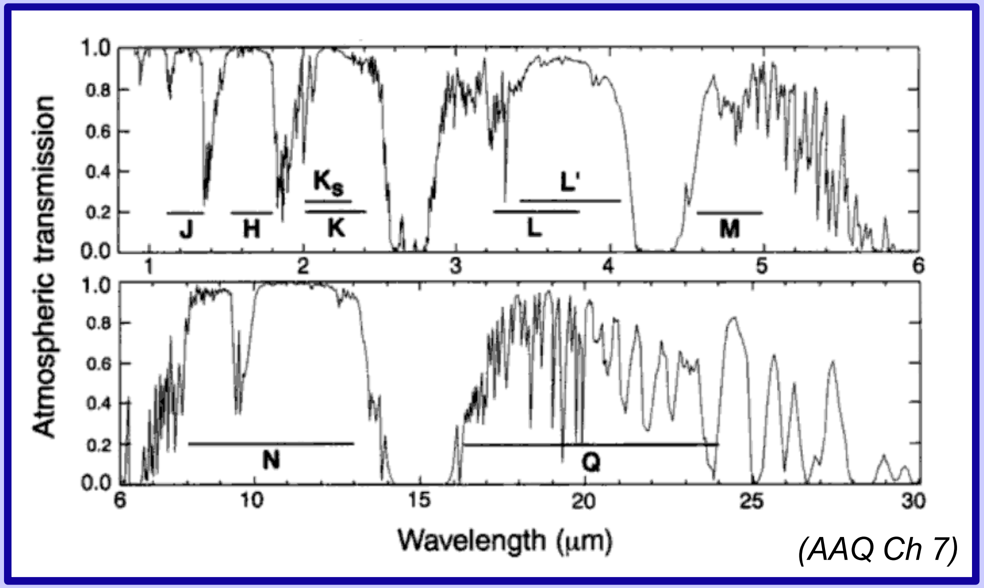
Advances in Telluric Characterization for Precision Spectroscopy

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.

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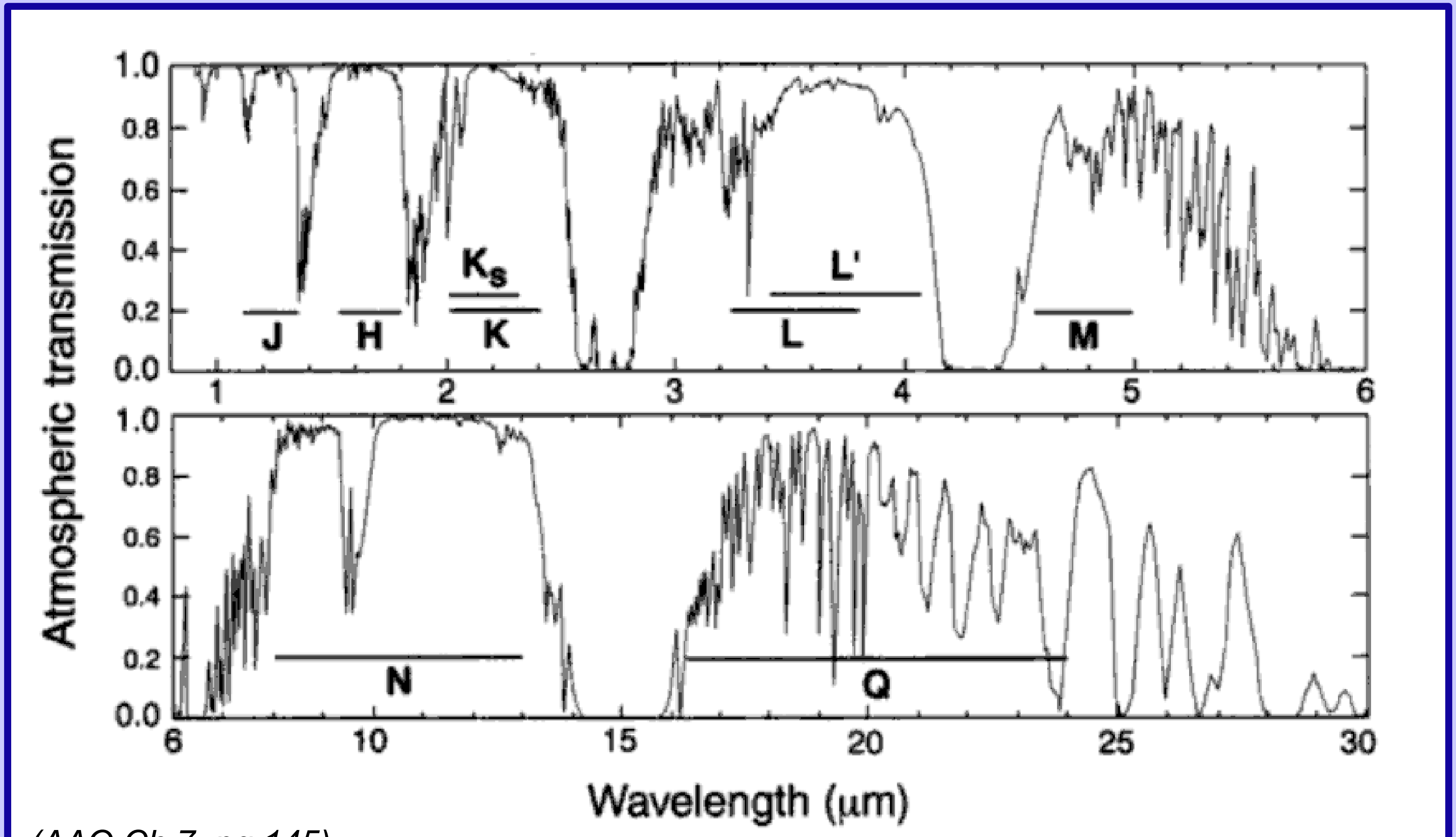
1) offer significant potential for increased sensitivity to low-mass planets
2) facilitate a vast amount of important non-exoplanet astronomy.

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).

