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Femtosecond Laser Frequency Comb for Precision Astrophysical Spectroscopy

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Abstract: High-resolution spectroscopy is a crucial tool for cosmology and the search for extrasolar planets. We present a laser comb with up to 40-GHz line spacing for use as a new spectrographic calibration source.

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Spectroscopy is crucial to the defining fields of 21st century astrophysics: cosmology and the search for extrasolar planets. Searches for extrasolar planets using the periodic Doppler shift of stellar spectral lines resulting from the motion of the host star around the barycenter of an exo-solar system, have recently achieved a precision of 60 cm/s [1], sufficient to find a 5-Earth-mass planet in a Mercury-like orbit around a Sun-like star. The earth produces a 5 cm/s variation in the sun's motion. Wavelength calibration sources currently limit spectroscopic precision [2, 3]. The combination of a laser frequency comb with a Fabry-Perot filtering cavity has been suggested as a promising approach to improved sensitivity [4–7]. We report the fabrication and tests of a filtered comb with up to 40-GHz ($\sim 1 \text{ \AA}$) line spacing, generated from a 1-GHz repetition-rate source, without compromising long-term stability or reproducibility. This “astro-comb” is well matched to the resolving power of high-resolution astrophysical spectrographs. The astro-comb should allow a precision as high as 1 cm/s in astronomical radial velocity measurements.

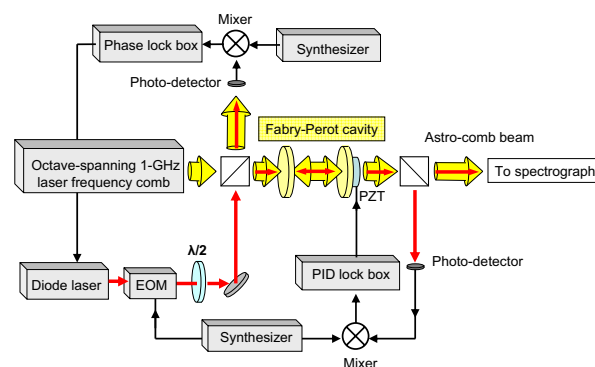


Fig. 1. Astro-comb schematic. An octave-spanning 1 GHz frequency comb is locked to RF synthesizers and filtered by an actively stabilized Fabry-Perot cavity to produce a 40 GHz comb which is fiber-fed to the spectrograph.

An ideal calibrator should have a large, uniform density of lines with even intensity in the spectral range of interest and good long-term stability. Existing calibration sources are sensitive to environmental changes such as pressure and temperature. Commonly used Th-Ar lamps deteriorate over timescales of a few years. Calibration sources are also limited in the red-to-near-infrared spectral bands, which are most useful for exoplanet searches around M dwarfs and dark matter studies in globular clusters. Meanwhile, a sensitivity of 1-40 cm/s is essential to the discovery and the characterization of Earth-like planets, and the direct measurement of the expansion of the universe. An octave-spanning frequency comb generated by a mode-locked femtosecond laser is nearly ideal as a calibrator [5]. A frequency comb

consists of millions of emission lines with equal spacing, corresponding to the repetition rate (f_{rep}) of the pulse train emitted by a femtosecond laser. The absolute frequencies of the comb lines are determined by f_{rep} and the carrier-envelope offset frequency (f_{ceo}): $f = f_{\text{ceo}} + m \times f_{\text{rep}}$, where m is an integer. Both f_{rep} and f_{ceo} can be synchronized with precise radio-frequency oscillators. Referenced to the Global Position System, comb line frequencies have a long-term fractional stability of better than 10^{-12} corresponding to a stability sufficient to detect 1 cm/s velocity variation of astronomical objects. However, f_{rep} is usually < 5 GHz [8], which would require a spectrograph with resolving power $\gg 10^5$ to resolve individual comb lines. Astrophysical spectrographs of such high resolving power are impractical. We have, therefore, designed a stable broadband Fabry-Perot cavity (FP) to increase f_{rep} up to 40 GHz over a range of up to 1,000 Å. This astro-comb can serve as a calibrator for spectrographs with resolving powers of $\gtrsim 10^4$.

Our 1 GHz repetition rate Ti:sapphire laser generates a spectrum spanning 6,000 Å to 12,000 Å. Once mode-locked, the laser is very robust, operating for days without extensive shielding against vibrations. Both f_{rep} and f_{ceo} (measured via 1f-2f self-referencing) are referenced to an atomic clock via low-noise synthesizers. Comb light passes through an FP that filters unwanted comb lines, increasing the line spacing (Fig. 1). The FP is stabilized to a diode laser ($\sim 7,947$ Å) which, in turn, is phase-locked to the comb. The plane-parallel FP mirrors have $\sim 99\%$ reflectivity and optimized group delay dispersion (GDD) (< 50 fs²) in the range of 7,550 Å to 9,200 Å. The FP finesse is 250-300, consistent with reflectivity and Fresnel losses. By matching the free spectral range of the FP to an integer multiple of f_{rep} , we have observed astro-comb lines with 38-GHz spacing, spanning almost 1,000- Å bandwidth.

We have operated this astro-comb at the Whipple Observatory to calibrate the Tillinghast Reflector Echelle Spectrograph (TRES) for the Tillinghast 1.5-m telescope. TRES is a multi-order echelle spectrograph with a resolving power of 60,000 and wavelength coverage from 3,800 Å–9,000 Å. A calibration image is shown in Fig. 2. The first 45 orders are calibrated by a Th-Ar lamp and the last 6 orders are calibrated by the astro-comb. Preliminary data analysis indicates that the astro-comb is able to improve the sensitivity of the TRES.

In summary, we have constructed a novel calibration source consisting of a frequency comb and Fabry-Perot filtering cavity, that provides $> 1,000$ ultra-stable calibration lines in the range of 8,000 Å–9,000 Å. This astro-comb has been deployed to calibrate the TRES spectrograph and has shown the ability to improve calibration of the spectrograph. By enabling improved Doppler velocity-shift precision with broad wavelength coverage and reproducibility over many years and between telescopes, astro-combs should revolutionize astrophysical spectroscopy.

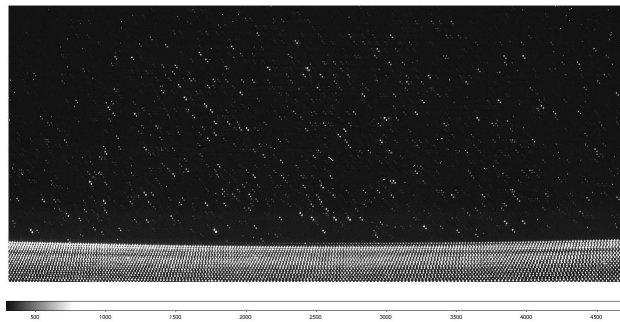


Fig. 2. Raw spectrograph image showing both the sparse, irregular ThAr spectrum (above) and the dense, regular astro-comb spectrum (below).

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