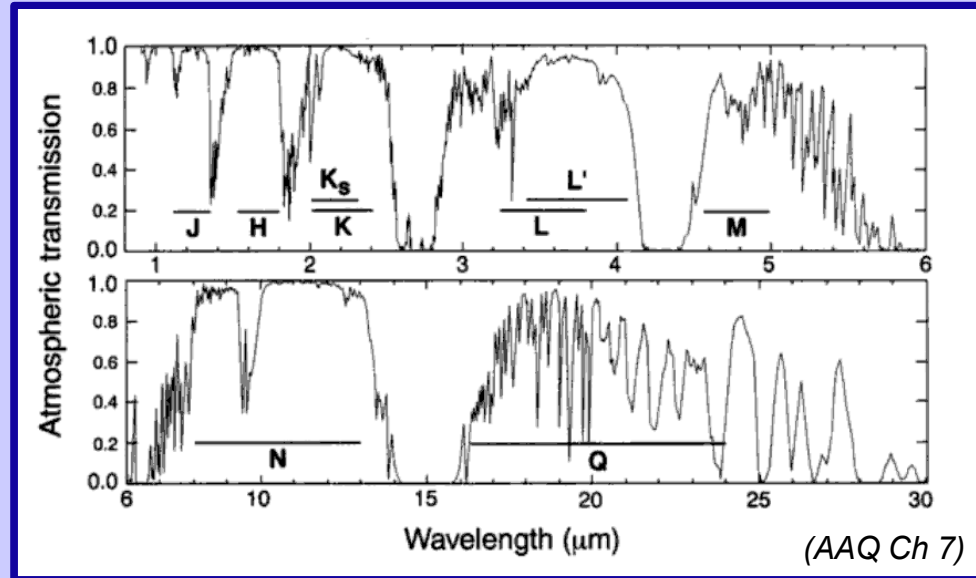


Advances in Telluric Characterization for Precision Spectroscopy

Chad Bender
Penn State University



Collaborators:

Brandon Botzer, Sara Gettel (PSU)

The PSU Pathfinder Team: Suvrath Mahadevan, Larry Ramsey, Steven Redman, Ryan Terrien (PSU)

John Carr (NRL)

The NIST Laser Comb Team: Scott Diddams, Frank Quinlan, Gabe Ycas (NIST), Steve Osterman (CASA)

Outline

- Motivation & traditional telluric correction techniques
- TERRASPEC: Synthetic forward modeling
- Examples
 - Keck + NIRSPEC (L-band)
 - HET + HRS (R-band)
 - HET + Pathfinder (Y-band, H-band)

Motivation

Near-IR observations

- 1) offer significant potential for increased sensitivity to low-mass planets
- 2) facilitate a vast amount of important non-exoplanet astronomy.

Motivation

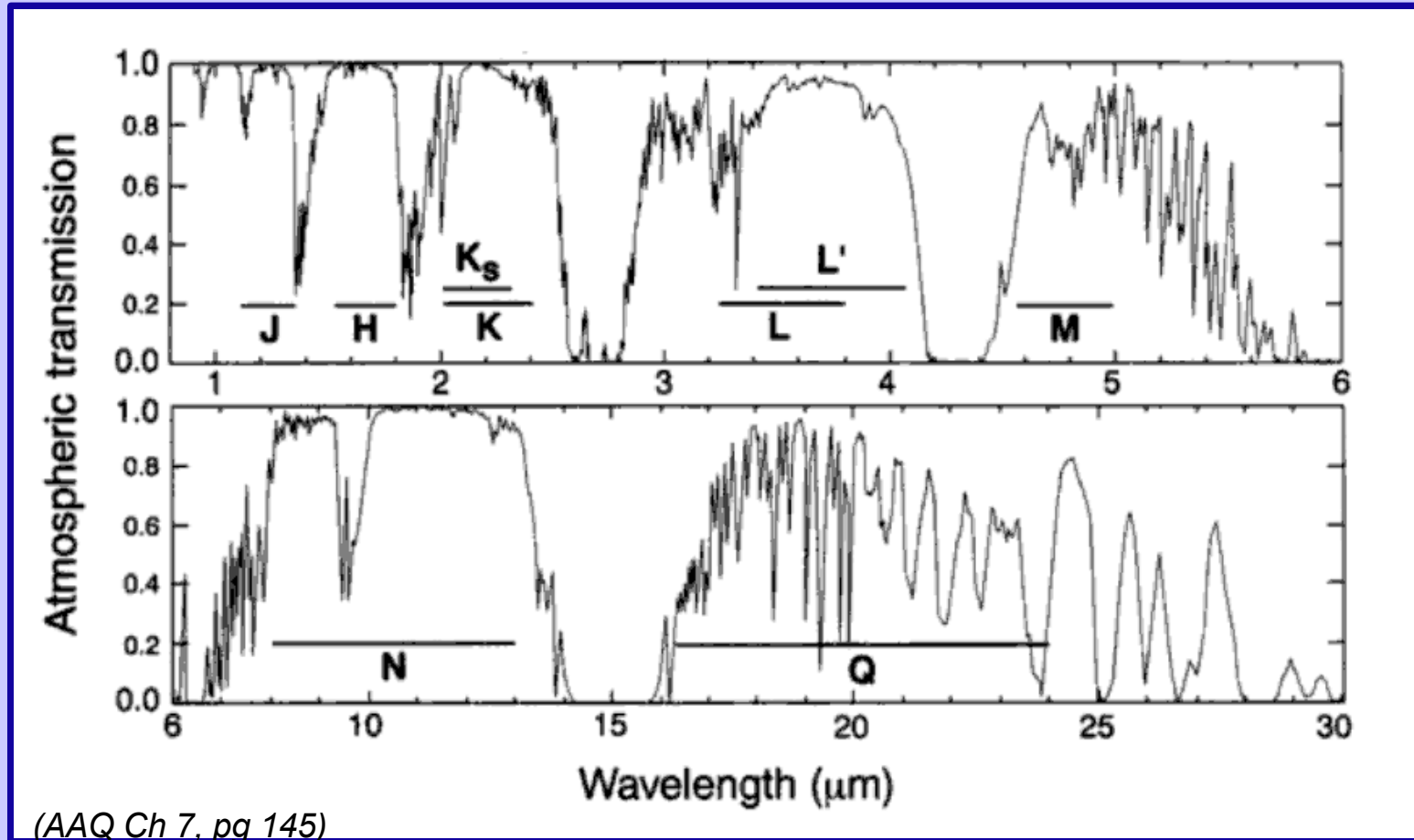
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- 1) offer significant potential for increased sensitivity to low-mass planets
- 2) facilitate a vast amount of important non-exoplanet astronomy.

Consequently:

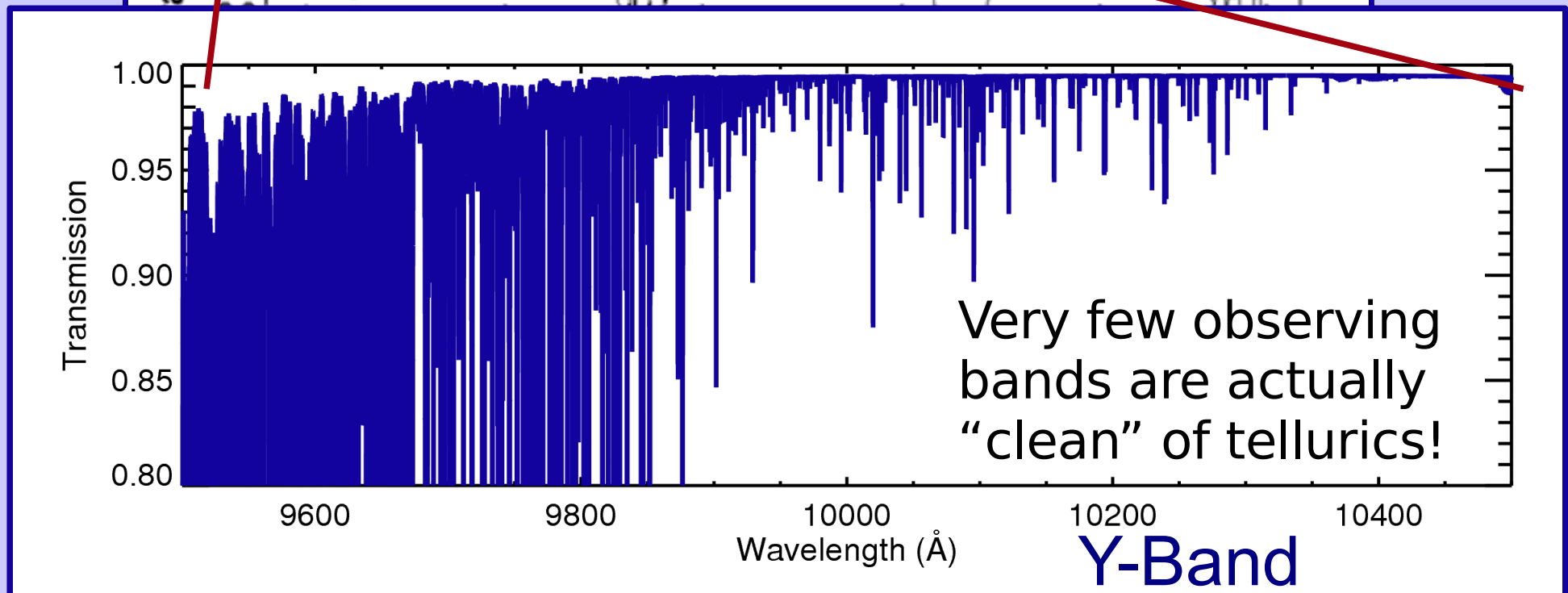
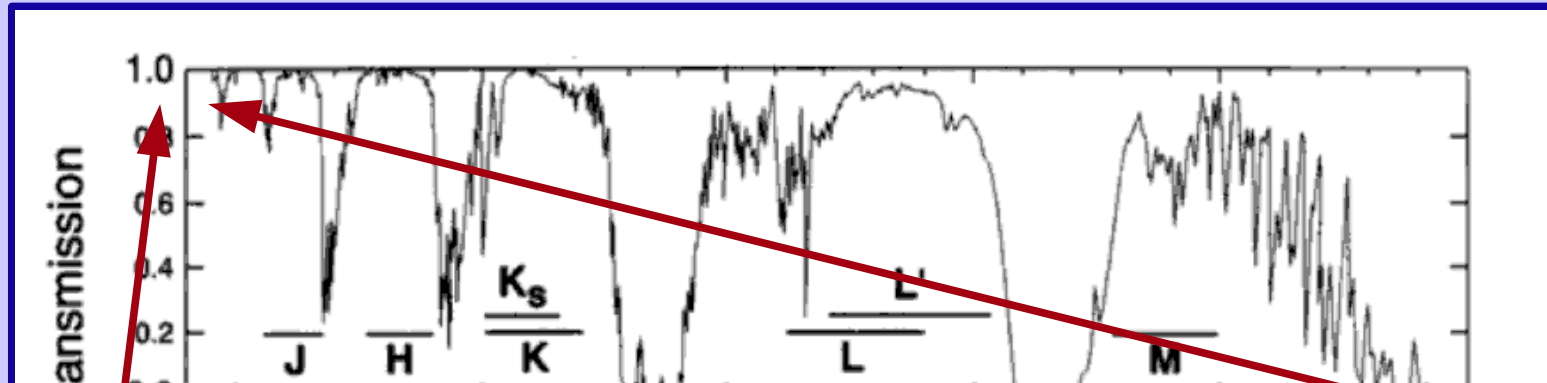
- many new near-IR spectrographs are planned, being built, or being commissioned (Barnes, Mahadevan, Martin, Quirrenbach)
- existing facilities are being re-examined and upgraded (Figueira, Plavchan).

