



# No Transits of Proxima Centauri Planets in High-Cadence TESS Data

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Proxima Centauri is our nearest stellar neighbor and one of the most well-studied stars in the sky. In 2016, a planetary companion was detected through radial velocity measurements. Proxima Centauri b has a minimum mass of 1.3 Earth masses and orbits with a period of 11.2 days at 0.05 AU from its stellar host, and resides within the star's Habitable Zone. While recent work has shown that Proxima Centauri b likely does not transit, given the value of potential atmospheric observations via transmission spectroscopy of the closest possible Habitable Zone planet, we reevaluate the possibility that Proxima Centauri b is a transiting exoplanet using data from the Transiting Exoplanet Survey Satellite (TESS). We use three sectors (Sectors 11, 12, and 38 at 2-min cadence) of observations from TESS to search for planets. Proxima Centauri is an extremely active M5.5 star, emitting frequent white-light flares; we employ a novel method that includes modeling the stellar activity in our planet search algorithm. We do not detect any planet signals. We injected synthetic transiting planets into the TESS and use this analysis to show that Proxima Centauri b cannot be a transiting exoplanet with a radius larger than  $0.4 R_{\oplus}$ . Moreover, we show that it is unlikely that any Habitable Zone planets larger than Mars transit Proxima Centauri.

**Keywords:** stellar activity, algorithms, exoplanet detection methods, stellar flares, M dwarf stars

## 1 INTRODUCTION

M dwarf stars' small sizes make them particularly advantageous when it comes to exoplanet detection via both radial velocity and transit methods. However, these low-mass stars are frequently highly magnetically active for long portions of their lifetimes, which can confound detection and further characterization of planets orbiting such stars. White light flares may induce radial velocity shifts, increasing noise in RV measurements and hindering planet detections (Saar and Donahue 1997; Korhonen et al., 2015; Andersen and Korhonen 2015). Furthermore, white light flares may also contaminate or even completely mask planetary transits in light curves, once again complicating planet detection (Oshagh et al., 2013; Gilbert et al., 2021).

Proxima Centauri (Proxima, Prox Cen) is the nearest star to our own Solar System and a well known flare star (Thackeray 1950; Shapley 1951). Proxima Centauri is an M5.5 dwarf star with an estimated age of  $\sim 5$  Gyrs (Thévenin et al., 2002). Proxima Centauri is extremely active, producing near-constant flares at a variety of wavelengths (e.g. MacGregor et al., 2021). Owing to its proximity, Proxima Centauri is one of the most well-studied stars in the sky, and as such, has been a prominent target for exoplanet searches for many years (e.g. Holmberg 1938; Benedict et al., 1999; Kürster et al., 1999; Endl and Kürster 2008; Lurie et al., 2014).

## OPEN ACCESS

### Edited by:

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### Specialty section:

This article was submitted to  
Exoplanets,  
a section of the journal  
Frontiers in Astronomy and Space  
Sciences

**Received:** 01 September 2021

**Accepted:** 11 October 2021

**Published:** 19 November 2021

### Citation:

Gilbert EA, Barclay T, Kruse E,  
Quintana EV and Walkowicz LM (2021)  
No Transits of Proxima Centauri  
Planets in High-Cadence TESS Data.  
Front. Astron. Space Sci. 8:769371.  
doi: 10.3389/fspas.2021.769371

Despite the challenges posed by observing an active star, in 2016 Anglada-Escudé et al. (2016) used radial velocity measurements to uncover Proxima Centauri b, a minimum mass  $1.3 M_{\oplus}$  planet orbiting Proxima Centauri with a period of 11.2 days. With an orbital semi-major axis of 0.05 AU, Proxima Centauri b has an estimated  $T_{eq}$  of  $T = 234$  K (Anglada-Escudé et al., 2016) and resides in the star's Habitable Zone (Kopparapu et al., 2013). A tentative detection of an outer companion, Proxima Centauri c, was announced later in 2020 (Damasso et al., 2020), once again detected through radial velocity. Proxima Centauri c has a minimum mass of  $5.8 \pm 1.9 M_{\oplus}$  and an orbital separation of 1.48 AU with a period of 5.2 years. Both of these planets were found via the radial velocity method, but from the geometry of the system, it is possible to determine the probability of transits of either planet occurring. Given its orbital separation from its host star, the geometric probability that planet b transits is around 1.5% (Anglada-Escudé et al., 2016), and at 1.5 AU, the probability of planet c transiting is negligible.

