Laser Frequency Combs for Precision Radial Velocity Measurements in Astrophysics

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A collaboration between astronomers (CfA), physicists (CfA) and electrical engineers (MIT)
~15 scientists
“Astro-Comb”

- Precision spectroscopy essential for advances in astrophysics
- Currently limited by spectrograph wavelength calibration
- Laser frequency combs can solve calibration problem
- Rapid progress in last 3 years:
  - concept => lab demo => operation at observatories
- **Coming soon**: discovery & characterization of Earth-like planets
- **10-20 years**: direct measurement of cosmological dynamics

**Diddams et al., Nature 445, 627 (2007).**
**Murphy et al., MNRAS 380, 839 (2007).**
Unique Opportunity

Origins of Life in the Universe

Over the next decade, we will:

• Discover the first Earth-like planets around other stars
• Search these planets for chemical signatures of life
• Image planets directly

Is the Earth special, or just another planet?

=> Complete Copernican revolution?

http://origins.harvard.edu/
Extrasolar Planets

> 400 exoplanets found to date
- Primarily hot Jupiters
- “Super Earths” now being found
- Soon, earth-like planets

Super Earths

- Jupiter mass planets close to their stars

Habitable zone

(D. Sasselov, Nature 451, 29 2008)
Transit Method

Kepler satellite has hundreds of exoplanet candidate systems. Need confirmation!

http://www.kepler.arc.nasa.gov/


HD 189733B
Hot Jupiter
63 light-years away
Mass = 1.13 M_J
Radius = 1.14 R_J
T=1000 K
P = 2.2 days

Spitzer space telescope at 8 µm
Radial Velocity Method

- Heavier planet causes larger Doppler shift in star light
- Gives planet mass and orbital period & radius, not size
- Doppler-shift from Earth-mass planet is VERY SMALL

Doppler shift:
\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta \text{RV}}{c} \]

<table>
<thead>
<tr>
<th>(\Delta \lambda)</th>
<th>(\Delta \text{RV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-7}) Å</td>
<td>1 cm/s</td>
</tr>
<tr>
<td>(10^{-6}) Å</td>
<td>10 cm/s</td>
</tr>
<tr>
<td>(10^{-5}) Å</td>
<td>1 m/s</td>
</tr>
<tr>
<td>0.01 Å</td>
<td>1 km/s</td>
</tr>
</tbody>
</table>

Stellar velocity due to planetary pull
\[ K_{\text{RV}} = 28.4 \left( \frac{P}{1 \text{ year}} \right)^{-1/3} \left( \frac{M_P \sin i}{M_J} \right) \left( \frac{M_*}{M_\odot} \right)^{-2/3} \text{ m/s} \]

Earth-mass planet around Sun-like star
Pre-comb sensitivity
"Hot Jupiter"

\[ v = 1 \text{ km/s}\]
\[ v = 1 \text{ GHz}\]
\[ \lambda = 2 \times 10^{-3} \text{ nm}\]
\[ x = 1 \text{ pixel} = 20 \mu\text{m}\]
Stellar Spectrum

100,000 absorption lines
few GHz linewidths
Spectrograph

Small frequency shifts => Use echelle spectrograph
=> broad spectral coverage & high-resolution

Slit is often a multimode fiber, allowing the spectrograph to reside in an environmentally controlled room, away from the telescope.

\[ v = 1 \text{ km/s} \]
\[ \nu = 1 \text{ GHz} \]
\[ \lambda = 2 \times 10^{-3} \text{ nm} \]
\[ x = 1 \text{ pixel} = 20 \mu\text{m} \]

http://www.eso.org/sci/facilities/lasilla/instruments/harps/index.html
Spectrograph

Small frequency shifts $\Rightarrow$ Use echelle spectrograph $\Rightarrow$ broad spectral coverage & high-resolution

State-of-the-art astrophysical spectroscopy is broadband, photon-starved
$\Rightarrow$ spectrograph resolution $R = \frac{\lambda}{\Delta \lambda} \sim 100,000$
$\Rightarrow$ minimum resolution element $\Delta \nu > 5$ GHz

$\nu = 1$ km/s
$\nu = 1$ GHz
$\lambda = 2 \times 10^{-3}$ nm
$x = 1$ pixel $= 20$ µm

http://www.eso.org/sci/facilities/lasilla/instruments/harps/index.html
Octave-Spanning Comb

**Octave-spanning comb** => atomic clock accuracy & stability for all comb lines

\[ \tau_{\text{pulse}} < 4 \text{ fs} \]

- 10⁵ comb lines
- narrow lines (<kHz)
- coherent
- equally-spaced
- intense (10 \( \mu \text{W/line} \))

We use Ti:Sapphire laser
Cr:Forsterite lasers and fiber lasers also used.