Motivation

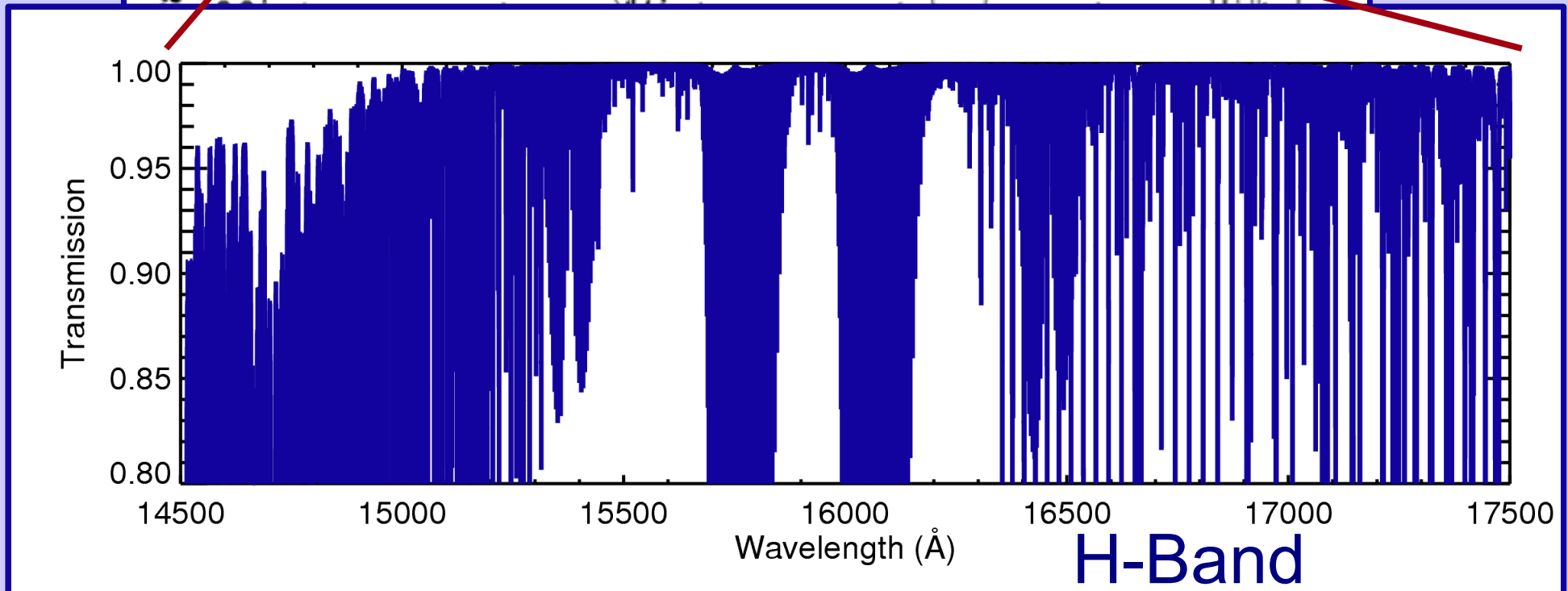
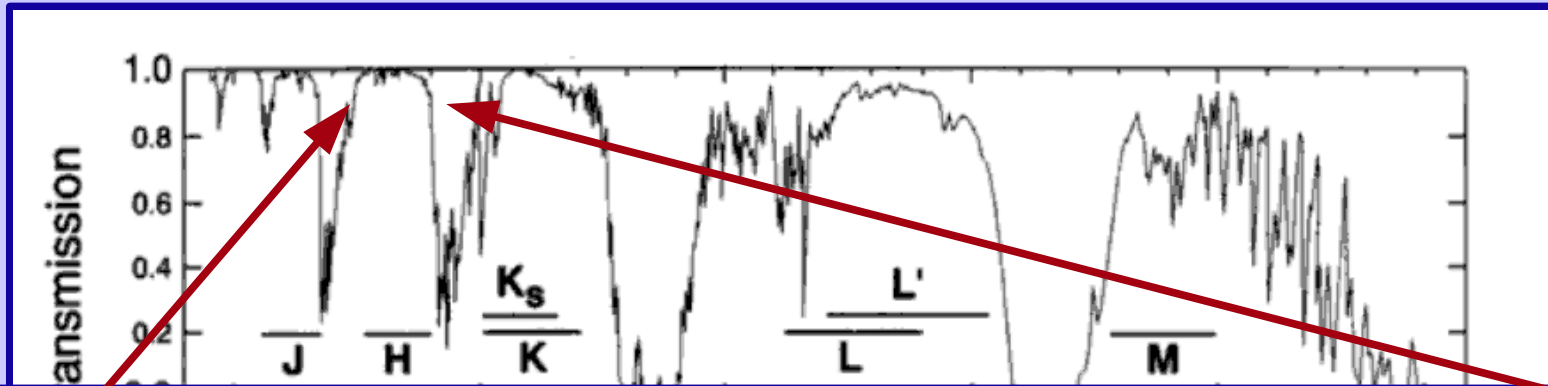


Telluric absorption in the spectrum is a significant problem in the infrared and must be precisely corrected!

Motivation



Motivation



Traditional telluric correction procedure

- 1) Observe “telluric standard” star(s) (e.g. w/out stellar features in waveband of interest)
- 2) Scale (1) to air-mass of target spectrum
- 3) Divide (2) into target spectrum
- 4) Plug the resulting perfectly corrected target spectrum into the next step in your data analysis pipeline.

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- 3) Divide (2) into target spectrum
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- 5) Iterate (2) & (3) until you get tired and give up.

Why doesn't this work?

- Atmosphere columns (particularly H₂O) are highly dependent on where and when you are looking.
 - Rarely are telluric standards spatially close to target stars.
 - Even if they are, observing them coincidentally with target observations adds overhead and complication
- Correct airmass scaling requires multiple telluric standards
 - Expensive in observing time
 - or specialized instrumentation (e.g. MOS)

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 - or specialized instrumentation (e.g. MOS)
- **Without heroic effort, observational correction typically good to a few percent.**

How to do we obtain a more precise correction?

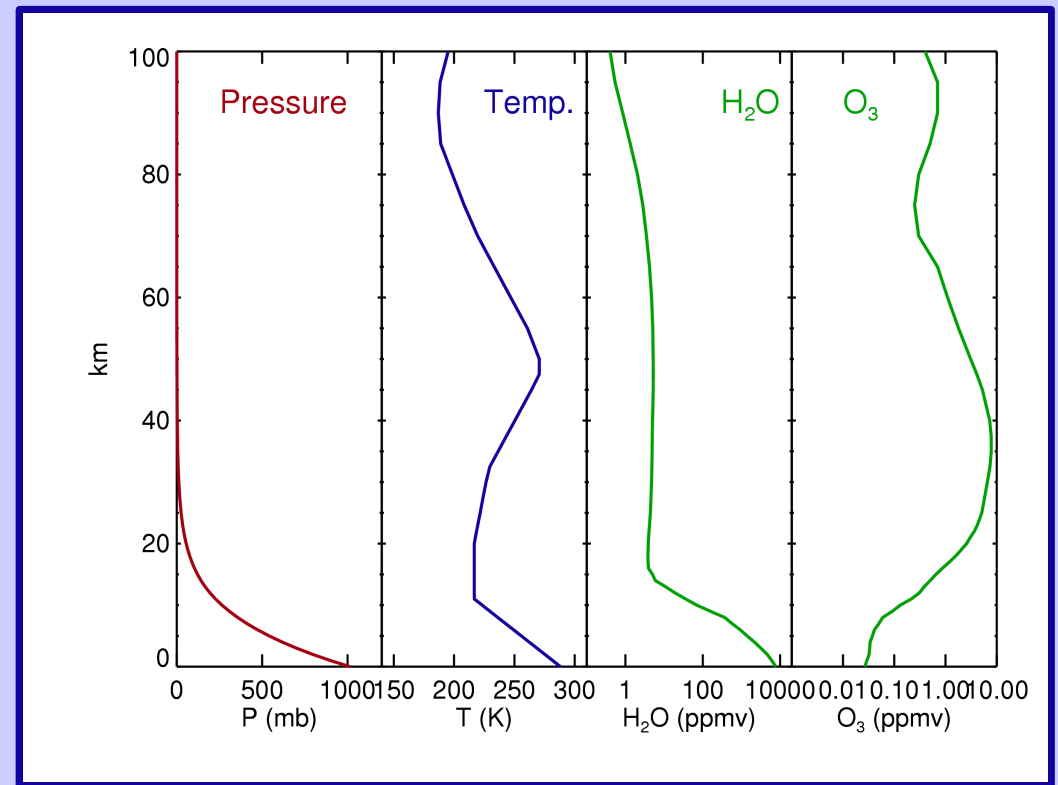
Get Help!

