LETTERS

A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

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Searches for extrasolar planets using the periodic Doppler shift of stellar spectral lines have recently achieved a precision of 60 cm s^{-1} (ref. 1), which is sufficient to find a 5-Earth-mass planet in a Mercury-like orbit around a Sun-like star. To find a 1-Earth-mass planet in an Earth-like orbit, a precision of ~5 cm s^{-1} is necessary. The combination of a laser frequency comb with a Fabry–Pérot filtering cavity has been suggested as a promising approach to achieve such Doppler shift resolution via improved spectrograph wavelength calibration[2–4], with recent encouraging results[5]. Here we report the fabrication of such a filtered laser comb with up to 40-GHz (~1-Å) line spacing, generated from a 1-GHz repetition-rate source, without compromising long-term stability, reproducibility or spectral resolution. This wide-line-spacing comb, or '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^{-1} in astronomical radial velocity measurements.

The accuracy and long-term stability of state-of-the-art astrophysical spectrographs are currently limited by the wavelength-calibration source[6,7], typically either thorium–argon lamps or iodine absorption cells[8]. In addition, existing calibration sources are limited in the red-to-near-IR spectral bands most useful for exoplanet searches around M stars[9] and dark matter studies in globular clusters[10]. Iodine cells have very few spectral lines in the red and near-IR spectral bands, while thorium–argon lamps have limited lines and unstable bright features that saturate spectrograph detectors. Recently, laser frequency combs[11] have been suggested as potentially superior wavelength calibrators[2,3] because of their good long-term stability and reproducibility, and because they have useful lines in the red-to-near-IR range. The absolute optical frequencies of the comb lines are determined by $f = f_{ceo} + m \times f_{rep}$, where f_{rep} is the repetition rate, f_{ceo} is the carrier-envelope offset frequency and m is an integer. Both f_{rep} and f_{ceo} can be synchronized with radio-frequency oscillators referenced to atomic clocks. For example, using the generally available Global Positioning System (GPS), the frequencies of comb lines have long-term fractional stability and accuracy of better than 10^{-12}. For the calibration of an astrophysical spectrograph, fractional stability and accuracy of 3×10^{-11} are sufficient to measure a velocity variation of 1 cm s^{-1} in astronomical objects. In addition, using GPS as the absolute reference allows the comparison of measurements at different observatories.

For existing laser combs, f_{rep} is usually <1 GHz (ref. 12), which would require a spectrograph with a resolving power of $R = \lambda/\Delta\lambda \gg 10^5$ to resolve individual comb lines (here $\Delta\lambda$ is the smallest difference in wavelengths that can be resolved at wavelength λ). In practice, astrophysical spectrographs tend to have a resolving power of

