nature photonics

LETTERS

https://doi.org/10.1038/s41566-018-0312-3

Searching for exoplanets using a microresonator astrocomb

Myoung-Gyun Suh[1], Xu Yi[1,8], Yu-Hung Lai[1], S. Leifer[2], Ivan S. Grudinin[2], G. Vasisht[2], Emily C. Martin[3], Michael P. Fitzgerald[3], G. Doppmann[4], J. Wang[5], D. Mawet[2,5], Scott B. Papp[6], Scott A. Diddams[6], C. Beichman[7]* and Kerry Vahala[1]*

Orbiting planets induce a weak radial velocity (RV) shift in the host star that provides a powerful method of planet detection. Importantly, the RV technique provides information about the exoplanet mass, which is unavailable with the complementary technique of transit photometry. However, RV detection of an Earth-like planet in the 'habitable zone'[1] requires extreme spectroscopic precision that is only possible using a laser frequency comb (LFC)[2]. Conventional LFCs require complex filtering steps to be compatible with astronomical spectrographs, but a new chip-based microresonator device, the Kerr soliton microcomb[3–8], is an ideal match for astronomical spectrograph resolution and can eliminate these filtering steps. Here, we demonstrate an atomic/molecular line-referenced soliton microcomb for calibration of astronomical spectrographs. These devices can ultimately provide LFC systems that would occupy only a few cubic centimetres[9,10], thereby greatly expanding implementation of these technologies into remote and mobile environments beyond the research lab.

The RV method (Fig. 1) measures periodic Doppler shifts in the stellar spectrum to infer the presence of an orbiting exoplanet[11] and relies on a highly stable and precisely calibrated spectrometer[12]. In astronomy, LFCs or simply astrocombs have enabled spectrograph calibration at the few cm s^{-1} level[13]. They do this by providing a spectrally broad 'comb' of optical frequencies that are precisely stabilized through the process of self-referencing[14]. Self-referencing ensures that both the comb's spectral line spacing and the common offset frequency of the spectral lines from the origin are locked to a radio-frequency standard, resulting in a remarkably accurate 'optical ruler'.

Astrocombs used in previous work[13,15–20] are derived from femtosecond mode-locked lasers and have a comb line frequency spacing that is not resolvable by astronomical spectrographs[2]. This has necessitated the addition of special spectral filters designed to coarsen the line spacing (typically 10–30 GHz)[13,15–20]. The added complexity of this filtering step has created interest in frequency comb generation by other means that can intrinsically provide a readily resolvable line spacing. For example, electro-optical (EO) modulation provides an alternative approach for direct generation of greater than 10 GHz comb line spacings[21,22]. Line-referenced EO-astrocomb devices[23] and self-referenced EO-combs[24,25] have been demonstrated, and more recently, 10 cm s^{-1} RV precision using a near-infrared EO-astrocomb[26] has been reported. However, these devices require additional optical or microwave filtering to suppress the impact of thermal noise in the wings of the broadened comb. Another optical source that produces wider comb line spacings is in the form of a tiny microresonator-based comb or microcomb[27,28]. Driven by parametric oscillation and four-wave-mixing[29], millimetre-scale versions of these devices have line spacings that are ideally suited for astronomical calibration[28]. However, until recently microcombs operated in the so-called modulation instability regime of comb formation[30], and this severely limited their utility in frequency comb applications.

The recent demonstration of soliton mode-locking in microresonators represents a major turning point for applications of microcombs[3–8]. Also observed in optical fibre[31], soliton formation ensures highly stable mode-locking and reproducible spectral envelopes. For these reasons, soliton microcombs are being applied to frequency synthesis[9], dual-comb spectroscopy[32–34], laser ranging[35,36] and optical communications[37]. Moreover, their compact (often chip-based) form factor and low operating power are ideal for ubiquitous application outside the lab, and even in future space-borne instruments. In this work, we demonstrate a soliton microcomb as an astronomical spectrograph calibrator. We discuss the experimental set-up, laboratory results and efforts to detect a previously known exoplanet.

The on-site soliton microcomb demonstration was performed at the 10 m Keck II telescope of the W.M. Keck Observatory to calibrate the Near-Infrared Spectrometer (NIRSPEC). A secondary goal was to detect the RV signature of the 0.5 M_{Jup} planet orbiting the G3V star HD 187123 in a 3.1-day period[38]. Calibrations and observations were performed during the first half nights of 2017-09-10 and 2017-09-11 (UTC) in the hope of detecting the 70 m s^{-1} semi-amplitude of this planetary signature. As a cross-check, the functionality of the soliton microcomb was compared with a previously demonstrated line-referenced EO-astrocomb[23]. The soliton and EO combs described here operate in the near-infrared (NIR), centred around 1,560 nm with a usable breadth of ~250 nm. NIR wavelengths are favoured over visible wavelengths for the study of very cool stars (that is, the M dwarfs). These comprise about 70 percent of the stars in our galaxy and emit predominantly at long wavelengths[26,39,40].