While neither planet is known to transit, if either planet (or another yet undiscovered planet) were found to transit, the prospects for follow-up would be significant. A precise radius would allow for accurate determination of the planets' compositions, and a transit would enable transmission spectroscopy observations. Furthermore, given the location of Proxima Centauri b within the habitable zone of its host star, and its short orbital period which would provide ample transit opportunities, it would be an ideal target to search for the presence of biosignatures. Missions such as the upcoming James Webb Space Telescope (JWST) would be able to confirm the presence of an atmosphere on Proxima Centauri b if it does in fact have one (Kreidberg and Loeb 2016) through thermal phase curve analysis.

Given the significance of a nearby, habitable zone planet, since the discovery of Proxima Centauri b, a number of teams have studied Proxima Centauri to definitively rule out Proxima b as a transiting exoplanet (Anglada-Escudé et al., 2016). found no evidence of transits in all available photometric light curves and noted a 1.5% geometric probability of transit.

Kipping et al. (2017) observed Proxima Centauri for 43.5 days from 2014–2015 with *MOST* space telescope. While they were unable to recover planet b in the photometry, they did see two candidate transit signals with the expected depth of a transiting planet the size of Proxima Centauri b. Their efforts were hindered by the frequent flaring of the host star, and they determined their false-negative detection rate to be 20–40%.

Li et al. (2017) used a robotic 30 cm telescope at Las Campanas Observatory to observe Proxima for 23 nights in 2016. They found inconclusive evidence for transits of planet b, and they also found an additional transit candidate that was inconsistent with the transit window of Proxima b, perhaps indicating an additional planet.

Liu et al. (2018) used the Bright Star Survey Telescope at the Zhongshan Station in Antarctica to observe Proxima Centauri, conducting a 10-days long photometric monitoring campaign in 2016. This work also detected a transit-like signal consistent with the RV orbital parameters of planet b, but were unable to definitively confirm a transit of Proxima b.

Blank et al. (2018) conducted a multi-year search for transits of Proxima Centauri b spanning 2006–2017. This search utilized of 329 observations from telescopes across the world and they were

unable to verify the previous claims of tentative transit detections corresponding to Proxima Centauri b, although they do confirm the presence of significant photometric variability of the host star due to flares. Feliz et al. (2019) built off of this work and conducted a transit search for periods ranging from 1–30 days using 262 high-quality light curves from the Blank et al. (2018) analysis. They conducted a series of planet injection tests and find that their methods are sufficiently sensitive to have detected transits of five millimagnitude depth and see no evidence of periodic transit-like events over the 1–30 day period range. However, due to incomplete phase coverage of the light curves and a lack of sensitivity to transits shallower than four millimagnitudes, they cannot rule out a detection of transits of Proxima Centauri b.

(Jenkins et al., 2019) used 48 h of *Spitzer* data to search for transits of Proxima b at 4.5 microns, going further to the infrared in an effort to mitigate the effects of stellar activity. With this data, they were able to rule out planetary transits at the 200 ppm level, putting a  $3\sigma$  upper limit on the radius of Proxima Centauri b at  $0.4 R_{\oplus}$ .

Many of the above searches indicate that the frequent flaring activity hinders their transit searches and may be masking transits of planet b, or other planets in the system. The Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al., 2015) has revolutionized our ability to study white light flares in great detail. TESS aims to observe the entire sky at optical/near-IR wavelengths in order to search for nearby, transiting exoplanets in high-cadence photometry. For 200,000 targets, spanning nearly the entire sky, TESS has collected high-precision photometry at 2-min cadence, allowing us an unprecedented window into the Proxima Centauri system.

In this work, we present a new analysis using TESS data to search for transits of Proxima Centauri b. In **Section 2**, we describe the TESS observations used in this analysis. Next, we describe our data reduction, transit search, and injection and recovery test in **Section 3**. We present a discussion of these results in **Section 4**, and conclude with a summary in **Section 5**.

## 2 DATA AND OBSERVATIONS

TESS observed Proxima Centauri in 2019 from April 23–June 18 during observing Sectors 11 and 12, and then again from April 29–May 26, 2021 in observing Sector 38<sup>1</sup>.

The Sector 11 observations totalled 26.04 days between orbits 29 and 30, from 2019 April 23 [1,596.77203 TESS Julian Date (TJD)] 2 to 2019 May 20 (1,623.89147 TJD) with 1.08 days of downtime in observations for data downlink using Camera 2, CCD<sup>2</sup>.

<sup>1</sup>Proxima Centauri was observed in Sectors 11, 12 and 38 through the inclusion of the star in 16 Guest Investigator programs: G011129 (PI: Jao, Wei-Chun), G011153 (PI: Pineda, J. S.), G011180 (PI: Dressing, C.), G011183 (PI: Kane, S.), G011185 (PI: Davenport, J.), G011231 (PI: Winters, J.), G011264 (PI: Davenport, J.), G011266 (PI: Schlieder, J.), G03273 (PI: Vega, L.), G03225 (PI: Pineda, J. S.), G03205 (PI: Monsue, T.), G03174 (PI: Howard, W.), G03250 (PI: Winters, J.), G03226 (PI: Silverstein, Mi.), G03202 (PI: Paudel, R.), G03227 (PI: Davenport, J.).

