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A search for optical laser emission from Proxima Centauri

G. W. Marcy ★
Center for Space Laser Awareness, 3388 Petaluma Hill Rd, Santa Rosa, CA 95404, USA

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ABSTRACT

A search for laser light from Proxima Centauri was performed, including 107 high-resolution, optical spectra obtained between 2004 and 2019 with the HARPS spectrometer. The search for laser light involved rejecting sharp peaks in the spectrum from stellar flares, fluorescent city lights, and elementary particles that directly hit the CCD detector. The search revealed unexpected spectral 'combs' found at equally spaced frequencies, which were not known to the observer nor to the builder of the spectrometer. But they came from stray, optical ghosts of light originating with an interferometric etalon filter and its light source at the telescope. Future observers must be aware of this contamination. The 107 spectra of Proxima Centauri show no evidence of any laser emission nor technological signatures of any type. Of special interest are 29 spectra obtained between March and July 2019 when the candidate technological radio signal, BLC1, was captured by Breakthrough Listen. This search would have revealed laser light from Proxima Centauri pointed toward Earth if the laser had a power at least 20 to 120 kilowatts (depending on wavelength) and was positioned within the 1.3 au field of view, assuming a benchmark laser launcher having a 10-m aperture. Smaller lasers would also have been detected, but would require more power.

Key words: extraterrestrial intelligence – sociology of astronomy – techniques: spectroscopic – stars: flare – stars: low-mass.

1 INTRODUCTION

Speculative models of the Milky Way Galaxy suppose that it may contain a network of mutually communicating spacecraft probes stationed near stars (e.g. Bracewell 1973; Freitas 1980; Maccone 2014; Gertz 2021; Hippke 2021; Maccone 2021). The probes may communicate by lasers to optimize privacy, achieve high bandwidth, and minimize payload, and the laser wavelengths may be ultraviolet, optical, or infrared (Schwartz & Townes 1961; Zuckerman 1985; Hippke 2018, 2020, 2021).

One signature of interstellar laser communication is the narrow range of wavelengths, nearly monochromatic, of its light (e.g. Su et al. 2014; Naderi et al. 2016; Wang et al. 2020). Searches for such laser communication have been carried out using high-resolution spectra of over 5000 normal stars of spectral type F, G, K, and M, yielding no detections and no viable candidates (Reines & Marcy 2002; Tellis & Marcy 2017). A similar search for laser emission from more massive stars of spectral type O, B, and A, has also revealed no viable candidates (Tellis et al., in preparation). These laser searches involved examining high-resolution spectra, $\lambda/\Delta\lambda > 60000$, in the wavelength range $\lambda = 3600$–9500 Å, for monochromatic emission lines. The required laser power for detection is 1–10 MW, assuming a diffraction-limited laser emitter consisting of a benchmark 10-m aperture. None was found.

Meanwhile, searches continue for radio-wave signatures of other technologies in the Milky Way, currently pursued by the Breakthrough Prize Foundation (e.g. Lebofsky et al. 2019; Price et al. 2020), the UCLA SETI Group (Margot et al. 2021), and by other radio telescopes. Using the Parkes radio telescope pointed at Proxima Centauri, the Breakthrough Prize Foundation LISTEN team discovered a signal at 982-MHz consistent with a technological origin (O'Callaghan & Billings 2020; Overbye 2020; Sheikh et al. 2020, 2021; Brin 2020; Koren 2021; Loeb 2021).

This radio signal and the proximity of its source of only 4.24 light years promote Proxima Centauri to the top of the target list in the sky for SETI observations. A technology there, only slightly advanced compared to ours, could detect specific human actions on Earth, digest them, and send an electromagnetic response to Earth within 8.5 yr. This paper describes a search for laser emission in 107 optical spectra of Proxima Centauri. A following paper describes another search, with a novel telescope, for laser emission coming from the Solar gravitational lens point of Proxima Centauri.

2 OBSERVATIONAL METHOD

I retrieved all 107 spectra of Proxima Centauri obtained with the HARPS spectrometer between 2004 February 25 and 2019 July 13 and kindly made available on the ESO public data archive (archive.eso.org). HARPS is a fibre-fed, high-resolution Echelle spectrometer at the ESO 3.6-m telescope at the La Silla Observatory in Chile (Mayor et al. 2003). I obtained the archived 1D extracted spectra, along with a wavelength scale calibrated in the Solar system barycentric frame (European Southern Observatory 2019). These wavelengths are Doppler shifted from the observatory frame to account for the orbital motion of the Earth around the Sun, the motion around the Earth–Moon barycenter, and the rotation of the Earth, accurate to within 0.1 ms^{-1}. The spectra have a nominal resolution of $\lambda/\Delta\lambda = 115\,000$ and span wavelengths, $\lambda = 3781$–6913 Å, and are rebinned to 0.01 Å per pixel.

★ E-mail: geoff.bnb@gmail.com

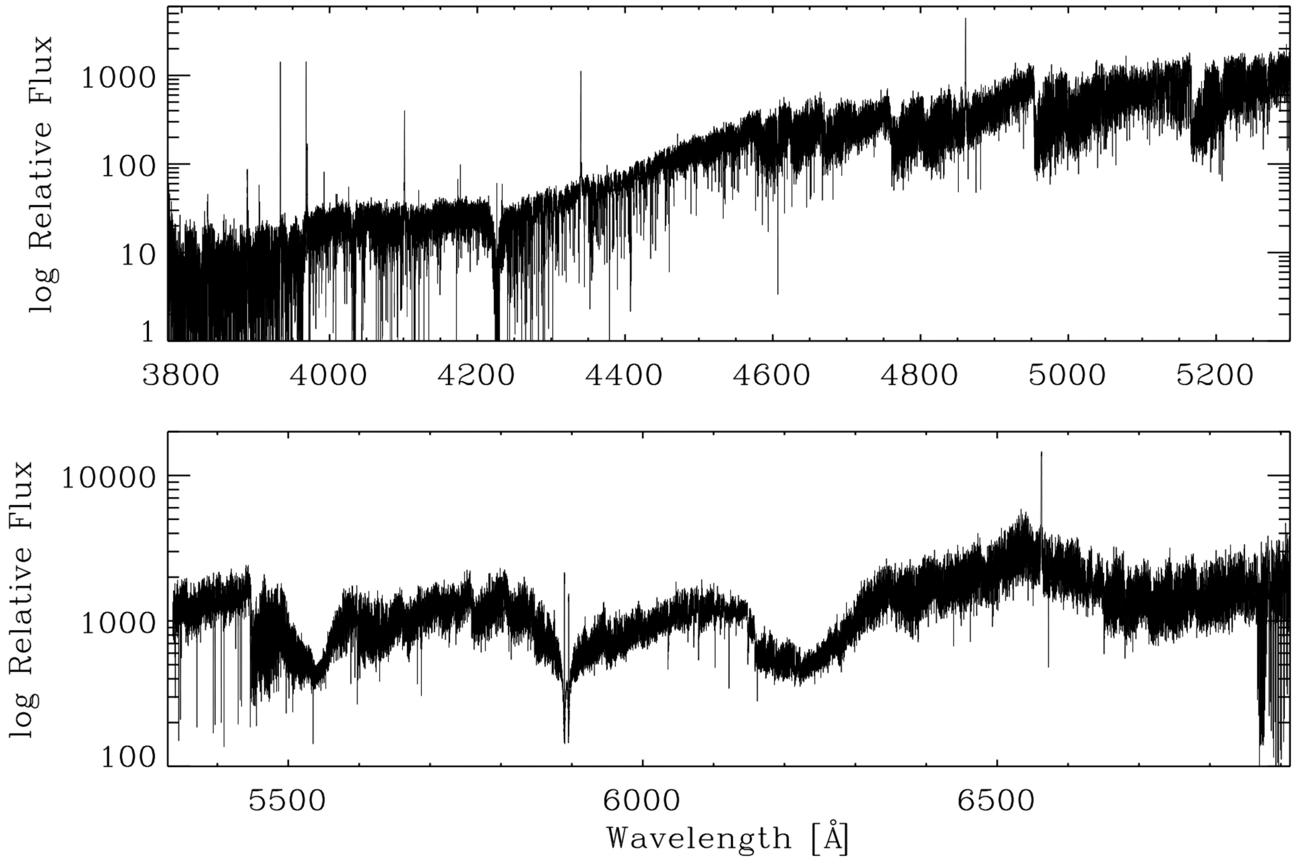

Figure 1. Representative optical spectrum of Proxima Centauri with no flare occurring, plotted as log photons per pixel vs. wavelength. Thousands of atomic and molecular absorption lines are visible, typical of spectral type dM5.5. The emission lines deserve examination and interpretation. The signal-to-noise ratio varies from 5 to 40 (blue to red) due to the spectral energy distribution of Proxima Centauri and throughput of the spectrometer.