The experimental apparatus for both combs was established in the computer room adjacent to the telescope control room. Both combs were active simultaneously and the output of either one could be fed into the integrating sphere at the input to the NIRSPEC

---

[1]T. J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA, USA. [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. [3]Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, CA, USA. [4]W.M. Keck Observatory, Kamuela, HI, USA. [5]Department of Astronomy, California Institute of Technology, Pasadena, CA, USA. [6]National Institute of Standards and Technology, Boulder, CO, USA. [7]NASA Exoplanet Science Institute, California Institute of Technology, Pasadena, CA, USA. [8]Present address: Department of Electrical and Computer Engineering, Department of Physics, University of Virginia, Charlottesville, VA, USA. *e-mail: chas@ipac.caltech.edu; vahala@caltech.edu

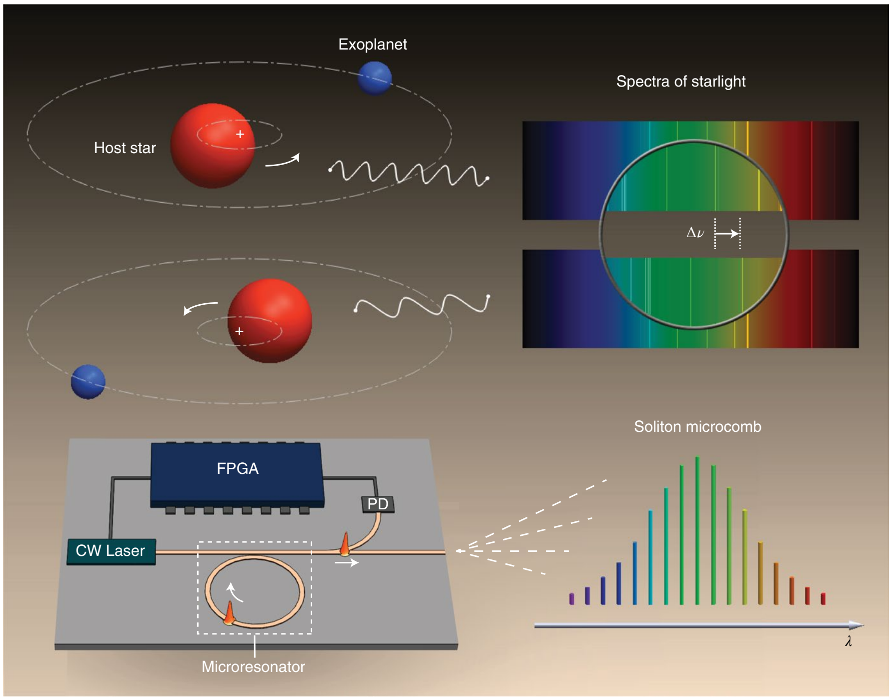

Fig. 1 | Concept of a microresonator astrocomb. While the host star (red sphere) and exoplanet (blue sphere) orbit their common centre of mass, light waves leaving the star experience a weak Doppler shift. The frequency shifts ($\Delta\nu$) of the stellar spectral lines are measured with a spectrograph calibrated by an evenly spaced comb of frequencies. Here, the comb of frequencies is produced by soliton emission from a microresonator, which can be potentially integrated with a continuous wave (CW) laser, a photodetector (PD) and a field-programmable gate array (FPGA) on a chip-scale device.