<sup>2</sup>TESS timestamps are Barycentric Julian Date—2,457,000.

Sector 12 observations of Proxima occurred during TESS orbits 31 and 32, on Camera 2, CCD 1, from 2019 May 21 (1,624.94979 TJD) to 2019 June 18 (1,652.89144 TJD) for a total of 26.90 days of science data with a 1.04 days gap for data downlink.

TESS Sector 38 observations of the target were conducted from 2021 April 29 (2,333.84945 TJD) to 2021 May 26 (2,360.55083 TJD) during orbits 83 and 84 for 25.74 days of science with a 0.96 days gap between the orbits to download data. These observations of Proxima were taken on Camera 2, CCD 2.

The 2019 data were collected at 2-min cadence and the 2021 data at both 2-min and in the new 20-s cadence mode. These data were processed by the TESS Science Processing Operations Center (SPOC) pipeline (Jenkins et al., 2016), and archived at the Mikulski Archive for Space Telescopes (MAST). We retrieved the light curves used in this analysis from MAST using *lightkurve* (Lightkurve Collaboration et al., 2018). Proxima Centauri is bright in the TESS bandpass at  $T_{\text{mag}} = 7.6$ , providing ideal an ideal target to search for planets.

### 3 METHODS

Proxima Centauri is an active star, emitting frequent white light flares. We see 2–3 + large flares every day in the 2-min cadence TESS light curve (Vida et al., 2019), and even with TESS 2-min cadence, optical photometry, it can be hard to fully resolve flare morphology in order to search for transits. Davenport et al. (2016) even suggest that the visible-light light curve of Proxima Centauri may be so dominated by flares that the time series can be thought of as primarily a superposition of many flares. This level activity can complicate the search for transiting exoplanet because of the additional noise in the data. Typical method of dealing with large flares is to identify them and remove them either by using flare detection algorithms or simple sigma-clipping. Here we take a different approach, we identify the flares using a custom algorithm, and then model the flares using a template, subtract these flares from the data, and then perform the transit search. We then inject transits into the light curve to test our sensitivity to transiting planets.

#### 3.1 Flare Detection and Modeling

We detected flares using an updated version of *bayesflare* (Pitkin et al., 2014) modified to process TESS data. For this look at Proxima Centauri, we used the 2-min cadence TESS data for Sectors 11, 12, and 38. Although 20-s cadence data exist for Sector 38, we elected to only use the 2-min cadence light curves for continuity and because 20-s data does not provide additional signal-to-noise in the transit search.

After identifying flares automatically with *bayesflare*, we opted to manually correct any poor estimates of flare parameters (primarily duration that were too long), added flares that may not have been detected through the flare detection routine, and ensured that complex flares are fitted properly by including additional secondary peaks. In total we included 201 flares in the model (67 in Sector 11, 78 in Sector 12, and 56 in Sector 38), and for each flare (or component of a complex flare) we have

estimates of the flare peak-time, full-width at half-maximum (FWHM), and amplitude.

We then used *xoflares* (Barclay and Gilbert 2020) to measure the properties of the flares. Typically, *xoflares* would use the PyMC3 framework to performing probabilistic sampling of flare properties. However, here we are less concerned with understanding the precise properties of the flares, but rather, just need a “good enough” model that can be calculated rapidly—our goal is not to be statistically principled in the flare modeling. Therefore, we calculated a *maximum a priori* (MAP) model through an optimization of the flare parameters and use that in our analysis. The model was parameterized in terms of the flare peak time, the inverse of the FWHM and the amplitude, and a mean level. The priors on the MAP fit are Gaussian for all parameters with a mean from the initial flare search and standard deviation of 0.003 days for the peak time, and 50% of the mean estimate for the inverse FWHM and amplitude. The flare amplitudes and FWHMs are constrained to be positive. We use a Student-t likelihood of the data rather than a Gaussian because it is more forgiving of outliers.

After calculating a MAP model we subtracted it from the observed data and then sigma-clipped large outliers. These outliers were usually the result of a sub-optimal fit to the flare amplitude (a few are visible in **Figure 1**). Data more than to  $+5/-10\sigma$  from the median of the MAP model subtracted data are clipped, where the asymmetry comes from not wanting to clip any transits. Then we calculated a second order Savitzky-Golay with a window-length of 1.1 days, and subtracted it from the original data (flare include) data to capture and remove long-term trends. We then went through the flare fitting and sigma-clipping steps a second time and were left with the “quiescent” light curve that can be searched for planets.

