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Astrocombs: Recent Advances.

Tobias Herr and Richard A. McCracken

***Abstract*—Precision calibration of astronomical spectrographs is essential to the hunt for exoplanets, the study of cosmology and determining variation of the fundamental constants. Frequency combs ('astrocombs') can serve as real-time references, providing unprecedented accuracy and precision. Here we provide a brief overview over demonstrated astrocombs and recent advances.**

***Index Terms*—frequency combs, spectrograph calibration**

I. Introduction

ASTROCOMBS [1–4] are broadband, high-repetition rate optical frequency combs that are used for the calibration of astronomical spectrographs. Their precision and accuracy make astrocombs a critical technology for astronomical spectroscopy and will likely enable ground-breaking observations in the fields of exoplanets, cosmology and fundamental physics [5, 6]. The conflicting requirements of resolvable comb line spacing (usually $>$10 GHz), broadband spectral coverage (from below 400 to above 2400 nm) and compatibility with low-maintenance operation represents a significant technical challenge. Here, we provide a concise updated overview of approaches to astrocomb generation (Section II) as well as recent progress in spectral broadening of comb spectra with multi-GHz mode spacing (Section III). For a more in-depth discussion of astrocombs, we direct the reader towards a comprehensive review carried out by McCracken *et al.* [7].

II. Approaches to astrocomb generation

Astrocombs were first generated by mode filtering of low-repetition rate lasers ($<$1 GHz) that were spectrally broadenend in nonlinear optical fiber. Recently, multi-GHz mode-locked lasers, electro-optic astrocombs, microresonator combs as well as combs based on four-wave mixing have emerged as new approaches to astrocomb generation that avoid the technically complex mode-filtering procedure. The operating wavelength ranges of different astrocombs are summarized in Figure 1.

A. Filtered mode-locked lasers

The vast majority of astrocombs deployed to date have used a sub-GHz mode-locked fiber lasers [2, 4, 8–21] as the source comb, with Fabry-Pérot etalons employed to suppress unwanted comb lines [22]. Care must be taken to prevent asymmetric mode suppression due to cavity dispersion, phase-mismatch or higher-order spatial modes [23] as well as to avoid unwanted re-amplification of suppressed modes during spectral broadening [24, 25].

Solid-state Ti:sapphire lasers cannot easily be amplified, however they can produce sub-30-fs pulses at 1-GHz repetition frequencies, enabling frequency conversion prior to filtering. Several GHz-Ti:sapphire-based astrocombs have been demonstrated [3, 26–30], primarily covering the visible spectrum. Mode-filtering of the fundamental comb is typically less critical when compared to sub-GHz fiber lasers due to the wide initial mode spacing, however side-mode suppression after spectral broadening requires etalons comprised of complementary dispersive mirrors, potentially operating over multiple spectral regions to provide different mode spacings that match the resolving power of the spectrograph [31, 32]. The efficacy of this multi-channel filtering approach remains undemonstrated.

Progress towards 'turn-key' mode-locked laser based astrocombs has been significant. Menlo Systems have deployed a hands-free Yb:fiber-based comb for the German Vacuum Tower Telescope [20] and a similar 25-GHz comb has been installed on the Chinese 2.16-m telescope [21]. A turn-key Ti:sapphire astrocomb has been developed by Laser Quantum and a team from Harvard [33]. Employing an off-the-shelf supercontinuum module, this comb provided a 16-GHz comb with a 90-nm bandwidth centered at 566 nm, and was characterised on the HARPS-N spectrograph.

B. High-repetition rate mode-locked lasers

Several solid-state laser materials can be Kerr-lens mode-locked, directly providing multi-GHz outputs and avoiding the need for(and resulting complexity of) mode-filtering. A Ti:sapphire laser with a 10-GHz repetition rate has been demonstrated [34] and developed into a commercial product (Laser Quantum). The pulses have sufficient energy for supercontinuum generation, or for nonlinear down-conversion in a degenerate optical parametric oscillator [35].

Multi-GHz operation has also been demonstrated in a number of Yb-doped materials [36, 37], most recently with a 20-GHz mode spacing [38]. The $\sim$200 fs pulse duration precludes direct nonlinear frequency conversion, however the output can be amplified and broadened in conventional Yb:doped fiber, and laboratory testing of a Yb:ceramic frequency comb on a high-resolution spectrograph has been reported [39]. The phase noise of many of these high-repetition rate lasers remains an open question, and the long-term performance is not yet well understood.