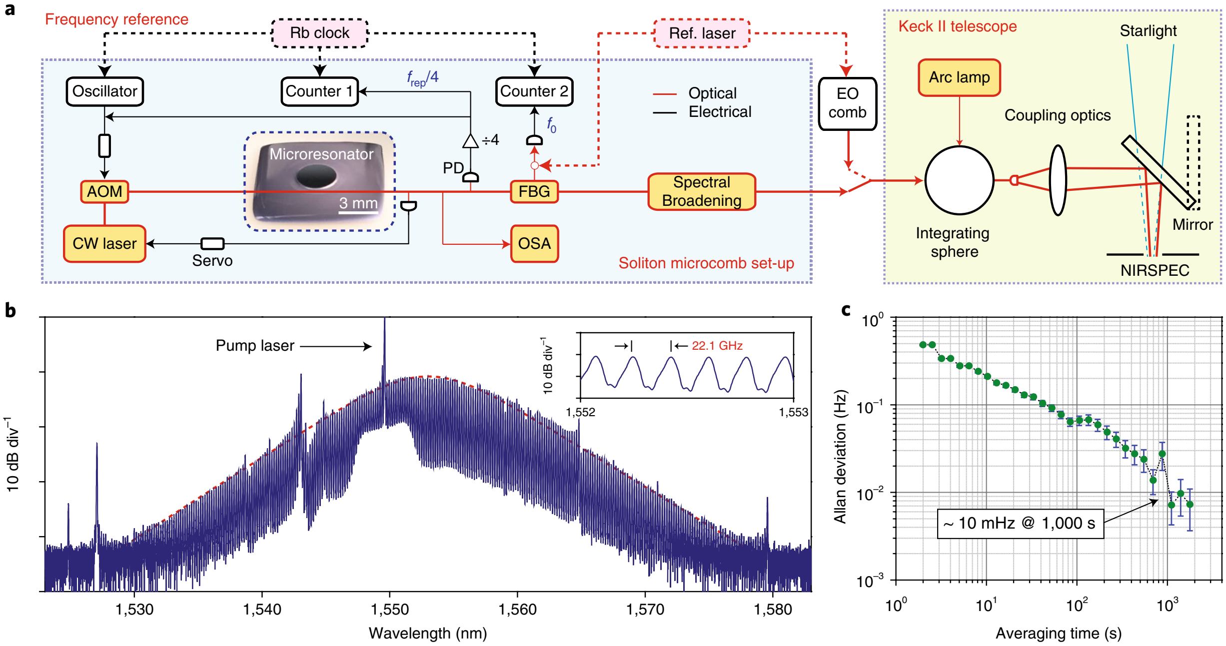

Fig. 2 | Experimental schematic and atomic/molecular line-referenced soliton microcomb. a, A continuous wave (CW) fibre laser is coupled into a silica microresonator via a tapered fibre coupler[50,51]. An acousto-optic modulator (AOM) controls the pump power. The soliton microcomb is long-term stabilized by servo control of the pump laser frequency to hold a fixed soliton average power[52]. The comb power is also tapped to detect and stabilize f_{rep}. After dividing by 4, f_{rep} is frequency-locked to an oscillator and monitored using a frequency counter. The depicted control electronics can potentially be replaced by a compact FPGA, as shown in Fig. 1. A rubidium (Rb) clock provides an external frequency reference. The value of f_0 of a soliton comb line is measured relative to a reference laser (stabilized to HCN at 1,559.9 nm). This comb line is filtered out by a fibre Bragg grating (FBG) filter and heterodyned with the reference laser. Finally, the soliton microcomb is spectrally broadened and sent to the integrating sphere of the NIRSPEC instrument on the Keck II telescope for spectrograph calibration. As a cross check, an EO comb (instead of a soliton microcomb) is also used. **b**, Optical spectrum of the soliton microcomb. The hyperbolic-secant-square fit (red dotted curve) indicates that the soliton pulse width is 145 fs. Inset: zoom-in of the spectra showing a 22.1 GHz line spacing. **c**, Allan deviation of the frequency-locked $f_{rep}/4$. PD, photodetector, OSA, optical spectrum analyser.