The spectra of Proxima Centauri were taken between 2004 and 2019 within four different observing programs, all listed and described in the Acknowledgments section. All spectra were obtained on the 3.6-m ESO telescope, with exposure times of typically 15 min and reduced by the standard HARPS pipeline, yielding signal-to-noise ratios in the stellar light-flux continuum of typically 30 per resolution element.

Figure 1 shows a typical spectrum of Proxima Centauri on a log intensity scale to exhibit the flux from blue to red in the stellar continuum. The spectrum contains thousands of atomic and molecular absorption lines (appearing as upside-down 'grass'), typical for stars of spectral type dM5.5. The spectrum also contains many emission lines that may compromise the search for laser emission. I also examined 95 HARPS spectra of 'comparison' stars that are located within 2° of Proxima Centauri (Vmag = 11.1), namely HD125881 (Vmag = 7.25, G2V), HD126793 (Vmag = 8.2, G0). Both comparison stars were observed with similar exposure times as was Proxima Centauri, and both stars are sufficiently faint to reveal night-sky lines or artefacts that could masquerade as laser emission.

I verified the spectral resolution by examining spectral lines that are intrinsically narrower than the nominal instrumental profile, notably the two night-sky emission lines [O I] 5577 and [O I] 6300 and telluric O_2 absorption lines. Those diagnostic lines displayed a full width at half-maximum (FWHM) of 6 pixels, corresponding to 0.06 Å, consistent with a spectral resolution of at least $\lambda/\Delta\lambda$ = 100 000, as shown in Fig. 2.

These diagnostic spectral lines normally exhibit widths slightly greater than the instrumental profile due to small pressure broadening and thermal broadening occurring in the Earth's atmosphere along the line of sight to the star. Both effects cause broadening of less than 20 per cent over that of the instrumental profile, which explains their widths being slightly greater than implied by the nominal resolution of $\lambda/\Delta\lambda$ = 115 000. *Any laser emission line at a wavelength, λ, must have a spectral width, $\Delta\lambda$, at least as broad as given by* $\lambda/\Delta\lambda$ = 115 000, as verified by these diagnostic spectral lines in Fig. 2.

The entrance fibre of HARPS has a diameter that projects to 1.00 arcsec on the sky. The original circular fibres were replaced with octagonal cross-section fibres in 2015 May of similar size cross-section. Proxima Centauri is 1.302 pc from Earth (Gaia DR3 2020). Thus, the fibre collects light from a cone extending outward with a 1-arcsec opening angle covering a footprint of diameter 1.30 au at Proxima Centauri. Any light emitted from within that cone and directed toward Earth could be detected in these spectra. Light originating outside that cone obviously cannot be detected. Thus, this search for laser emission from Proxima Centauri can identify laser sources located within a cone-shaped volume having a diameter of 1.3 au there and extends into the background behind the star, along the line to Earth. The small fibre aperture prevents us from assessing, in the raw CCD images, the angular extent on the sky of any spectral emission, as enabled by a long entrance slit (Tellis & Marcy 2017).

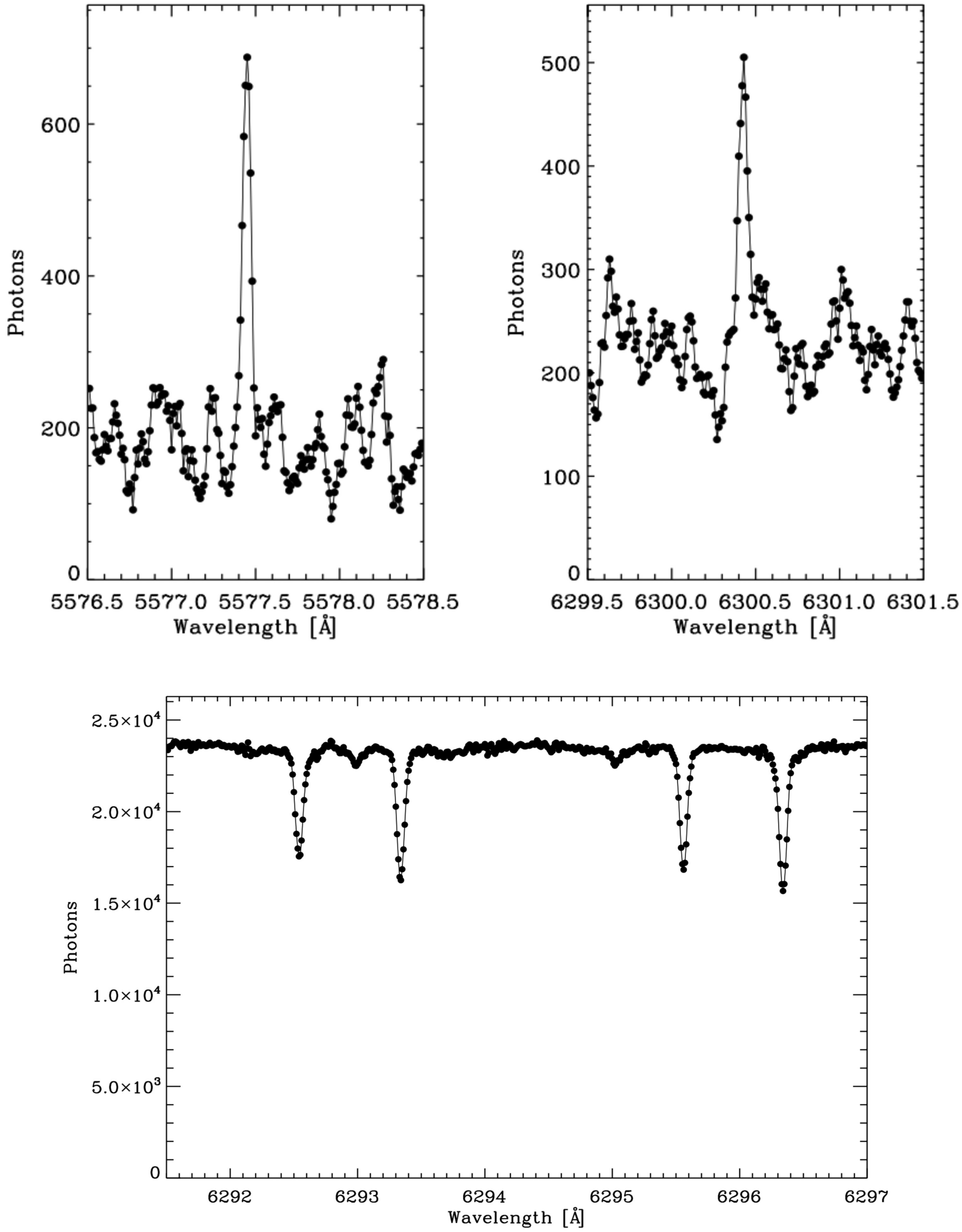

Figure 2. Proxies of the instrumental profile of HARPS in photons per pixel at the CCD vs. wavelength. Top panel: observed night sky emission lines, [O I] 5577 Å and [O I] 6300 Å in the spectrum of Proxima Centauri. Bottom panel: absorption lines due to molecular oxygen in the Earth's atmosphere. All proxies exhibit FWHM = ∼6 pixels (0.060 Å), implying resolution better than $\lambda/\Delta\lambda = 100\,000$. Any laser emission line must have FWHM at least 6 pixels wide.

3 SPECTRAL EMISSION DURING FLARES ON PROXIMA CENTAURI

I searched for laser emission lines in all 107 spectra of Proxima Centauri. The emission could arrive as a single frequency of light emitted by a single laser. Alternatively, the emission could arrive as a series of closely spaced frequencies of light that are smeared together by the instrumental profile of HARPS, creating an apparent spectral emission line that is broader than the instrumental profile. We thus search for non-astrophysical emission lines that are as broad or broader than the instrumental profile (Fig. 2).

I first identified the astrophysical emission lines associated with flares and chromosphere on Proxima Centauri. All of the spectra show prominent Balmer lines in emission, typical of heating by magnetic fields in the upper atmospheres of M dwarfs (e.g. Reiners & Basri 2008; Hawley et al. 2014). The Balmer emission lines are ten times more intense during times of flaring compared with times of no flares, as shown in Fig. 3, in the bottom panel compared to the top panel. During flares, emission also occurs at the NaD lines 5892 Å, He I 5876 Å, He II 4868 Å, and the Ca II H&K lines, all typical during flares of M dwarfs.

