Etalons as ultra-precise wavelength calibrators

Dr. Christian Schwab
NASA Sagan Fellow, Penn State University
Radial velocities still not dead...
Powerful technique by itself and as part of the toolbox to detect and characterize exoplanets. Several ambitious projects underway.

→ Technical challenges in the search for earth-like planets:
  • *Expand wavelength coverage to the IR*
  • *Improve calibration to cm/s*
  • *Eliminate modal noise, stabilize the spectrum*
Wavelength calibration

- Simultaneously send star light and known spectrum through spectrograph
- Use known lines to find wavelength solution
Features of ideal calibrator

- Lines are uniformly spaced & cover entire spectrum
- All lines are equally bright
- Line spacing > spectrograph resolution
- Linewidth << spectrograph resolution
- Lines at known wavelengths determined by fundamental physics
- Wavelengths are stable over long timescales
- Easy to use/low maintenance
- Reasonably low cost
Calibration: ThAr lamp and Iodine cell
Calibration deluxe: LFC!
Calibration deluxe: LFC!

Menlo Systems LFC, 2015
Transmission peaks occur at

\[ 2nL \cos \theta = m\lambda \]
ThAr – etalon comparison
Features of ideal calibrator

• Lines are uniformly spaced & cover entire spectrum
• All lines are equally bright
• Line spacing > spectrograph resolution
• Linewidth << spectrograph resolution
• Lines at known wavelengths determined by fundamental physics
• Wavelengths are stable over long timescales
• Easy to use/low maintenance
• Reasonably low cost
Stabilizing the etalon spectrum

\[ 2nL \cos \theta = m\lambda \]

\[ \frac{\delta v}{c} = \frac{\delta v}{\nu} = \frac{\delta \lambda}{\lambda} = \frac{\delta x}{x} \]

\( n \) - pressure, temperature
\( L \) - temperature
\( \theta \) - alignment

\( x = n, L, \) or \( \cos \theta \)

3 cm/s RV precision
- Air-gap etalon with Zerodur spacer: 5 mK
- Fused silica fiber etalon: 14 \( \mu \)K
- Plane etalon: 8x10\(^{-4}\) deg alignment
- Fiber with f=100 mm collimating lens: 1.4 \( \mu \)m

HARPS calibration etalon

- Temp: 1-2 mK rms
- Press: 0.002 mbar
- 2 cm/s precision in 40 s exposure (7 cm/s with ThAr)
- <10 cm/s drift overnight
- <1 m/s over 60 days
- Recalibrate with ThAr lamp every night

A temperature stabilized single mode fiber fabry perot (FFP) device provides <1m/s stability over many days and relaxes constraints on the laser frequency comb; Halverson et al. 2014
Laser-locked etalon

Diagram showing a laser, an etalon, a photodiode, an Rb cell, and another photodiode. The diagram illustrates the path of light through these components. A graph shows the laser frequency with peaks and troughs.
Fiber Fabry-Perot & confocal etalon

External cavity diode laser
LLFP: Apparatus
Saturated absorption spectroscopy

Atom sees

\[ \nu'_{pump} = \nu_L \left(1 + \frac{v_z}{c}\right) \]
\[ \nu'_{probe} = \nu_L \left(1 - \frac{v_z}{c}\right) \]

Pump is resonant for atoms with velocity

\[ v_{z,0} = c\left(\frac{\nu_0}{\nu_L} - 1\right) \]
Saturated absorption of rubidium

Rb properties and transition frequencies: [http://steck.us/alkalidata](http://steck.us/alkalidata)

Rubidium D$_2$ transition

519 MHz
Software lock and control GUI
Thermal response: fiber etalon

\[ \Delta T = 0.1435 \text{ K} \]

Tuning rate: 2.09 MHz/mK

375 m/s
Locking stability: fiber etalon

Confocal FP, PZT actuator (FAST!)

Fiber FP, thermally controlled (SLOW!)
Summary

• Wavelength calibration is crucial for Doppler programs sensitive to Earth-like planets
• Reliable and affordable emission line source with 3cm/s stability and wide wavelength coverage is enabling technology for the significant RV capacity we need to follow up ambitious space-based transit surveys
• Laser-locked etalon is a near ideal calibrator based on well-understood technique and anchored to a ultra-stable Rubidium frequency reference.
Thanks!