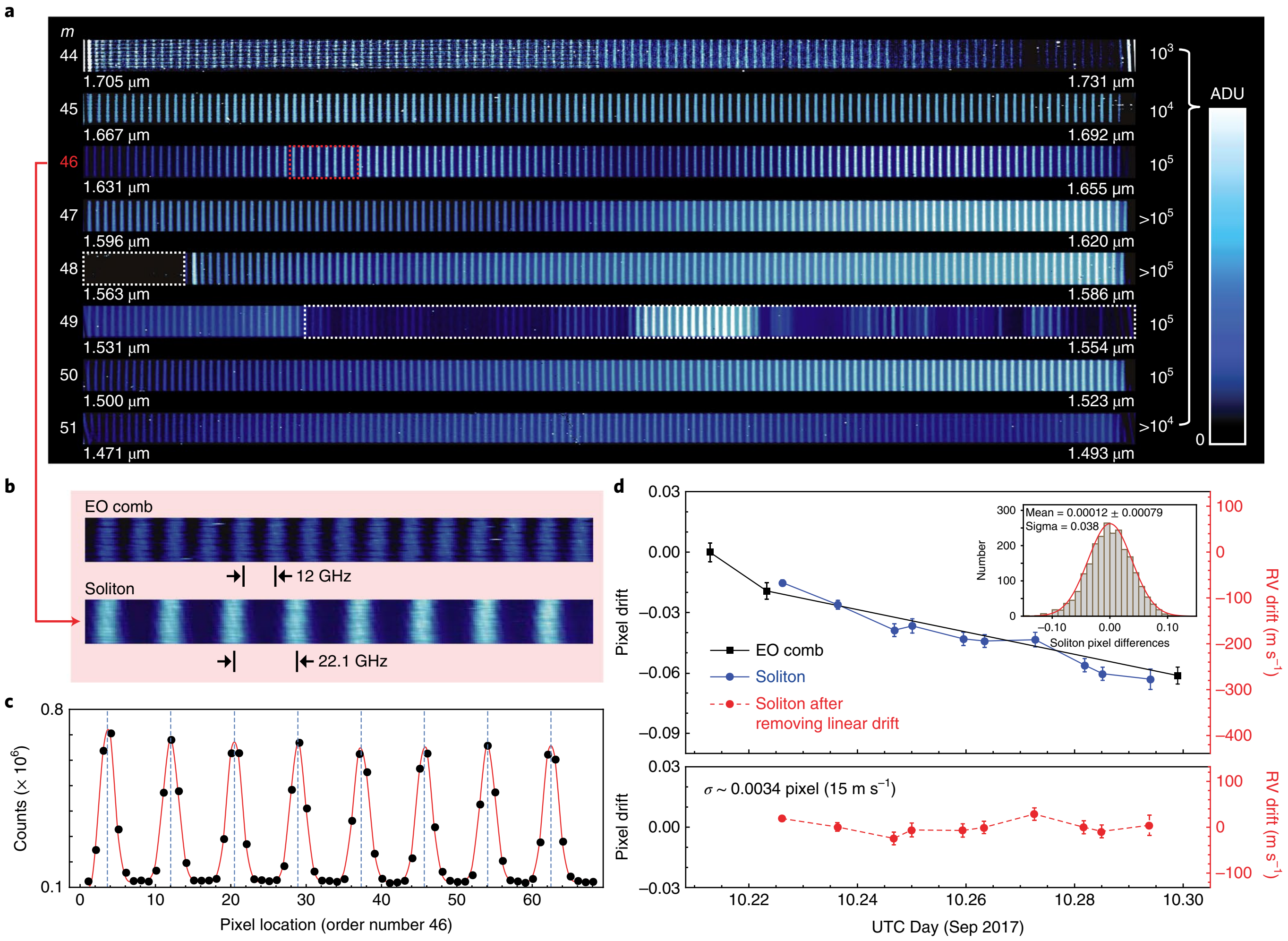

Fig. 3 | Data from testing at Keck II. a, Image of the soliton comb projected onto the NIRSPEC from the echelle orders 44 to 51. Soliton emission (white dashed box) has been strongly filtered to prevent potential damage to the spectrograph. ADU, analogue-to-digital units. **b**, A zoom-in of echelle order 46 (red dashed box in **a**) of the EO comb (top) and soliton (bottom). **c**, Gaussian profiles of eight adjacent soliton comb lines in echelle order 46 are shown (see Methods). **d**, Top: average centroid drift within echelle order 46 relative to the first frame in the time series with both the soliton (blue) and EO combs (black) with the telescope in a quiescent configuration on 2017-09-10 UTC. The EO comb data bracketing the soliton comb data shows the drift of the NIRSPEC wavelength scale. Bottom: NIRSPEC drift after subtracting a linear trend gives a residual of 0.0034 pixel, which corresponds to approximately 15 m s^{-1} in a single order. The inset in the upper panel shows that the distribution of centroid differences is defined well by a Gaussian distribution (see Methods). As discussed in the text, the final wavelength calibration across the entire echellogram would be ≲5 m s^{-1}.

calibration subsystem via single-mode fibre. The switch between the two combs could be carried out in the computer room within less than a minute by changing the input to the fibre without disturbing NIRSPEC itself.

The primary elements of the soliton comb calibration system are detailed in Fig. 2a. The LFC light (soliton microcomb or EO comb) is sent to the fibre acquisition unit (light green box) to calibrate the NIRSPEC spectrometer[41]. Soliton generation uses a silica microresonator fabricated on a silicon wafer[42]. The resonator had a 3 mm diameter, corresponding to an approximate 22.1 GHz soliton comb line spacing, and had an unloaded quality factor of approximately 300 million (see Methods). Figure 2b shows the optical spectrum of the soliton microcomb. The soliton repetition frequency (f_{rep}) was locked to a rubidium-stabilized local oscillator by servo control of the pump power using an acousto-optic modulator (AOM) to vary the soliton repetition rate. Allan deviation measurement of the locked and frequency-divided signal show an instability of 10 mHz at 1,000 s averaging time (Fig. 2c). The frequency of one of the soliton comb lines is monitored by heterodyne detection with a reference laser, which is locked to a hydrogen cyanide (HCN) absorption line at 1,559.9 nm. The resulting offset frequency f_0 is recorded at every second using a frequency counter stabilized to the Rb clock with a time stamp for calibration of the frequency comb over time. For calibration of the frequency comb over time, f_0 was determined over a 20 s averaging time (that is, acquisition time for a single spectrum) with a standard deviation less than 1 MHz. Over this time, the absolute optical frequency of the HCN reference laser has an imprecision of less than 1 MHz (ref. [23]; see Methods). Because the soliton repetition rate (that is, comb line spacing) is frequency locked, the offset frequency imprecision was the principal source of instability in the comb calibration, equivalent to about 1 m s^{-1} of RV imprecision. Finally, the soliton microcomb is spectrally broadened using highly nonlinear optical fibre (HNLF; see Methods).

Figure 3a shows the echellogram of the soliton microcomb measured by NIRSPEC (eight echelle orders ranging from 1,471 nm to 1,731 nm, which represents almost the entire astronomical H band). The raw echellograms were rectified spatially and spectrally. Zoomed-in images of a single order from both the soliton and