Figure 4 shows the detailed shape of the spectral emission lines from He I and He II during one of the flares of Proxima Centauri. Atmospheric modelling of optical emission lines from Proxima Centauri indicates gas in excess of 10 000 K in its chromosphere, its flare regions, and in an extended corona-like hot envelope (Pavlenko et al. 2017). The flares on Proxima Centauri occur many times

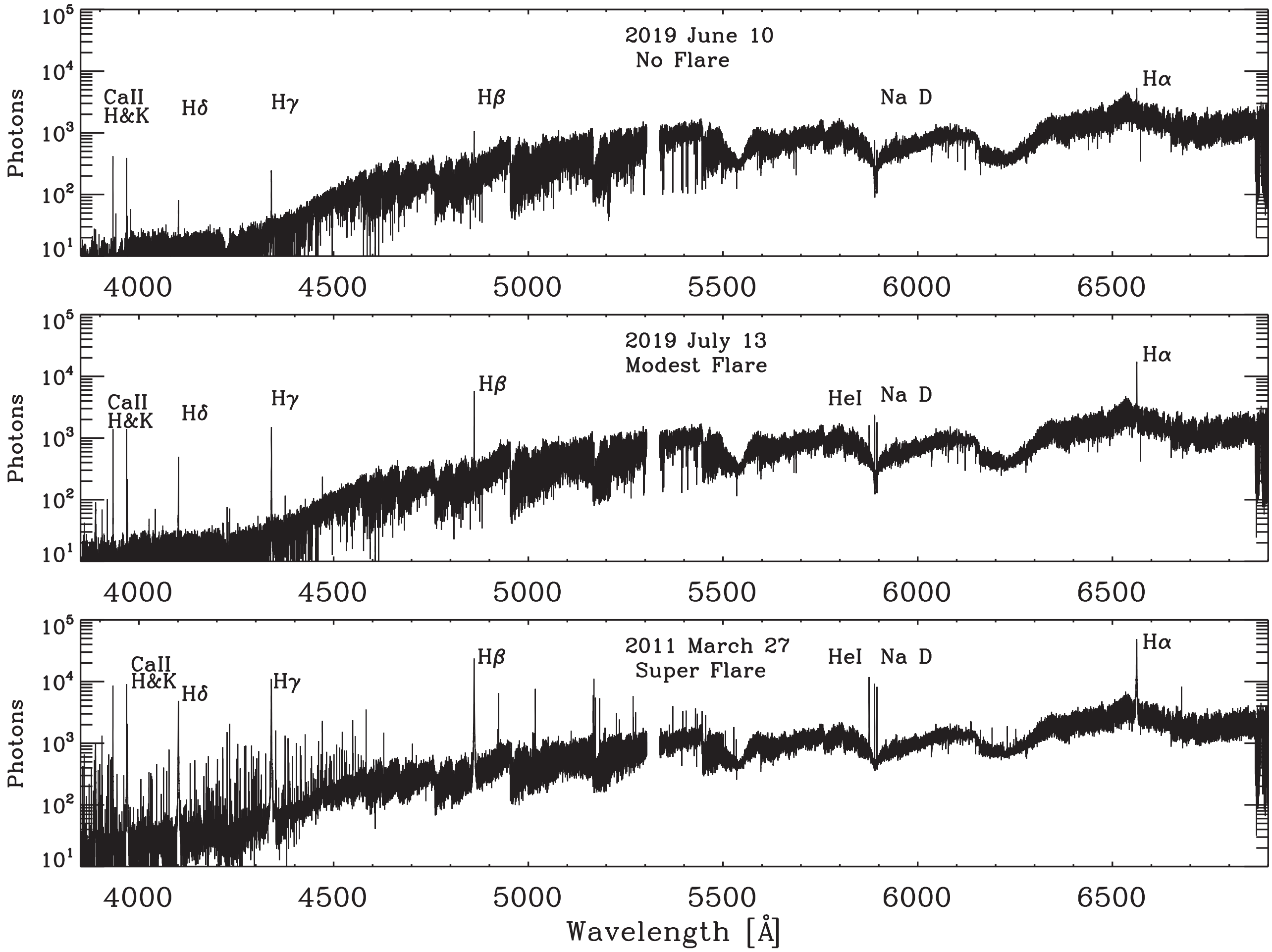

Figure 3. Three representative spectra of Proxima Centauri, during times of no flare (top panel), modest flare (middle panel), and superflare (bottom panel) in photons per pixel at the CCD per 0.01 Å, on a log intensity scale. Emission in Balmer lines, NaD, He I, and Ca II H&K are prominent, and many other transitions from heavy elements appear during superflares.

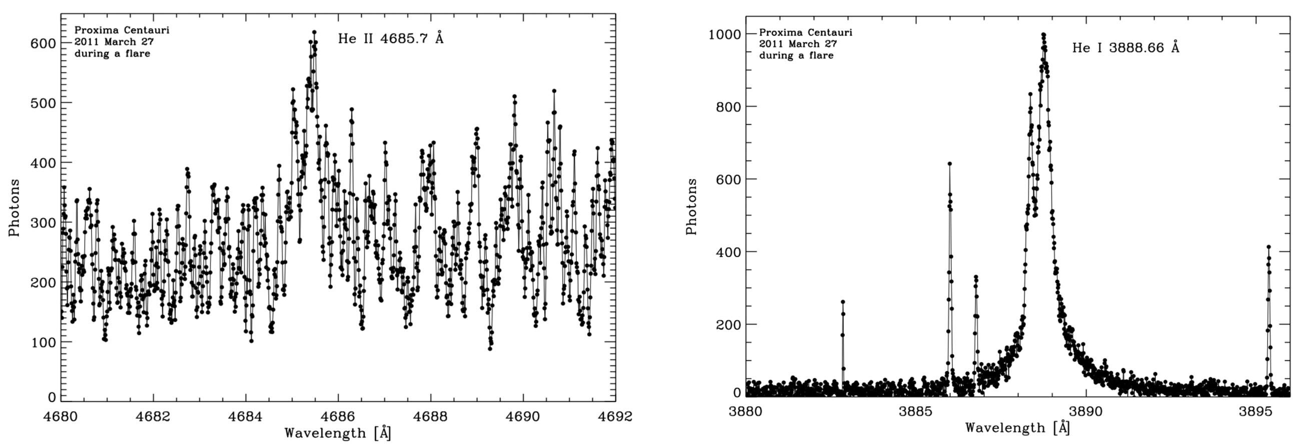

Figure 4. Photons per pixel vs. wavelength showing emission from He II 4685.7 and He I 3888.66 during strong flares that occur in 5 out of 95 spectra of Proxima Centauri, indicating plasma temperatures of ∼10 000 K and production of UV and X-ray photons, consistent with direct measurements (e.g. Howard et al. 2018 and Zic et al. 2020). The narrow emission lines are from heavy elements (Fig. 5).

per day, last for many minutes, and emit bursts of electromagnetic radiation at radio to X-ray wavelengths, including brightening at visible wavelengths by a factor of 100 during its 'super flares' (e.g. Howard et al. 2018; Zic et al. 2020). I searched for high-excitation and high-ionization emission in the HARPS Echelle spectra of Proxima Centauri, and indeed there are several prominent examples. Fig. 4 shows emission from ionized and neutral helium, requiring temperatures over 10 000 K and excitation of 20 eV, consistent with