Broadband gain, Kerr effect => octave spanning
Kerr-lens mode-locking => stabilize pulsing
Cavity sets \( T_{\text{rep}} \sim 1 \text{ GHz} \)
Double-chirped mirror pairs => compensate broadband dispersion

RF beat frequencies =>
lock \( \omega_r \) & \( \omega_{CE} \)
to atomic clock

Filter out most comb lines with a stabilized Fabry-Perot Cavity to yield line-spacing up to ~40 GHz

Astro-Comb

Octave-spanning 1-GHz laser frequency comb

Diode laser

EOM

λ/2

Fabry-Perot cavity

PZT

Astro-comb beam

Phase lock box

Synthesizer

Photo-detector

PID lock box

Synthesizer

Photo-detector
Astro-Comb

FSR = m × f_{rep}
Astro-comb tested using a 1.5 m telescope with high-resolution echelle spectrograph (TRES)
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Calibration Spectrum

TRES spectrograph on 1.5 m Tillinghast reflector at Mt. Hopkins
2 dimensional spectrum on spectrograph CCD
Red Astro-Comb

• 100 nm bandwidth.
• 32 GHz spacing.
• 10 GHz FWHM on spectrograph.
• 100 nW per line.
• 25000-40000 counts in 5 minutes through integrating sphere.
Red Astro-Comb SNR

\[ \delta \nu = A \frac{\text{FWHM}}{S/N \times \sqrt{n}} \]

\( A \approx 0.7 \)

\( \text{FWHM} \approx 10 \text{ GHz} \)

\( (S/N)_{300 \text{ s}} \approx 200 \)

\( (S/N)_{\text{max}} \approx 300 \)

\( n \approx 6 \text{ pixels} \)

\( \Delta \nu \approx 15 \text{ MHz or } 15 \text{ m/s for one peak} \)

250 peaks/order: \( \Delta \nu \approx 1 \text{ MHz in one order} \)
**Fit Model**

**Comb**
- $\Delta \nu = 1$ GHz $S \cdot \delta I / I$
- $S = \text{side mode suppression}$
- $\Delta \nu = 3$ MHz $\cdot \delta I / I$
- Negligible at the 1 m/s level

**Fiber**
- 100 µm fiber
- Modeled as flat top in 2D
- Half circle in 1D
- Add skew

**Optics**
- Modeled as Hermite-Gaussians
- Up to 16 terms

**CCD**
- Model as flat
- Tails from charge diffusion don’t appear to help

**One order of comb lines superimposed**

**Residuals of fit**
- Near shot noise floor
• Calculate wavelength calibration order by order.
• Compare calibration to reference frame.
• Calculate deviation of all orders from mean drift.
Blue Astro-Comb

- 1 GHz Ti:Sapphire source laser
- BBO doubling crystal
  - 50 nm bandwidth
- Fabry-Perot Cavity:
  - Bragg Mirror Stack
  - Bandwidth limited by air dispersion to ~15 nm
- Improved flux to spectrograph
- Phase scrambling

A. Benedick, Optics Express, 18, 19175-19184 (2010).
Blue Astro-Comb

One order of comb lines superimposed

Residuals of fit

faster data rate

50 cm/s resolution

Much closer to shot noise!

420 nm with less fringing.

Fiber shaking active.
Green Astro-Comb

Octave-spanning 1-GHz laser frequency comb
Diode laser → EOM → λ/2

Synthesizer → Phase lock box → Photo-detector

Fabry-Perot cavity
PZT

Astro-comb beam
Photo-detector

Photonic Crystal Fiber (PCF)
High nonlinear coefficient
Zero-dispersion wavelength ~700 nm
Four-wave mixing
Near Gaussian mode profile

FP Cavity
Complementary-Chirped Mirror Pair
Green Astro-Comb

- 45 GHz green astro-comb
- Various Ti:Sapphire settings
- Astro-comb lines not resolved on OSA
- Lab demo. Next, test at telescope

- 240 GHz green astro-comb
- demo for low-resolution OSA
- Side suppression minimal
What’s Next?

- Observe Earth candidates found by *Kepler*
- Use Doppler-shift method to distinguish new Earths from exotics

Harvard, Smithsonian, Geneva Observatory

HARPS clone for northern hemisphere

Astro-comb calibrator $\Rightarrow$ $\Delta RV < 10$ cm/s

William Herschel telescope, Canary Islands, 4.2 meter mirror