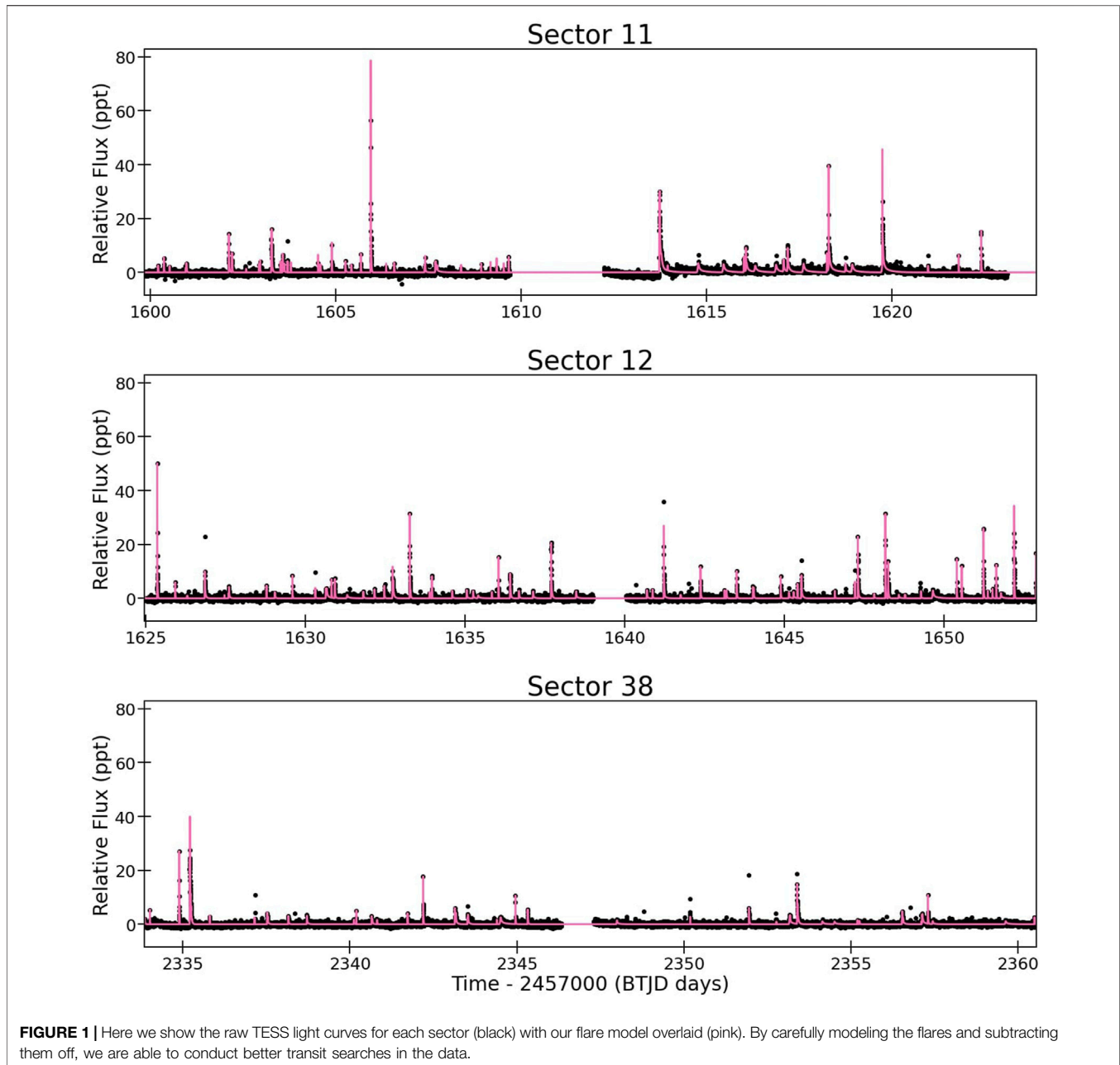
The flare model can be seen in **Figure 1** and the cleaned light curve with flare model subtracted (and sigma-clipped) that we use to search for planets is shown in **Figure 2**. There is still come non-Gaussian noise in the data, but it is low enough to facilitate transiting planet searches for low signal-to-noise signals.