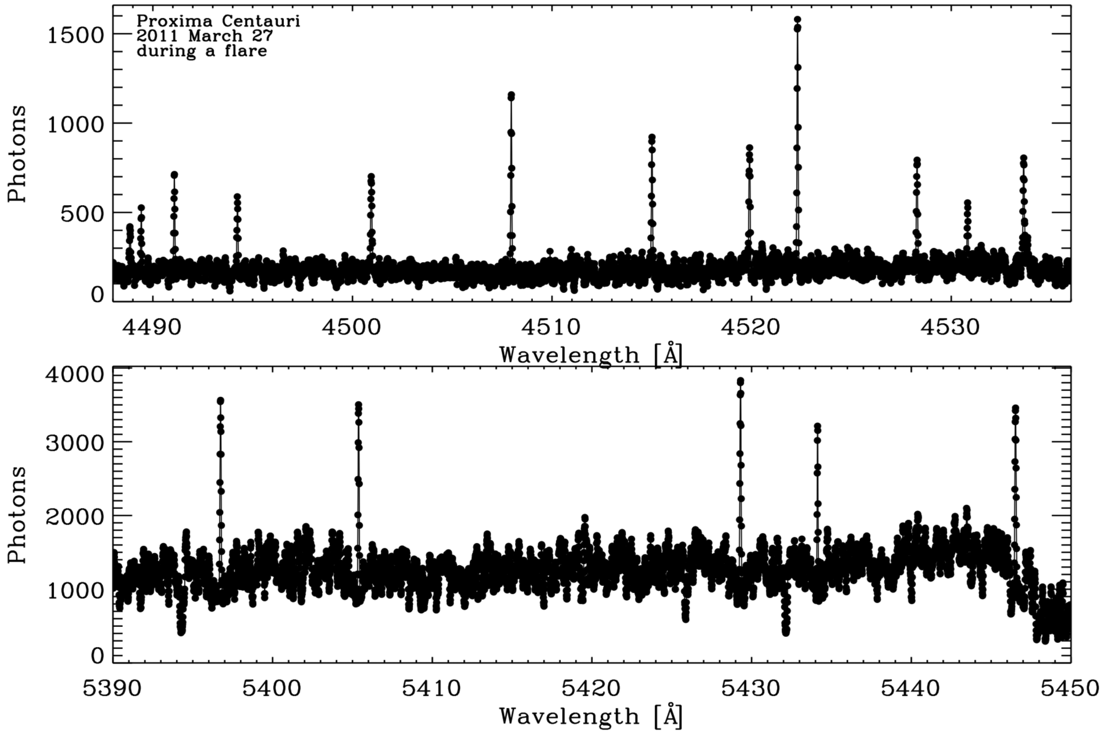

Figure 5. Emission lines from atomic transitions that normally appear in absorption from the photosphere, arising from Fe I, Fe II, and Ti II during a flare on Proxima Centauri. The plot gives photons per pixel vs. wavelength. The lines have widths (FWHM) of ∼6 pixels consistent with the instrumental profile of the HARPS spectrometer convolved with a small thermal broadening in gas at a temperature of 10 000 K. These natural emission lines have widths indistinguishable from those of technological lasers, making optical SETI difficult.

UV and X-ray from flares, and radio-wave emission from cyclotron processes.

Remarkably, hundreds of narrow emission lines also appear in spectra of Proxima Centauri during the strongest flares, as shown in the bottom panel of Fig. 3 and in the zoom of wavelength regions shown in Figs 5 and 6. Figs 5 and 6 show emission lines arising from common atoms such as iron and titanium normally formed in absorption in the photosphere due to a declining source function. These remarkable lines in emission include prominently Fe I, Fe II, and Ti II (e.g. Davenport et al. 2012).

These flare lines are formed at ∼10 000 K, causing thermal broadening widths of ∼2.3 $\mathrm{km\,s^{-1}}$ coupled with convective overshoot fluid motion in the photosphere of ∼1 $\mathrm{km\,s^{-1}}$, yielding a quadrature sum of 2.5 $\mathrm{km\,s^{-1}}$. The instrumental profile has a width of 2.6 $\mathrm{km\,s^{-1}}$ ($\lambda/\Delta\lambda = 115\,000$), giving an expected line width from the quadrature sum of 3.6 $\mathrm{km\,s^{-1}}$, corresponding to an expected linewidth of 6.0 pixels at 5000 Å. Indeed, the observed widths of the flare lines in Figs 5 and 6 are typically slightly more than 6 pixels.

These spectral emission lines shown in Figs 5 and 6 arise from heavy atoms in the magnetically heated upper atmosphere where the radiative transfer source function is inverted. These lines appear commonly in emission in other M dwarf flare stars and T Tauri stars, and they appear in the spectra of Solar-type stars in absorption. These narrow emission lines from heavy elements in Proxima Centauri have roughly the same shape as spectral lines arising from technological laser emission. *Thus, the identification of candidate laser emission from Proxima Centauri is complicated by the hundreds of stellar emissions lines, having widths only slightly greater than the instrumental profile, that occur naturally and commonly during flares of Proxima Centauri*

4 SEARCH FOR LASER LINES

I established a method to search for laser emission in the 107 high-resolution spectra of Proxima Centauri. The algorithm must avoid the rich molecular bands in absorption and dozens of spectral lines in emission that occur sporadically and often in the magnetic chromosphere and flare regions. This spectral and temporal variability forces adoption of a generous threshold for candidate laser lines at five times the stellar continuum intensity. I created a continuum-normalized spectrum by computing a median-smoothed spectrum with a smoothing width of 1000 pixels corresponding to 10 Å. I divided each spectrum of Proxima Centauri by its median-smoothed spectrum to produce a spectrum with a pseudo-continuum normalized to 1.0.

Setting the detection threshold for laser lines is not simple. Qualitatively, emission lines (from chromosphere or flares) can be securely detected against the diverse molecular features if they extend to a normalized intensity of 5.0 and higher, suggesting a threshold for laser emission. This threshold is not rigorously optimized by a statistical criterion, nor can it be. Thousands of absorption lines from molecules in the photosphere prevent the identification of a definite spectral 'continuum'. Also, there are hundreds of emission lines that come and go with flare activity. Further, direct cosmic-ray hits often rise as high as 10x the stellar counts in the pixels. The spectral landscape does not offer a statistically definable topography against which to set a statistically rigorous threshold for culling laser-line candidates. Eyeball examination of the 107 spectra of Proxima Centauri reveals that a threshold of five times the pseudo-continuum will yield a few dozen candidate laser lines.

Specifically, the detection criterion for emission lines is as follows. The observed peak intensity within a 0.01-Å pixel must be five times

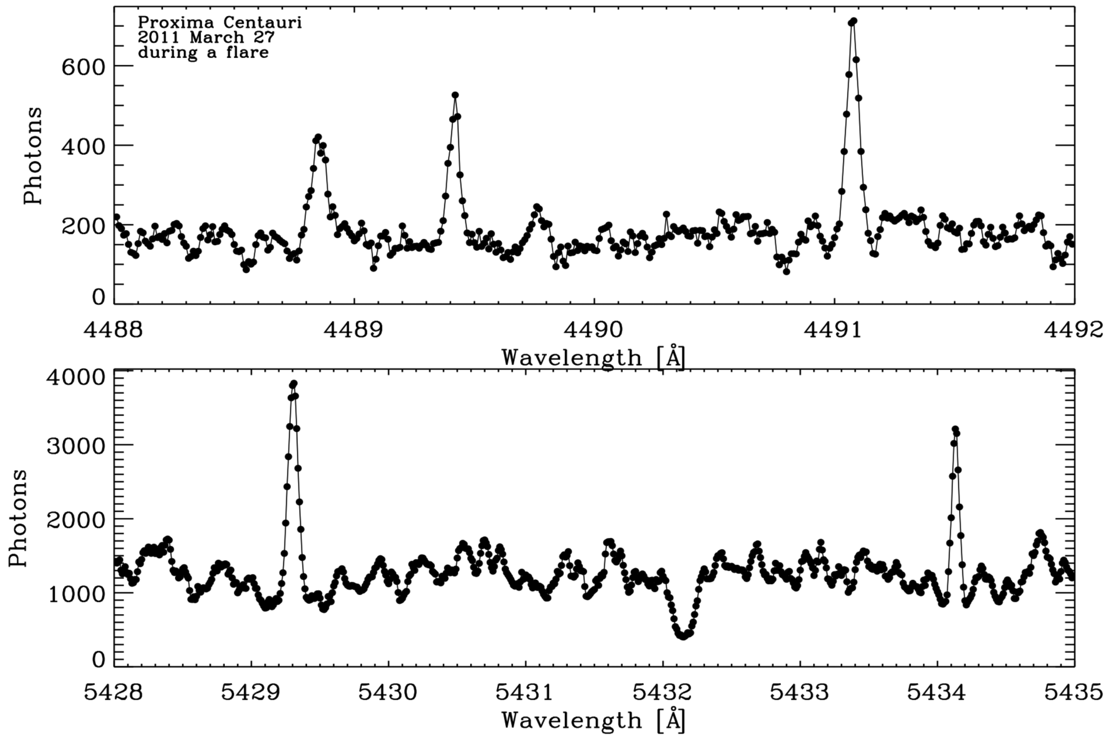

Figure 6. Magnified view of a few emission lines appearing in Fig. 5. The lines arise from Fe and Ti in the 10 000 K flare regions. The widths of the lines are ~6 pixels, caused by the instrumental profile convolved with thermal broadening resulting from flare temperatures of roughly 10000 K, making these lines difficult to distinguish from the technological, monochromatic emission expected from an optical laser. Lasers of kW and MW power may have intrinsic line widths up to many Angstroms due to structural and thermal imperfection caused by high energy density.

the median intensity of the star's spectrum within 0.01 Å, with the running median computed in 10-Å segments. The star's 10-Å median intensity is, of course, a function of wavelength. Further, there is a criterion for the line width in wavelength. Candidate emission lines must have a width (FWHM) between that of the instrumental profile (~0.05 Å) and 5 Å. The upper limit in line width at 5 Å is set by the median smoothing width noted above. I note that broad emission, up to 5 Å wide, can occur either by a tight cluster of narrow laser lines smeared by the spectrometer's instrumental profile or by one fat laser line.