LBLRTM – A line-by-line radiative transfer model of the Earth's atmosphere

A public release RT code from Atmospheric and Environmental Research, Inc., (Clough et al. 2005) (FASCODE heritage)

```
kauai.astro.psu.edu: /home/cbender/work/pathfinder/20100806/vega
HI=1 F4=1 CN=1 AE=0 EM=1 SC=0 FI=0 PL=0 TS=0 AM=1MG= 0 LA=0 OD=0 XS=0 0 0
6.500E+03 7.000E+03 4.000E+00 0.000E+00 4.000E-02 3.600E+01 0.000E+00 0.000E+00 0 0.000E+00 0
0.000E+00
0 3 0 0 0 7 0 0 0 6378.390 100,000 0,000
4.123 0,000 0,000 0,000 0,000 0,000 0
1.500 5,000 8,000 0,000 100,000
50
Tropical
0.000E+00 1.013E+03 2.397E+02 11 11111111
2.593E+04 3.300E+02 2.869E-02 3.200E-01 1.500E-01 1.700E+00 2.090E+05
1.000E+00 9.040E+02 2.337E+02 11 11111111
1.949E+04 3.300E+02 3.150E-02 3.200E-01 1.450E-01 1.700E+00 2.090E+05
2.000E+00 8.050E+02 2.877E+02 11 11111111
1.534E+04 3.300E+02 3.342E-02 3.200E-01 1.399E-01 1.700E+00 2.090E+05
3.000E+00 7.150E+02 2.837E+02 11 11111111
8.600E+03 3.300E+02 3.504E-02 3.200E-01 1.349E-01 1.700E+00 2.090E+05
4.000E+00 6.330E+02 2.770E+02 11 11111111
4.441E+03 3.300E+02 3.561E-02 3.200E-01 1.312E-01 1.700E+00 2.090E+05
5.000E+00 5.590E+02 2.703E+02 11 11111111
3.546E+03 3.300E+02 3.767E-02 3.200E-01 1.303E-01 1.700E+00 2.090E+05
6.000E+00 4.300E+02 2.639E+02 11 11111111
2.101E+03 3.300E+02 3.989E-02 3.200E-01 1.289E-01 1.700E+00 2.090E+05
7.000E+00 4.320E+02 2.570E+02 11 11111111
1.288E+03 3.300E+02 4.222E-02 3.200E-01 1.247E-01 1.699E+00 2.090E+05
8.000E+00 3.780E+02 2.502E+02 11 11111111
7.637E+02 3.300E+02 4.471E-02 3.200E-01 1.185E-01 1.697E+00 2.090E+05
9.000E+00 3.290E+02 2.436E+02 11 11111111
4.098E+02 3.300E+02 5.000E-02 3.195E-01 1.094E-01 1.693E+00 2.090E+05
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1.912E+02 3.300E+02 5.595E-02 3.179E-01 9.962E-02 1.688E+00 2.090E+05
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2.800E+00 3.300E+02 2.400E+00 2.051E-01 1.232E-02 1.272E+00 2.090E+05
2.300E+01 3.500E+01 2.170E+02 11 11111111
2.900E+00 3.300E+02 3.400E+00 1.967E-01 1.307E-02 1.191E+00 2.090E+05
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2.500E+01 2.570E+01 2.214E+02 11 11111111
3.250E+00 3.300E+02 5.400E+00 1.756E-01 1.521E-02 1.055E+00 2.090E+05
20100806/vega>
```

6 built-in atmospheres (or custom):
column profiles for P, T, 38 species



example: 1976 Standard US Atmosphere

HITRAN Line Database

Journal of Quantitative Spectroscopy & Radiative Transfer 110 (2009) 533–572



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Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt



The *HITRAN* 2008 molecular spectroscopic database

L.S. Rothman^{a,*}, I.E. Gordon^a, A. Barbe^b, D.Chris Benner^c, P.F. Bernath^d, M. Birk^e, V. Boudon^f, L.R. Brown^g, A. Campargue^h, J.-P. Champion^f, K. Chance^a, L.H. Coudertⁱ, V. Dana^j, V.M. Devi^c, S. Fally^{k,1}, J.-M. Flaudⁱ, R.R. Gamache^l, A. Goldman^m, D. Jacquemartⁿ, I. Kleinerⁱ, N. Lacomeⁿ, W.J. Lafferty^o, J.-Y. Mandin^j, S.T. Massie^p, S.N. Mikhailenko^q, C.E. Miller^g, N. Moazzen-Ahmadi^r, O.V. Naumenko^q, A.V. Nikitin^q, J. Orphalⁱ, V.I. Perevalov^q, A. Perrinⁱ, A. Predoi-Cross^s, C.P. Rinsland^t, M. Rotger^{b,f}, M. Šimečková^{a,2}, M.A.H. Smith^t, K. Sung^g, S.A. Tashkun^q, J. Tennyson^u, R.A. Toth^g, A.C. Vandaele^v, J. Vander Auwera^k

Outline

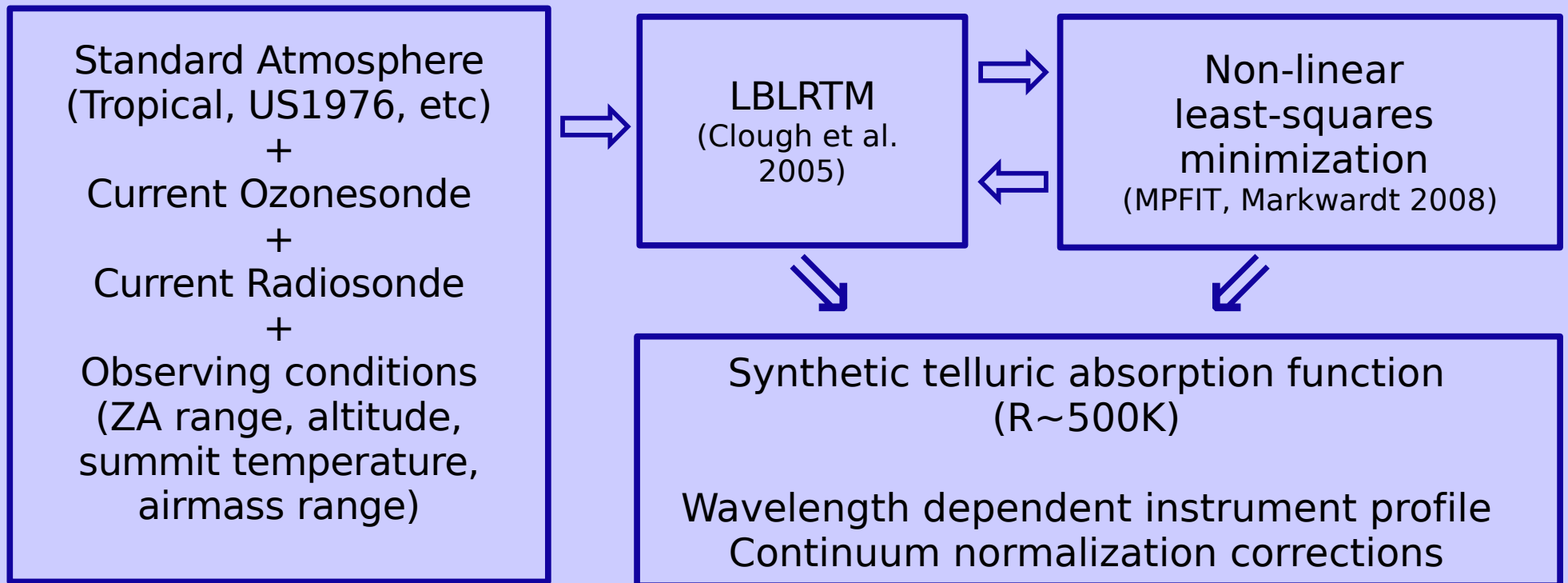
- Traditional telluric correction techniques
- **TERRASPEC: Synthetic forward modeling**
- Examples
 - Keck + NIRSPEC (L-band)
 - HET + HRS (R-band)
 - HET + Pathfinder (Y-band, H-band)

The TERRASPEC Algorithm

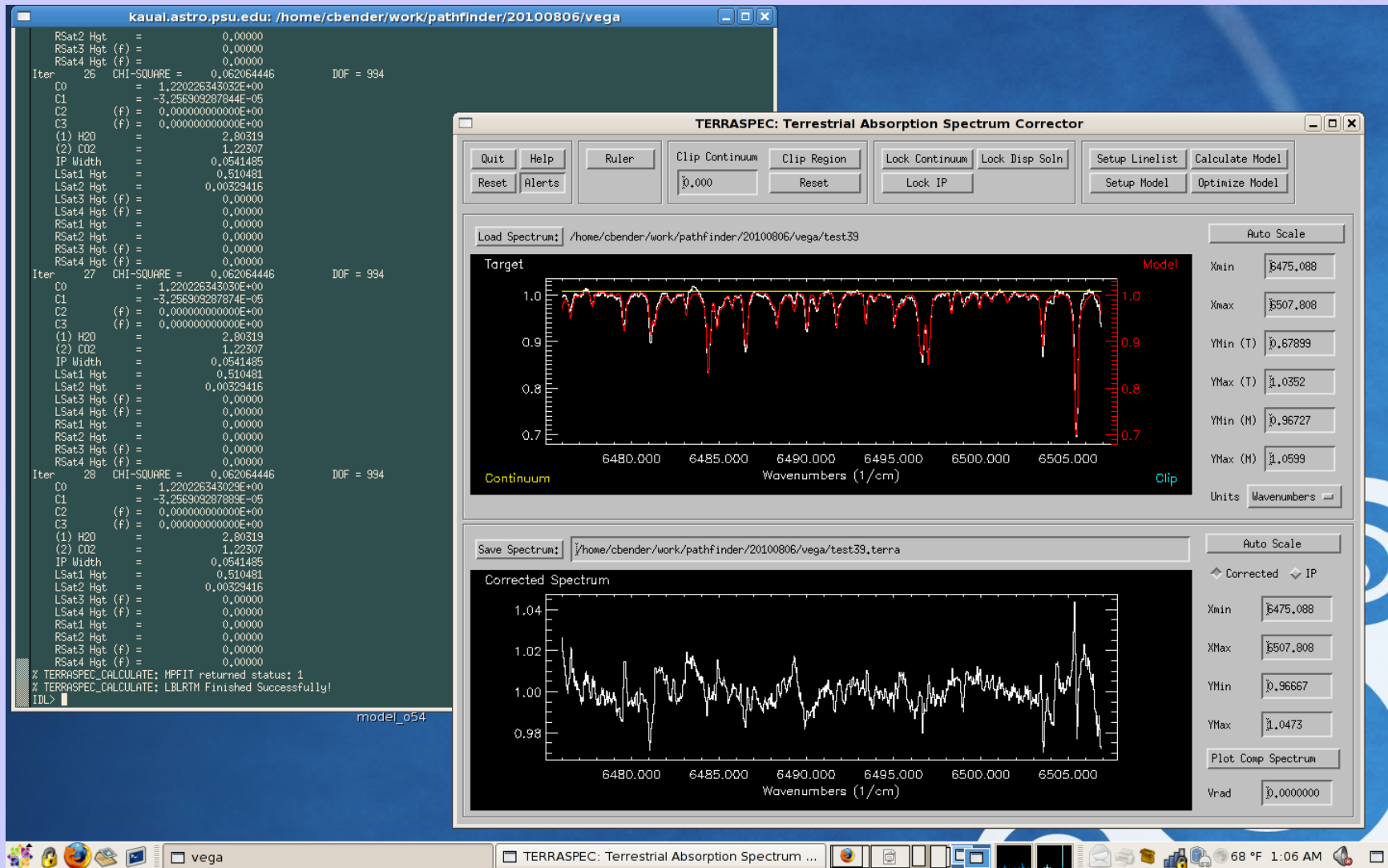
(Terrestrial Absorption Spectrum Corrector)

