Astro-comb : Extremely Accurate "Ruler of Light"

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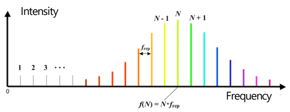
1. Introduction

What is "Astro-comb"?

A laser light source with a comb-shaped frequency spectrum with many evenly spaced emission lines

- Absolutely stable wavelength standard
- Can cover a wide wavelength range
- Has enough emission lines



Spectrum of astro-comb

Astro-comb makes it possible to calibrate spectrograph with ~cm accuracy

2. Applications of Astro-comb

Application to Exoplanet Exploration

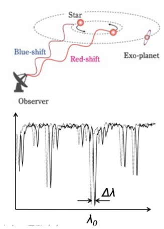
Astro-comb will enable the discovery of **Earth-sized exoplanets** by measuring the radial velocity of stars with extreme precision

Radial Velocity Method

A method to measure the Doppler shift of absorption lines in a star's atmosphere and detect changes in the radial velocity of a planet-bearing star

✓ Detecting Earth-sized planets requires measurements with a precision of **~cm/s**

(The amplitude of the change in the radial velocity of the Sun due to the Earth is **~10 cm/s**)



Conceptual diagram of radial velocity method

Radial Velocity Determination Accuracy

- **Statistical Error**

  Errors depending on photon yield, spectral shape, and the number of emission lines measured

- **Systematic Error**

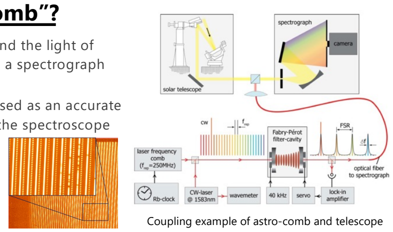
  Errors caused by deformation of the spectrograph due to temperature changes, expansion of the detector, etc.

✓ When measuring radial velocity over a wide wavelength range, the influence of **systematic errors** in the spectrograph becomes large

How to Use "Astro-comb"?

Measure the light from the star and the light of astro-comb **simultaneously** with a spectrograph

The light of astro-comb can be used as an accurate "**wavelength ruler**" to calibrate the spectroscope

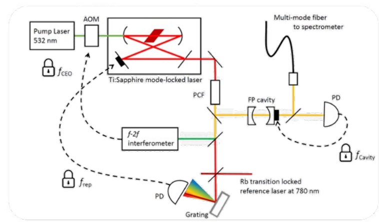


Coupling example of astro-comb and telescope

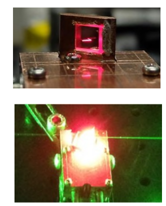
3. Example of Astro-comb

Ti:Sapphire Astro-comb

- One of the major types of astro-comb
- Titanium sapphire crystal is used as the laser medium
- A laser is oscillated in a resonator to create light that becomes "comb"



Conceptual diagram of Ti:S astro-comb



Titanium sapphire crystal

Mode-locked Laser

- Inside the resonator, there are various frequencies of light that satisfy the resonance conditions
- The phase between the light of each frequency (called longitudinal mode) is random, but fixing the phase relationship between these modes is called **mode locking**
- A mode-locked laser generates a **pulse wave** by periodically matching the phases of the longitudinal modes and interfering with each other.

$$E(t) = \sum_{n=-N}^{N} E_n \exp[i(\omega_n t + \phi_n)]$$

Sum of 2N+1 longitudinal modes

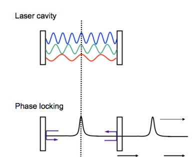
$$\omega_n = \omega_0 + n\Delta\omega, \quad \phi_{n+1} - \phi_n = \Delta\phi$$

Fixing the phase relationship between mode

$$E(t) = E_0 \frac{\sin[(2N+1)(\Delta\omega t + \Delta\phi)/2]}{\sin[(\Delta\omega t + \Delta\phi)/2]} \exp(i\omega_0 t)$$

$$I(t) = I_0 \frac{\sin^2[(2N+1)(\Delta\omega t + \Delta\phi)/2]}{\sin^2[(\Delta\omega t + \Delta\phi)/2]}$$

Pulse wave is generated



Concept of mode locking

Optical Frequency Comb

Fourier transform a pulse train with equal intervals on the time axis

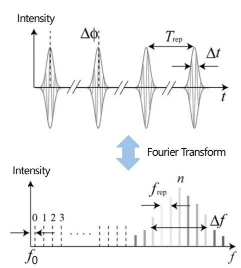
A longitudinal mode train with equal intervals on the frequency axis is obtained

$$f_n = n \cdot f_{rep} + f_0$$

f_{rep} : Repetition Rate

f_0 : Offset Frequency

(Originates from the difference between the phase velocity and group velocity of the pulse)



Schematic diagram of the spectrum of optical frequency comb

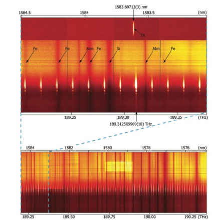
✓ Frequency of an optical frequency comb can be precisely controlled using **only two parameters**

4. Past and Future of Astro-comb

First Astro-comb

Steinmetz+, 08

- First use of an astro-comb as a calibration light source for an observatory spectrograph
- Erbium fiber optical frequency comb was used
- Calibration of the spectrograph (resolution 0.8Hz) of the Vacuum Tower Telescope in Germany around 1560nm
- The calibration accuracy using 60 emission lines was 9 m/s

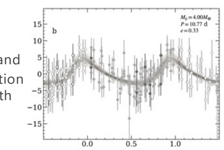


✓ This study shows that astro-comb can be used to calibrate spectrograph with greater precision than conventional methods

Observation Example Using Astro-comb

IRD-SSP Survey

- IRD-SSP survey measured the radial velocity of the M-type star Ross 508 using the astr0-comb
- By simultaneously acquiring the light from the star and astro-comb, the deformation of the spectral absorption contour caused by the instrument was estimated with high precision, and the Doppler shift of the stellar spectrum was precisely measured.
- Precise measurements of the radial velocity of Ross 508 lead to the **discovery of the super-Earth Ross 508 b**



RV of Ross 508

Current Problems of Astro-comb

1. Bandwidth is not wide enough

- ➢ When using astro-comb, external resonator is required to thin out the comb light according to the resolution of the spectrograph
- ➢ Bandwidth of astro-comb is limited by the performance of external resonator.

➡ Development of an astro-comb that does not require an external resonator is underway

2. Difficult to operate stably for a long period of time

- ➢ The repetition rate and offset frequency must be kept stably locked in a long period of time
- ➢ The effects of external environmental fluctuations such as temperature and air pressure also need to be controlled

➡ Efforts are being made to remotely control f_{rep} and f_0, automate the alignment of the optical system, etc.

5. References

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