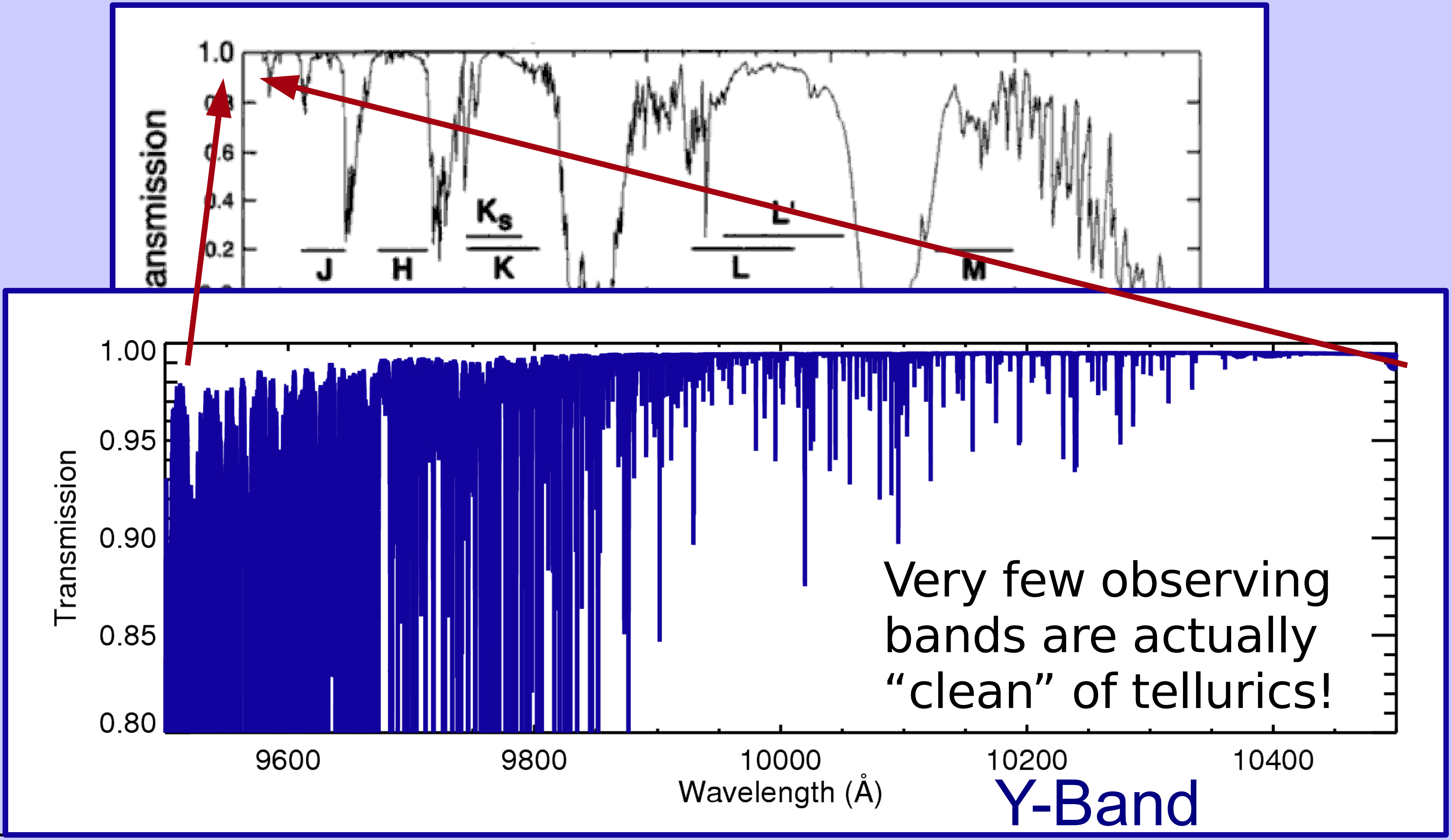
Motivation



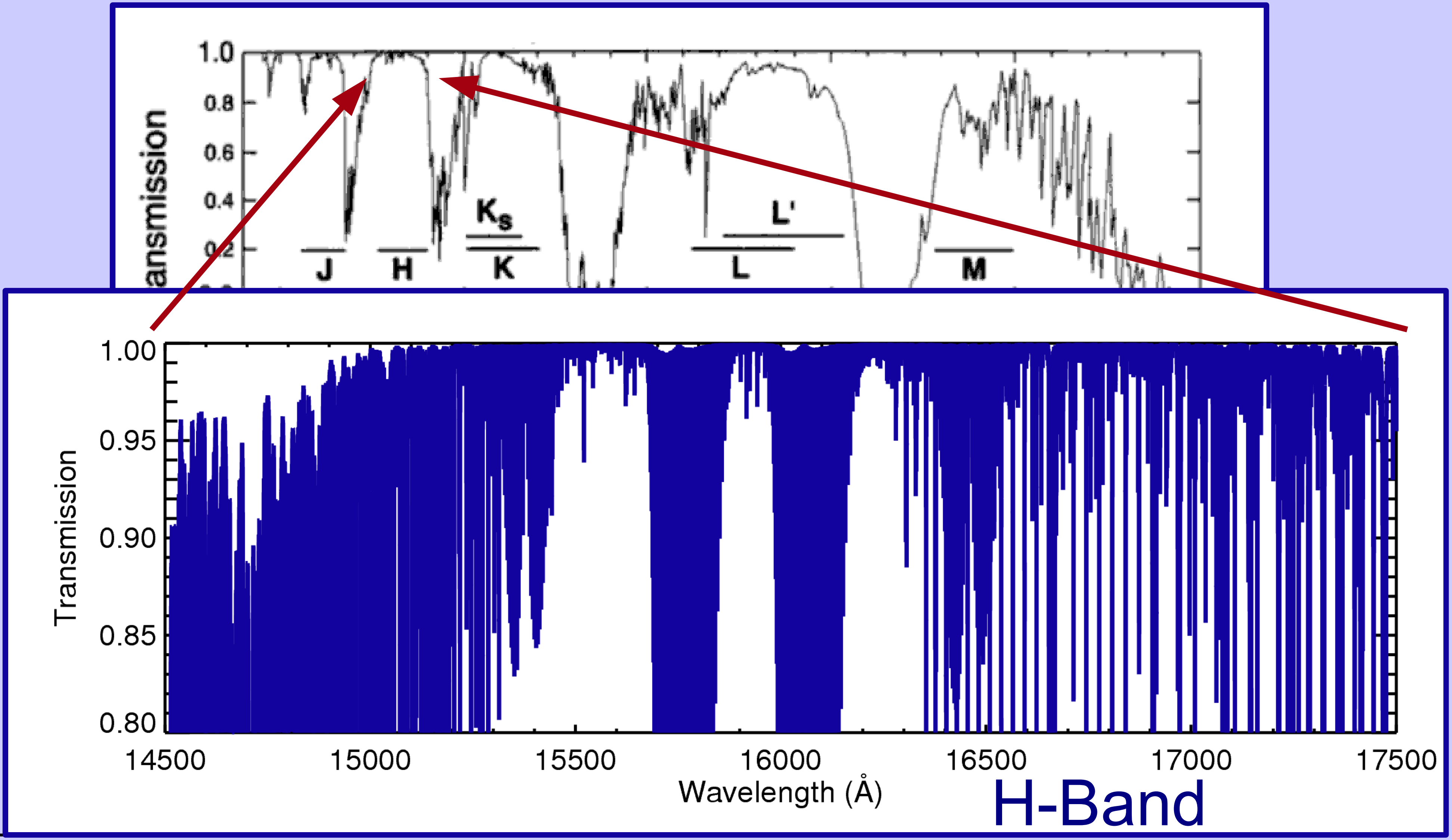
(AAQ Ch 7, pg 145)

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

Motivation


1.0
0.8
0.6
0.4
0.2
ansmission
J
H
K_s
K
L'
L
M
1.00
0.95
0.90
0.85
0.80
Transmission
9600
9800
10000
10200
10400
Wavelength (Å)
Very few observing bands are actually "clean" of tellurics!
Y-Band

Motivation



1.0
0.8
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ansmission
J
H
Ks
K
L'
L
M
1.00
0.95
0.90
0.85
0.80
Transmission
14500
15000
15500
16000
16500
17000
17500
Wavelength (Å)
H-Band

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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4) ~~Plug the resulting perfectly corrected target spectrum into the next step in your data analysis pipeline.~~
5) Iterate (2) & (3) until you get tired and give up.

Why doesn't this work?

- Atmosphere columns (particularly H_2O) 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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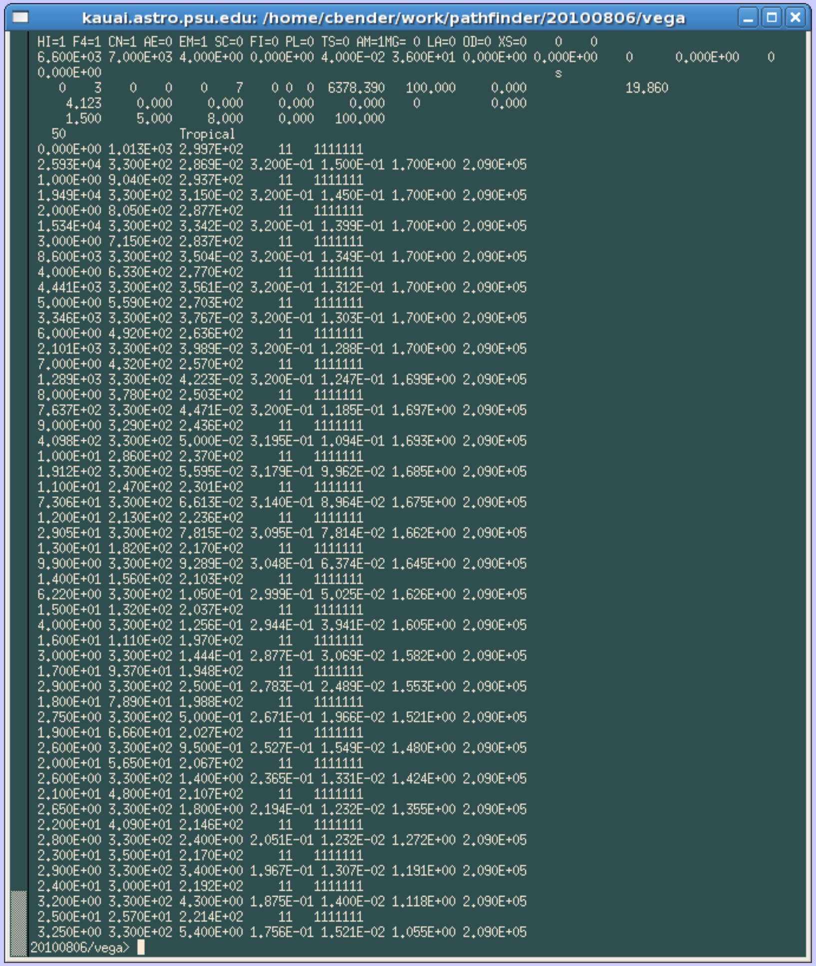
  - or specialized instrumentation (e.g. MOS)
- Without heroic effort, observational correction typically good to a few percent.

How to do we obtain a more precise correction?

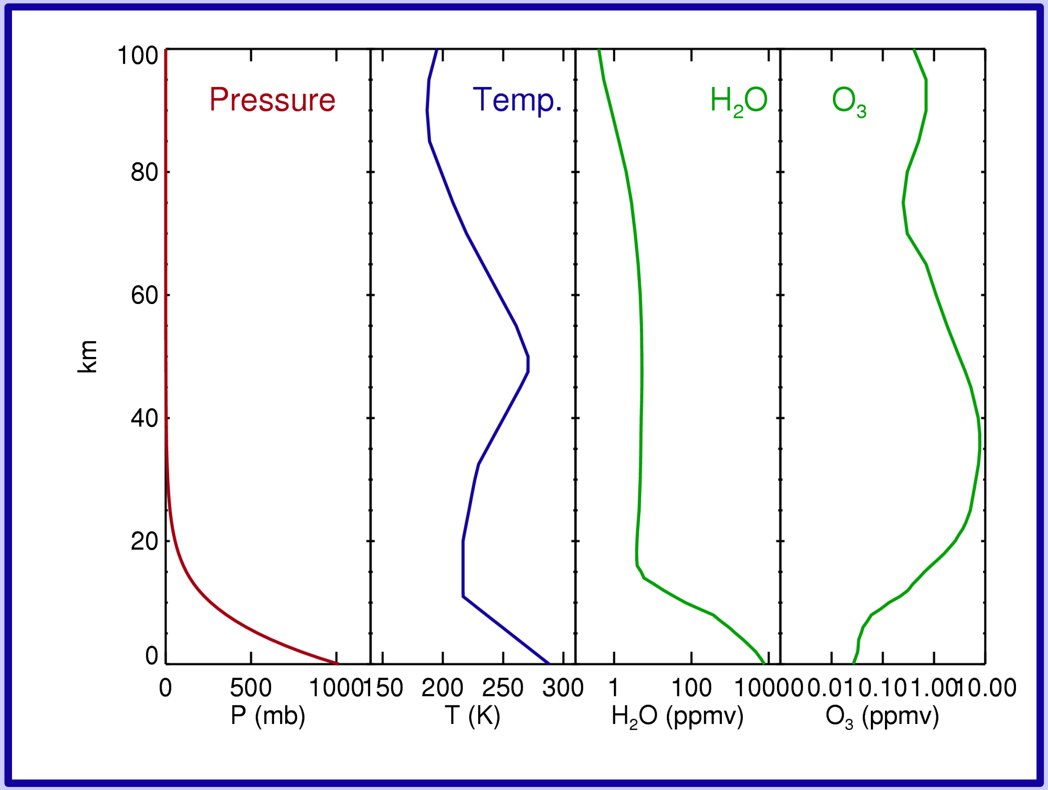
Get Help!