Observing hot stars is not practical because of H₂O variability & observing time constraints

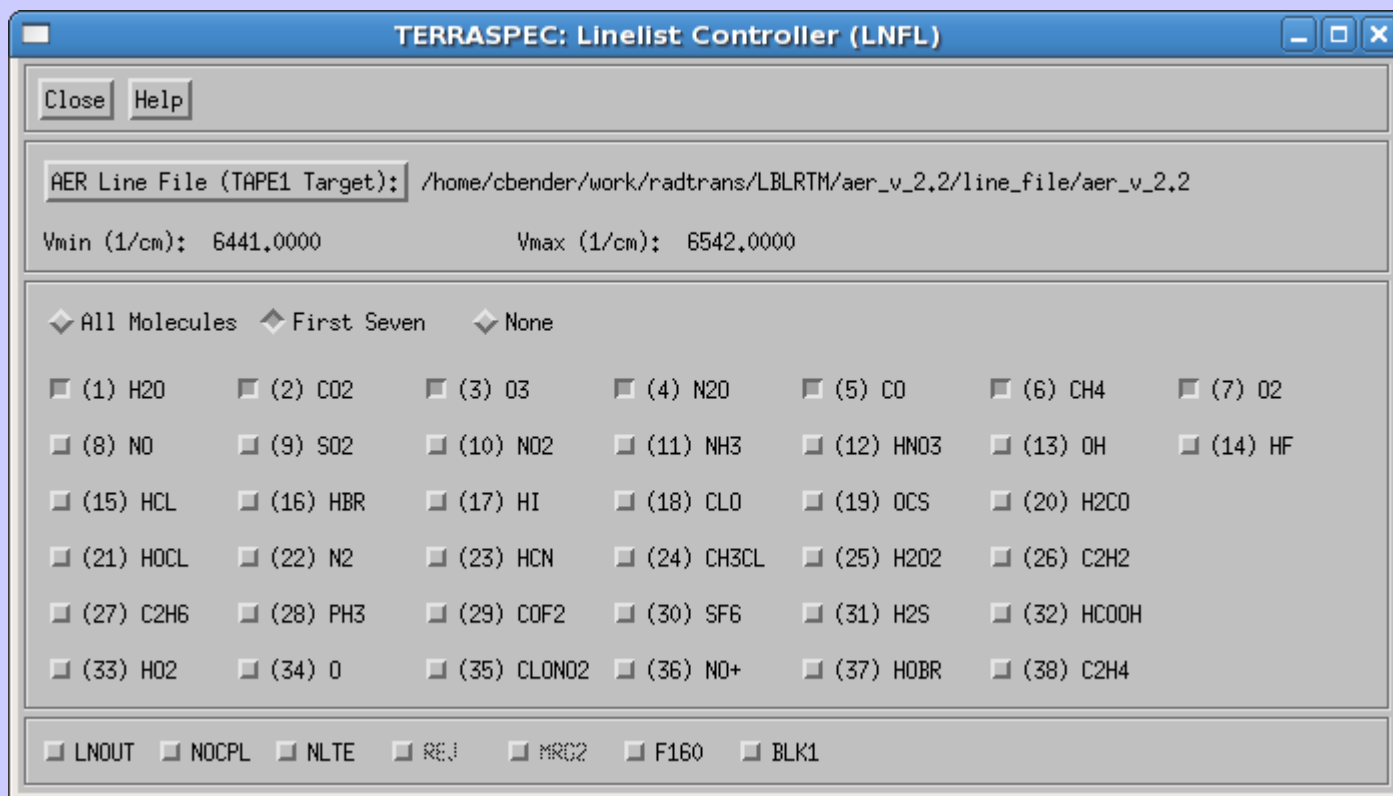
Forward model telluric absorption using Line-By-Line RT Model



The TERRASPEC IDL wrapper



The TERRASPEC IDL wrapper



The TERRASPEC IDL wrapper

TERRASPEC: Line-by-Line Radiative Transfer Model Controller (LBLRTM)

Close Help

Summary Record 1 Record 1.2 Record 3 Model = 0 Record 12

Calculation Range: Vmin (1/cm): 6471.0142 Vmax (1/cm): 6511.8818

Atmospheric Model: 6: US Standard 1976

Num. Mol. Scaled: 6

Scaling Value: 2.8031911E+00

Observer Location (default: Mauna Kea): Latitude (deg) 19.860 Height (km) 2.075

Observation Zenith Ang (deg): Fixed 35.000 Integrate Over Range

Continuum Fit Coeff.:

C(0) 1.22023 C(1) -3.25691E-05 C(2) 0.00000 C(3) 0.00000

Response Coeff. Width 0.0541485

L Sat 1 0.510481 L Sat 2 0.00329416 L Sat 3 0.00000 L Sat 4 0.00000

R Sat 1 0.00000 R Sat 2 0.00000 R Sat 3 0.00000 R Sat 4 0.00000

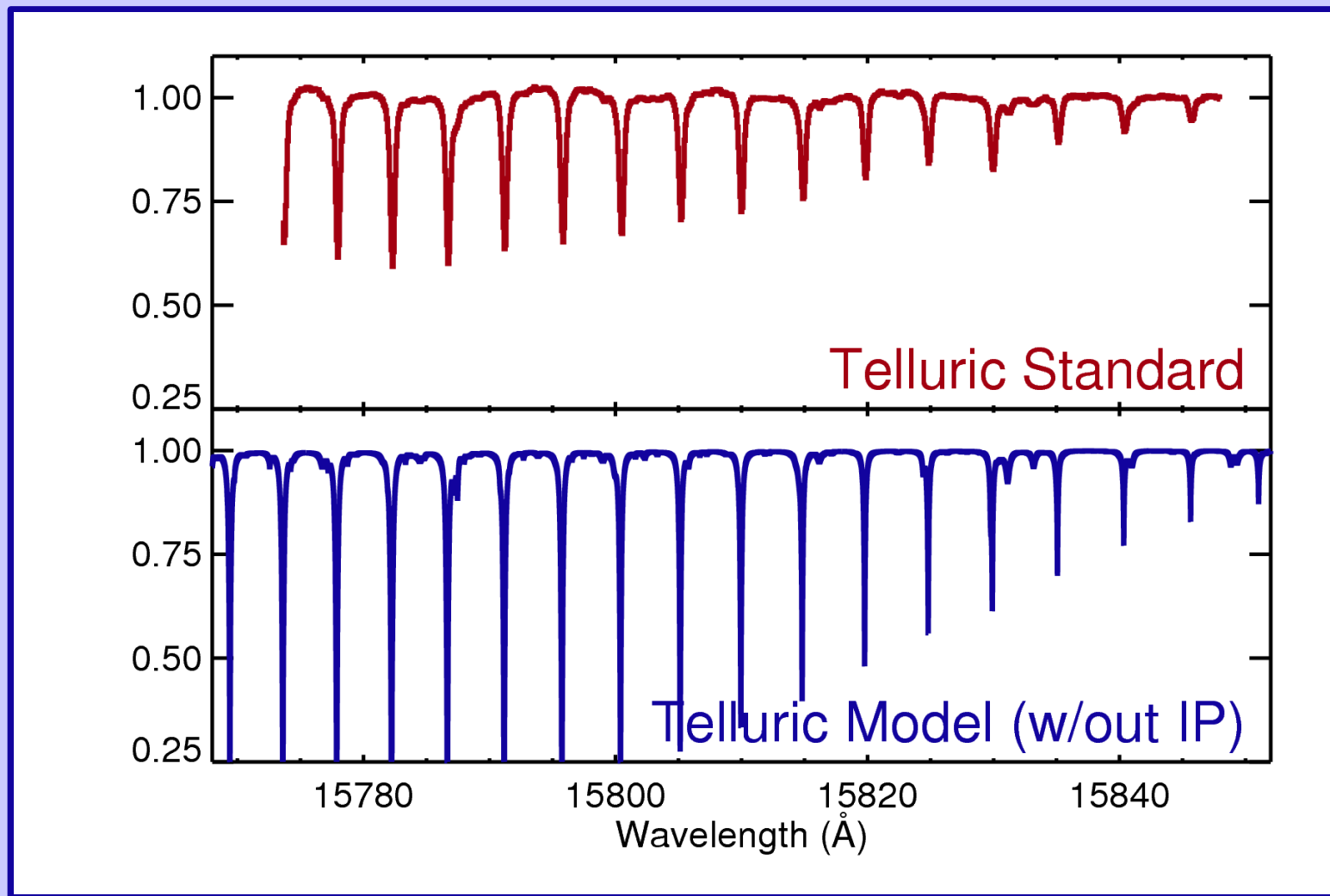
Optimize Parameters:

Continuum Fit:	Column Scaling:	Response Function:	Other Pars:
<input type="checkbox"/> C(0)	<input type="checkbox"/> (1) H2O <input type="checkbox"/> (5) CO	<input type="checkbox"/> L Sat 1 <input type="checkbox"/> R Sat 1	<input type="checkbox"/> Zenith Ang
<input type="checkbox"/> C(1)*X	<input type="checkbox"/> (2) CO2 <input type="checkbox"/> (6) CH4	<input type="checkbox"/> L Sat 2 <input type="checkbox"/> R Sat 2	
<input type="checkbox"/> C(2)*X^2	<input type="checkbox"/> (3) O3 <input type="checkbox"/> (7) O2	<input type="checkbox"/> L Sat 3 <input type="checkbox"/> R Sat 3	
<input type="checkbox"/> C(3)*X^3	<input type="checkbox"/> (4) N2O	<input type="checkbox"/> L Sat 4 <input type="checkbox"/> R Sat 4	