#### 3.2 Planet Searches

We used two different planet search algorithms to attempt to detect a planet in the Proxima Cen data. We first used the Transit Least Squares (TLS) software (Hippke & Heller 2019), with all three sectors of data, and then again with just Sector 11–12. We used the default search parameters aside from changing the mass and radius of the host star to match that of Proxima Centauri. No planetary signals were detected with orbital periods between 1 and 30 days at a significant above  $2\sigma$  in each of the search methods. Following the methods of Kruse et al. (2019), we also used the Quasiperiodic Automated Transit Search (QATS) planet search method. QATS allows planets to have a transiting-timing variations and still be recovered, but we again did not find any significant signals.

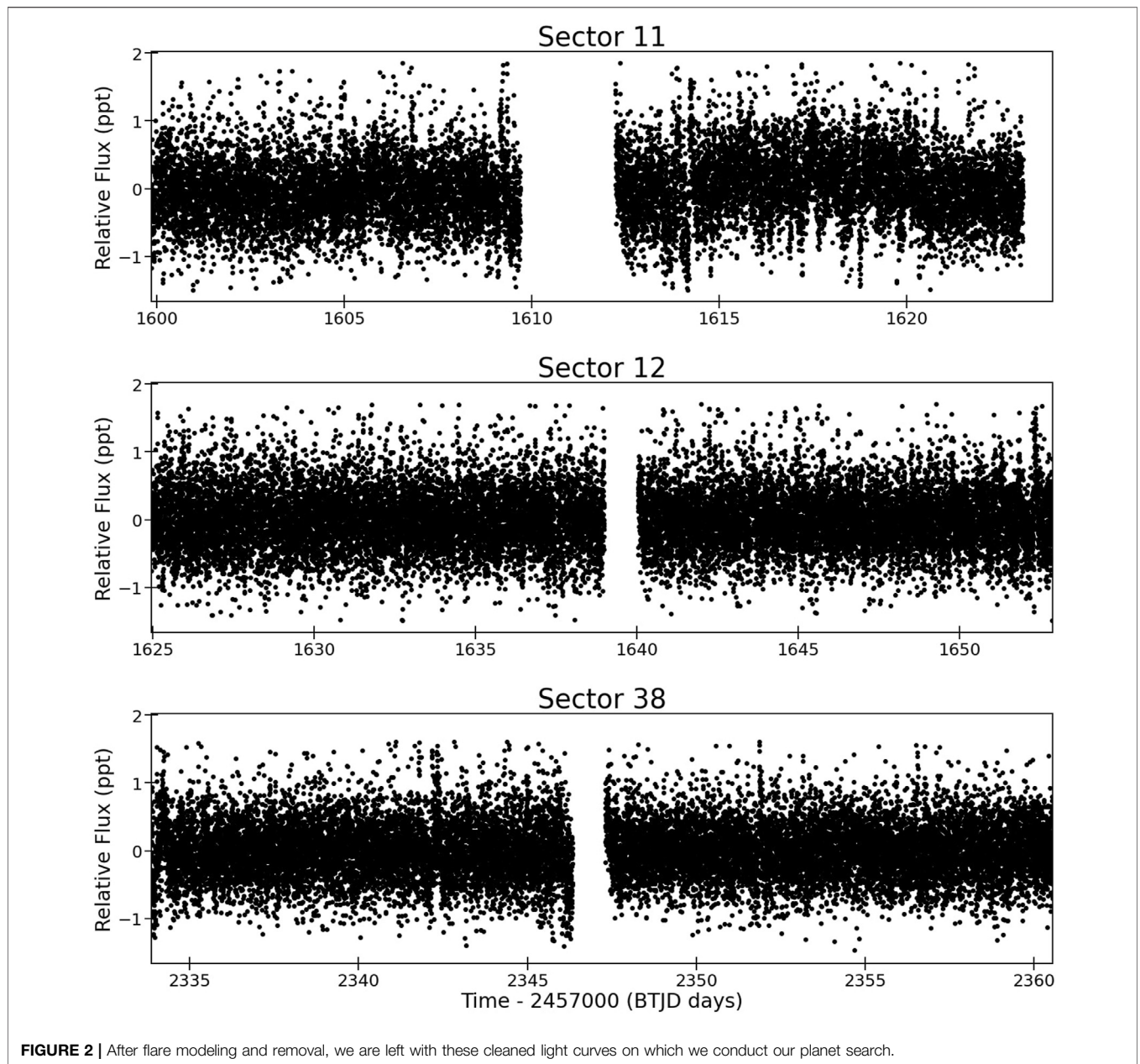
#### 3.3 Planet Injection

While we did not detect any planet, it is essential that we characterize our sensitivity. To determine the sensitivity of our method, we injected transits into the light curves before any type