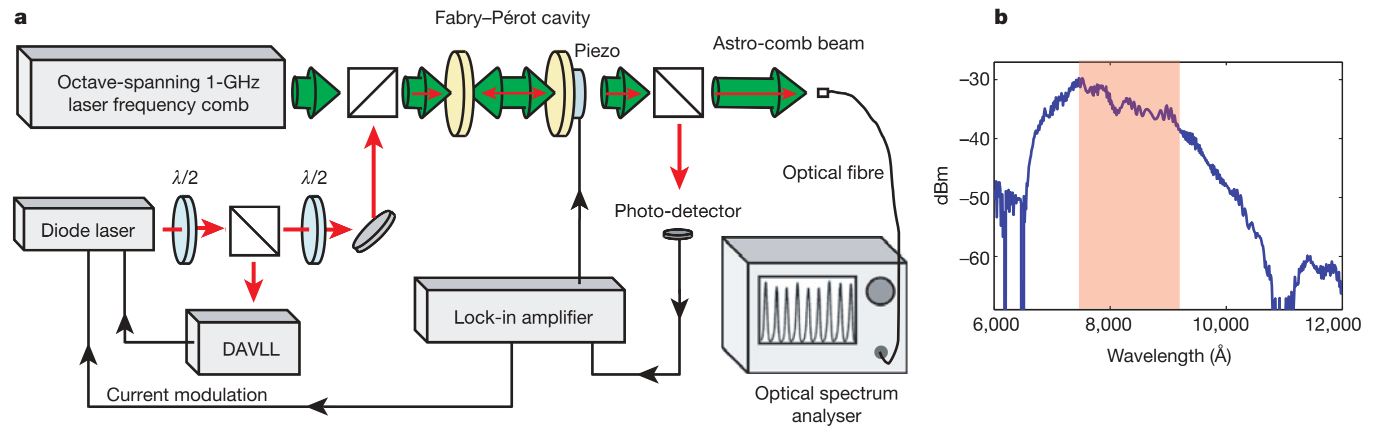

Figure 1 | Block diagram of the astro-comb. a, A stabilized 1-GHz frequency comb ('source-comb') using a mode-locked femtosecond laser passes through an FP cavity that filters out unwanted comb lines and increases the line spacing to at most 40 GHz (~1 Å). For the demonstration spectra shown in this paper (**b** and Fig. 2), the output beam from the astro-comb is collected by a single-mode fibre and measured using an optical spectrum analyser (Ando 6317) with resolution ~8 GHz and reproducibility ~2 GHz. **b,** Output spectrum of the 1-GHz source-comb. Typical operating parameters of the source-comb[13] are 600 mW of output power and an output spectrum from 6,000 Å to 12,000 Å with 9.3 W of pump power. The shaded area is the spectral range in which the current FP cavity mirrors have small GDD and hence provide good suppression of extraneous comb lines. The quantity dBm is ten times the logarithm of the power referenced to 1 mW.

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$R \approx 10^4$–10^5 owing to physical limitations on the instruments, including the telescope aperture, the grating collimator diameter and the grating blaze. Thus, a laser comb must have line spacing >10 GHz to serve as a practical wavelength calibrator. Therefore, we augmented a 1-GHz-repetition-rate laser comb with a stable broadband Fabry–Pérot (FP) cavity to increase the comb line spacing to 40 GHz over a range >1,000 Å. This novel[2], wide-line-spacing 'astro-comb' can provide improved wavelength calibration for a wide range of existing and planned astrophysical spectrographs.

The astro-comb set-up is shown schematically in Fig. 1. An octave-spanning optical frequency comb with a 1-GHz repetition rate ('source-comb') is generated by a mode-locked Ti:sapphire femtosecond laser[13]. The linewidth of each comb line is <1 kHz, with both f_{rep} and f_{ceo} stabilized using low-noise frequency synthesizers, which can be referenced to an atomic clock. The stabilized source-comb light passes through an FP cavity that filters out unwanted comb lines and increases the line spacing. The FP cavity is stabilized by an injected diode laser signal that is itself stabilized to the Rb D1 line (7,947 Å) using a dichroic-atomic-vapour laser lock (DAVLL[14]).

To realize an astrophysical wavelength calibrator, the FP cavity must filter comb lines over a broad spectral range. The mirrors used in the plane-parallel FP cavity have ~99% reflectivity and optimized group delay dispersion (GDD) (<10 fs^2) in the range of 7,700 Å to 9,200 Å. We measured the finesse of the FP cavity to be ~250 at 7,947 Å, which is consistent with the theoretical limit estimated from the mirror reflectivity and Fresnel losses. The GDD-optimized mirrors enable the generation of a filtered comb spanning a bandwidth of ~1,000 Å. With straightforward adjustment of the free spectral range of the FP cavity to approximately equal an integer multiple of f_{rep}, we realized such comb-line filtering. For example, Fig. 2 shows the measured astro-comb output spectrum spanning a bandwidth of ~1,000 Å, with 37-GHz line spacing and power ~10–100 nW in each comb line. If the ratio of free spectral range to f_{rep} is not an integer, the span of the filtered comb lines is narrower and groups of filtered comb lines appear repeatedly within the bandwidth of the mirrors (Fig. 2c). This 'Vernier-like' pattern can be shifted in wavelength and modified by varying the source-comb f_{ceo} and f_{rep} or the free spectral range of the FP cavity. The adjustability of the astro-comb-line pattern may assist the calibration of spectrographs over the bandwidth of the mirrors.