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)



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



example: 1976 Standard US Atmosphere

HITRAN Line Database

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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. Coudert [i], V. Dana [j], V.M. Devi [c], S. Fally [k,1], J.-M. Flaud [i], R.R. Gamache [l], A. Goldman [m], D. Jacquemart [n], I. Kleiner [i], N. Lacome [n], 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. Orphal [i], V.I. Perevalov [q], A. Perrin [i], 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]

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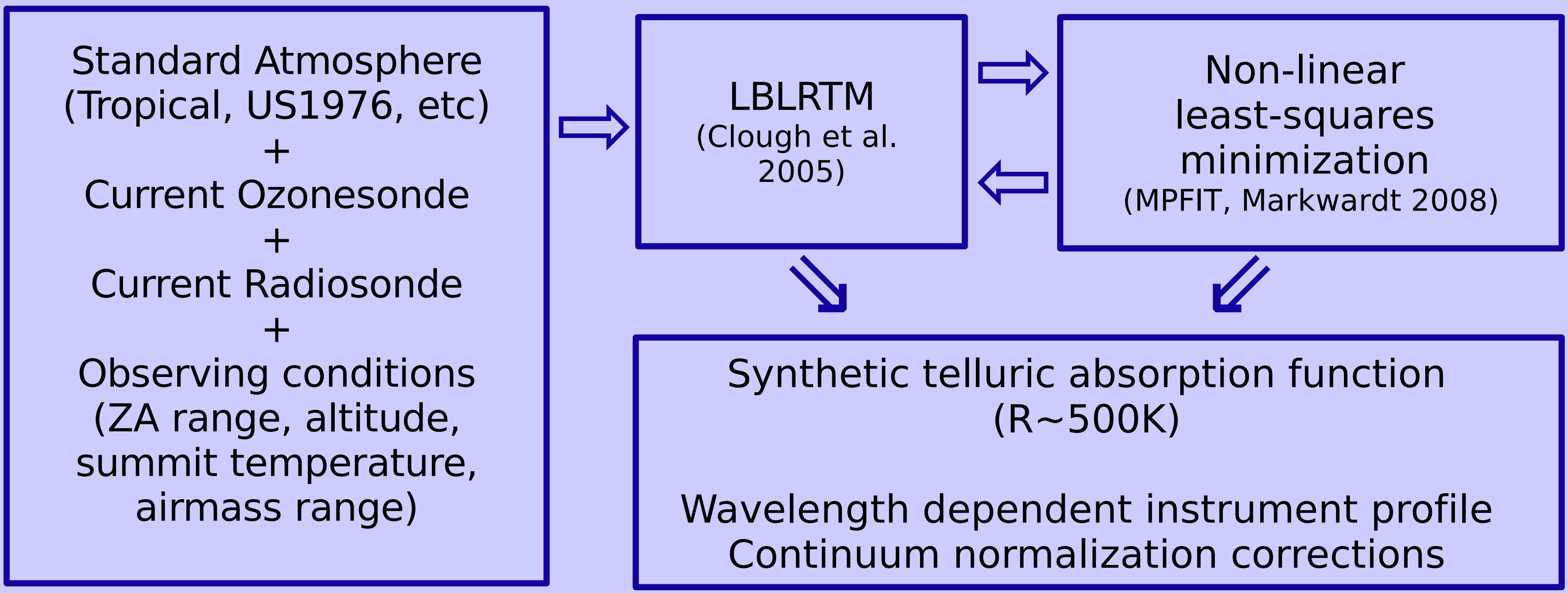
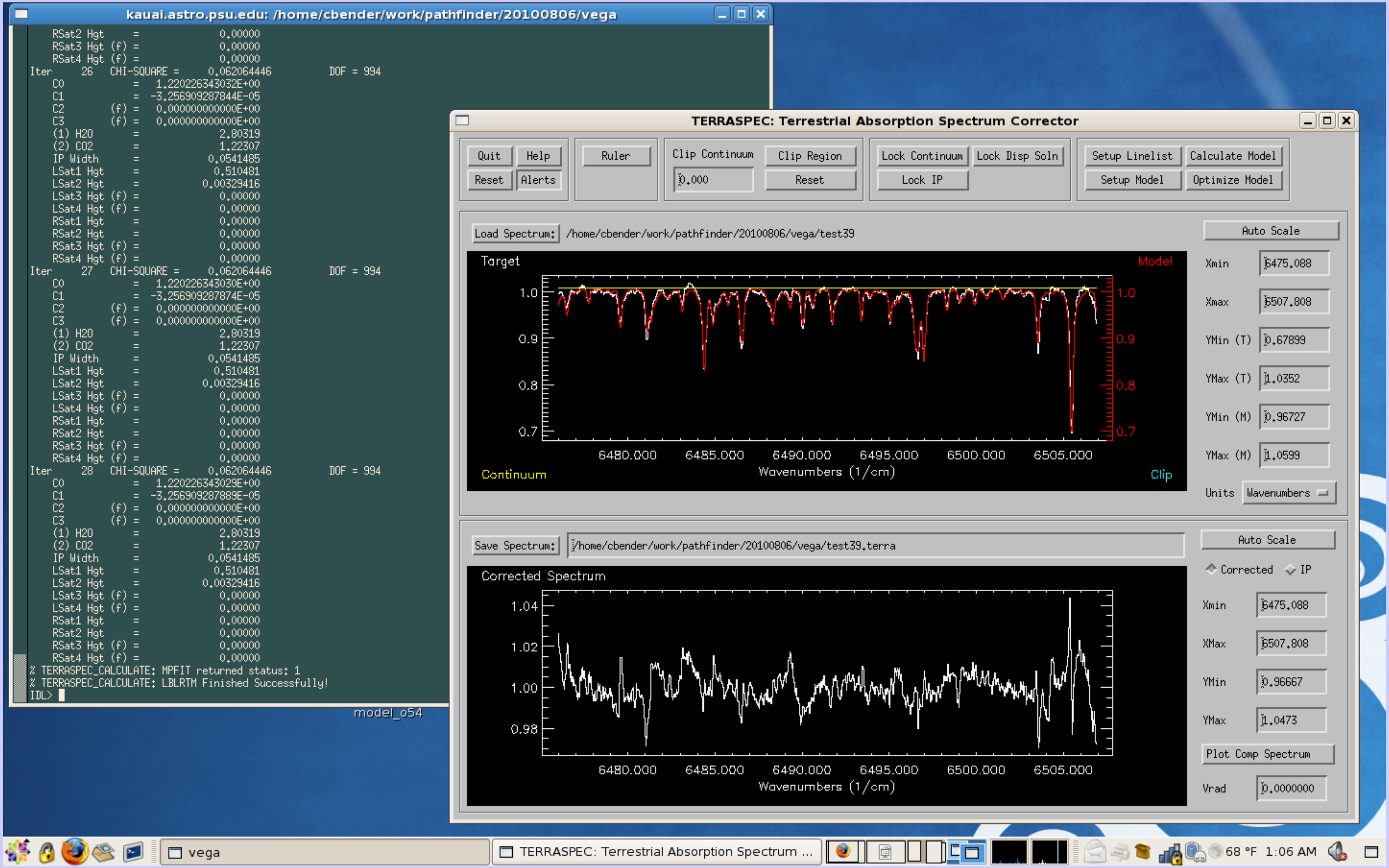
The TERRASPEC Algorithm
(Terrestrial Absorption Spectrum Corrector)

Observing hot stars is not practical because of H_2O variability & observing time constraints