I searched the full wavelength extent of all 107 spectra of Proxima Centauri for any 'emission line' meeting the detection threshold defined above. Roughly, one-third of the spectra have such emission. Many of these emission lines were narrower than the FWHM of 6 pixels that characterizes the instrumental profile (see Fig. 2). These narrow 'emission' features are likely due to elementary particles hitting the CCD directly, including cosmic rays (often secondary muons) and beta and gamma-rays coming from natural radioactivity in the Earth and observatory structures. Fig. 7 exhibits two of these events from elementary particles. They are too narrow to be from light that passed through the spectrometer, eliminating them as candidate laser lines.

I searched all 107 spectra of Proxima Centauri for emission lines having a peak intensity at least five times the continuum intensity and having widths with FWHM > 5 pixels, consistent with the instrumental profile. Six candidates emerged, all shown in Fig. 8. Among them, close examination revealed five having widths slightly less than the minimum, FWHM > 6 pixels, required to be consistent with the instrumental profile of the HARPS spectrometer (Fig. 2). In addition, some candidate lines have wings or double peaks inconsistent with the instrumental profile, making them not credible candidates of laser emission that entered the telescope and optical system. They are likely to be due to direct impacts on the sensor by elementary particles.

The remaining candidate consists of a cluster of approximately 10 emission lines, all within 1.5 Å in the wavelength interval, 4184.0–4185.5 Å. The 'comb' of lines exhibits an arch-like envelope of intensity, weakest at the short and long wavelengths and stronger near the central wavelengths. This comb appears in all 57 spectra taken during 10 nights between 2013 May 4 and May 14 (UT). The comb is accompanied by regions of excess, noise-like light at UV and blue wavelengths both shortward of 4000 Å and less so longward. In contrast, none of the 49 spectra of Proxima Centauri taken on other dates between 2004 and 2019 exhibits that emission comb. This emission comb is not mentioned in the published paper by Anglada-Escudé et al. (2016) that presents these spectra, nor does that paper mention using any unusual calibration lamp or light source.

Figure 9 displays the 57 comb emission spectra overplotted (left-hand panel) and summed (right-hand panel). These show that the wavelengths of the teeth of the comb were nearly the same, within 0.05 Å, in all exposures on 10 nights. Many possible explanations for the spectral combs were considered, one by one, requiring a careful consideration of the viability of each one. Among the explanations were some flare-related emission, contamination from laser guide star beams at La Silla Observatory, sum-frequency pairing of those laser wavelengths, Zeeman splitting of some atom (Reiners & Basri 2008) in Proxima Centauri, and emission of technological origin. There was no Doppler drift relative to the observatory, pointing to a local source, rather than at Proxima Centauri.

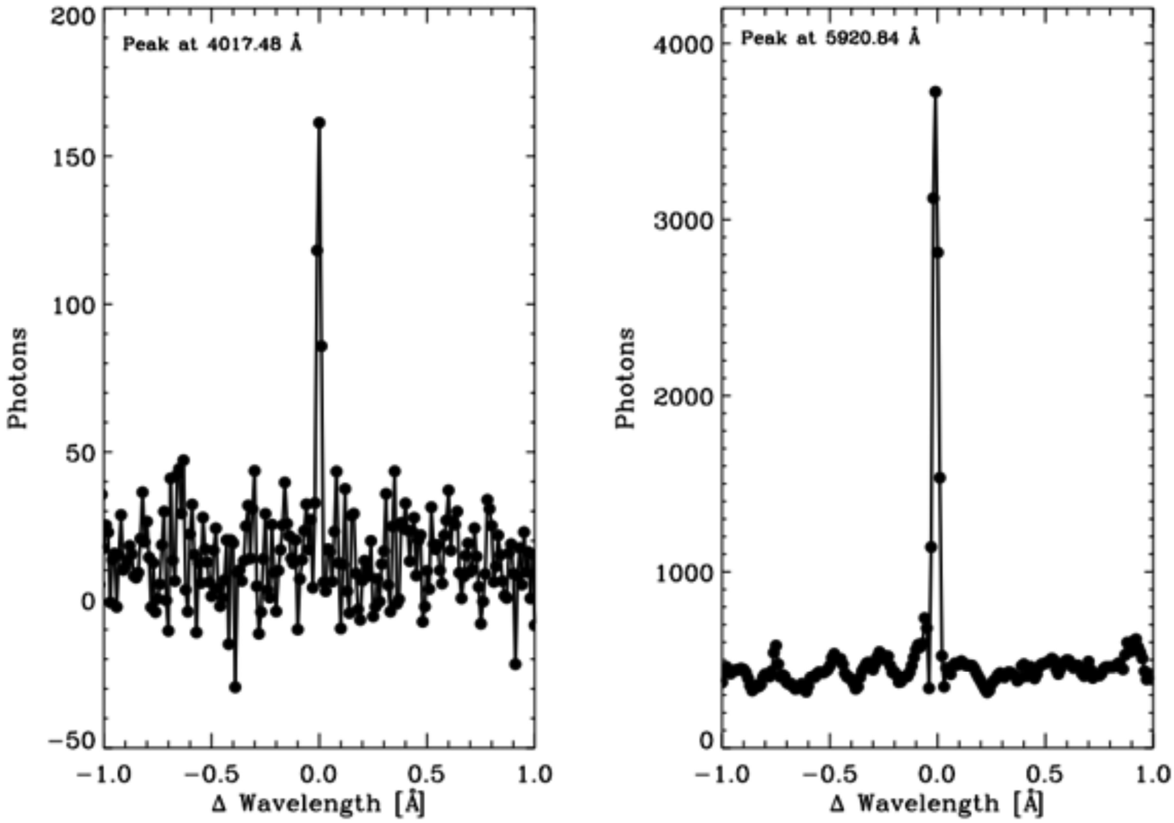

Figure 7. Two representative 'emission features' more intense than our threshold for laser emission from Proxima Centauri, in photons per pixel vs. wavelength. However, they have widths narrower than the ∼5-pixel FWHM of the instrumental profile of the HARPS spectrometer. Such features did not pass through the spectrometer and are likely due to high-energy particles hitting the CCD directly. We reject such features from further consideration.

5 EXPLANATIONS OF THE COMBS IN THE SPECTRA OF PROXIMA CENTAURI

One possibility is that the ESO 3.6-m telescope itself was experimenting with, or using, Fabry–Perot etalons or laser combs, with an option to use such calibration lamps to obtain high Doppler precision (European Southern Observatory 2019). The FITS headers of the spectra in 2013 May contain no reference to a Fabry–Perot etalon, a simultaneous th-ar lamp, nor any other fringe-producing device such as a laser comb. The paper by Anglada-Escudé et al. (2016) describing these spectra of Proxima Centauri does not contain a mention of a Fabry–Perot etalon nor a laser comb. That paper describes each HARPS spectrum, 'the wavelength of which is calibrated using a hollow cathode lamps (Th-Ar)'. Anglada-Escudé et al. (2016) describe this observing run, '2013 May: 143 spectra obtained on three consecutive nights between 4 and 7 May and 25 additional spectra between 7 and 16 May with exposure times of 900 s'. There is no mention of any source of 'combs', 'fringes', 'Fabry–Perot etalons', or any interferometric device.

To investigate the origin of the combs, I communicated with the principal investigator of the observations of Proxima Centauri in May 2013, Guillem Anglada-Escudé in January 2021. He kindly offered much useful information, and he wrote that no interferometric devices were used. He kindly offered the possibility that 'ghost spectra come from the secondary fibre'. But he stated that he 'switched off the calibration light completely . . . to avoid that precisely'. I thank Dr. Anglada-Escudé for his generous information. However, it appears a lamp was actually on, as described below.

The raw CCD images of Proxima Centauri are shown in Fig. 10, exhibiting the expected horizontal stripes that are the spectral orders of the stellar spectrum of Proxima Centauri from the HARPS spectrometer. Absorption lines are apparent to the eye. Parallel and above each stellar spectral order is a sequence of emission lines, barely resolved. This is clearly light from a Fabry–Perot etalon filter and a lamp shining through it. No such Fabry–Perot filter nor lamp was supposed to be on, according to published papers and the astronomers present during that run. That spectrum from the Fabry–Perot filter is parallel to the stellar spectrum and does not overlap it. Therefore, by itself, the Fabry–Perot spectrum is not the cause of the combs.