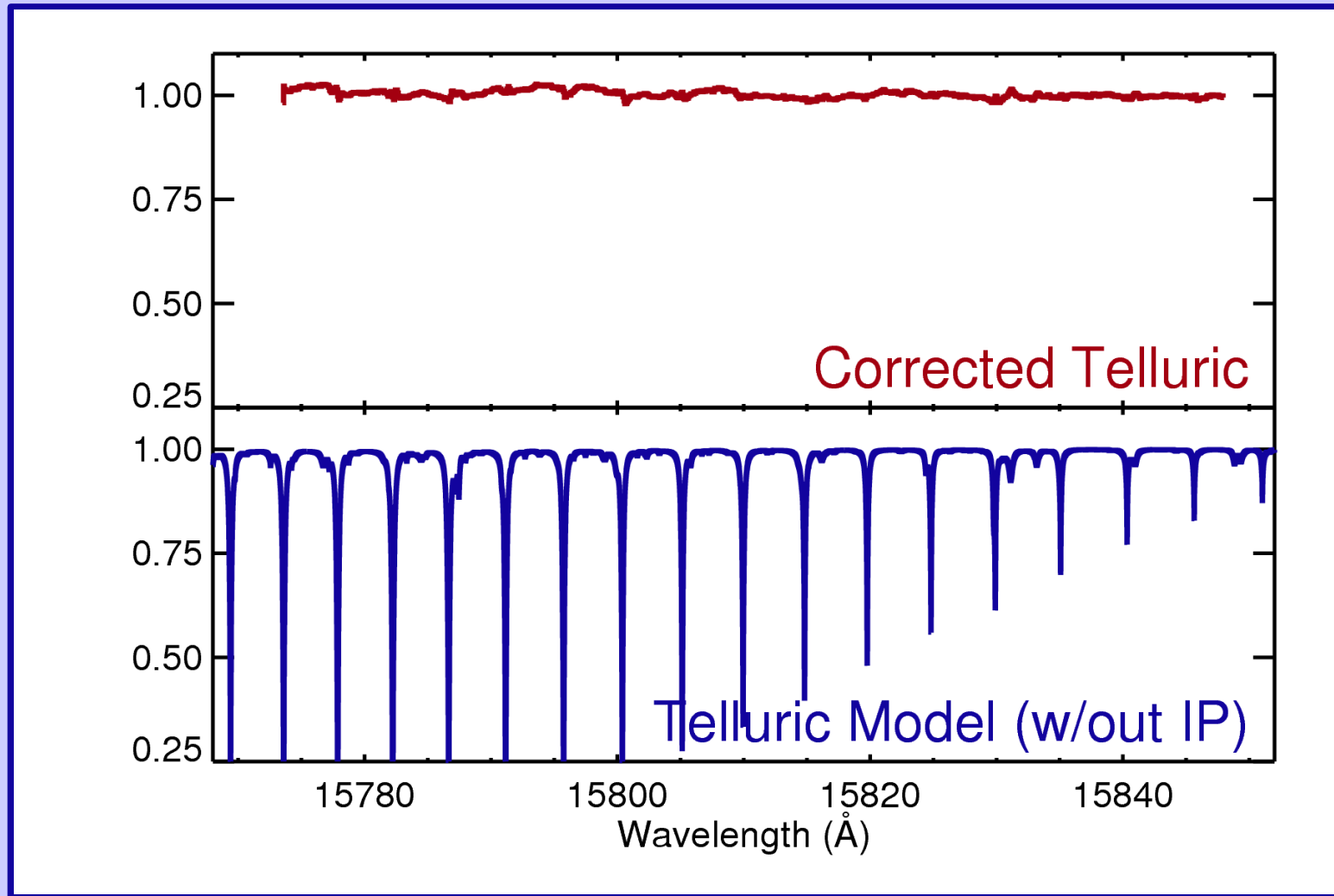
Outline

- Traditional telluric correction techniques
- TERRASPEC: Synthetic forward modeling
- **Examples**
 - HET + Pathfinder Telluric Standard
 - Keck + NIRSPEC (L-band)
 - HET + HRS (R-band)
 - HET + Pathfinder (Y-band, H-band)

HET + PATHFINDER (H-band) Telluric Std: (Brandon Botzer)



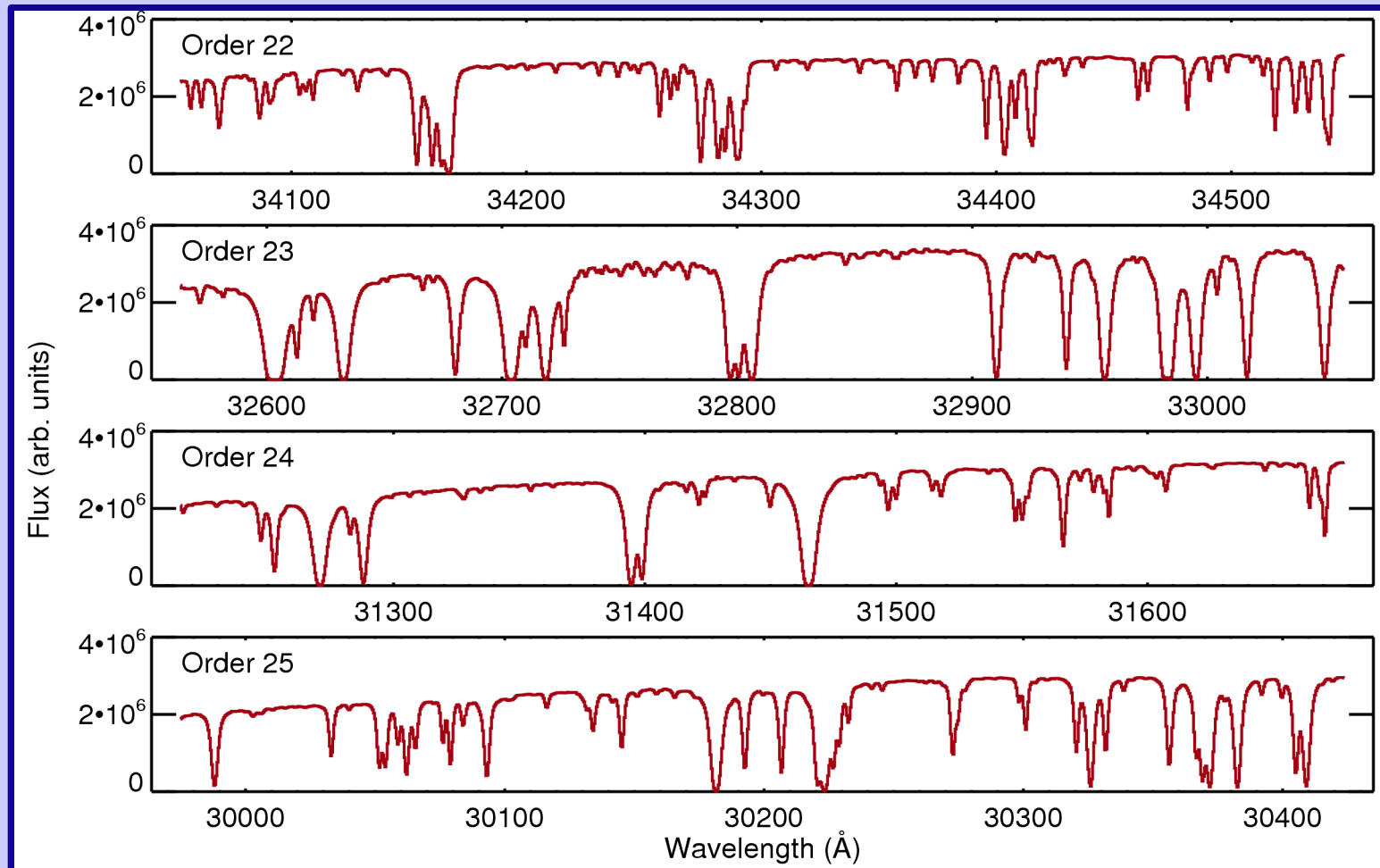
HET + PATHFINDER (H-band): (Brandon Botzer)



Keck + NIRSPEC @ L-band:

A worst case scenario (hopefully)

Observed Spectrum

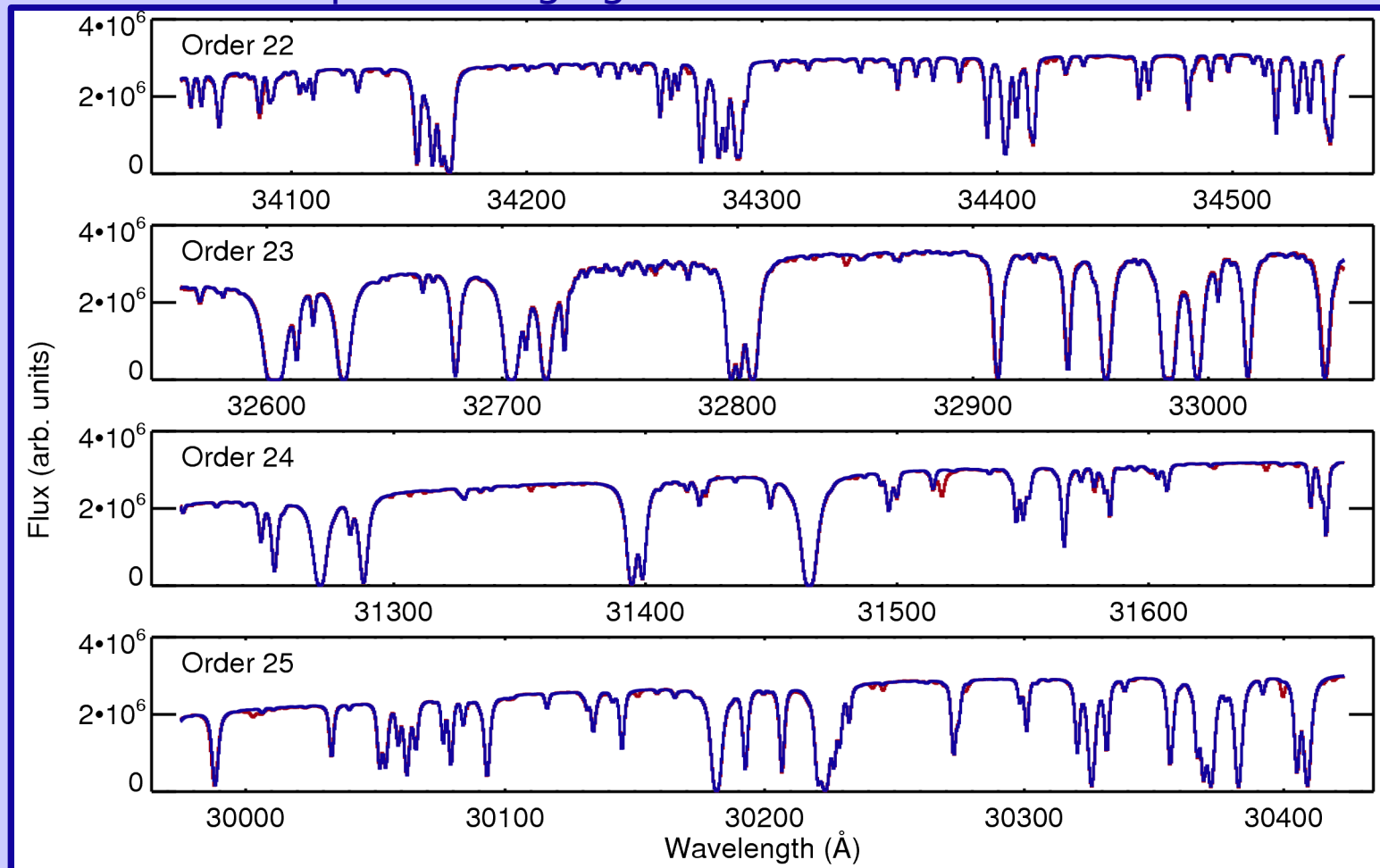


Keck + NIRSPEC @ L-band:

A worst case scenario (hopefully)

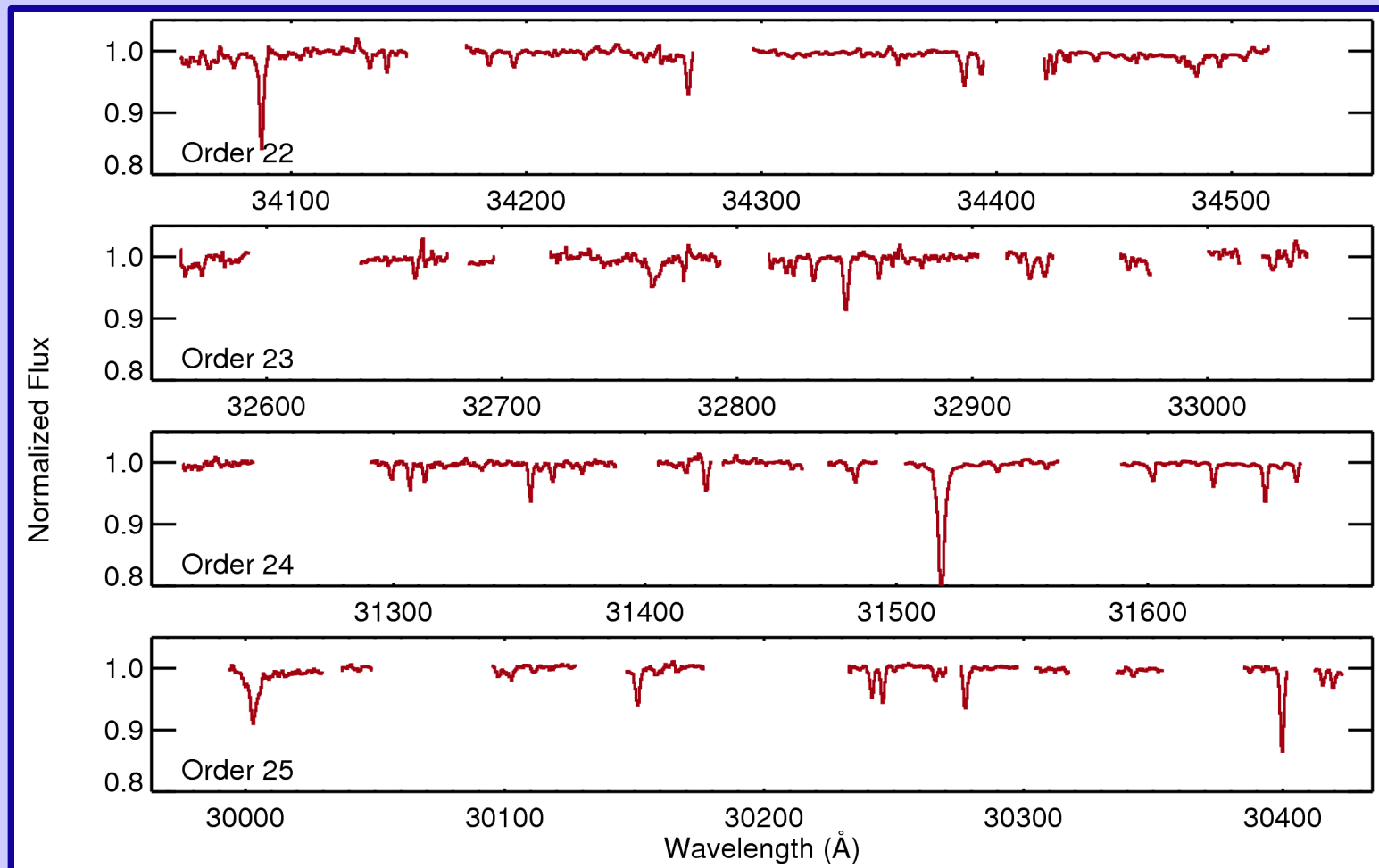
Observed Spectrum

Telluric Correction \times Optical Fringing



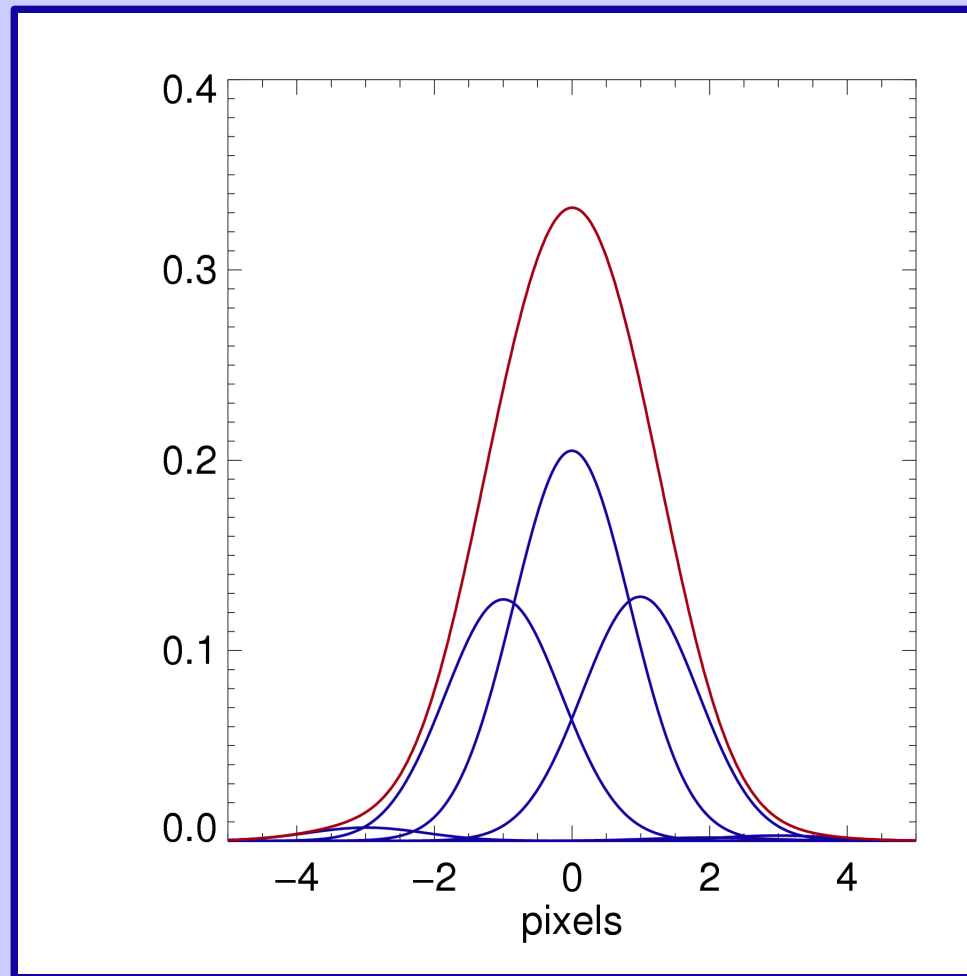
Keck + NIRSPEC @ L-band: A worst case scenario (hopefully)

Observed Spectrum \div (Telluric Correction \times Optical Fringing)

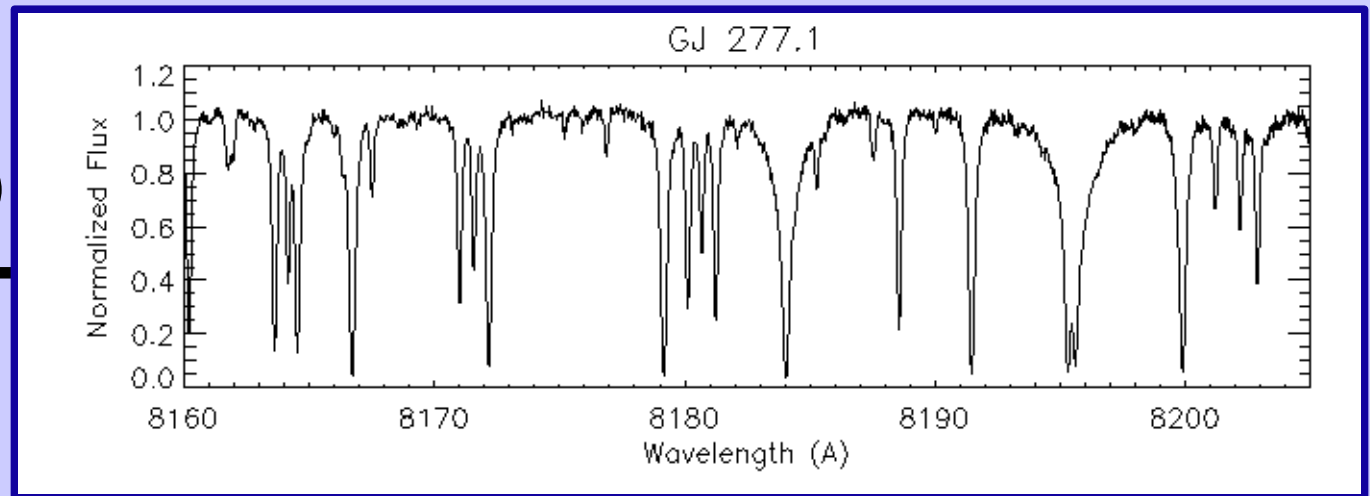


Keck + NIRSPEC @ L-band: A worst case scenario (hopefully)