In addition to tunable line spacing up to 40 GHz, appropriate for use with astrophysical spectrographs, the astro-comb exhibits the stability and extraneous-line suppression necessary in an improved wavelength calibrator. By comparisons with a hydrogen maser, we determined the frequency fractional stability of the source-comb (characterized by f_{rep} and f_{ceo}) to be better than 10^{-12} on timescales of seconds to hours. Ideally, the FP cavity changes only the amplitude of the astro-comb's output lines, and not their frequency. Thus, the required stability of the FP cavity is much less stringent than that of the source-comb. However, several source-comb lines lie inside the resolution bandwidth of a typical astrophysical spectrograph. Although the FP cavity has finite suppression of neighbouring comb lines, instability in it leads to changes in the line shape of the astro-comb output spectrum as measured by an astrophysical spectrograph. In Fig. 3, we show a direct measurement of the suppression of extraneous lines of the astro-comb. The measured single-sided suppression of extraneous comb lines of more than 25 dB is consistent with the measured FP cavity finesse of 250. The FP cavity is stabilized by locking one transmission resonance maximum to a DAVLL-stabilized diode laser. The DAVLL-stabilized FP cavity is quite robust, remaining locked for periods of days. The absolute uncertainty in the DAVLL stabilized system is below 0.5 MHz, which is more than sufficient to maintain a sensitivity of 1 $cm\,s^{-1}$. (As noted above, the required FP cavity stability is much less stringent than the

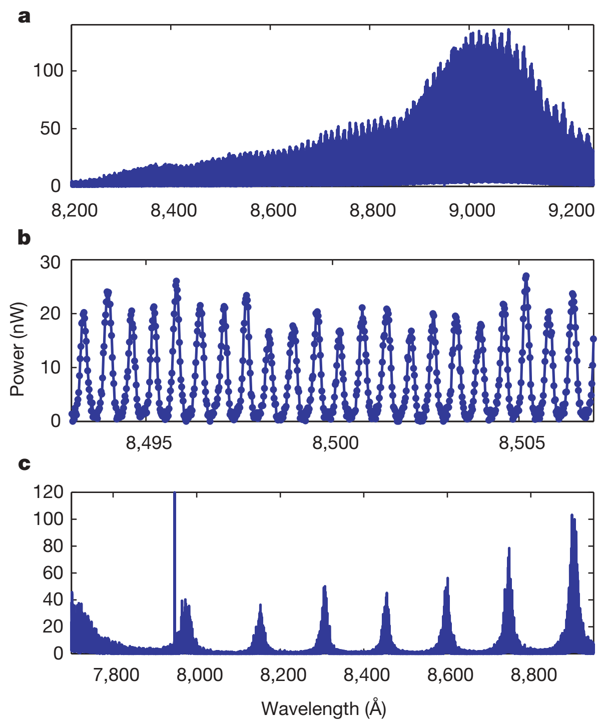

Figure 2 | Example astro-comb output spectrum with 37-GHz line spacing. **a**, The astro-comb is tuned to span a bandwidth of ~1,000 Å. The resolution of the figure is not high enough to show individual lines. The observed amplitude variation is primarily due to the amplitude variation of the source-comb, with a minor contribution from 'mismatch' of the source-comb lines and the transmission resonances of the FP cavity caused by the residual GDD of the mirrors (~0–5 fs^2). Small line shifts due to residual mirror GDD can be determined experimentally to high precision (<1 $cm\,s^{-1}$). For the TiO_2/SiO_2 multi-layer mirrors used in the FP cavity, line stability ~1 $cm\,s^{-1}$ is expected on timescales of several years. **b**, A small portion of the full output spectrum, showing individual filtered comb lines. The width of the lines is set by the optical spectrum analyser's resolution (~8 GHz). **c**, Intentional mismatch between source-comb spacing f_{rep} and FP cavity free spectral range causes groups of filtered comb lines to appear repeatedly within the bandwidth of the mirrors. The prominent line at 7,947 Å is the injected diode laser signal used to stabilize the FP cavity.

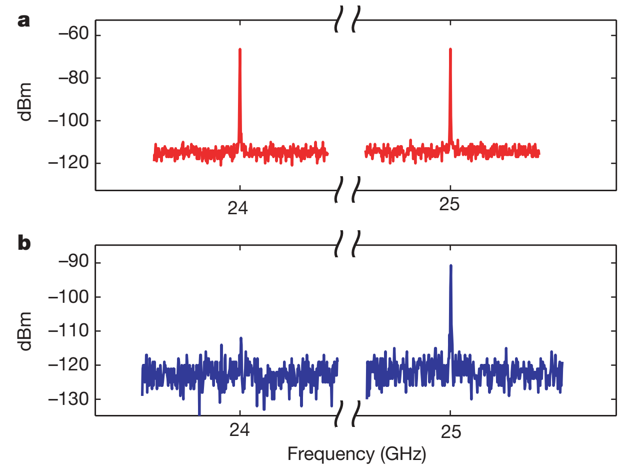

Figure 3 | Suppression of extraneous source-comb lines for the astro-comb. Here, the FP cavity is tuned such that the astro-comb has a 25-GHz line spacing. A fast photo-diode and spectrum analyser are used to measure the power in the 24-GHz and 25-GHz beatnotes from the 1-GHz source-comb (**a**) and the 25-GHz astro-comb (**b**) in the band 8,150–8,450 Å. The ~22-dB suppression of the 24-GHz beatnote in the astro-comb output signal corresponds to a ~25-dB single-sided suppression of extraneous comb lines, consistent with the FP cavity finesse of 250. When the astro-comb is used as a wavelength calibrator for an astrophysical spectrograph, the extraneous-line suppression will be regularly monitored.