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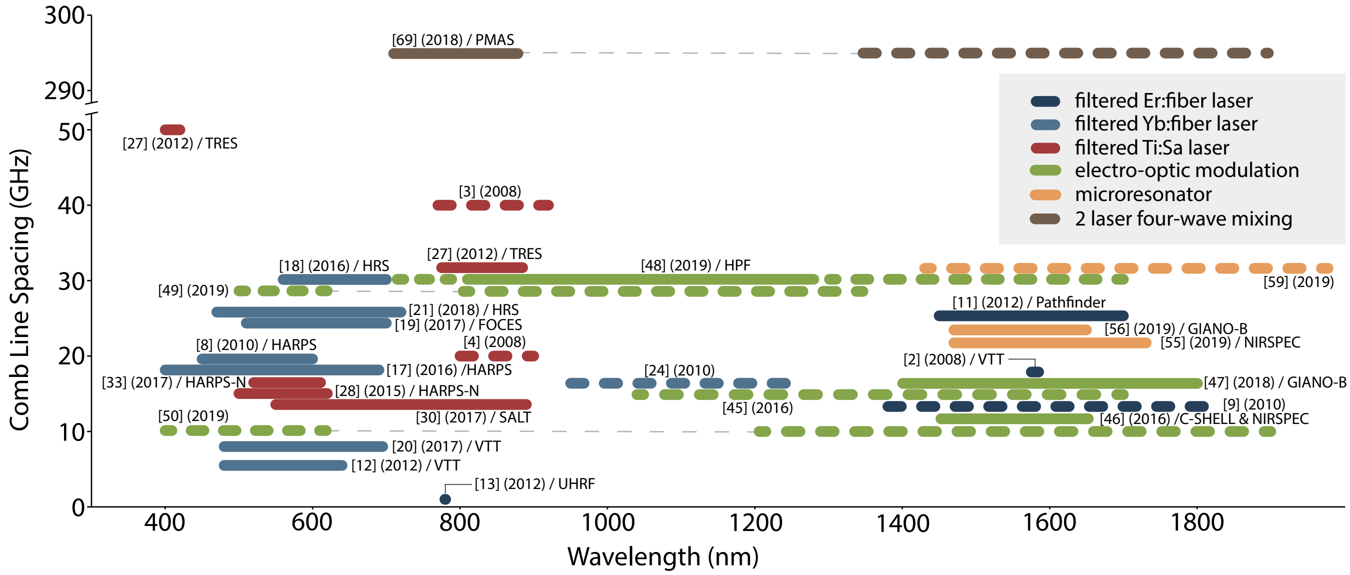

Fig. 1. **Examples of astrocombs.** Different colors represent different astrocomb technologies. Dashed bars refer to combs that have been demonstrated with spectrograph calibration in mind, solid bars to those systems that have actually been demonstrated in conjunction with an astronomical spectrograph. The definition of the combs's bandwidth is not standardized and the length of the bars is only indicative. Thin, grey dashed lines connect different spectral parts generated simultaneously by one system. Colour version available online.

C. Electro-optic modulation combs

Electro-optic modulation (EOM) combs rely on strong phase-modulation of a continuous-wave (CW) laser [40] and subsequent compression of the chirped waveform into picosecond pulses via dispersive optical elements or waveshapers [41]. The EOM frequency can be chosen such that the sidebands are directly resolvable by the spectrograph. Optical amplification and nonlinear optical effects in conjunction with pulse compression in fiber or free-space compressors yield high-peak power pulses with tens-of-femtoseconds pulse duration suitable for nonlinear spectral broadening. The simplicity of the EOM approach comes at the cost of imprinting the inherent phase noise of the microwave source onto the optical comb lines [42] and, for very broadband spectra, necessitates phase noise suppression in the optical domain [43].

The potential of EOM astrocombs has been recognized early in the development of the IRD instrument [44, 45], and first demonstrated on the CSHELL and NIRSPEC near-infrared spectrographs [46]. Recent advances include validation of a low maintenance all-fiber system, fully stabilized to a fundamental atomic frequency standard on the GIANO-B spectrograph [47] as well as the first permanently deployed system providing continuously calibration to the HPF instrument [48]. EOM is best developed in the near-infrared wavelength but recent efforts have shown broadband nonlinear frequency conversion via sum-frequency generation to below 500 nm [49] and triple-sum frequency generation to below 400 nm wavelength [50].

