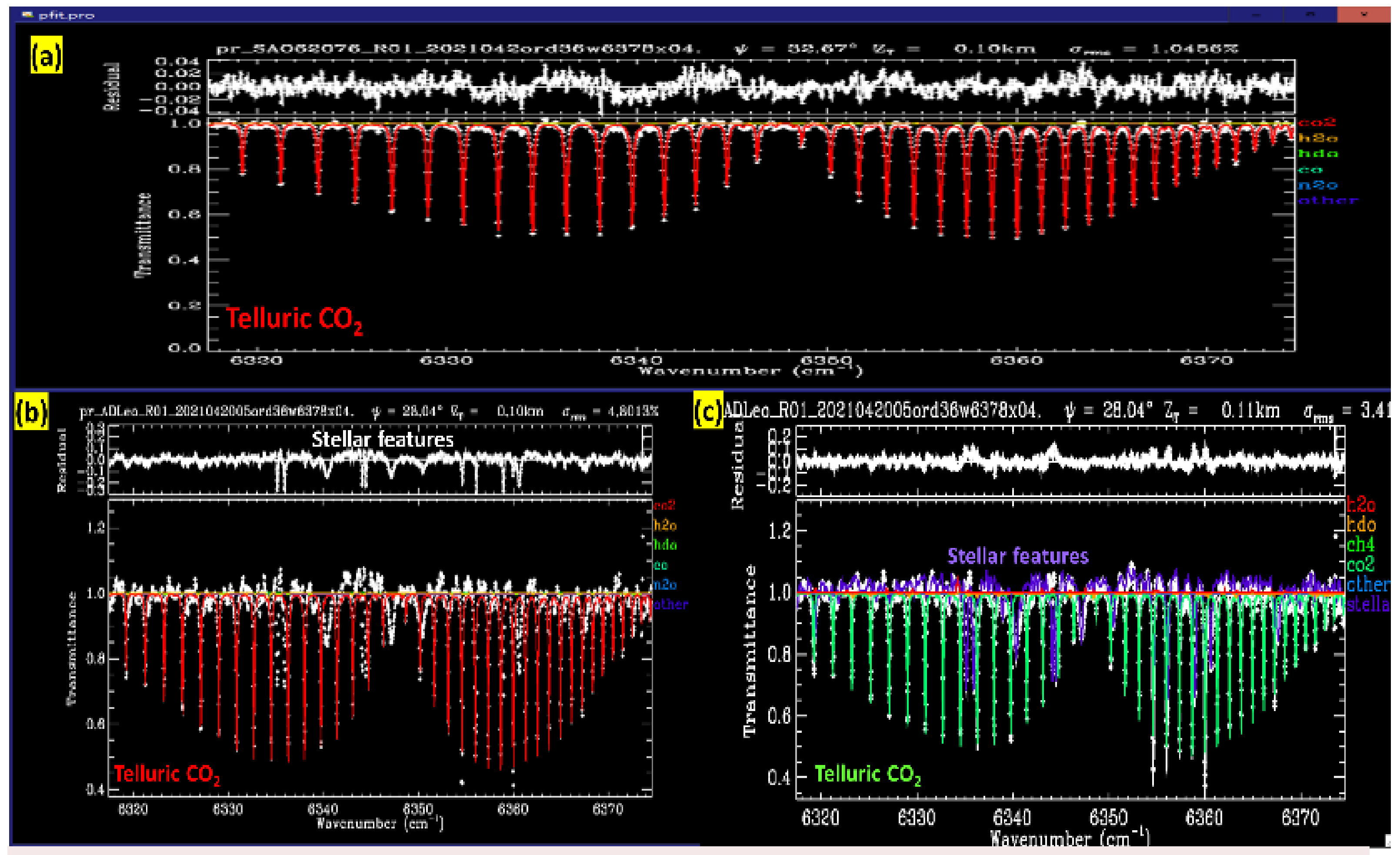

Fig. 3 Successfully modelled telluric features from atmospheric CO_2 captured in the PARVI stellar spectra of (a) SAO 62076 A-type hot star, (b&c) AD Leo M-type dwarf having the stellar features separate and integrated in the spectrum fitting, respectively, all of which are observed at the Palomar Obs. Panel (a) confirms the state-of-the-art performance of the newly developed Stellar-GFIT, which assures all the residual features in the lower-upper panel (b) are stellar origin. Thus, the residual spectrum in the upper panel is one sample of telluric-free stellar spectrum of PARVI. In lower-right panel (c), the stellar features have been integrated to the spectrum fitting enabling a retrieval of the Doppler shifts with respect to the stellar feature in the rest frame.