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



The TERRASPEC IDL wrapper



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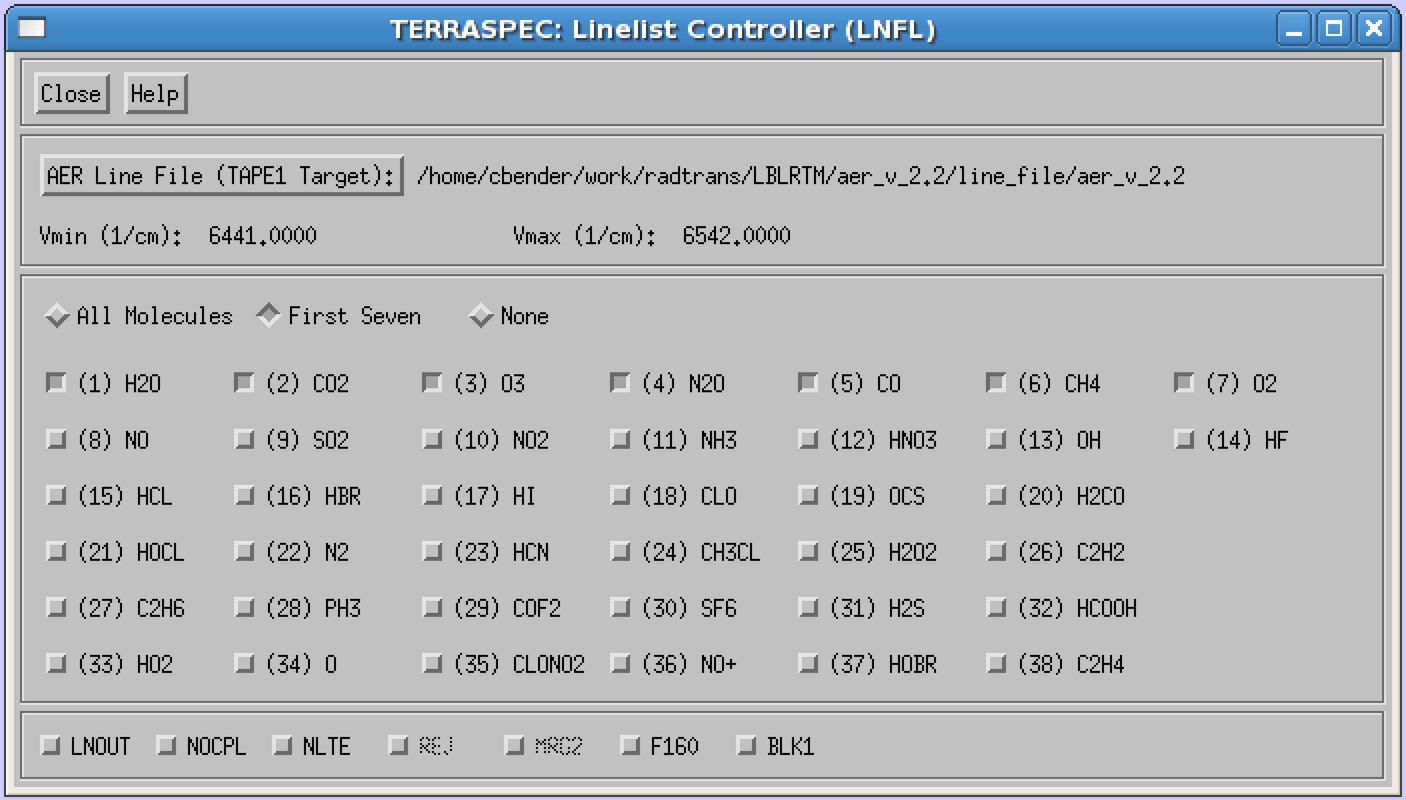
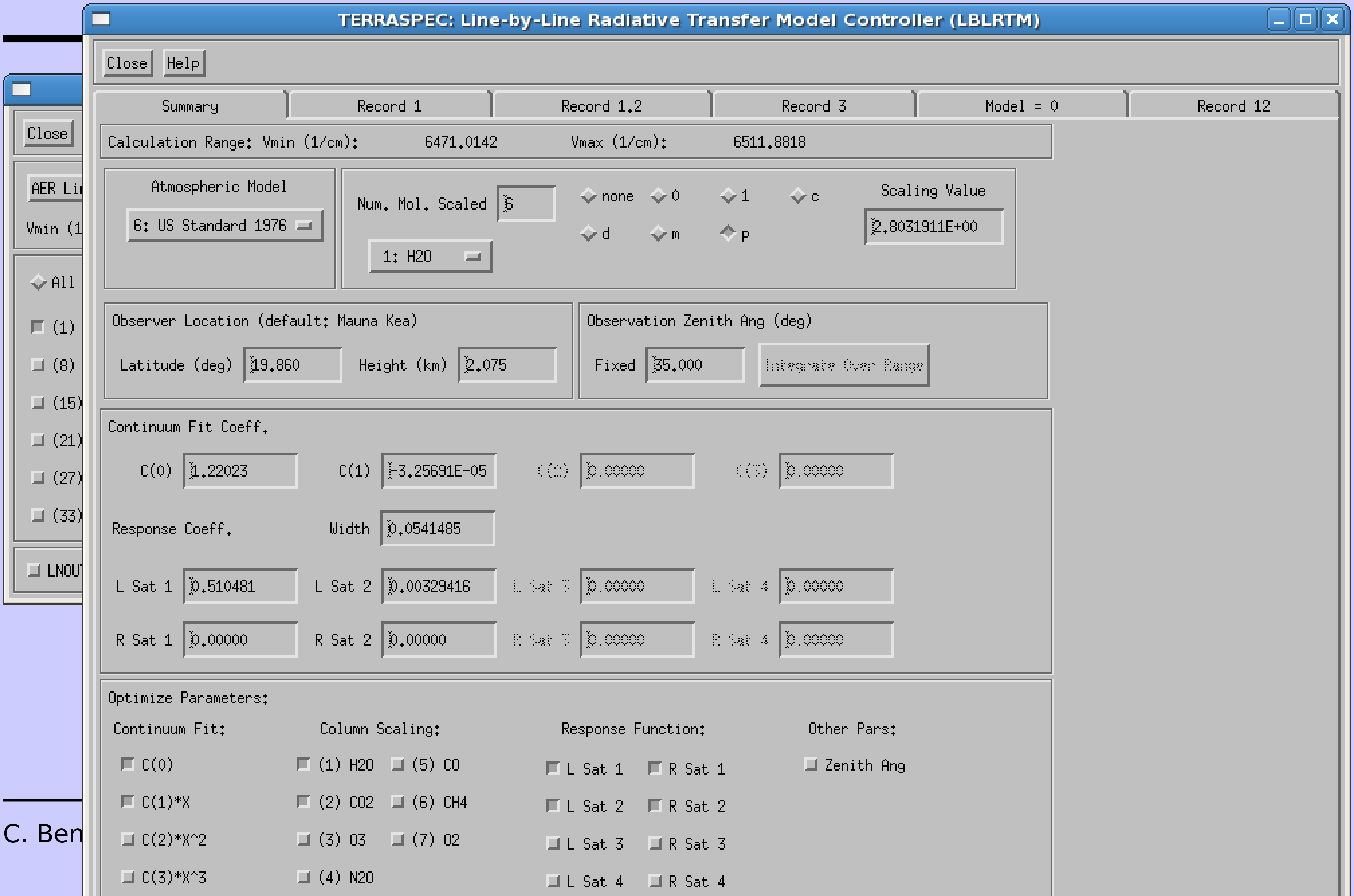


The TERRASPEC IDL wrapper



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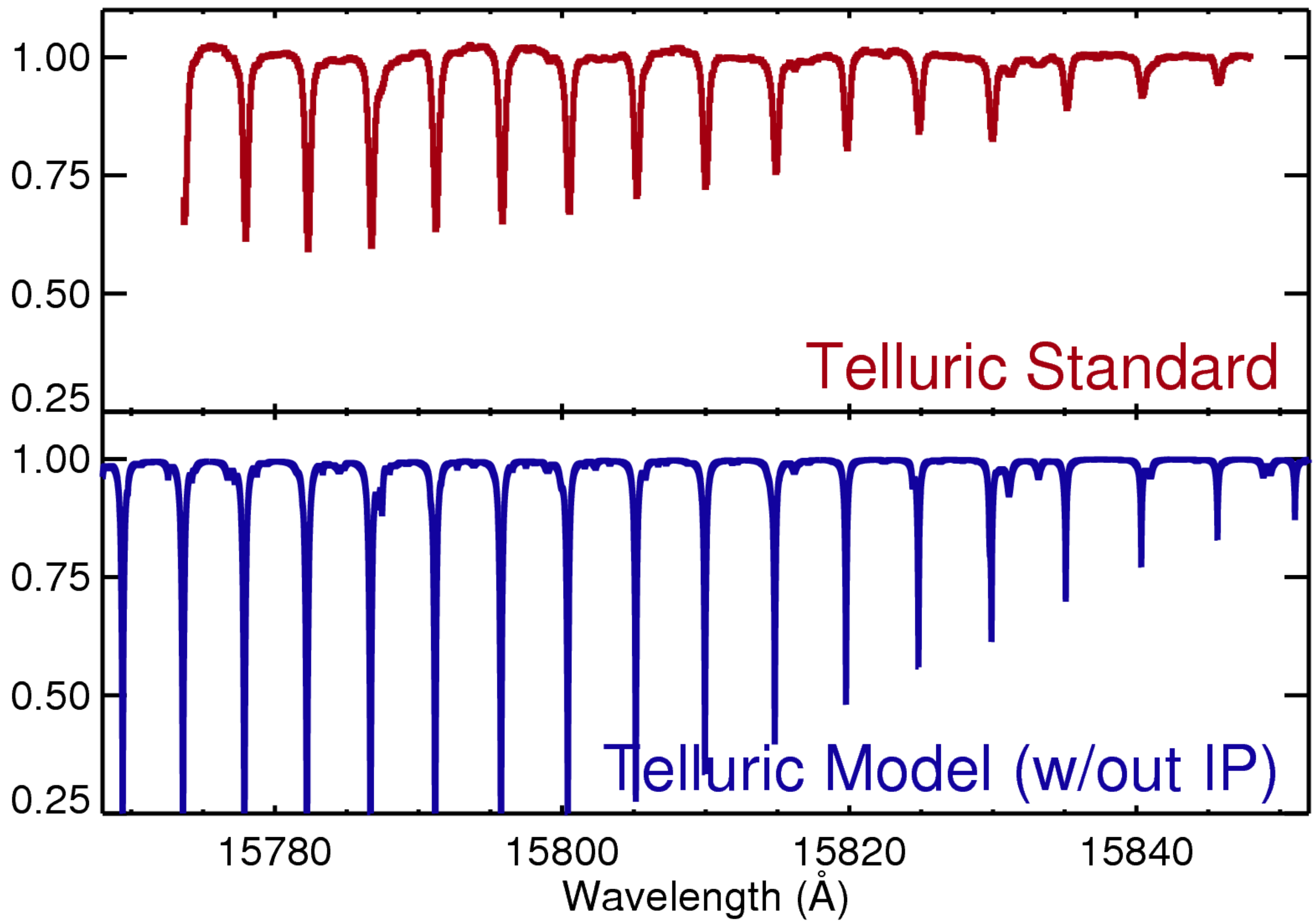
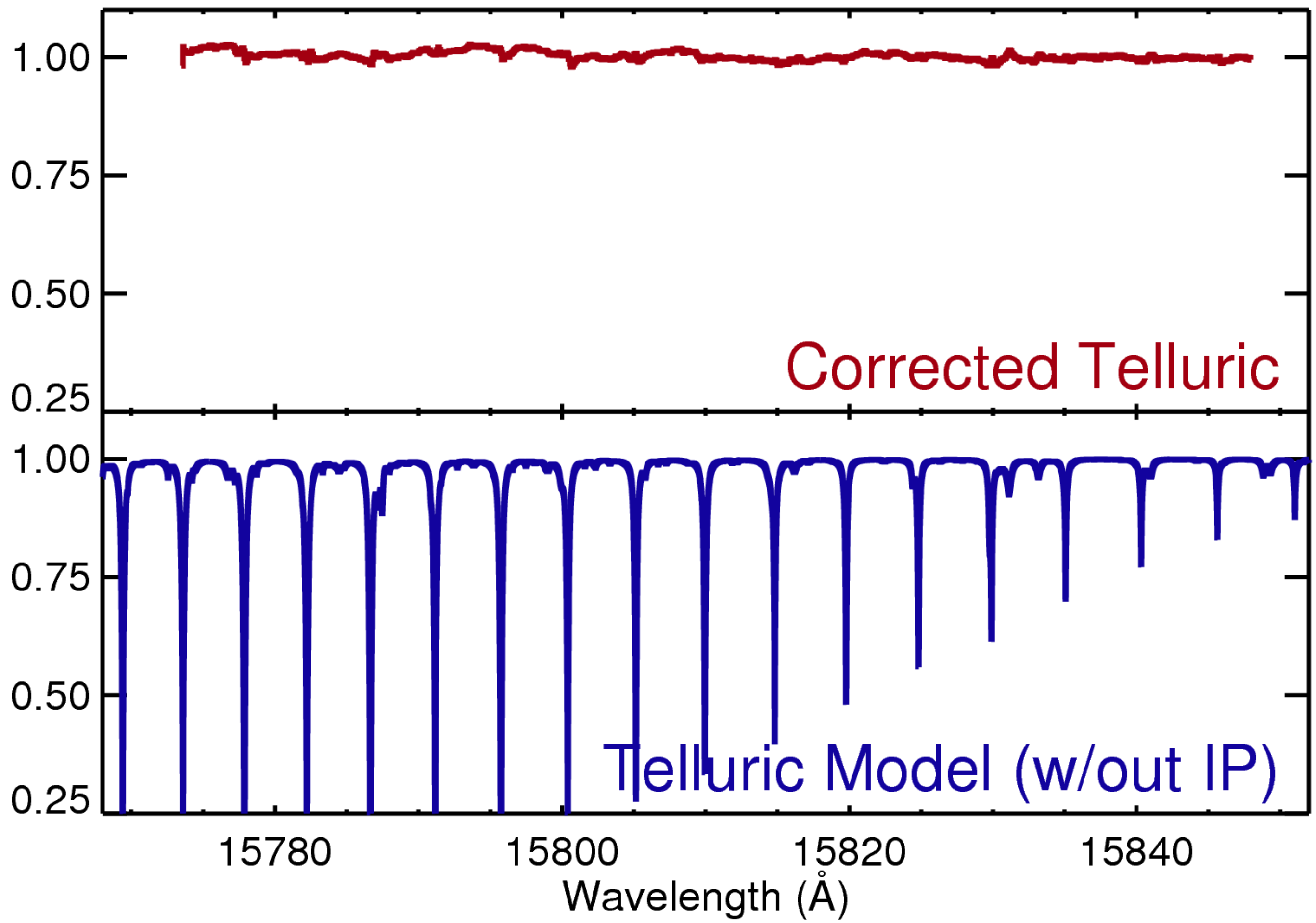
HET + PATHFINDER (H-band) Telluric Std:
(Brandon Botzer)