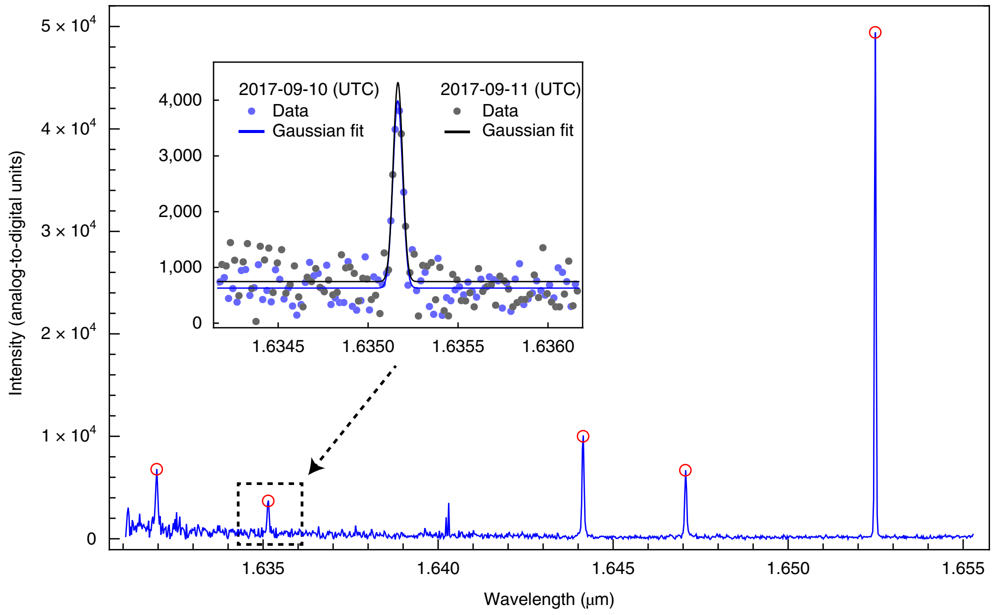

Fig. 4 | Arc lamp data for absolute wavelength calibration. NIRSPEC arc lamps with lines of Kr, Ar and Xe (https://www2.keck.hawaii.edu/inst/nirspec/lines.html) were used for the absolute wavelength calibration of the soliton comb lines, alternately configuring NIRSPEC to observe the arcs and the soliton. The figure shows a section of data from echelle order 46. Gaussian fits were performed on five prominent lines from the two nights (blue and black data points in the inset). The average difference between the five line centroids is $0.98 \pm 1.3 \times 10^{-6}$ nm, which corresponds to 0.041 ± 0.025 pixel. This shift is consistent with short-term drifts seen through the two nights.

EO comb data (Fig. 3b) show that individual comb lines are resolved at the NIRSPEC resolution of $R \sim 25{,}000$ and spaced approximately four pixels apart (0.1 nm) for the EO comb and eight pixels apart (0.2 nm) for the soliton comb.

The soliton and EO comb time series data shown in Fig. 3 consist of 450 data frames taken every 20 s over the course of a 2.5 hr interval when the telescope and instrument were in a quiescent state. The reduced echellograms were analysed by fitting a Gaussian to each comb line (Fig. 3c) to determine its pixel location (see Methods). For this analysis we chose echelle order 46, which spans 1.631 to 1.655 μm. The centroids of each comb line were determined across this 2.5 hr interval. The average drift for the entire order, consisting of $N = 122$ (225) lines in the soliton (EO comb) dataset, was computed with respect to the first frame in the time series and examined as a function of time to reveal drifts within NIRSPEC.

In the absence of external disturbances such as telescope-induced vibrations, the drift measured continuously in approximately five to ten minute intervals over two hours was extremely regular and could be removed by a simple first-order fit. Subtracting the linear drift from the soliton data in the upper panel of Fig. 3d results in the red dashed line (lower panel). Our calculation (see Methods) shows that this level of drift corresponds to 3–5 m s^{-1} precision in wavelength solution. Thus the ability to calibrate NIRSPEC at the few m s^{-1} level has been demonstrated using the soliton microcomb NIR technology. We emphasize that this wavelength precision is inherent to NIRSPEC's resolution and stability, and it is only the large number of LFC comb lines and their inherent high precision that have revealed the performance of NIRSPEC at this level (see Methods).

In routine astronomical operation (that is, without an LFC), NIRSPEC has achieved radial velocity measurements at the 50–100 m s^{-1} level[43]. Sources of uncertainty previously known or revealed during these observations include: changing illumination due to guiding errors of the star within the slit or shifting from the slit to the integrating sphere; short- and long-term drifts of 0.02–0.05 pixel due to internal vibrations and environmental effects; and sudden grating offsets due to telescope motions (0.25 pixel).

Observations of HD 187123 were bracketed by soliton measurements, but analysis of the stellar spectra and of telluric absorption lines within those spectra revealed variations at the 100 m s^{-1} level (0.025–0.05 pixel) which we attribute to the sources of wavelength shifts as described above. Although planet detection could not be achieved, we were able to measure the two combs sequentially with respect to the arc lamps used for absolute wavelength calibration (see Fig. 4).

A funded upgrade presently underway will enhance NIRSPEC's thermal and mechanical stability, and future upgrades would enable simultaneous observation of an LFC and a stellar image stabilized via a single-mode fibre using adaptive optics. Finally, a new generation of spectrographs in development will make use of diffraction-limited adaptive optics imaging to enable $R > 100{,}000$ spectral resolution and enhanced image stability using single-mode fibres. These new instruments will be able to take full advantage of the wavelength precision available with a new generation of microresonator astrocombs[44].

In summary, we report in situ astronomical spectrograph calibrations with a soliton microcomb, which is an important milestone for future chip-based astrocomb research. The internal instrumental precision at the few m s^{-1} level was limited by internal drifts of NIRSPEC and not by the performance of the soliton microcomb, which already possesses the desirable qualities of approximately 20 GHz mode spacing, low-noise operation and short-pulse generation. Rapidly progressing research in this field has resulted in microcomb spectral broadening and self-referencing with integrated photonics[45], as well as direct generation at shorter wavelengths[46]. These advances will greatly enhance the microcomb stability and bandwidth, and will eventually allow a new generation of astronomical instruments to attain the precision needed to detect the 10 cm s^{-1} RV signature of Earth-like exoplanets orbiting solar-type stars at visible wavelengths. The current prototype system occupies approximately 1.3 m in a standard instrument rack, but significant effort towards system-level integration[9,10] could ultimately provide a microcomb system in a chip-integrated package with a footprint measured in centimetres.

