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Determining the Presence of Transits of the Three Known Companions of Proxima Centauri

Xinyao Liu[1†], Xinqing Hao[2†], Yuzhu Sun[3*†]

[1]*Chengdu Jiaxiang Foreign Language School, Chengdu, China*
[2]*Shanghai Satrriver Bilingual School, Shanghai, China*
[3]*Shenghua Zizhu Academy, Shanghai, China*
**Corresponding Author. Email: sunyuzhu0620@163.com*
†These authors contributed equally to this work and should be considered as co-first author.

Abstract: Upon analyzing TESS data, we searched through 4 months of photometric observations of Proxima Centauri, focusing on Proxima b 's 1.5% geometric transit probability. Our primary attention was directed towards four key lightcurves, each with 120-second exposures, as processed by SPOC. To minimize uncertainties from instrumental noise and stellar flares, we implemented some advanced data processing techniques. Searching for transits, we zeroed in on times corresponding to integral multiples of Proxima Centauri b's known 11.2-day period. To evaluate our sensitivity, we injected synthetic transits and found we could confidently detect those exceeding 3 millimagnitudes, which resembles a planet of radius around 5500 km. However, our analysis failed to confirm any apparent transits for Proxima Centauri b, and data for d and c were inconclusive due to uncertainties in their periods and transit times.Using the Box Least Squares method, we explored shorter periods, noting an elevated transit likelihood within 0-4 days, suggested by peaks in the transit probability graph. This hints at a possible low-period planet. In conclusion, while we found no definitive evidence of transits, data limitations prevent us from ruling out existence of transits of magnitude smaller than 3 milimagnitudes entirely.

Keywords: Proxima Centauri, BLS, ransits, lightcurve, companions

1. Introduction

Proxima Centauri, nestled within the Centaurus constellation at a distance of approximately 4.244 light-years, stands as the closest stellar neighbor to our Sun. With a radius and mass that are merely 14% and 12% of the Sun's respective dimensions, Proxima Centauri emits but a feeble fraction of the Sun's radiant glory, rendering it imperceptible to the unaided human eye. Despite its diminutive stature and subdued luminosity, Proxima Centauri has garnered immense scientific intrigue owing to its proximity and the tantalizing prospect of hosting habitable worlds. Discovered in 2016 [1], Proxima b orbits its host star every 11.2 days and is considered a potentially habitable planet due to its orbit within the habitable zone. The discovery of Proxima b has sparked speculation about the possibility of life on other worlds and the potential for future interstellar exploration. And with deeper investigation of the star, Proxima Centauri c [2] and d [3] are claimed to be additional candidate planet of Proxima Centauri.

All the three companions were discovered by measuring the radial velocity of the planets, while still no convincing transits pattern of Proxima Centauri have been discovered. Many scientists had studied the lightcurve of Proxima Centauri. However due to the restriction on the precision of the raw data or the fact that the orbital inclinations are not close enough to 90°, no transits were detected. There were candidate transits suggested but the evidence are insufficient and no periodic transits were seen as the candidate transits provided till now are mainly isolated ones[4]. Therefore It is controversial that whether Proxima Centaur exhibits a transit. Nevertheless, the potential for Proxima Centauri's companions, particularly the habitable Proxima b, to exhibit transits holds immense scientific value [5]. Such an event would empower scientists to delve into the planet's atmospheric composition through transit spectroscopy, a pivotal tool in assessing its habitability. Despite the geometric transit probability hovering around a mere 1.5%, the allure of unraveling Proxima Centauri's secrets persists. Unfortunately, because of the significant flaring properties of Proxima Centauri, scientists were struggling to distinguish the declination in flux intensity.

However, the advent of data processed by the Transiting Exoplanet Survey Satellite (TESS) has revolutionized our observational capabilities, enabling us to discern with greater precision the intricate variations in the star's luminosity, effectively filtering out the majority of flare-induced anomalies. So in our research, we studied the lightcurves cautiously, used some computational methods to clean our lightcurves and searched on them to see if there indicate possible transits. This paper presents our attempts to pinpoint the elusive transits of Proxima Centauri, detailing our data selection, preprocessing methodologies, transit period investigation strategies, and sensitivity assessments.