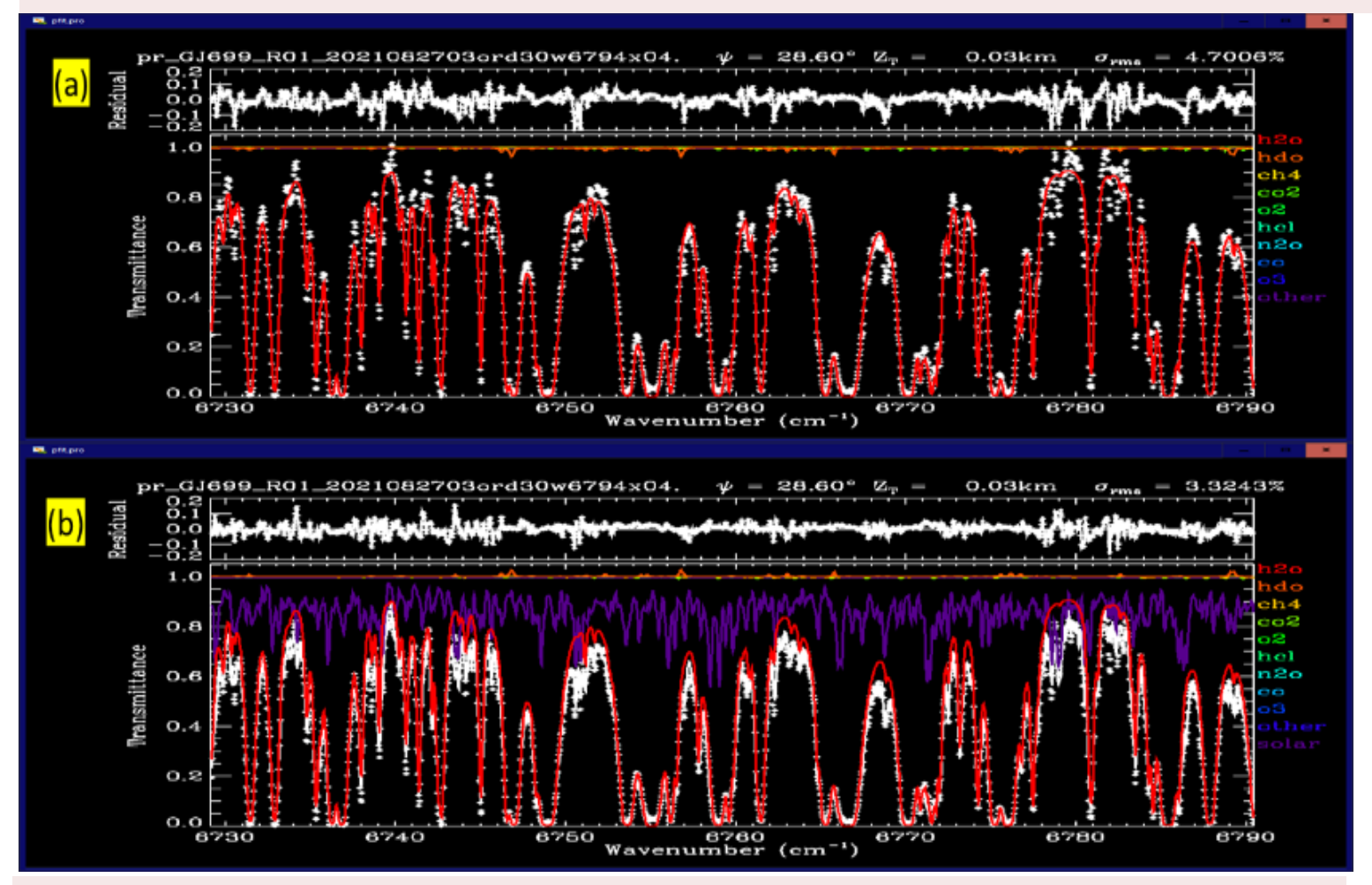

Fig. 4 The fitting residuals from PARVI GJ699 spectrum are presented in Panels (a&b) when without and with having the GJ 699 stellar template included in the fitting, respectively. Using the Stellar-GFIT, we were also able to fit the notorious atmospheric water features, but they also show further improvements needed for spectroscopic database as well as GJ 699 model template.