Such a dramatic reduction in size is accompanied by reduced weight and power consumption, which would be an enabling factor for ubiquitous frequency comb precision RV calibrations, and other metrology applications in mobile and even space-borne[47,48] instrumentation. *Note added in proof*: The authors would like to draw the readers' attention to another microresonator astrocomb demonstration[49], which was reported while preparing this manuscript.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41566-018-0312-3.

Received: 29 April 2018; Accepted: 5 November 2018;

References

1. Kasting, J. F., Whitmire, D. P. & Reynolds, R. T. Habitable zones around main sequence stars. *Icarus* **101**, 108–128 (1993).
2. Diddams, S. A. The evolving optical frequency comb. *J. Opt. Soc. Am. B* **27**, B51–B62 (2010).
3. Herr, T. et al. Temporal solitons in optical microresonators. *Nat. Photon.* **8**, 145–152 (2014).
4. Yi, X., Yang, Q.-F., Yang, K. Y., Suh, M.-G. & Vahala, K. Soliton frequency comb at microwave rates in a high-*Q* silica microresonator. *Optica* **2**, 1078–1085 (2015).
5. Brasch, V. et al. Photonic chip-based optical frequency comb using soliton Cherenkov radiation. *Science* **351**, 357–360 (2016).
6. Wang, P.-H. et al. Intracavity characterization of micro-comb generation in the single-soliton regime. *Opt. Express* **24**, 10890–10897 (2016).
7. Joshi, C. et al. Thermally controlled comb generation and soliton modelocking in microresonators. *Opt. Lett.* **41**, 2565–2568 (2016).
8. Grudinin, I. S. et al. High-contrast Kerr frequency combs. *Optica* **4**, 434–437 (2017).
9. Spencer, D. T. et al. An optical-frequency synthesizer using integrated photonics. *Nature* **557**, 81–85 (2018).
10. Stern, B., Ji, X., Okawachi, Y., Gaeta, A. L. & Lipson, M. Battery-operated integrated frequency comb generator. *Nature* **562**, 401–405 (2018).
11. Perryman, M. *The Exoplanet Handbook* (Cambridge University Press, Cambridge, UK, 2011).
12. Pepe, F., Ehrenreich, D. & Meyer, M. R. Instrumentation for the detection and characterization of exoplanets. *Nature* **513**, 358–366 (2014).
13. Wilken, T. et al. A spectrograph for exoplanet observations calibrated at the centimetre-per-second level. *Nature* **485**, 611–614 (2012).
14. Jones, D. J. et al. Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. *Science* **288**, 635–639 (2000).
15. Murphy, M. T. et al. High-precision wavelength calibration of astronomical spectrographs with laser frequency combs. *Mon. Not. R. Astron. Soc.* **380**, 839–847 (2007).
16. Li, C.-H. et al. A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}. *Nature* **452**, 610–612 (2008).
17. Braje, D. A., Kirchner, M. S., Osterman, S., Fortier, T. & Diddams, S. Astronomical spectrograph calibration with broad-spectrum frequency combs. *Euro. Phys. J. D* **48**, 57–66 (2008).
18. Steinmetz, T. et al. Laser frequency combs for astronomical observations. *Science* **321**, 1335–1337 (2008).
19. McCracken, R. A., Charsley, J. M. & Reid, D. T. A decade of astrocombs: Recent advances in frequency combs for astronomy. *Opt. Express* **25**, 15058–15078 (2017).
20. Glenday, A. G. et al. Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph. *Optica* **2**, 250–254 (2015).
21. Murata, H., Morimoto, A., Kobayashi, T. & Yamamoto, S. Optical pulse generation by electrooptic-modulation method and its application to integrated ultrashort pulse generators. *IEEE J. Sel. Top. Quantum Electron.* **6**, 1325–1331 (2000).
22. Huang, C., Jiang, Z., Leaird, D. & Weiner, A. High-rate femtosecond pulse generation via line-by-line processing of phase-modulated CW laser frequency comb. *Electron. Lett.* **42**, 1114–1115 (2006).
23. Yi, X. et al. Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy. *Nat. Commun.* **7** ,10436 (2016).
24. Beha, K. et al. Electronic synthesis of light. *Optica* **4**, 406–411 (2017).
25. Carlson, D. R. et al. Ultrafast electro-optic light with subcycle control. *Science* **361**, 1358–1363 (2018).
26. Metcalf, A. J. et al. Infrared astronomical spectroscopy for radial velocity measurements with 10 cm/s precision. *CLEO: Sci. Innovations* JTh5A-1 (2018).
27. Del'Haye, P. et al. Optical frequency comb generation from a monolithic microresonator. *Nature* **450**, 1214–1217 (2007).
28. Kippenberg, T. J., Holzwarth, R. & Diddams, S. Microresonator-based optical frequency combs. *Science* **332**, 555–559 (2011).
29. Kippenberg, T., Spillane, S. & Vahala, K. Kerr-nonlinearity optical parametric oscillation in an ultrahigh-*Q* toroid microcavity. *Phys. Rev. Lett.* **93**, 083904 (2004).
30. Wabnitz, S. Suppression of interactions in a phase-locked soliton optical memory. *Opt. Lett.* **18**, 601–603 (1993).
31. Leo, F. et al. Temporal cavity solitons in one-dimensional Kerr media as bits in an all-optical buffer. *Nat. Photon.* **4**, 471–476 (2010).
32. Suh, M.-G., Yang, Q.-F., Yang, K. Y., Yi, X. & Vahala, K. J. Microresonator soliton dual-comb spectroscopy. *Science* **354**, 600–603 (2016).
33. Dutt, A. et al. On-chip dual-comb source for spectroscopy. *Sci. Adv.* **4**, e1701858 (2018).
34. Pavlov, N. et al. Soliton dual frequency combs in crystalline microresonators. *Opt. Lett.* **42**, 514–517 (2017).
35. Trocha, P. et al. Ultrafast optical ranging using microresonator soliton frequency combs. *Science* **359**, 887–891 (2018).
36. Suh, M.-G. & Vahala, K. J. Soliton microcomb range measurement. *Science* **359**, 884–887 (2018).
37. Marin-Palomo, P. et al. Microresonator-based solitons for massively parallel coherent optical communications. *Nature* **546**, 274–279 (2017).
38. Feng, Y. K. et al. The California Planet Survey IV: A planet orbiting the giant star HD 145934 and updates to seven systems with long-period planets. *Astrophys. J.* **800**, 22 (2015).
39. Mahadevan, S. et al. The habitable-zone planet finder: a stabilized fiber-fed NIR spectrograph for the Hobby–Eberly telescope. *Ground-Based and Airborne Instrumentation for Astronomy IV* **8446**, 84461S (2012).
40. Kotani, T. et al. Infrared Doppler instrument (IRD) for the Subaru telescope to search for Earth-like planets around nearby M-dwarfs. *Ground-Based and Airborne Instrumentation for Astronomy V* **9147**, 914714 (2014).
41. McLean, I. S. et al. Design and development of NIRSPEC: a near-infrared echelle spectrograph for the Keck II telescope. *Infrared Astronomical Instrumentation* **3354**, 566–579 (1998).
42. Lee, H. et al. Chemically etched ultrahigh-*Q* wedge-resonator on a silicon chip. *Nat. Photon.* **6**, 369–373 (2012).
43. Blake, C. H., Charbonneau, D. & White, R. J. The NIRSPEC ultracool dwarf radial velocity survey. *Astrophys. J.* **723**, 684 (2010).
44. Crepp, J. R. et al. iLocater: a diffraction-limited Doppler spectrometer for the Large Binocular Telescope. *Ground-Based and Airborne Instrumentation for Astronomy VI* **9908**, 990819 (2016).
45. Lamb, E. S. et al. Optical-frequency measurements with a Kerr microcomb and photonic-chip supercontinuum. *Phys. Rev. Appl.* **9**, 024030 (2018).
46. Lee, S. H. et al. Towards visible soliton microcomb generation. *Nat. Commun.* **8**, 1295 (2017).
47. Lezius, M. et al. Space-borne frequency comb metrology. *Optica* **3**, 1381–1387 (2016).
48. Plavchan, P. et al. EarthFinder: A precise radial velocity probe mission concept for the detection of Earth-mass planets orbiting Sun-like stars. Preprint at https://arXiv.org/abs/1803.03960 (2018).
49. Obrzud, E. et al. A microphotonic astrocomb. *Nat. Photon.* https://doi.org/10.1038/s41566-018-0309-y (2018).
50. Cai, M., Painter, O. & Vahala, K. J. Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system. *Phys. Rev. Lett.* **85**, 74 (2000).
51. Spillane, S., Kippenberg, T., Painter, O. & Vahala, K. Ideality in a fiber-taper-coupled microresonator system for application to cavity quantum electrodynamics. *Phys. Rev. Lett.* **91**, 043902 (2003).
52. Yi, X., Yang, Q.-F., Youl, K. & Vahala, K. Active capture and stabilization of temporal solitons in microresonators. *Opt. Lett.* **41**, 2037–2040 (2016).