This introduction is section 1. In section 2, we include our selection to the lightcurve data, the way we pretreat the data, the way to investigate the transits' periods and described how we confirmed our sensitivity to the change in lightcurves. In section 3, the results of our analysis are located. We discussed our results in section 4.

2. Methodology

2.1. Data selecting and processing

The Transiting Exoplanet Survey Satellite (TESS) is NASA's latest exoplanet search project. Scientists hope that TESS can observe at least 200000 stars during its two-year space mission and ultimately discover thousands of new exoplanets. Using the lightcurves gained by TESS, we chose to focus solely on sectors 11, 12, 38, and 65, specifically targeting the entity with the name 388857263 and an exposure time of 120 seconds. We made this selection as the data was of high accuracy, and the exposure time was deemed suitable for our research purposes.

Given that Proxima Centauri is renowned for its frequent flares with notable magnitudes, we had to process our raw data to prevent any misinterpretation stemming from these flares. Firstly, we removed intervals on the lightcurves where the flux was either abnormal or undetected entirely, as indicated. Then, to minimize the flares' influence, we normalized the lightcurves by dividing each value by its average, establishing a range from 0.098 to 1.0015 and discarding any data points falling outside this range. This approach was wide enough to avoid excluding potential transit data while effectively mitigating the flares and outliers.

Despite these efforts, the lightcurves still exhibited some fluctuating trends. Consequently, we flattened the lightcurves by fitting polynomial functions of time to the fluctuation trends and subtracting the fitted curve. The parameters utilized for this flattening process are presented in Table 1, while the processed lightcurves are showcased in Fig.1.

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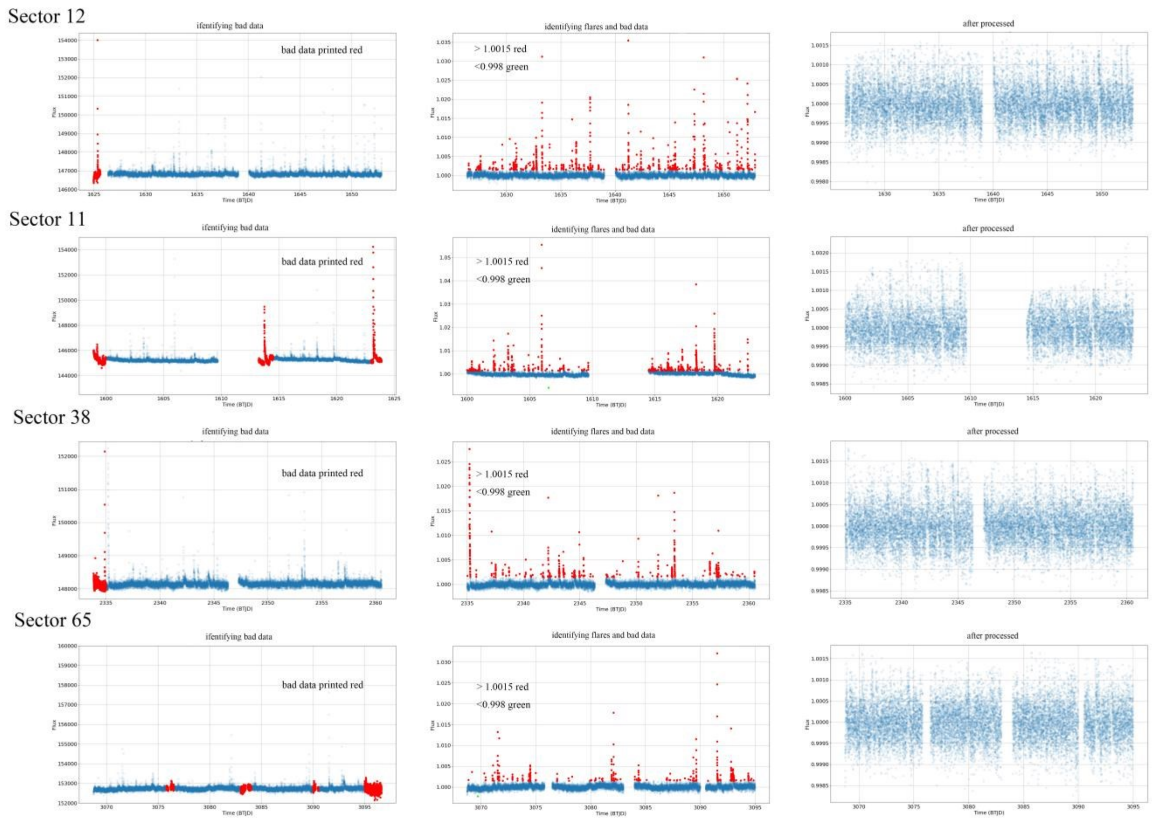