However, there are faint diagonal stripes of light slicing through the spectral orders (Fig. 10). These are optical 'ghosts' caused by internal reflections within the grism cross-dispersor of the HARPS spectrometer. Neither the Fabry–Perot fringes nor the ghosts were known to exist in these spectra. The diagonal ghosts consist of interferometric fringes that intersect and thus contaminate the spectra of Proxima Centauri, creating the combs.

Apparently, the Fabry–Perot etalon and its lamp were left on during the entire 10-night observing run in 2013 May, which was not known. I queried the chief scientist of the HARPS spectrometer, Francesco Pepé. He kindly investigated the images and stated, 'I confirm that simultaneous Fabry–Perot was used. I confirm that what you observe is on both 1D and 2D spectra. It is localized to about 1-Å width and occur once per Echelle order at "arbitrary" position'. The source of the comb is now confirmed to be the Fabry–Perot etalon and its lamp, along with an optical ghost.

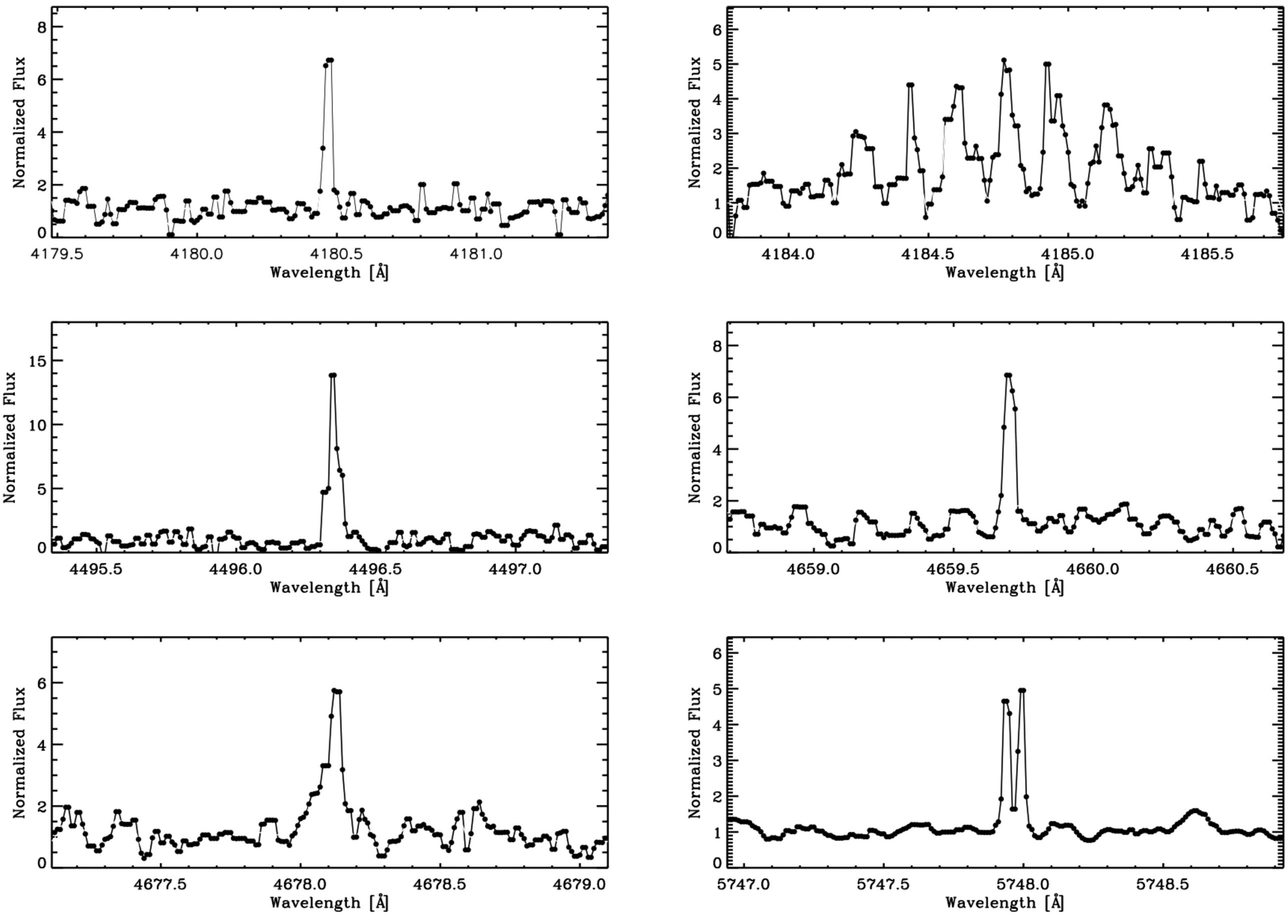

Figure 8. Unvetted candidate laser lines that emerged from our search of 107 high-resolution spectra of Proxima Centauri. All spectra are normalized to place the stellar continuum at 1. Five candidates have widths less than that of the instrumental profile FWHM = 6 pixels (see Fig. 2), thereby eliminating them as light that passed through the optics. They may be elementary particles that hit the CCD. The last candidate (upper right-hand panel) consists of a comb of perhaps 10 emission lines between 4184 and 4185.5 Å that were unidentified. This emission comb appears in 57 of 107 spectra of Proxima Centauri, but not in the 75 spectra of comparison stars, HD125881 or HD126793.

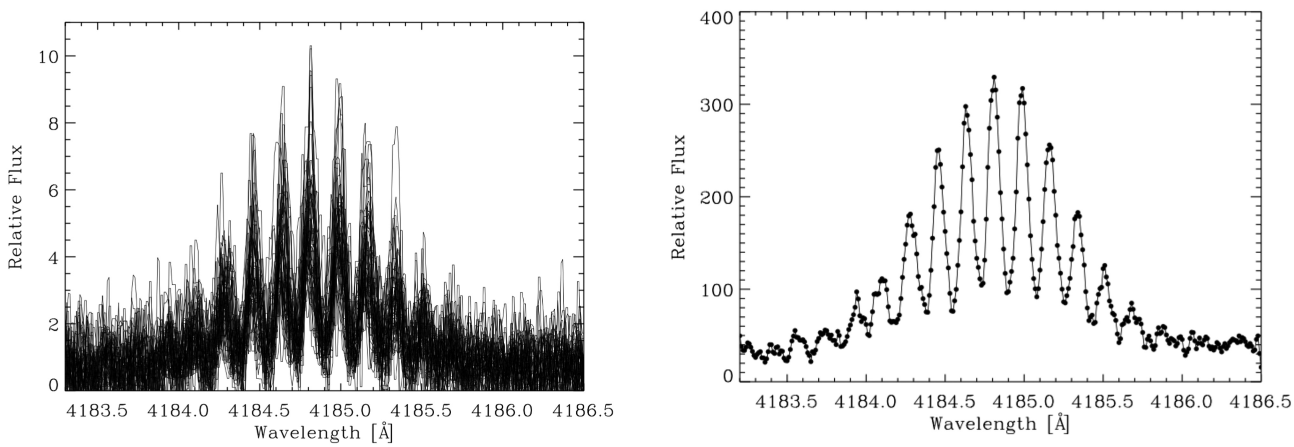

Figure 9. The repeated occurrence of a spectra comb in the spectra of Proxima Centauri. Left-hand panel: overplot of all 57 spectra of Proxima Centauri near 4184.8 Å, of Proxima Centauri taken between 2013 May 5 and 14. The comb fringes appear at nearly the same wavelengths on all 10 nights, within ∼0.05 Å, implying a Doppler drift $<4\ \mathrm{km\ s^{-1}}$. Right-hand panel: the sum of the 57 spectra at the comb region. The fringes are nearly equally spaced by 0.175 Å and have shapes only slightly wider than the instrumental profile (Fig. 2), indicating narrower intrinsic shapes.