D. Microresonator Kerr frequency combs

Frequency combs in Kerr-nonlinear optical microresonators [51] rely on resonantly enhanced nonlinear optical processes driven by an external pump laser. Temporal dissipative Kerr solitons (DKS) [52–54] enable the generation of low-noise ultra-short femtosecond pulses with repetition rates that can readily reach and exceed tens of GHz.

So far, microresonator combs have been employed in two proof-of-concept demonstrations of near-infrared astronomical spectrograph calibration. A DKS comb generated in a fused silica chip-based resonator whose line spacing of 22 GHz was stabilized and whose free-drifting offset was tracked was used for calibration of the NIRSPEC spectrograph [55]. In a parallel demonstration [56] a 24 GHz DKS comb, fully stabilized via pulsed driving [57, 58], was generated in a silicon nitride photonic-chip microresonator and used for calibration of the GIANO-B spectrograph. Recently, pulsed driving has enabled spectra comprising thousands of comb lines [59] and demonstrations of octave-spanning near-infrared spectra [60, 61] show that coverage of the entire near-infrared is possible. Moreover, first progress towards visible microresonator combs has been made using advanced waveguide geometries or exploiting second order optical nonlinearities [62–65]. Dark pulse combs operating in the normal dispersion regime [66] may provide new opportunities. An exciting prospect for microresonators might be their potential integration in future space-based observatories where compactness and low power consumption are key.

E. Four-wave mixing of continuous-wave lasers in fibers

Cascaded four-wave mixing (FWM) of two CW lasers in fiber can generate new laser frequencies with a line spacing defined by the original pump laser pair. While not ideal for high-resolution spectrographs, they are however of interest to low- and medium resolution instruments [67] and near-infrared systems with hundreds of GHz line spacing have been developed [68]. Sum-frequency generation in a BBO crystal provided additional wavelength coverage at red wavelengths and led to on-sky testing on the PMAS instrument [69]. FWM combs currently only offer wavelength-meter precision and accuracy. Phase-locking the two pump lasers to an auxiliary self-referenced low-repetition rate frequency comb could overcome these limitations.

III. Towards ultra-broadband astrocombs

The bandwidth demonstrated thus far by astrocombs has primarily been limited by challenges in nonlinear spectral broadening, which is difficult due to the high repetition rates and low pulse energies. Most astrocombs have relied on either highly-nonlinear optical silica fiber (HNLF) when centered around 1.5 μm, or photonic crystal fibers (PCF) when centered at 1 μm and below. While ongoing development shows the tremendous potential of PCF for ultra-broadband astrocomb generation [70], there are open challenges with regard to optically induced degradation by short wavelength light that can lead to rapid deterioration of the PCF performance [71].

Besides optical fibers, photonic chip-integrated waveguides have recently emerged as a nonlinear optical platform and already found use in one astrocomb system [48] . The ability to chose materials with high optical nonlinearity and geometries with favorable dispersion characteristics [72] combined with a small mode-cross section results in efficient nonlinear optical frequency conversion. Broadband spectra from sub-nJ pulses reaching also the visible domain [73–75], exploitation of combined second and third order optical nonlinearity [76, 77], broadband triple sum-frequency generation [50] as well as self-organized grating for phase-matching [78] have been demonstrated. The immunity of integrated waveguides to short-wavelength light remains to be investigated.

IV. Conclusion

Currently the most frequently deployed astrocombs are based on mode-filtered mode-locked lasers. Overcoming the complexity of the mode-filtering is a major motivation for the development of new approaches to astrocombs including higher repetition rate lasers, EOM-, microresonator- and FWM-based combs. Regardless of which approach to astrocomb generation is pursued, advances in nonlinear fibers and integrated nonlinear waveguides provide new opportunities for ultra-broadband spectral generation. Overall, the appearance of a new generation of ultra-stable high-precision spectrographsand improving analysis techniques are paralleled by rapid advances in astrocombs boding well for a new era of high-precision astronomical spectroscopy, in which the astrocomb forms one component of the complex radial velocity characterisation system.

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