Figure 1: The first column indicate the interval of bad data deleted. The second column is the lightcurves with flares printed red and bad data printed green. The last column are the lightcurves processed and used for BLS in 2.2

Table 1: The parameters used for flattening

Sector	Data spanning time interval	Polynomial order
12	3	2
11	2	2
38	3	2
65	2	2

2.2. Box-fifitting Least-Squares algorithm

The Box-fitting Least-Squares (BLS) algorithm [6] is a method for identifying candidate transits by modeling transits as periodic inverted hat functions with four parameters. It relies on the fundamental principle of least-squares optimization to determine the relevant parameters for each frequency. By applying BLS to our processed light curve in Python, we can obtain a series of graphs revealing the relative power of each period. We carefully observed the resulting graphs and annotated the claimed periods for the three companions, Proxima Centauri b (11.1868 days), c (1900 days), and d (5.122 days). We then conducted the BLS search using 1000 trial periods ranging from 0.3 to 15 days and 8 trial durations spanning from 15 minutes to 4 hours. However, due to the limited time span of our data, we were unable to search for a 1900-day period signal using BLS, as even the total duration of the entire light curve is shorter than 1900 days.

2.3. Inject stimulated transits

When examining our ability to investigate a potential transit of Proxima Centauri, we simulated several theoretical transits of its companions based on the known stellar parameters such as the stellar mass, stellar radius, and the companions' orbital radius, orbital period, and planet radius. The relevant stellar and planetary data are listed in Table 2. We utilized the occultquad function [7] from the mandelagol library in Python to plot these simulated transits. This function incorporates parameters such as period, t_c, u, k, b, and a. Here, t_c represents the time of conjunction, which marks the midpoint of a transit. k is the ratio of the companion's radius to the central star's radius. a denotes the ratio of the companion's orbital semi-major axis to the star's radius. And b is the transit impact parameter, k, a, b were defined below. Finally, u quantifies the effect of limb-darkening.

$$k = \frac{R_*}{\boldsymbol{R}_\odot} \tag{1}$$

$$a = \frac{d_\star}{R_\odot} \tag{2}$$

$$b = \frac{a \cdot \cos i}{R_\odot} \tag{3}$$

We sourced the quadratic limb-darkening coefficient from the limb-darkening tables [8,9], using data retrieved from the EXOFAST website. For the R band, the coefficients are (0.425, 0.298), and we adopted their mean value of 0.36 as our input. With the other five parameters held constant, we varied the value of b from 0.5 (our initial guess) to 1 (its maximum value). Notably, b is intimately linked to the orbital inclination, with smaller values of b providing a higher likelihood for us to observe a transit, as it will be more easy to identify. By setting an upper limit on b, we gained confidence in distinguishing subtle transits from the overall light curve trend, thanks to the precision of TESS data processing.

3. Results

3.1. BLS power spectrum

Utilizing the TESS (Transiting Exoplanet Survey Satellite) data, we applied the box-fitting least-squares (BLS) methodology to scrutinize the potential transit epochs of Proxima Centauri's companions, specifically Proxima Centauri b, c, and d.

After normalization and excision of flaring events, we inspected the transit signatures across four distinct sectors: 12, 11, 38, and 65 (Fig. 2). Although NASA's Exoplanet Science Institute archives suggest transit periods of approximately 11.167 days, 5.122 days, and 1900 days for these planets, respectively, our BLS analysis did not reveal consistent periods that matched these expectations. Notably, in sector 12's BLS plot, an anomalous peak appeared at a period of 0.457 days, which deviated significantly from the anticipated periods. The peak is accompanied by smaller but notable peaks at 5.07 days, which is very close to the known period. And as for sector 11, 38, 65, peaks around the 5.122 were also shown. However, the max BLS power signals at periods of0.457days, 0.821 days, 5.01 days, and 9.46 days, respectively, and the surrounding peaks are out of the confidence interval of periods measured by RV methods. Thus this result further emphasizing the inconsistency with NASA's reported values.