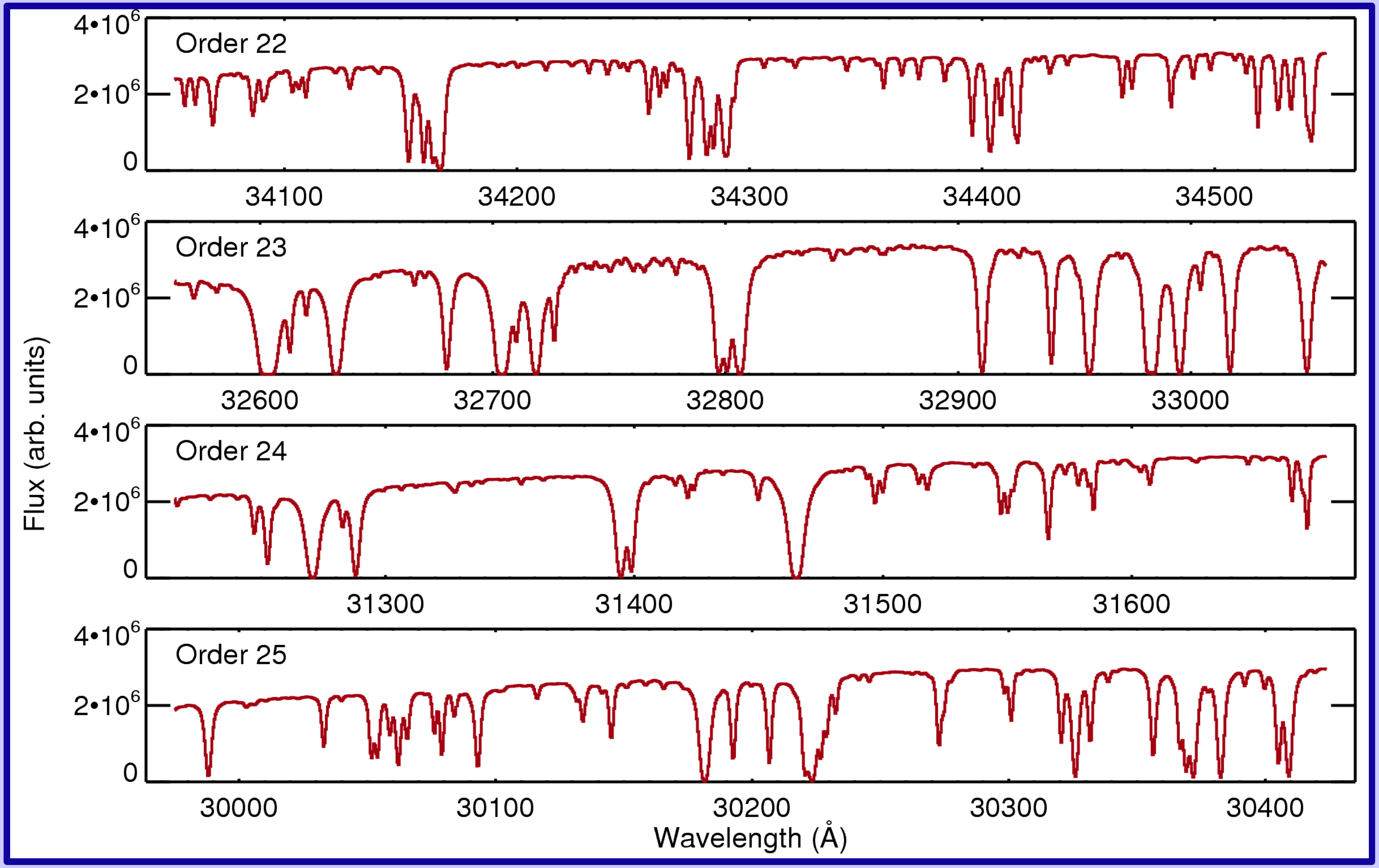


HET + PATHFINDER (H-band):
(Brandon Botzer)



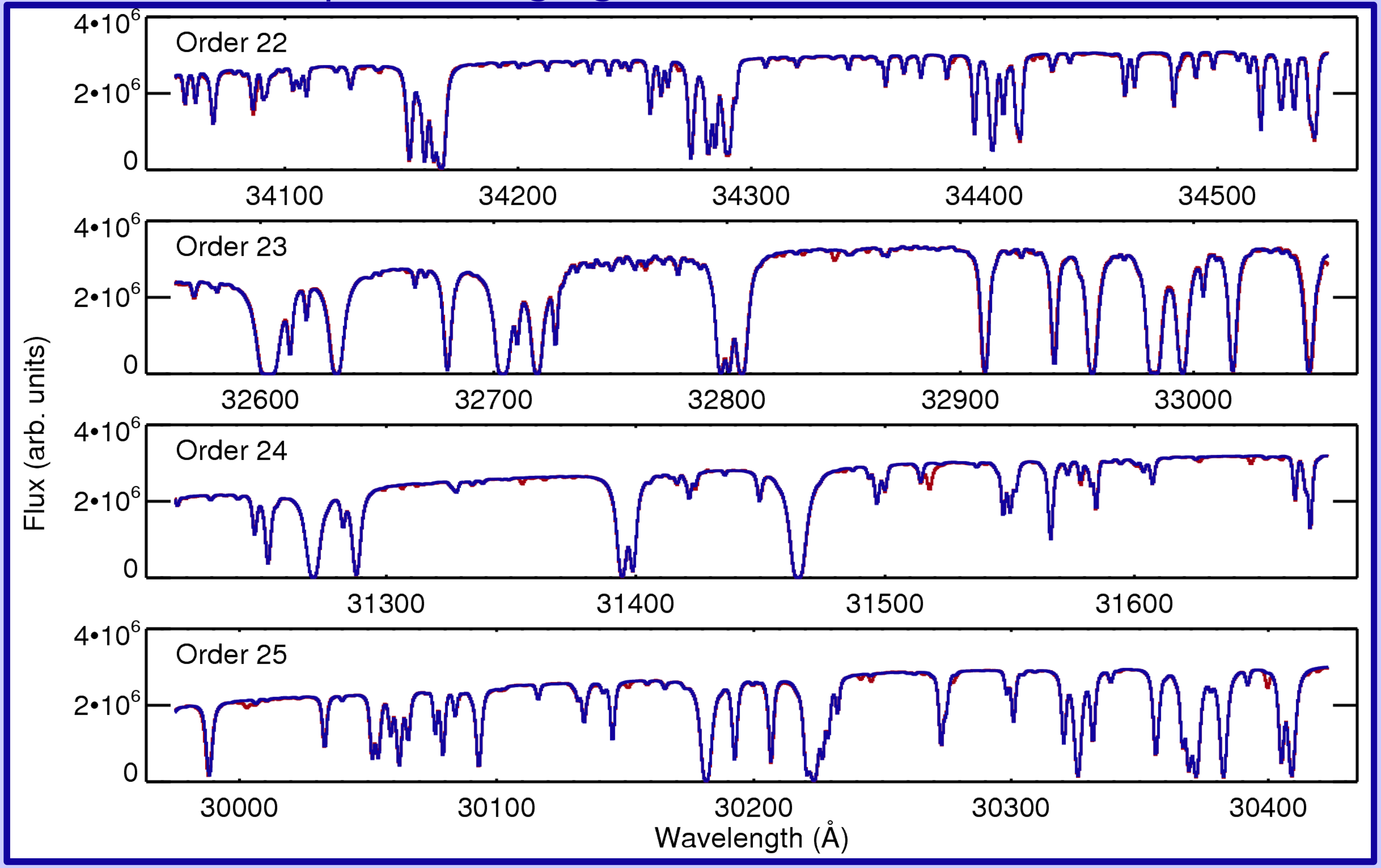
Keck + NIRSPEC @ L-band:
A worst case scenario (hopefully)