Acknowledgements

We gratefully acknowledge J. Schlieder, A. Howard, F. Hadaegh and the support of the entire Keck summit team. We thank D. Carlson and H. Timmers for preparing the HNLF. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. The data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and NASA. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. This paper made use of data available in the NASA Exoplanet Archive and the Keck Observatory Archive. S.D. and S.P. acknowledge support from NIST. K.V., M.-G.S., X.Y. and Y.-H.L. thank the Kavli Nanoscience Institute and NASA for support under KJV.JPLNASA-1-JPL.1459106. This research was carried out at JPL and the California Institute of

Technology under a contract with NASA and funded through the JPL Research and Technology Development Program.

Author contributions

M.-G.S., S.L., G.V., M.P.F., D.M., S.B.P., S.A.D., C.B. and K.V. conceived the experiments. All co-authors designed and performed experiments. M.-G.S. and X.Y. built the soliton microcomb set-up and EO comb set-up with S.L., I.S.G., S.A.D., S.B.P. and Y.-H.L. providing assistance. G.D. managed operations and the experimental interface of the Keck II telescope. E.C.M., J.W. and C.B. analysed NIRSPEC data. C.B. and K.V. supervised the experiment. M.-G.S., C.B. and K.V. prepared the manuscript with input from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to C.B. or K.V.