Given these inconsistencies and the absence of definitive transit signals that align with the known orbital periods, we cautiously conclude that the available TESS data do not conclusively support the existence of transits for Proxima Centauri b, c, or d. This necessitates further observations or analysis to validate or refute our preliminary findings.

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Table 2: The relevant data of Proxima Centauri b,c and d[10]

	$R_{\odot}$ (km)	$d_{\star}$ (au)	$R_{\star}$ (km)	T (period)
Proxima Centauri	100000			
b		0.04856	6817	11.1868
c		1.48	13000	1900
d		0.02885	5150	5.122

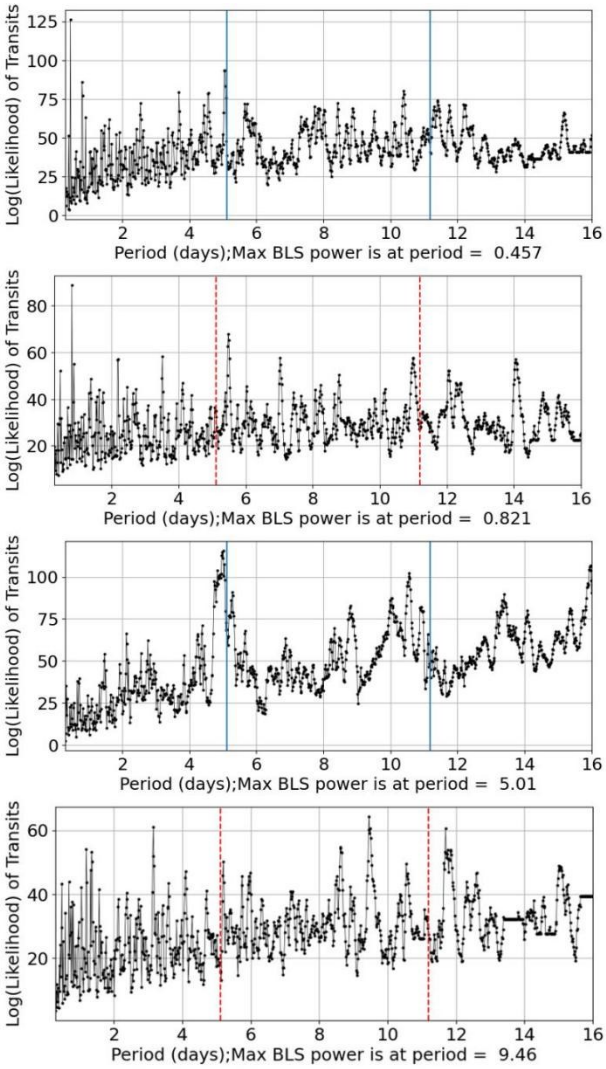

Figure 2: The BLS graph for sector 12,11,38,65 from the top to the bottom. Maximum BLS power period is labeled on the axes

3.2. Transit injection

Our Python-based simulations of transit light curves for the exoplanets orbiting Proxima Centauri have been conducted with meticulous precision, adhering to the parameters provided by the NASA Exoplanet Science Institute. These parameters are derived by some vital celestial dimensions obtained by RV method, including the planetary and stellar radii, the orbital characteristics, the transit impact parameter, and the limb darkening coefficient, all of which are essential in accurately replicating the expected photometric variations. To make the simulated transits as similar to the real transits as possible, we used some simple calculations of parameters k, a and b, based on the given data (Table

2) Specifically, for Proxima Centauri b,c and d, with the data measured by RV methods, we theoretically anticipated characteristic 3 kinds of inverted hat-shaped transit lightcurves to the lightcurve of Proxima Centauri to mimic the transits of each three companion in sector 12.