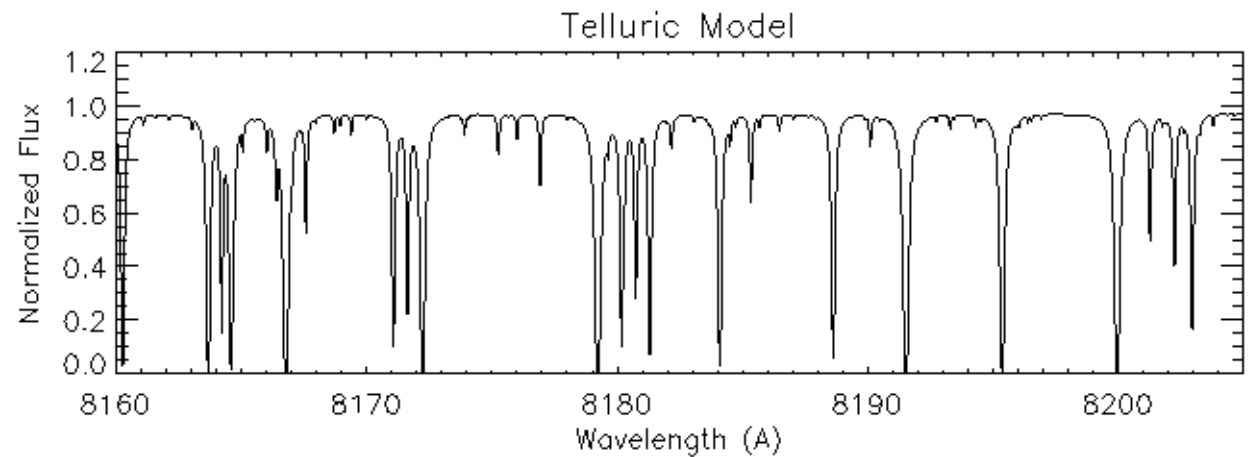
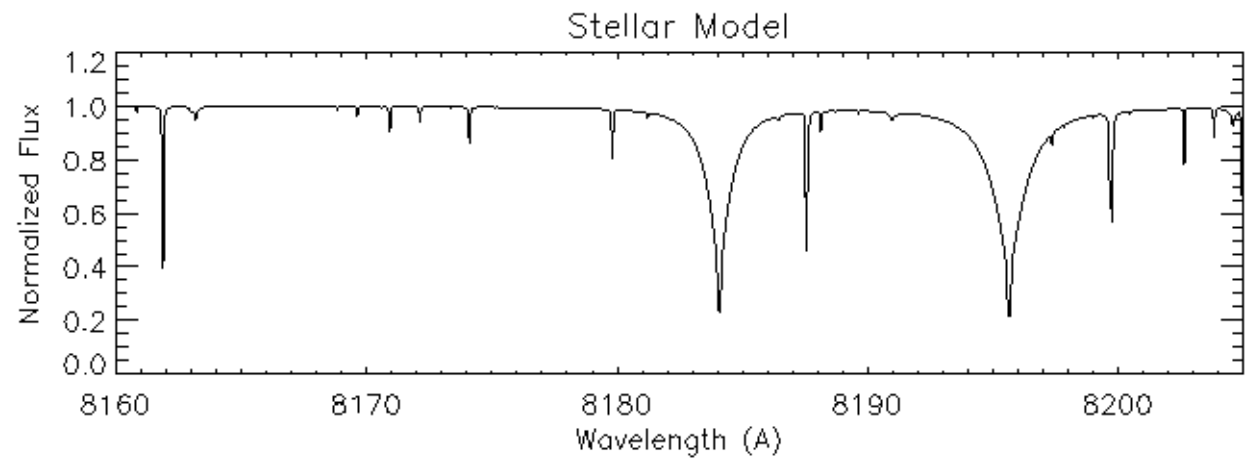
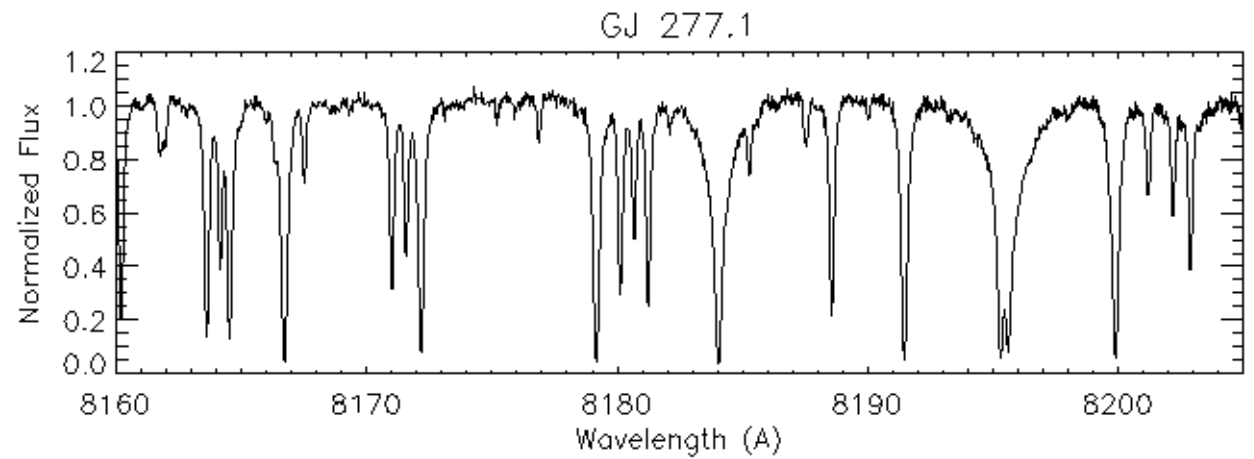
Derived instrument profile (aka. Valenti, Butler, & Marcy 1995)



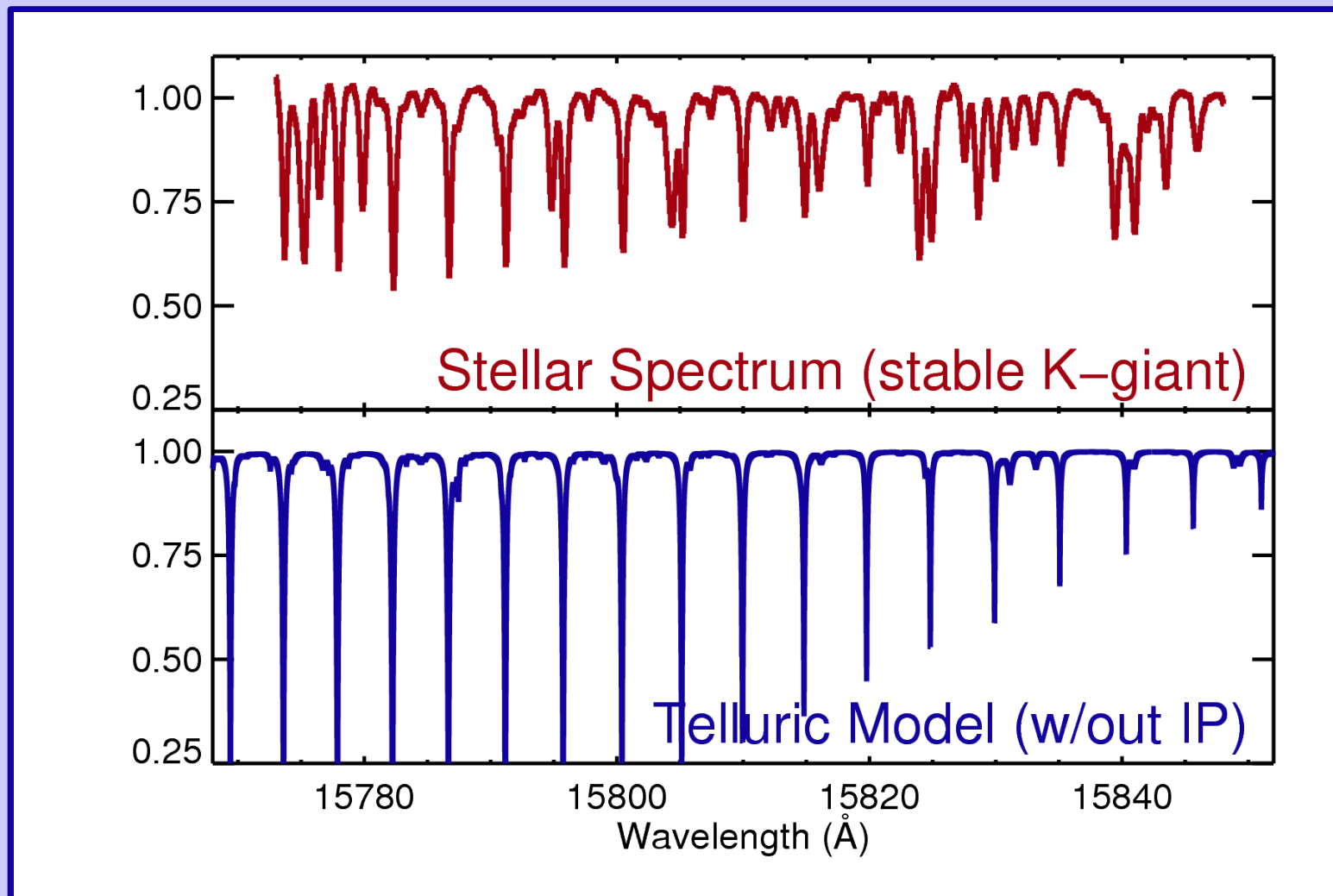
HET + HRS @ R:(Sara Gettel)