of flare modeling or detrending. Then, after the transits are injected, we performed the steps described in **Section 3.1**. We used *batman* (Kreidberg 2015) to calculate transit models and injected planets that transit the center of the star on circular orbits, with linear orbital ephemerides. The planet size and orbital periods were randomly drawn from log-uniform distributions with radii ranging from  $0.07$  to  $1.5 R_{\oplus}$  and orbital periods from 10 to 12 days. The transit epoch was randomly drawn from a uniform distribution between zero and the orbital period. The 10–12 day period of the injected planets enables us to test out sensitivity to the finding the 11.2 days orbital period planet Proxima Centauri b. We injected over 3,000 planets and ran the TLS algorithm to search for planets. We used Sectors 11–12 in

this search between it speeds up the computation very significantly, and we found that the additional sector only provided limited additional sensitivity to small planets with orbital periods shorter than 25 days. The results of this injection are shown in **Figure 3**. We found that we are sensitive to planets larger than approximately  $0.4$ – $0.5 R_{\oplus}$  across the period-range that we searched, and every planet larger than  $0.55 R_{\oplus}$  that we injected was detected. To better quantify our detection probability we used the *k*-nearest neighbors algorithm implemented in as the *KNeighborsClassifier* in *scikit-learn*, with  $k = 12$ , to calculate a decision boundary between the parameter space where planet planets were recovered from where we have no sensitivity. The



decision boundary between recovered and not-recovered signals is relatively flat, and has a mean value of  $0.40 R_{\oplus}$ , as shown in **Figure 3**.

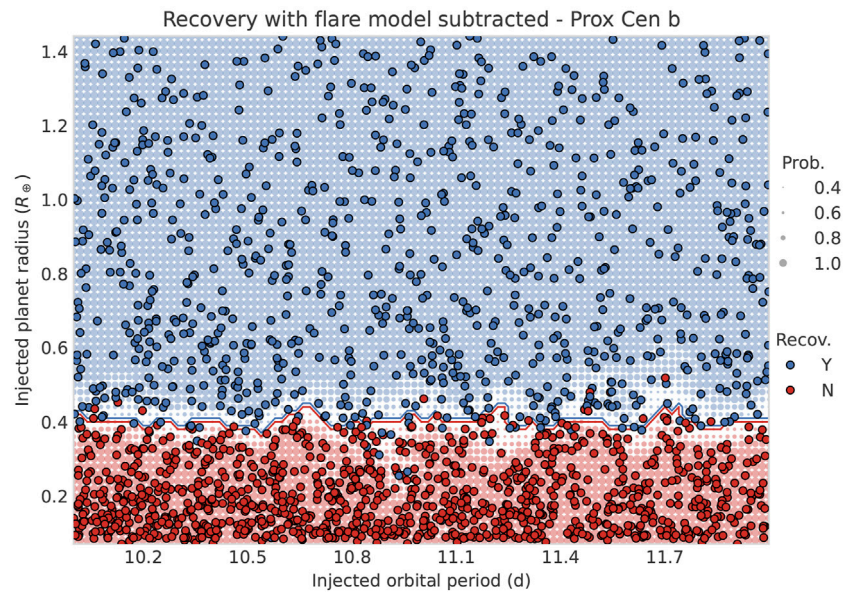
## 4 DISCUSSION

Herein, we discuss the implications of flare modeling when it comes to planet detection. In **Subsection 4.1**, we compare our injection and recovery results with and without modeling the flares. In **Subsection 4.2**, we confirm that we do not detect any evidence of transits of Proxima Centauri b in the three available sectors of TESS data. Finally, in **Subsection 4.3**, we look at the rest

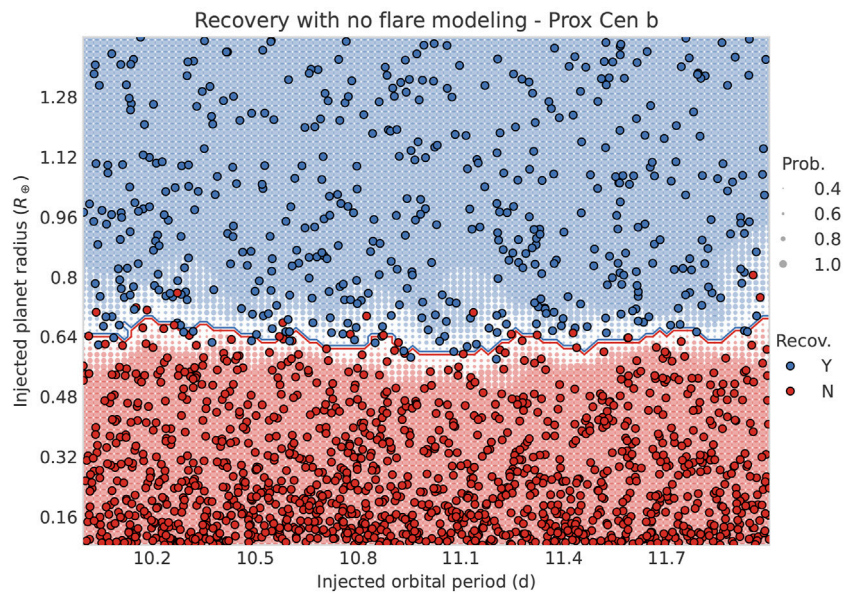
of the Proxima Centauri Habitable Zone and comment on the possibility of transiting planets in this regime.