Methods

Silica microresonator and the device package. The resonator is an 8-µm-thick disk resonator supporting whispering-gallery optical modes at the approximately 30°-wedged perimeter[42]. For transport to the observatory, the microresonator was mounted inside a brass package with FC/APC fibre connectors. The package was temperature-controlled using a thermoelectric cooler to stay within an operating range of 30 mK. The measured temperature stability was <10 mK over an hour.

HCN reference laser. Both the centre-lock (reference) mode and the side-lock (line narrowing) mode of the HCN reference laser (Clarity laser manufactured by Wavelength References, Inc.) were tested in the laboratory experiment. Stabilization of f_0 to a rubidium-referenced local oscillator was possible by shifting the entire soliton microcomb frequency using an acousto-optic frequency shifter when the reference laser was in side-lock mode. However, centre-lock mode, which provides better precision (<1 MHz), is used and the free-running f_0 is monitored for the on-site demonstration at the W.M. Keck Observatory. Because the comb precision of <1 MHz is sufficient to detect the RV signature of HD 187123b, further improvement of the precision was not attempted to simplify the system as a first out-of-lab demonstration. In principle, full stabilization of the soliton microcomb is possible using a better optical frequency reference or via a self-referencing technique.

Spectral broadening of the soliton microcomb. The initial soliton microcomb out of the microresonator had approximately milliwatt optical power and was amplified to more than 1 W before entering the HNLF. After spectral broadening, the high-power peaks near the pump laser frequency are filtered out to prevent potential damage to the spectrograph. The broadened soliton microcomb had ~100 mW optical power and was further attenuated to the order of milliwatts before entering the integrating sphere. The HNLF[25,45,53] spectral broadening medium had three sections of fibre, fusion-spliced together (5 m of HNLF with $-1.3\,\mathrm{ps\,nm^{-1}\,km^{-1}}$ normal dispersion, 60 cm of Corning SMF 28, and 2 m of HNLF with $1.5\,\mathrm{ps\,nm^{-1}\,km^{-1}}$ anomalous dispersion). The first piece of normal dispersion provides an efficient spectral broadening and a pulse output that can be temporally compressed with SMF 28. The anomalous HNLF section provides supercontinuum and dispersive-wave formation around 1,200 nm.

Calibration of NIRSPEC. We calculate the relative drift in the NIRSPEC wavelength solution, $z(t)$, at time t by taking the average difference in centroid positions of each comb line ($j = 1$ to N) in echelle order 46 at time t, $x_j(t)$, (Fig. 3c) relative to the first frame in the time series, $x_j(t = 0)$ as defined in equation (1).

$$z(t) = \frac{1}{N} \sum_{j=1}^{j=N} (x_j(t) - x_j(t=0)) \tag{1}$$

Figure 3d shows $z(t)$ with its associated uncertainty, $\sigma(t)/\sqrt{N}$, as measured by both the EO comb (black line) and the soliton microcomb (blue line). After subtracting the linear drift from the soliton data in Fig. 3d, the soliton comb data reduced the wavelength drift over the two-hour interval from 0.027 ± 0.002 pixel h^{-1} ($120 \pm 10\,\mathrm{m\,s^{-1}\,h^{-1}}$) to 0 ± 0.002 pixel h^{-1} ($\pm 10\,\mathrm{m\,s^{-1}\,h^{-1}}$). The 1 σ residual around the linear fit in Fig. 3d is 0.0034 pixels (or $15\,\mathrm{m\,s^{-1}}$). Other soliton-only datasets taken during these two days showed residuals as low as 0.0021 pixel after removal of a linear fit (or $9\,\mathrm{m\,s^{-1}}$). These values represent the difference between two frames so that the wavelength precision in a single frame is $\sqrt{2}$ smaller (that is, $10.6\,\mathrm{m\,s^{-1}}$ and $6.5\,\mathrm{m\,s^{-1}}$).

The wavelength precision obtained above is based only on echelle order 46, but there are four other orders in the echellogram with comparable amplitude and number of comb lines (Fig. 3a). Adding in these other lines would improve the wavelength solution by an approximate factor of two, to roughly 3–$5\,\mathrm{m\,s^{-1}}$.

The inset in Fig. 3d demonstrates that the distribution of differences between comb-line centroids from one time step to the next after the subtraction of the mean shift, $(x_j(t) - x_j(t=0)) - z(t)$, is well characterized by a Gaussian distribution. The precision in determining the frame-to-frame shift is dominated by the centroiding uncertainty (0.038 pixel in the differences, or $0.038/\sqrt{2} = 0.027$ pixel in a single frame) and the total number of comb lines considered. The mean value of this distribution over the two-hour period is 0.0001 ± 0.00079 pixels, equivalent to $0.4 \pm 3.4\,\mathrm{m\,s^{-1}}$.

Performance limit of NIRSPEC. A complete error-budget analysis for NIRSPEC shows that in a 900 sec observation, NIRSPEC could achieve 1, 1.6 or $4.4\,\mathrm{m\,s^{-1}}$ on a magnitude H = 6, 8 or 10 M3 star after including the following effects: photon noise, simultaneous single-mode fibre feeds of AO-stabilized starlight and the LFC, upgraded mechanical and thermal stability, stellar jitter and residual telluric effects.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

References

53. Cole, D., Beha, K., Diddams, S. & Papp, S. Octave-spanning supercontinuum generation via microwave frequency multiplication. *J. Phys. Conf. Ser.* **723**, 012035 (2016).