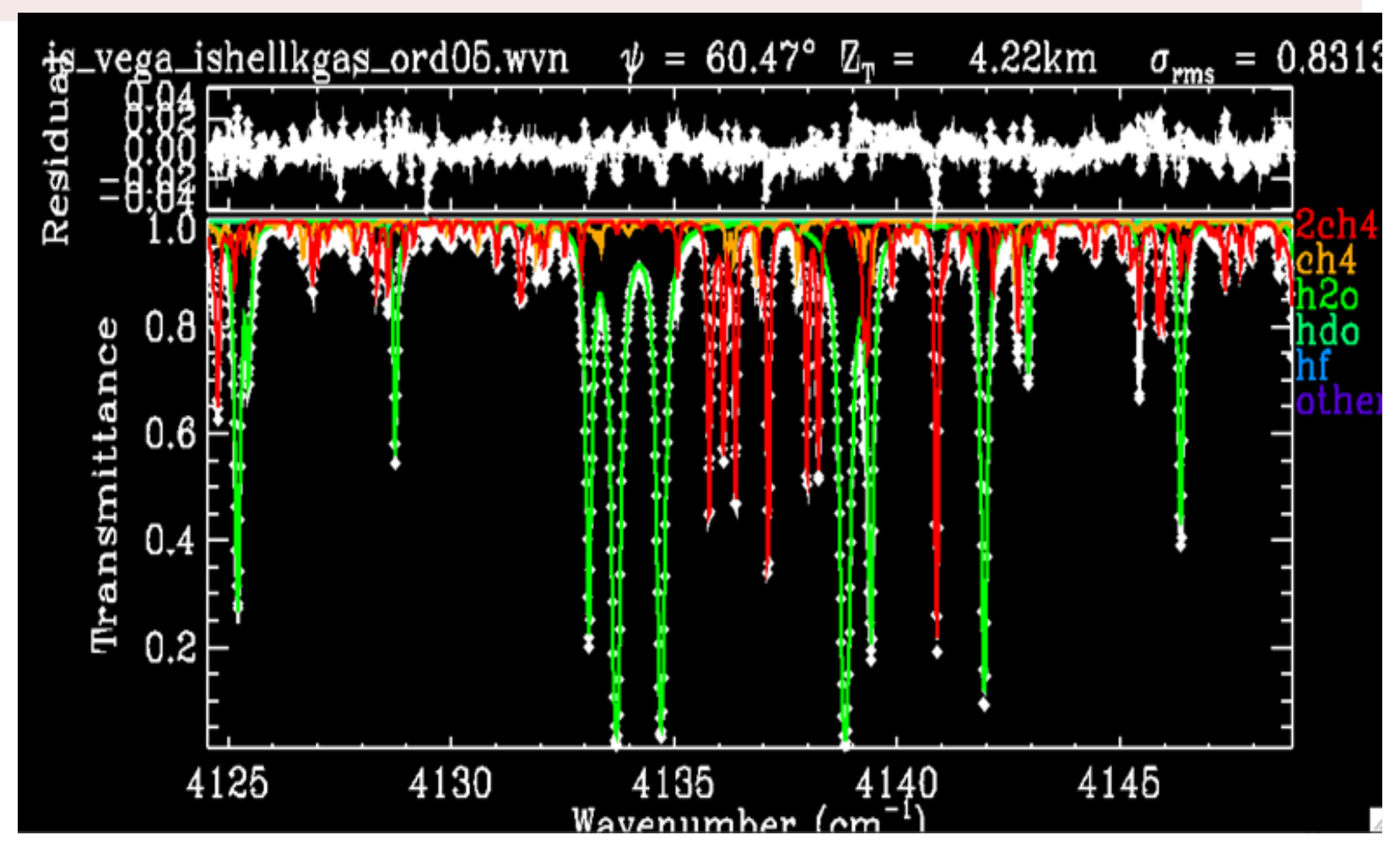

Fig.5 Using the Stellar-GFIT, we were able to fit the telluric features captured in the iSHELL spectrum of Vega obtained at IRTF at Mauna Kea, HI. Note that this spectrum contains $^{13}CH_4$ features from a gas cell placed in the beam as frequency calibration reference. The $^{13}CH_4$ gas cell features have been fit together with telluric features in this work, showing additional versatility of Stellar-GFIT in addition to its use for different instruments and at different observation sites.

Approach:

In this proposal period, we have tackled the problem of telluric contamination in Extreme Precision Radial Velocity (EPRV) measurements. First of all, we have successfully adapted the existing state-of-the-art atmospheric spectrum fitting package (GFIT) [4] to develop a working version of Stellar-GFIT, which can be regarded as extension of GFIT to fit spectra of any star (not just the sun) . For atmospheric models and the initial volume mixing ratio profiles of atmospheric trace gases, we use meteorological data (e.g., NCEP [5] and GEOS-FPIT [6]) and trace gas profile climatology represented in PV-Theta space. This is the same scheme as is used by the Total Carbon Column Observing Network (TCCON) [7], http://www.tccon.caltech.edu/). We have also defined spectral fitting windows optimized for PARVI and iSHELL observations. As part of showing the proof-of-concept, we have analyzed (1) a few samples of PARVI lunar and stellar spectra observed at Palomar Obs., CA, and (2) iSHELL sample spectra in the SWIR obtained at the IRTF, Mauna Kea with a $^{13}CH_4$ gas cell in the beam. For this, we have also characterized PARVI instrumental line shape (ILS) as a Gaussian of constant width within each order of the PARVI spectrograph, esp. in the 5900 – 7100 cm^{-1} regions.(See Fig. 2).

Results:

Figs. 3-5 present their fitting residuals for PARVI and iSHELL spectra, demonstrating that our innovative methodology can be applied to precision modeling of the telluric features for a variety of instruments, target stars, and observation sites. In Fig. 3a, in particular, the residuals from a PARVI spectrum of a hot star (with no significant molecular features) demonstrate telluric feature fitting down to the noise level. In Fig. 3b for a low mass star, AD Leo, one can clearly see multiple stellar features in the residuals plot when the telluric CO_2 features are modelled out. The AD Leo stellar features have later been integrated to be part of the spectrum fitting, as shown in Fig. 3c, by which the Doppler shift parameter could be determined with respect to the model stellar feature template in the rest frame. Fig. 4 shows spectrum fitting residuals of a PARVI spectrum from another star, GJ 699, near 1.48 micron, where telluric water features become dominant. Stellar-GFIT could model the notorious atmospheric water features out fairly well across the spectral region to make the stellar features visible in the upper panel of Fig. 4a. The fitting residuals in Fig. 4b have been improved when a GJ 699 stellar template was included in the fitting. Excellent spectrum fitting residuals were also obtained from an iSHELL spectrum for telluric H_2O and CH_4, as shown in Fig. 5.

We note that molecular-specific spectroscopy updates are needed, but access to our spectroscopy laboratory has been limited in this fiscal year due to COVID-19. As such, major spectroscopy updates are still in progress for H_2O and CH_4. All of these features will be integrated to the Stellar-GFIT program package, which will facilitate its application with minimal human intervention, as demanded for automated analysis of spectra.

Acknowledgements:.

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