### 4.1 The Consequence of Not Modeling the Flares

We have shown that by modeling the flares in the Proxima Centauri light curve, we can have sensitivity to very small planets (as small as Mars-sized). However, we have not yet demonstrated that we are more sensitive to small planets because we are modeling the flares. To determine whether there is any improvement we performed the same steps as before, but this time did not attempt to model the flares. We examined two



**FIGURE 3** | By subtracting a flare model from the light curve of Proxima Centauri, we are able to significantly increase the probability of recovering small planets. We are able to reliably recover planets down to around the radius of Mars across the period range searched, effectively ruling out any transit of Proxima Centauri b.

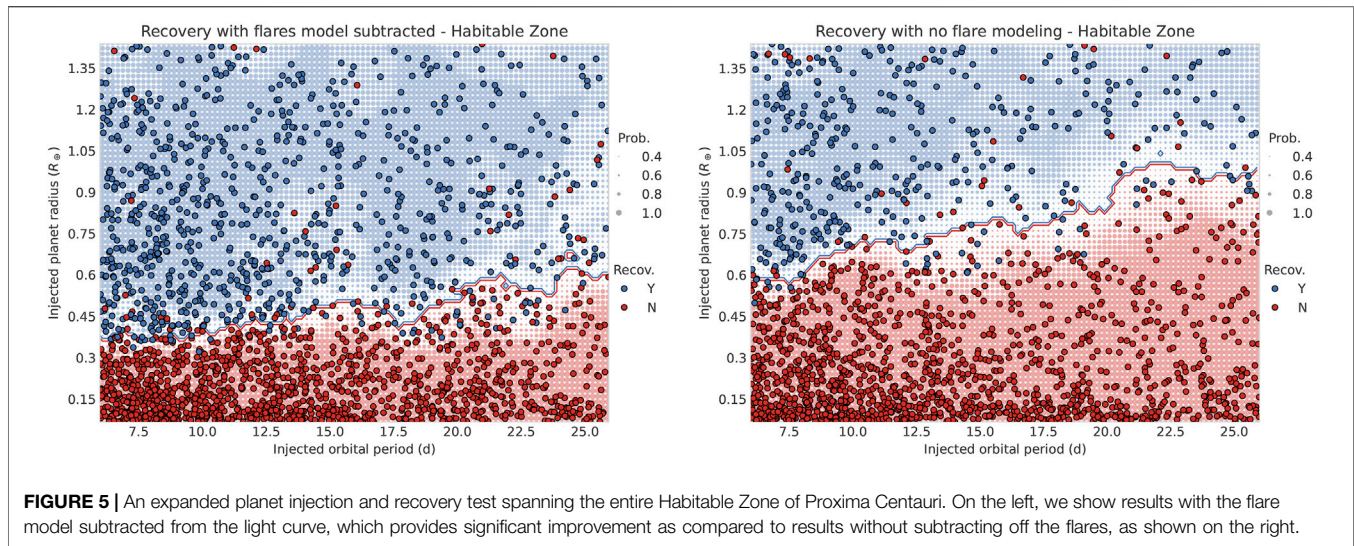


**FIGURE 4** | Without accounting for flares in our planet injection and recovery tests, we are less likely to recover the smallest planets. This figure shows the sensitivity to transiting planet when using sigma-clipping of flares, rather than flare model subtraction. Compared to the flare modeling sensitivity is 68% poorer.

different methods, firstly we simply interactively sigma-clipped out data-points, and secondly we tried use the flare model but clipping out the data point that occur during times that flare occur rather than subtracting the model.

We found that both methods for more naively dealing with the flares resulted in significantly poorer sensitivity to planets.

**Figure 4** shows the planets recovered when sigma-clipping the data. The mean of the recovery boundary is  $0.67 R_{\oplus}$ , which is 68% higher than when we created a model of the flares. The second method of masking data points that are during flares resulted in even much poorer results with regions of period-space with no sensitivity, and should not be used.



## 4.2 Proxima Centauri b Does Not Transit

We find no evidence for Proxima Centauri b in TESS data. This is not surprising because previous efforts using different telescopes have been similarly fruitless.