Observed Spectrum



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

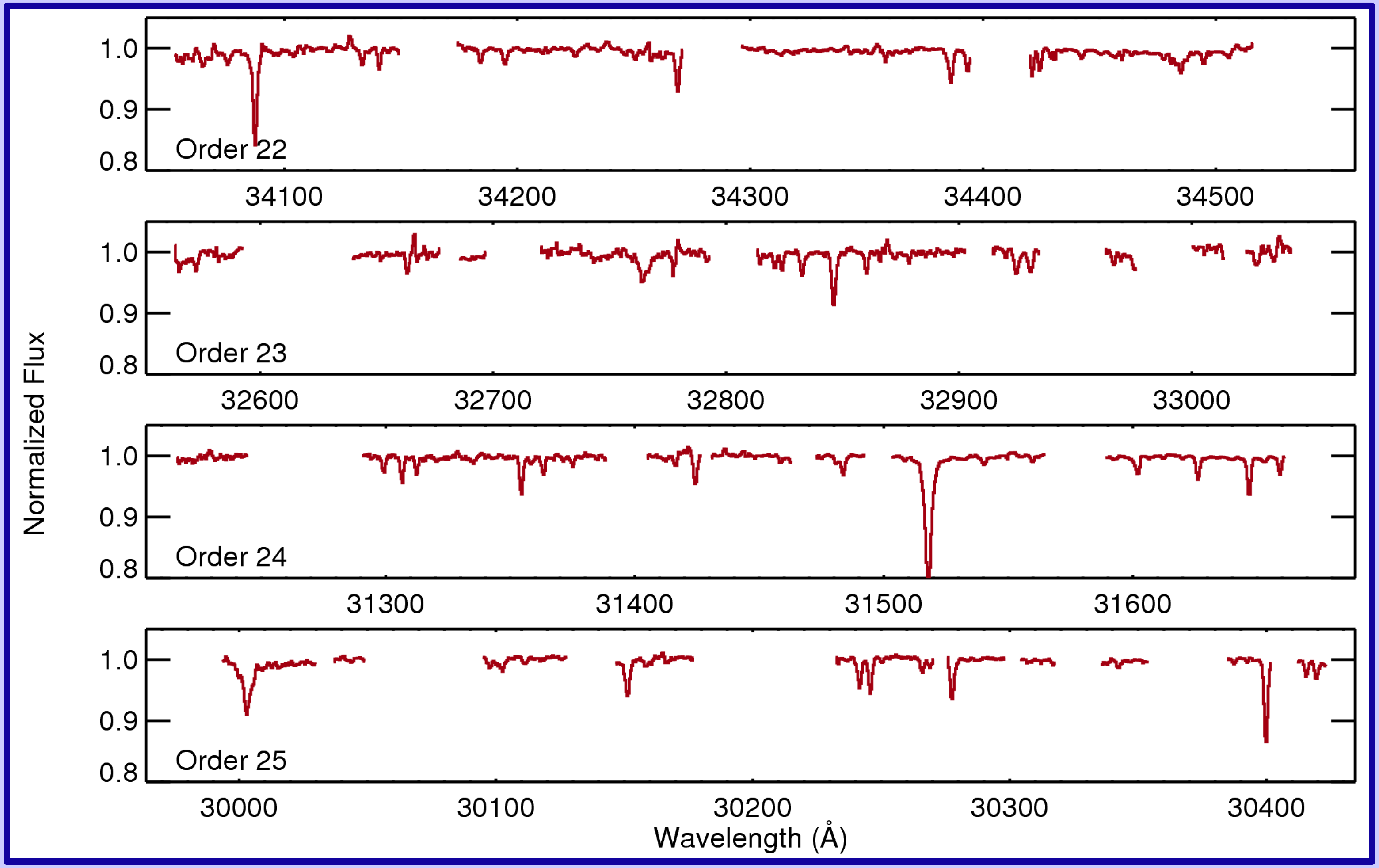
Observed Spectrum
Telluric Correction × Optical Fringing



Keck + NIRSPEC @ L-band:

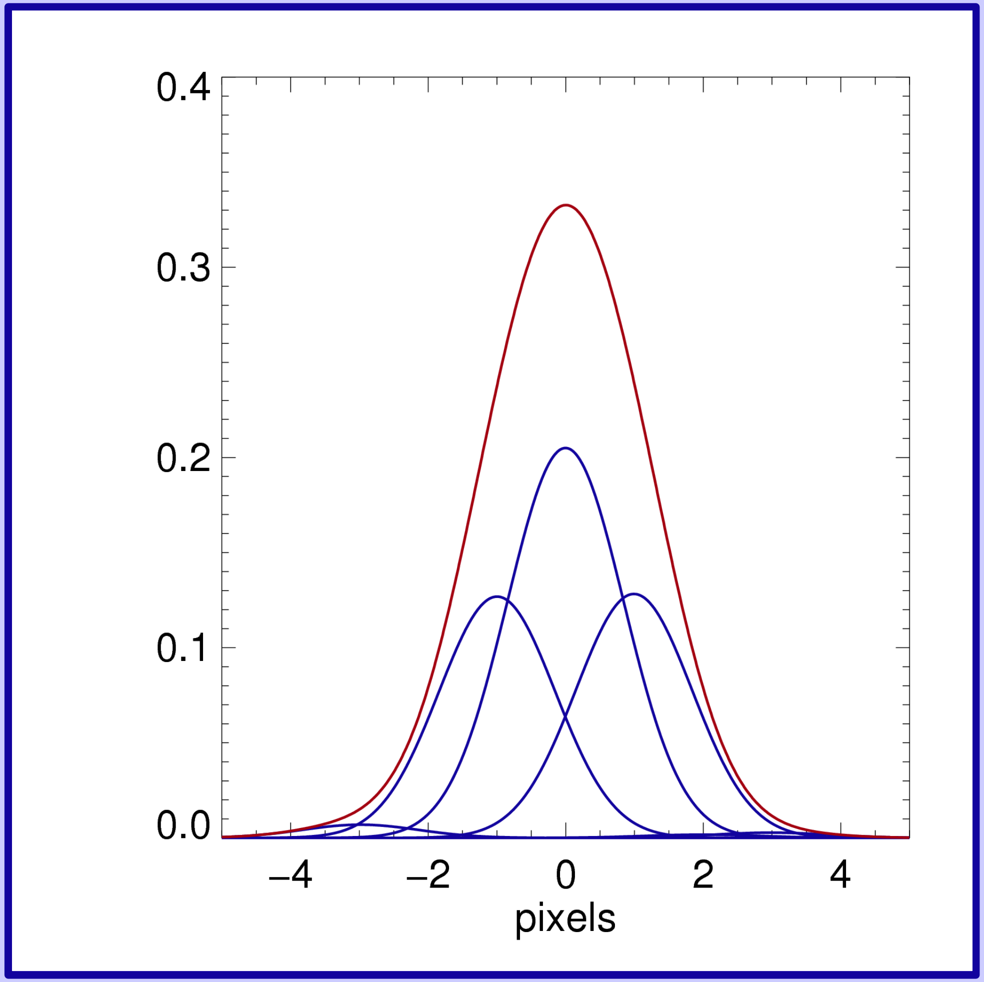
A worst case scenario (hopefully)

Observed Spectrum ÷ (Telluric Correction × Optical Fringing)

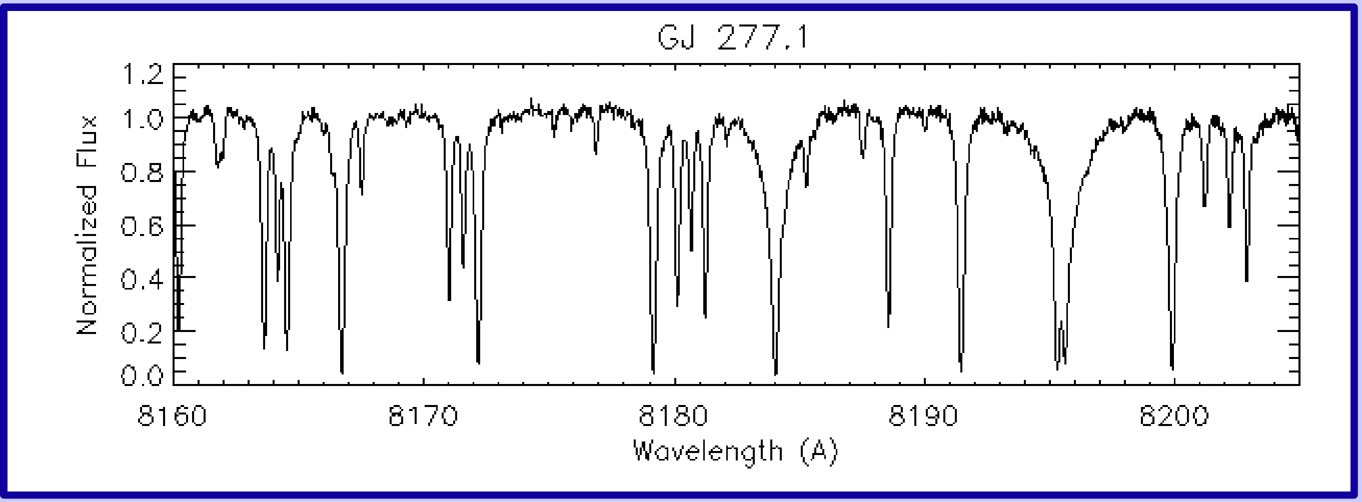


Keck + NIRSPEC @ L-band:
A worst case scenario (hopefully)