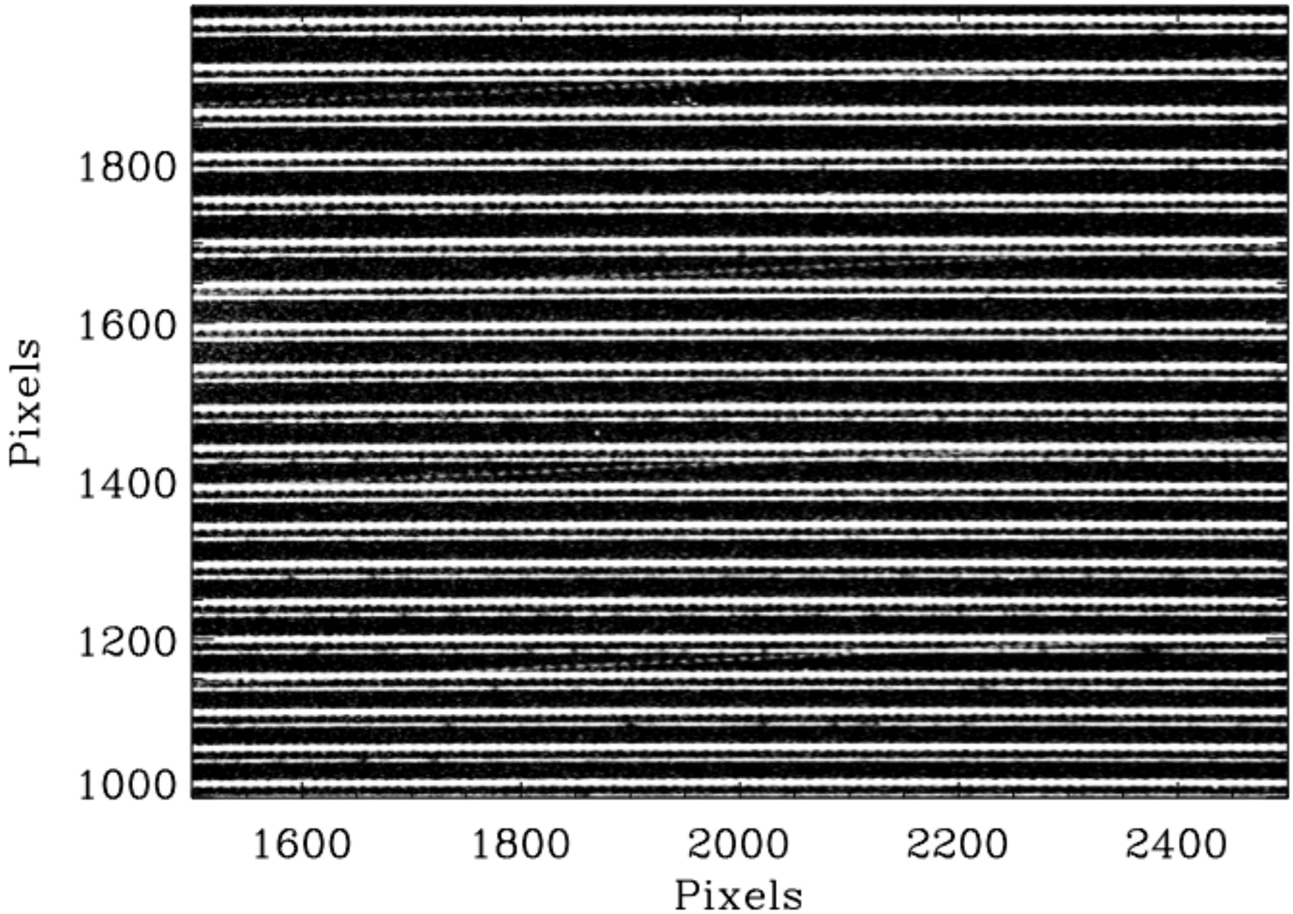

Figure 10. A portion of the raw CCD image of the HARPS Echelle spectrum of Proxima Centauri, with longer wavelengths at the top. The double horizontal stripes are the spectral orders, containing two spectra. Fainter and below is the spectrum of the star, as expected. Above each of them is the spectrum of the Fabry–Perot wavelength calibration lamp, which was not previously known to be present. Faint diagonal stripes are caused by the ghost produced by the unintended internal reflections in the grism cross dispersor. These ghosts send faint interferometric fringes slashing through the spectrum of Proxima Centauri.

The 12 comb fringes in each of hundreds of spectra obtained during that 10-night run may have slightly compromised the Doppler measurements used to search for planets. The combs appear at wavelengths that are artificially Doppler shifted in each spectrum, on time-scales of hours, days, and months. The comb emission does not participate in the Doppler shift caused by the Earth's motion around the Solar system's barycenter, while the light from Proxima Centauri (and all observed stars) is Doppler shifted by the Earth's motion. The combs cover a total of 20 Å of spectrum and are ∼five times brighter than the light from Proxima Centauri, implying spectral contamination that is Doppler shifting in the Solar system barycenter frame. Thus, the 12 combs that are stationary in wavelength may dilute the measured Doppler shift of the spectrum. One amelioration is that the spectrum 'template' against which the Doppler shifts are measured presumably does not contain comb-like fringes. If so, the Doppler measurements may suffer from extra noise rather than systematic errors. I suspect the Doppler measurements were affected only slightly.

6 THE CHALLENGE OF SETI

This paper summarizes a lengthy effort to explain the 'comb' feature in the spectra of Proxima Centauri. As the feature surely comes not from that star but from the HARPS spectrometer at the observatory, the report of this circuitous effort could be removed from this paper. However, the effort represents a common challenge of SETI observations, worthy of discussion.

A challenge of SETI is that every unexpected attribute of the data might be a 'signal'. Every data quirk must be examined in sufficient depth to explain it in terms of known phenomena. All unexpected results in the data, i.e. 'non-canonical phenomena' (Singam et al. 2020), could be caused by such effects as the unexpected performance of novel equipment, an unexpected natural phenomenon here on Earth, human error in data-taking technique or analysis, or none of the above. SETI is the search for 'none of the above'.

SETI research thus requires that every data quirk be understood, *a posteriori.* One cannot go back in time to the moment the quirk appeared in the original data to confirm, with care, the arrival of a signal. Such time-travel would permit the use of other telescopes, spectrometers, cameras, or calibrations that were specifically designed to confirm or reject the original candidate signal. Such hypothesis-driven experiments are profoundly different, and simpler, than searching for unknown phenomena (Singam et al. 2020). When a data-quirk is detected, any actual electromagnetic wave comprising the signal has already passed the Earth at light speed.

One cannot let any unexpected data quirks go unvetted because the first extraterrestrial signal will be unprecedented. Any unexplained, potential signal must be examined exhaustively, lest the cherished signal remain dubious. Cutting-edge scientific equipment and the experiments at the frontier are particularly fraught with unexplained quirks in the data. SETI observations, per force, examine domains where no one has gone before.

Equally daunting is that the Bayesian 'prior' probability of credibility is low for any claim of a detected extraterrestrial signal. A casual poll of astronomers shows that the prior is less than 10 per cent, no matter the apparent quality of the claimed SETI detection, for many reasons.

1. Astronomers have searched the night sky for 40 yr, every night, using advanced imaging and spectroscopy, at all wavelengths and employing dozens of professional 3–10-m class telescopes. The yield is no technological signals. Thus, a large slice of the multidimensional search space observable by modern technology has already been observed. See Wright, Kanodia & Lubar (2018) for a broader view.

2. Artefacts of other technologies have been sought, including images of the Moon and Mars and the Lagrange points in the Solar System. Those implicit searches yielded no artefact

3. The past 60 years of explicit SETI searching has yielded no detections (Wright, Kanodia & Lubar 2018).

4. The past century of exploration of the Earth has yielded no non-human eroded spacecraft or structures on land nor under the ocean (Wright 2017; Frank et al. 2018; Schmidt & Frank 2019; Shostak 2020).

5. Technological entities will likely build optical or IR interferometric telescope arrays in space having kilometer baselines enabling the detection of chlorophyll, oxygen build-up, and city lights on Earth, encouraging them to send probes here (Zuckerman 2019). If so, the lack of detections of those probes may reflect their desire to remain hidden. The prior must reflect this possibility.

Some of these five reasons may be overstated, but probably not all of them. The product of these priors cannot be quantified, but yields a probability of successful detection much less than 1, to be multiplied by the claimed probability of veracity of each reported signal. The final prior probability is much less than unity, and is the origin of the common intuition that SETI may require decades or centuries for success.

7 LASER DETECTION THRESHOLDS FOR PROXIMA CENTAURI

This search for light of technological origin from Proxima Centauri revealed no such spectral signatures nor even any candidates. One may determine the laser power that would have been detected from Proxima Centauri, following the approach of Tellis & Marcy (2017). The dominant obstacle against detecting laser light is the flux of light from the star at each wavelength. Proxima Centauri has such low intrinsic luminosity, $L = 0.0017 L_{\rm SUN}$, that laser light of relatively little power can outshine the star as seen by a telescope in the beam.

The detection threshold for laser emission applied to the spectrum was five times the photon flux of starlight, shown in Fig. 3. The photons gathered in the pixels varied from ~20 photon pixel^{-1} at 4000 Å, to 1000 photon pixel^{-1} at 5000 Å, to just over 4000 photon pixel^{-1} at 6500 Å (Fig. 3), representing the approximate number of photons acquired by the 3.6-m telescope in the 900-s exposure. One may translate those photon rates to intrinsic luminosity at each wavelength using the absolute spectrophotometry by Stone (1996) of M dwarf standard stars, shown in figure 15 of Tellis & Marcy (2017). A laser must be five times as intense as the stellar luminosity, at a specific wavelength, to meet the detection criterion here. Any such laser emission that spans a range of wavelengths between the width of the instrumental profile (~0.05 Å) and up to 10 Å would be detected.