Using the known minimum mass of Proxima Centauri b ( $M_{\text{sin}i} = 1.27 M_{\oplus}$ ), we used the relationship from Chen and Kipping (2017) to derive an expected planet radius to be  $R = 1.08 \pm 0.14 R_{\oplus}$ . A 100% Iron planet would have an expected radius of  $0.88 R_{\oplus}$  (Zeng et al., 2019). Therefore, given our injection and recovery tests show that no planets larger than  $0.4 R_{\oplus}$  transit Proxima Centauri at periods between 10 and 12 days, we are confident that we would recover the signal from Proxima Centauri b if it were to transit.

## 4.3 Searching for Additional Transiting Planets in the Proxima Centauri Habitable Zone

We performed our initial search for transiting planets over orbital periods ranging from 1 to 30 days and did not identify any planets. Using the method demonstrated in the previous sections, we can also quantify additional the sensitivity we have to previous undetected transiting planets in the Proxima Centauri data from TESS. We limited our search to the optimistic Habitable Zone (Kopparapu et al., 2013) which spans from orbital periods of 6–26.6 days and injected planets with the same sizes, and ran the same recovery simulation. The results of this search are shown in Figure 5 for the two cases where flares are modeled. We are sensitive to planets as small as  $0.35 R_{\oplus}$  at the short end of the period range, and  $0.6 R_{\oplus}$  at long period end. When the flares are just sigma-clipped the sensitivity ranges from 0.6 to  $1.0 R_{\oplus}$ , demonstrating a 60% improvement in our sensitivity to small planets over standard methods.

No transiting planets larger than  $0.6 R_{\oplus}$  orbit within Proxima Centauri's habitable zone.

## 5 CONCLUSIONS

Proxima Centauri is the closest star to the Sun, and one of the best studied stars in the sky. The detection of a planet orbiting our nearest stellar neighbor was a ground-breaking moment for exoplanet science. While unlikely, if Proxima Centauri b were to transit, it would enable new insights into exo-atmospheres through transmission spectroscopy methods. Unfortunately we have confirmed prior results that Proxima Centauri b is not a transiting planet. We rule out any planet larger than  $0.4 R_{\oplus}$  with an orbital period comparable to Proxima Centauri b.

Modeling the flares resulted in a very significant improvement in the sensitivity to transiting planets ( $0.4$  versus  $0.6 R_{\oplus}$ ). By careful treatment of the flares observed in TESS photometry of Proxima Centauri, we were able to place rigorous limits on the probability of transiting planets orbiting the host star.

We also searched for transiting planet in the Habitable Zone of Proxima Centauri but we again came up short. We showed that no planet smaller than Mars transits the star from our point of view within the entire Habitable Zone.

The methods presented here for detecting transiting planets by modeling the flares were highly effective. Proxima Centauri is an unusually active star, and therefore our method is especially successful for this target. However, it is likely to be generally applicable for all active stars. There are many low-mass active nearby stars, and the methods we have presented here are could significantly improve our sensitivity to small planets transiting these stars.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>.

## AUTHOR CONTRIBUTIONS

EG conducted the flare detection and wrote the manuscript. TB ran the planet injection and recovery tests. EK searched for additional planets with QATS. EQ and LW provided additional guidance, ideas, and text.

## FUNDING

The material is based upon work supported by NASA under award number 80GSFC21M0002. This work was also supported by NASA award 80NSSC19K0315. This work was supported by the GSFC Sellers Exoplanet Environments Collaboration (SEEC), which is funded by the NASA Planetary Science Division's Internal Scientist Funding Model.

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## ACKNOWLEDGMENTS

This paper includes data collected by the TESS mission, which are publicly available from the Mikulski Archive for Space Telescopes (MAST). Funding for the TESS mission is provided by NASA's Science Mission directorate. E.A.G. thanks the LSSTC Data Science Fellowship Program, which is funded by LSSTC, NSF Cybertraining Grant #1829740, the Brinson Foundation, and the Moore Foundation; her participation in the program has benefited this work. This work made use of the following software: *astropy* (Astropy Collaboration et al., 2013; Astropy Collaboration et al., 2018), *IPython* (Perez & Granger 2007), *Jupyter* (Kluyver et al., 2016), *Lightkurve* (Lightkurve Collaboration et al., 2018), *Matplotlib* (Hunter 2007), *NumPy* (Harris et al., 2020), *PyMC3* (Salvatier et al., 2016), *scikit-learn* (Pedregosa et al., 2011), *Theano* (Theano Development Team, 2016), *xoflars* (Barclay & Gilbert 2020).

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