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



HET + HRS
@ R: (Sara Gettel)



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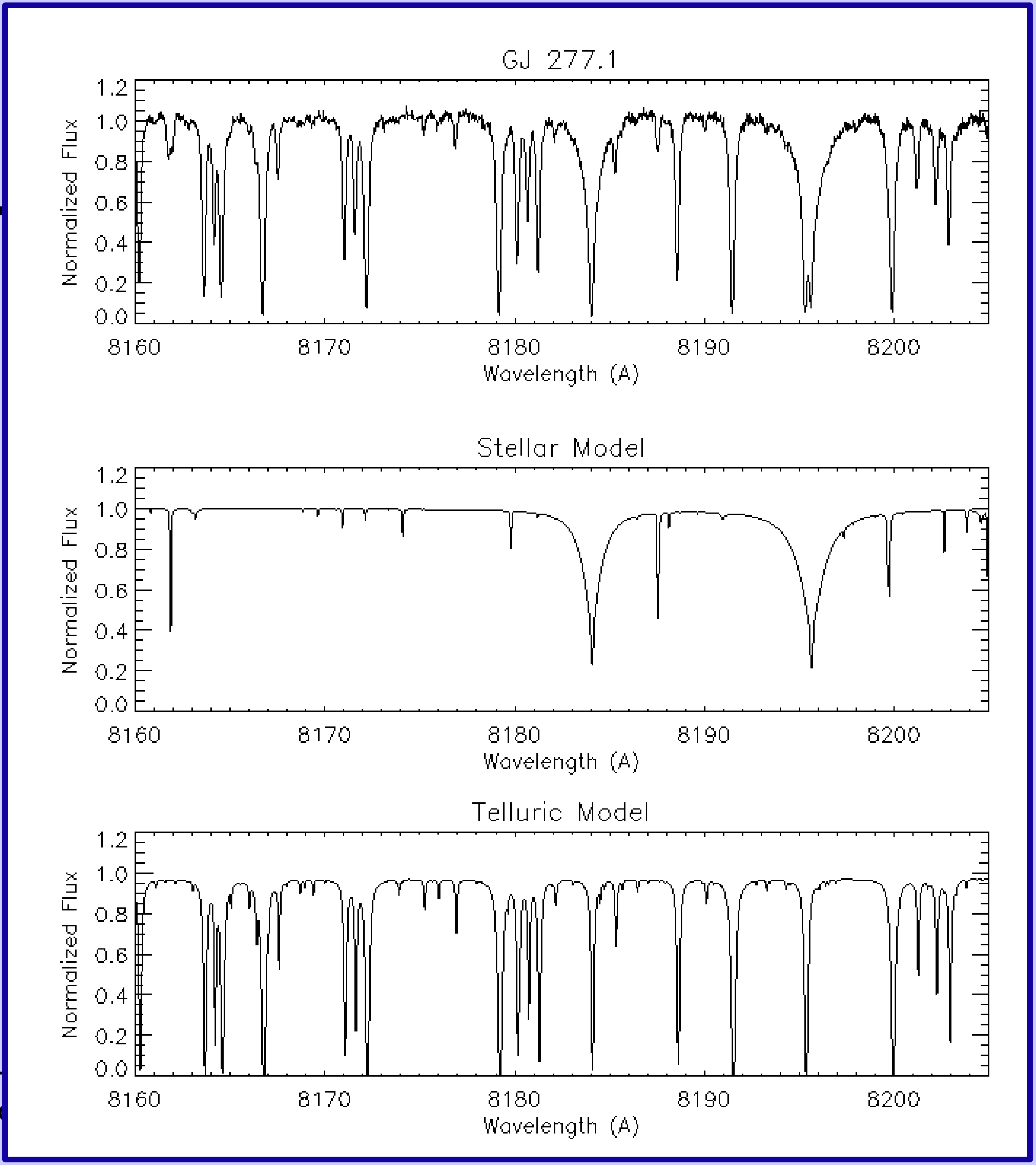
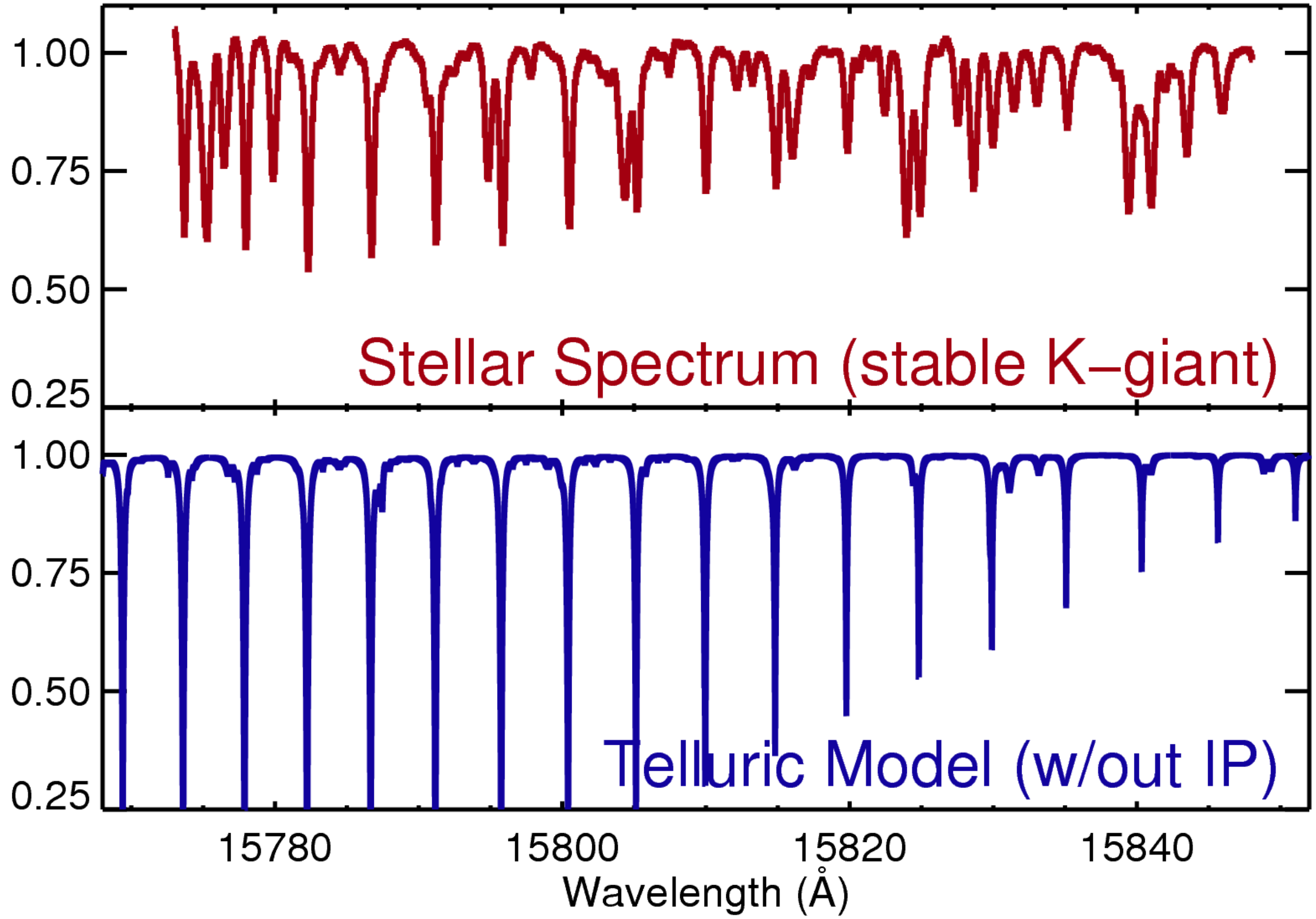


HET + PATHFINDER (H-band):
(Brandon Botzer)