required 10-kHz source-comb stability.) Residual frequency noise in the DAVLL is $<300\,\mathrm{kHz\,Hz^{-1/2}}$; corresponding to an amplitude fluctuation of <0.1% for the suppressed (extraneous) comb lines. The resultant frequency noise in the desired astro-comb line spacing is $<3\,\mathrm{kHz\,Hz^{-1/2}}$. Taking advantage of the ultrastable source-comb lines, the astro-comb output spectrum measured by the spectrograph is more stable than the FP cavity by more than two orders of magnitude. Consequently, the stability of the astro-comb is more than adequate for wavelength calibration of astrophysical spectrographs to $1\,\mathrm{cm\,s^{-1}}$ sensitivity.

In May 2008, we will deploy an astro-comb wavelength calibrator at the Multiple Mirror Telescope (MTT) on Mt Hopkins, Arizona. We will demonstrate the ability of the astro-comb to calibrate the Hectochelle multi-object echelle spectrograph[15] in a 150-Å bandwidth around 8,500 Å, which will be especially useful for the study of dark matter and other phenomena in globular clusters. Here we estimate the expected wavelength calibration precision of the astro-comb over a typical 10-hour MMT/Hectochelle measurement. The 1-GHz source-comb, referenced to GPS, will have spectral lines with accuracy and long-term fractional stability better than 10^{-12}. The FP cavity will use mirrors (Lambda Research) with 99% reflectivity and minimal GDD ($<1\,\mathrm{fs^2}$ over the 150-Å bandwidth of one Hectochelle order). The free spectral range of the FP cavity will be set to ~25 GHz, which maximizes the calibration sensitivity[2]. Residual FP cavity mirror GDD and fluctuations of the FP cavity resonance[16] (width ~150 MHz) will lead to changes in the extraneous-line suppression, which is typically $\sim 4\times10^{-3}$ (that is, 25 dB), of up to 0.2%. Therefore, an upper-limit estimate of the uncertainty of astro-comb-line centres is $(4\times10^{-3})\times0.2\%\times1\,\mathrm{GHz}\approx8\,\mathrm{kHz}$. This uncertainty results in a systematic error in astrophysical velocity measurements of approximately $(8\,\mathrm{kHz}/377\,\mathrm{THz})\times(3\times10^{10}\,\mathrm{cm\,s^{-1}})<1\,\mathrm{cm\,s^{-1}}$. In practice, the precision of Doppler-shift/redshift measurements will also be affected by telescope instability and astronomical light-source fluctuations[6].

Beyond our first demonstration, astro-combs should enable many observations that have previously been considered technically unachievable. One example is the search for a 1-Earth-mass planet in an Earth-like orbit around a Sun-like star, which requires a sensitivity of $5\,\mathrm{cm\,s^{-1}}$ and stability on at least a 1-year timescale. In 2009 or 2010 we will deploy an astro-comb at the HARPS-NEF (High-Accuracy Radial-velocity Planet Searcher of the New Earths Facility) spectrograph ($R=120{,}000$) being built by the Harvard Origins of Life Initiative for the William Herschel telescope to search for exoplanets. We will use broadband mirrors with 99% reflectivity and optimal GDD in the FP cavity to generate stable calibration lines in appropriate spectral bands, which we expect will make the HARPS-NEF spectrograph sensitive enough to find Earth-like planets. Additional wavelength coverage can also be realized by frequency doubling the source-comb. Another possible application of the astro-comb is the Sandage–Loeb test[17,18], a direct measurement of the decelerating expansion of the early Universe. This test requires an observation period of >10 years with existing wavelength calibrators, but should be feasible with an observation period of ~3 years using astro-combs. Thus, by enabling a velocity-shift preci>sion of $\sim1\,\mathrm{cm\,s^{-1}}$, broad wavelength coverage and reproducibility over many years and between telescopes, astro-combs should revolutionize astrophysical spectroscopy.

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