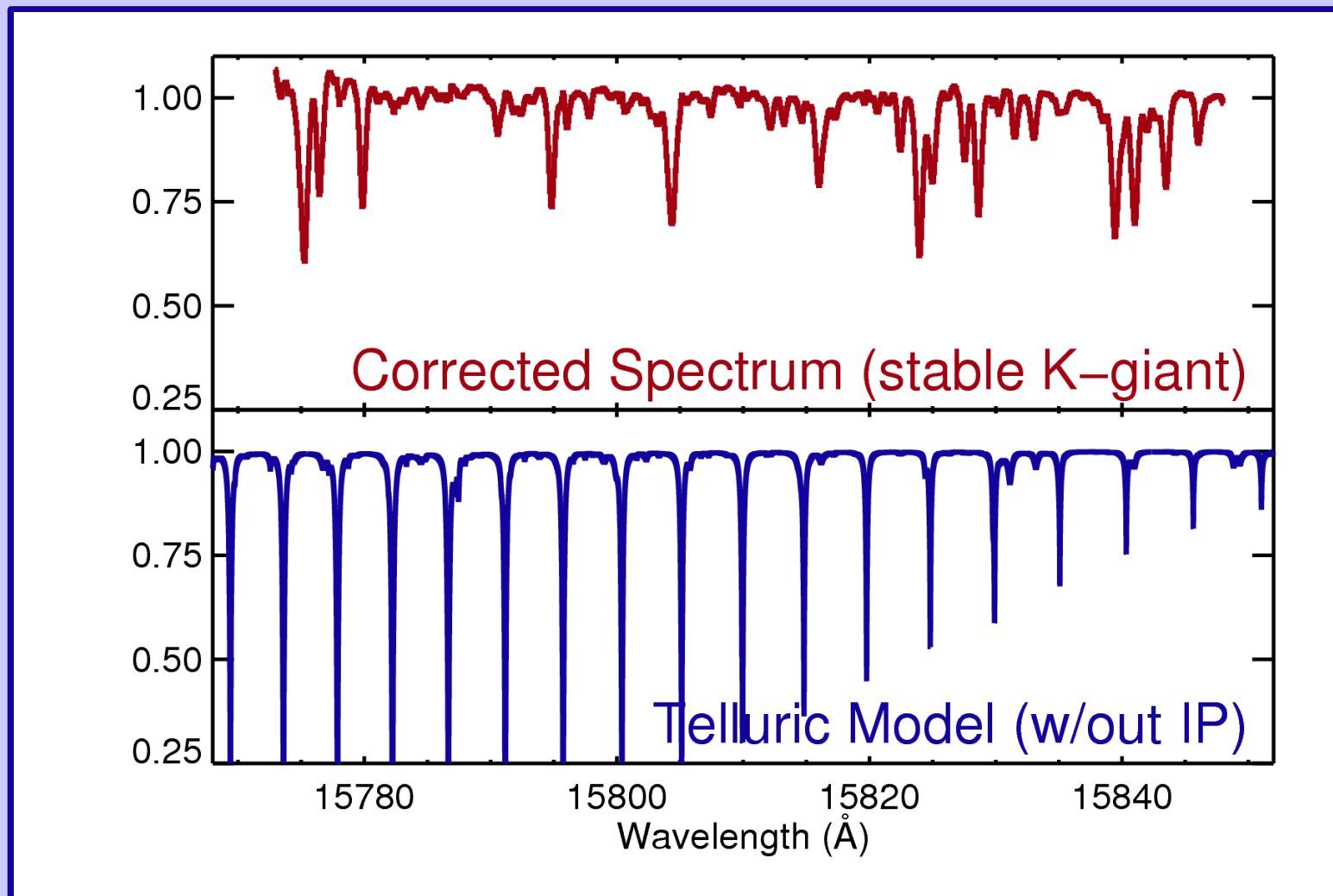
HET + HRS @ R:(Sara Gettel)



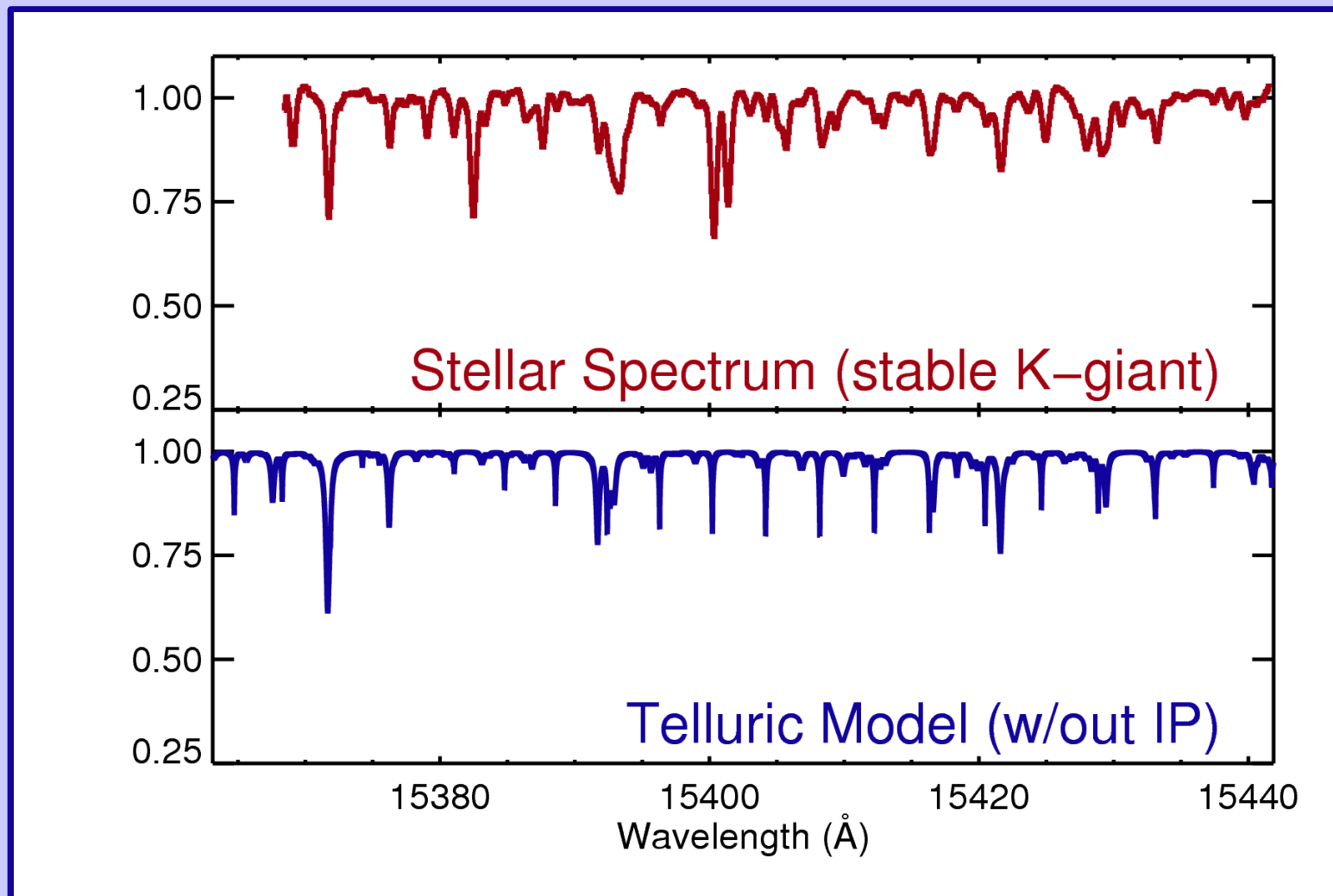
HET + PATHFINDER (H-band): (Brandon Botzer)



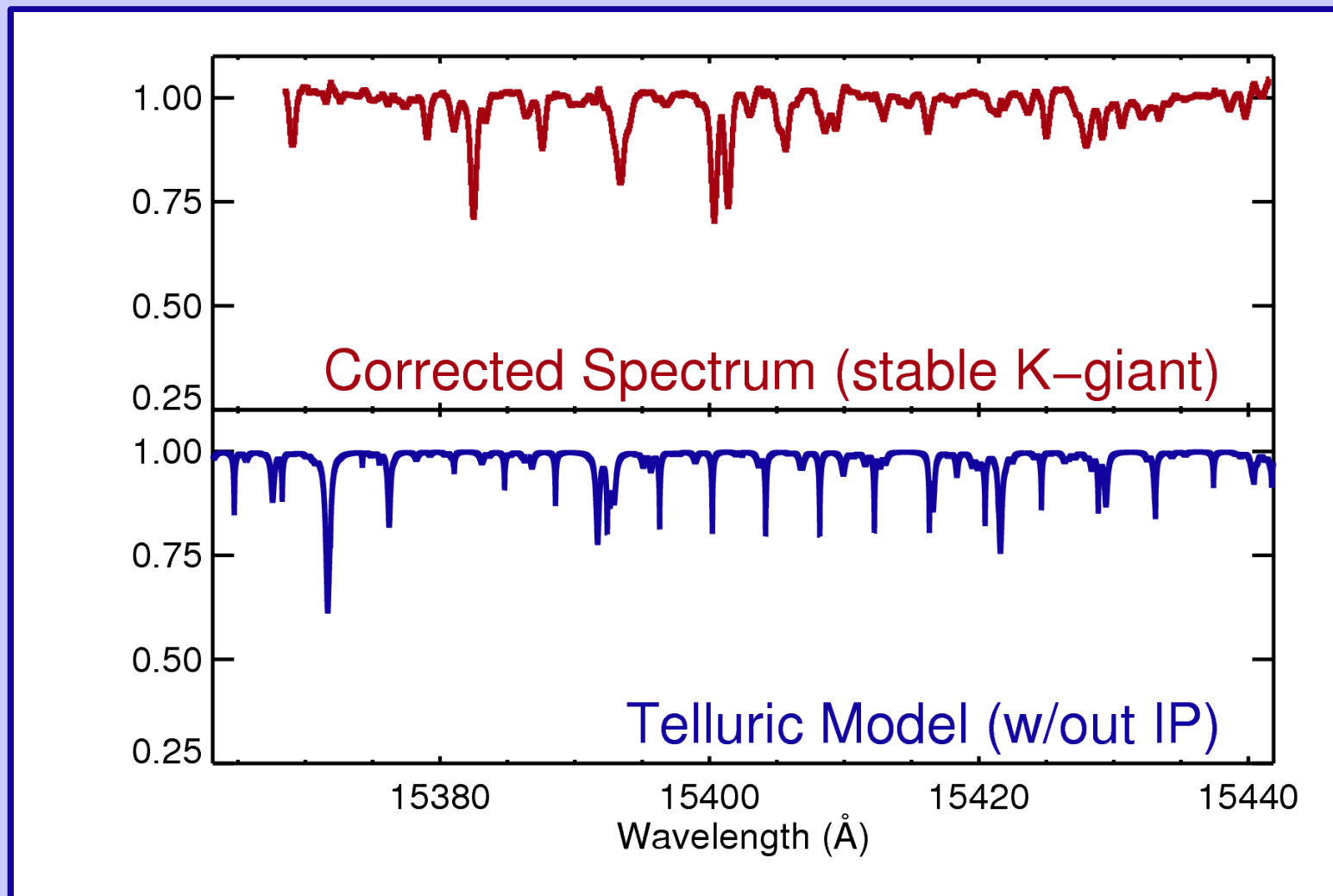
HET + PATHFINDER (H-band): (Brandon Botzer)



HET + PATHFINDER (H-band): (Brandon Botzer)



HET + PATHFINDER (H-band): (Brandon Botzer)



Some comments...

- The telluric absorption function can be forward modeled with sufficient precision to remove it from spectra, without the aid of a telluric standard.
- The achieved correction can be at the S/N of the target spectrum, considerably better than possible with observed tellurics.
- The modeling procedure can use the synthetic telluric solution to derive the instrument profile.

Future efforts

- Improve correction speed to enable use by large surveys
- Multi-order corrections that automatically derives species information over full spectrograph bandwidth
- Explore limits on velocity precision of near-IR, telluric corrected spectra