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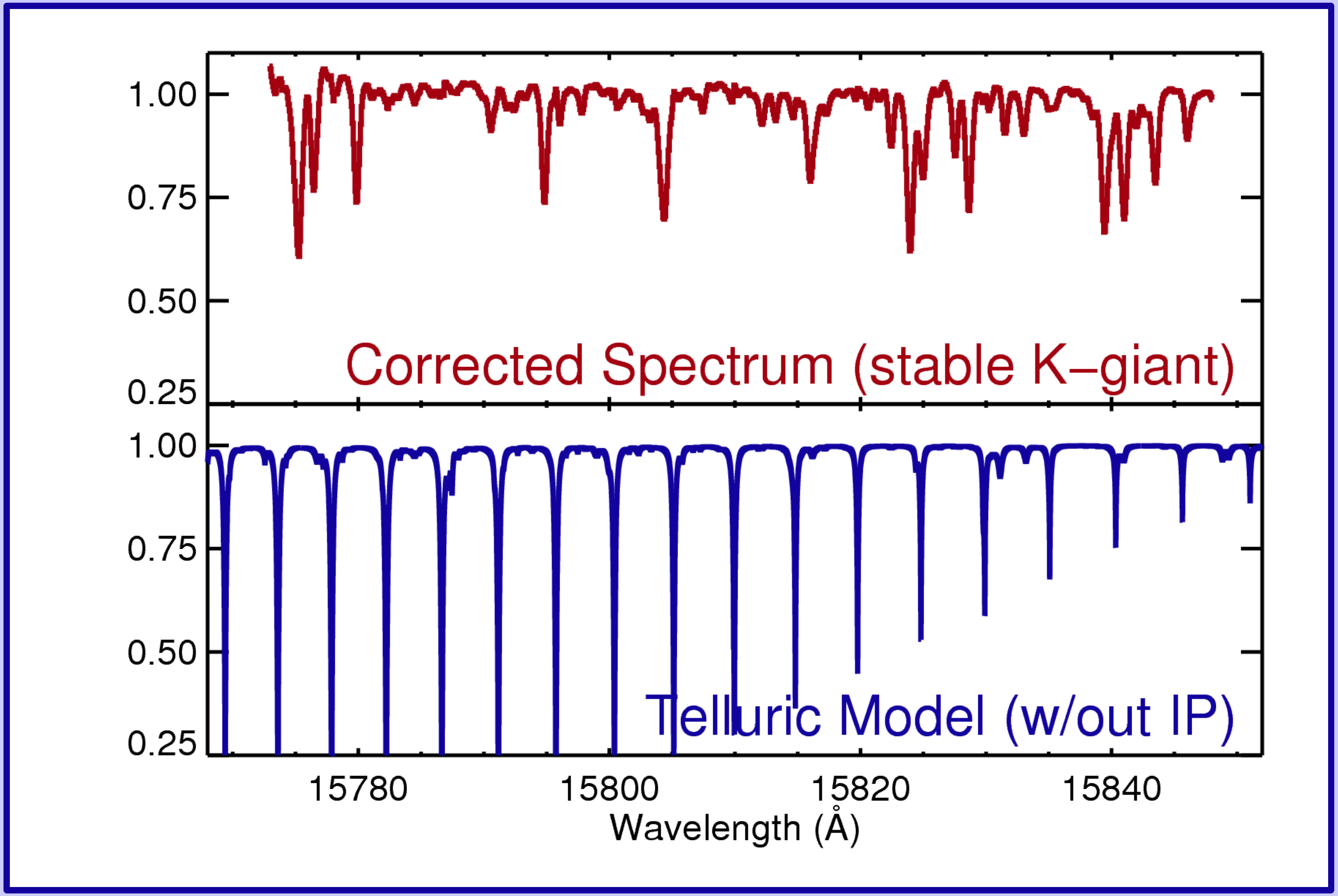

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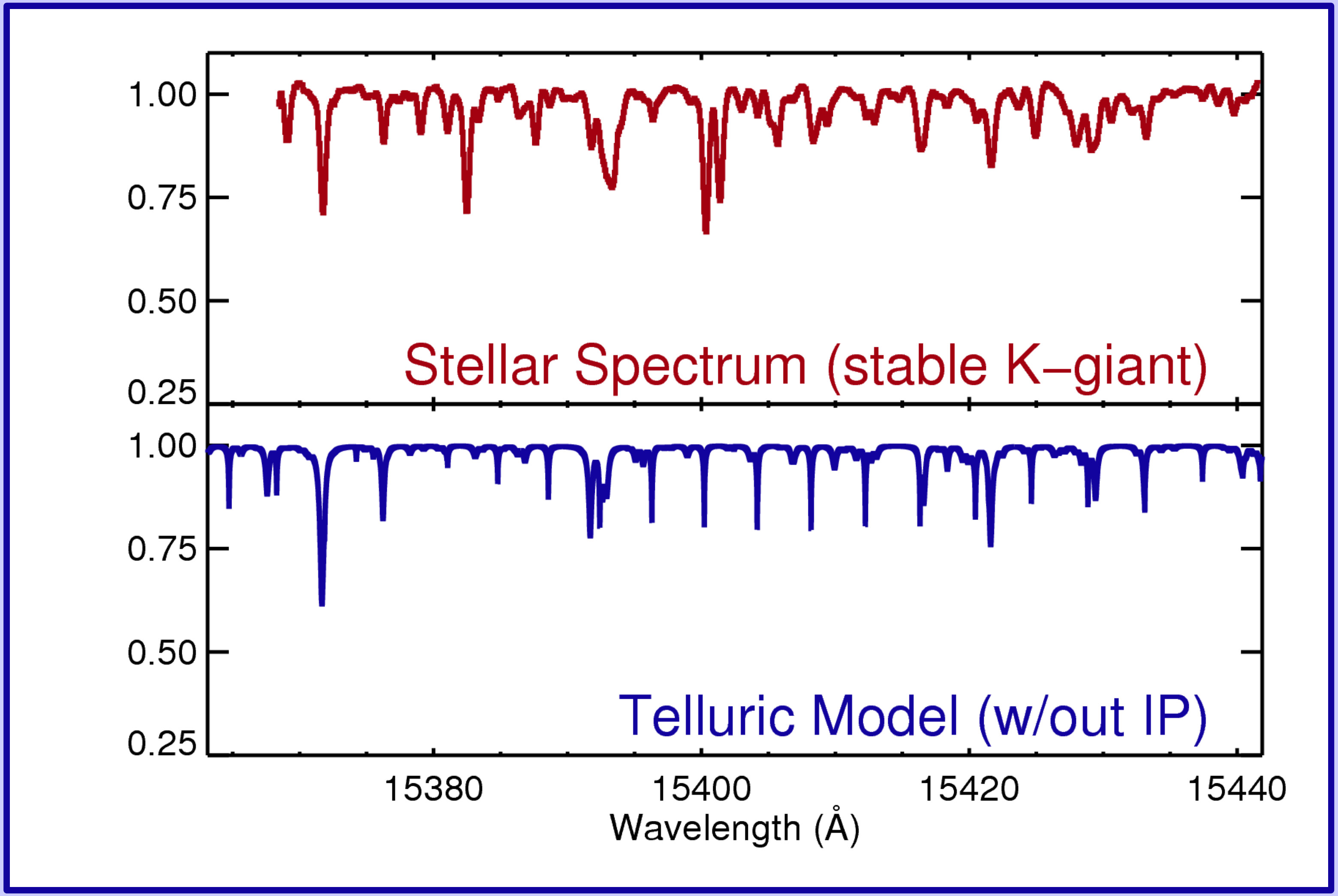

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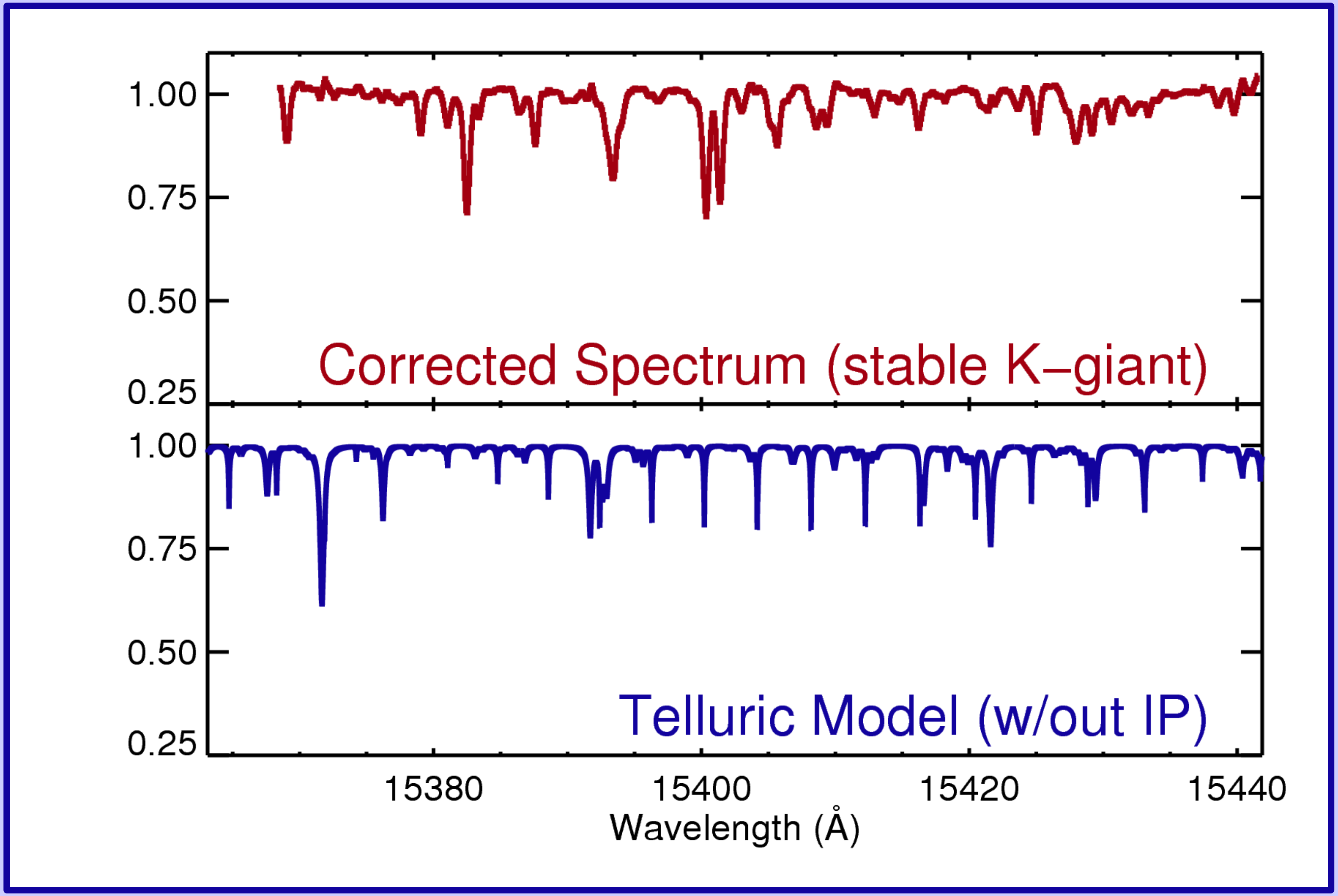

Some comments...

- 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