To determine the required laser power that can be detected, one may adopt a touchstone laser light launcher yielding power requirements that can be scaled to any other laser. The touchstone laser emits a diffraction-limited beam from a laser-launcher with an aperture having a diameter of 10 m. The laser is located in the vicinity of Proxima Centauri. The beam has an opening angle with a first null at an angle, theta = 1.2 λ/D from the optical axis, where λ is the wavelength of light and D is the laser aperture equal to 10 m. The opening angle is 0.013 arcsec at 5000 Å. Such a laser beam intercepts the Earth with a circular footprint having area, $A = \pi\,(1.2\,\lambda\, d/D)^2$, where d is the distance to Proxima Centauri, $d = 1.302$ pc (Gaia DR3 2020). At 5000 Å, the footprint at the Earth of the laser beam has a radius of 0.013 au and an area of 1.2×10^{19} m^2.

For Proxima Centauri, the power required to detect the light from a touchstone laser is 20 kW at 4000 Å, 50 kW at 5000 Å, and 120 kW at 6500 Å. These power requirements are remarkably low because of the low luminosity and the proximity of Proxima Centauri. A dim star is easily outshined by a laser, as viewed from within its beam and at its wavelength. This analysis would have detected visible-light lasers of such power if launched from a 10-m laser launcher at Proxima Centauri that was pointed at Earth. For reference, continuous-wave lasers on Earth can operate for many minutes at power levels over 1 Megawatt.

For assumed laser launchers of a smaller aperture, the required laser power would have to be greater to permit detection. For example, a 1-m laser launcher would have to be hundred times more powerful than the requirements above. Short laser pulses from Proxima Centauri would also have been detected. The efficiency of HARPS is 5 per cent and the 3.6-m telescope collecting area is ~10 m^2. The detection method here would have detected a pulse of photons at Earth greater than 300 photon m^{-2} at 4000 Å and 10000 photon m^{-2} at 5000 Å, for laser pulses of arbitrarily short duration, including sub-nanosecond. The 900-s exposure of the spectrum simply integrates the arriving photons for the duration the pulse. No such laser pulses were detected.

8 DISCUSSION AND SUMMARY

Examination of 107 high-resolution spectra of Proxima Centauri, obtained during the years 2004 to 2019, revealed no spectral features of technological origin, notably laser light. Laser beams having power of 20 to 120 kW, depending on wavelength, would have been detected, if launched from optics similar to the largest telescopes on Earth of 10-m diameter. For smaller laser launchers, the power requirements for detection increase inversely as the square of their size. The laser power requirement of 20–120 kW is remarkably small, as solar panels on a roof-top can generate such power, and continuous lasers on Earth can emit such power. The required technology is not exotic, as even modern humanity can construct such lasers.

The Breakthrough Listen team, using the Parkes radio telescope in 2019 April and May, recorded a radio signal at 982 MHz lasting 2.5 h, calling it 'BLC1' (O'Callaghan & Billings 2020; Overbye 2020; Koren 2021; Loeb 2021; Sheikh et al. 2021). The radio signal resides within a narrow frequency range, less than a few Hertz, which is much narrower than emitted by most astrophysical sources such as flares and cyclotron radiation from magnetic fields and stellar coronae. The BLC1 signal had a slight *upward* frequency drift (Sheikh et al. 2021), which is unexpected. The Doppler effect caused by the Earth's orbital motion around the sun would cause a *downward* Doppler frequency shift (i.e. the 'eeeeooooow' pitch of a race car going by—in either direction), thus presenting a puzzle regarding the origin of the frequency drift. The signal appears to come from a region within a cone 20-arcmin wide, centred on Proxima Centauri, but it could come from one of the sidelobes of the Parkes telescope and receiver.

Among the 107 optical spectra of Proxima Centauri described in this paper, 29 were observed between 2019 March and July, fortuitously encompassing the 2019 April/May radio-wave detection of BLC1. None of the 29 optical spectra exhibited any sign of laser light or other technological signals. We thus failed in our effort to support BLC1.

This non-detection of laser light from Proxima Centauri was complicated by interferometric, optical 'ghosts' from the HARPS spectrometer. Such undocumented and idiosyncratic behaviour of frontier-level optics highlights the challenge of SETI. Every unprecedented 'signal' in the data may require weeks or months to discover the quirk of Earth-bound technology (or even nature) that actually produced it. Any fruitless search for the cause of the quirk still leaves conventional explanations viable, albeit unidentified. Most conventional explanations for quirks are located near, or above, the observatory. Thus, *SETI observations would benefit from simultaneous operation of at least two telescopes, separated by at least 1 km, to rule out local false alarms, to provide parallax of signals from satellites, and thus to promote plausibly real signals for further analysis. The second telescope can be smaller, sufficient to produce 3σ confirmation of 10σ detections.*

Proxima and Alpha Centauri are optimal targets for continued SETI observations. Any technological entities there could use a radio telescope or an interferometric infrared telescope (e.g. Dandumont et al. 2020) to detect signals coming from Earth, such as our radar beacons or city lights (Zuckerman 2002). Detecting such signals from Earth starting 80-yr ago, they could deploy a probe for closer surveillance (Gertz 2021; Hippke 2020, 2021). Travelling at a mere 1/20 the speed of light, a probe could traverse the 4.2 light years, and be near the Solar system already.

The ensuing communication between the probe here and its home-base at Proxima or Alpha Centauri may be accomplished with lasers emitting infrared, optical, or UV frequencies. Tight laser beams offer private communication, 10-GHz bandwidth, and vital defensive stealth. A modest, meter-size laser at Proxima Centauri could spotlight a region smaller than the Earth–Sun distance near our Solar system, enabling their transmission to avoid Earth entirely. This scenario is consistent with the non-detection of laser light found here.

A variation of this scenario involves using the Sun as a gravitational lens to amplify the laser communication (Hippke 2020, 2021). We have carried out observations of the Solar gravitational lens point of both Proxima and Alpha Centauri to search for ongoing laser communication between the two neighbouring star systems (Marcy et al., in preparation).

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DATA AVAILABILITY

This paper is based on data products, reduced spectra, and raw images, obtained with ESO 3.6-m Telescope at the La Silla Observatory. All data are available to the public at the ESO archive: https://www.eso.org/sci/facilities/lasilla/instruments/harps/tools/archive.html.

The data can be retrieved by entering 'Proxima Centauri' into the archive website.

The spectra used in this paper were obtained on the ESO 3.6-m telescope and the HARPS spectrometer between 2004 and 2019 within four programs. The first program was under the direction of PI/Co-I Mayor, Benz, Bertaux, Bouchy, Pepe, Perrier, Queloz, Sivan, Udry, Delfosse, Forveille, Santos, Moutou, Barge, Deleuil, Schmidt, Guillot, Lovis, and Bonfils, titled 'A high-precision systematic search for exoplanets in the Southern Sky'. The second program had PI/Co-I Bonfils, Delfosse, Forveille, Gillon, Perrier, Santos, and Udry titled, 'Transits of Telluric Exoplanets Orbiting M Stars'. The third and fourth programs were led by PI Anglada-Escude and others to study M dwarfs, including Proxima Centauri.

The spectra were obtained under four programs. The first was ID 072.C-0488E, HARPS-Guaranteed Time, led by Michel Mayor, contributing 19 spectra obtained between May 2005 and July 2008, with integration times between 450 and 900 s. The second and third programs were ID 082.C-0718(B) and ID183.C-0437(A), both led by X.Bonfils that contributed 8 and 46 spectra with exposure times of 15 min. The fourth program, 191.C-0505(A), was led by G. Anglada-Escuda contributing 70 spectra between 2013 May 4 and 16, and another 23 spectra between 2013 December 30 and 2014 January 10. We are grateful for the publicly archived high-resolution spectra obtained with the HARPS spectrometer maintained by the European Southern Observatory (ESO). We thank the PI and CoI's of the HARPS program for the design, construction, observations, and reduction of the HARPS spectra, namely, Drs Mayor, Benz, Bertaux/Bouchy, Pepe, Perrier, Queloz, Sivan, Udry, Delfosse, Forveille, Santos, Moutou, Barge, Deleuil, Schmidt, Guillot, Lovis, Bonfils, Delfosse, Forveille, Gillon, Perrier, Santos, and Anglada-Escude et al.

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