However, upon comparing our simulated curve with the actual photometric data, we observed no significant periodic declination, failing to detect the predicted transit signature within our observational images. This in-congruence prompts further investigation into potential sources of error or variability not accounted for in our models. For Proxima Centauri b, with period 11.1868, we are able to detect transits for $b<0.97$. That means we are able to distinguish a transit larger than 3 milimagnitudes, while the theoretical value of transits of Proxima Centauri b is around 5 milimagnitudes. Similarly, our simulation for Proxima Centauri d, orbiting with a period of 5.122 days, also predicted a distinct transit light curve. As for Proxima Centauri C, its relatively extensive orbit results in a significant ratio of orbital radius to stellar radius, which means its transits must be very noticeable. So for Proxima Centauri c and d, we are able to recognize a transit with $b \leq 0.99$ and $b \leq 0.97$ respectively. (Fig.3) Nevertheless, upon examination of the corresponding photometric data, we found no evidence of a matching transit events. Parameters used to define the function are listed in Table 3.

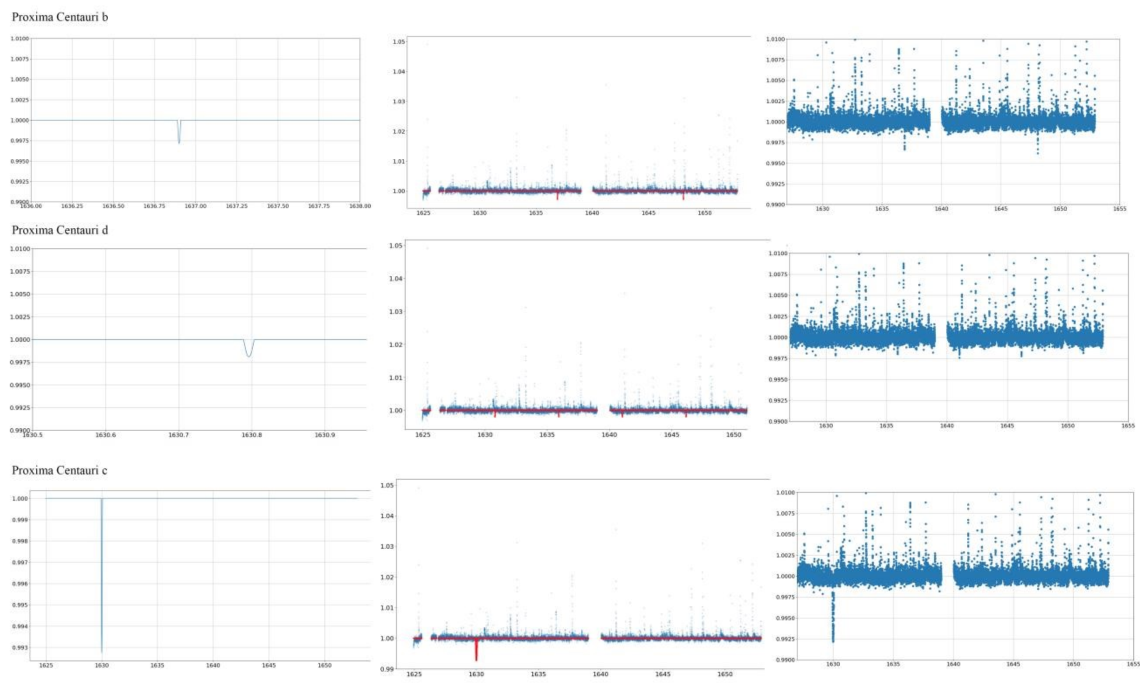

Figure 3: The first column shows single simulated transits for the three planets. The second column is the combined initial lightcurves with our simulated ones, with simulated signals printed red. The third column lays the combined lightcurves in scatter form

Table 3: Parameters used in simulated transits

	period	tc (randomly chose)	k	b(max)	a	u
Prox Cen b	11.2	1.7	0.06637	0.97	74	0.36
Prox Cen d	5.122	2	0.0524	0.97	44	0.36
Prox Cen c	1900	1630	0.1324	0.99	2269	0.36

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4. Discussion

In our research, we investigated the lightcurves and we didn't find evidence for transits. However, we can't confirm there is no transits for Proxima Centauri. We can only say that there's very little possibility for transits if b is smaller than 0.97.

Compared to former studies,since we are using TESS data,we narrowed the upper limit of detecting transits, from 5 mili-magnitude [5]to approximate 3 milimagnitude for Proxima Centauri b, as the depth of our simulated transits is 0.997152(6 decimal place). Also, we weren't bending our efforts to a generalized search on all possible transits while mainly focusing on the possible transits caused by the three claimed companions. But we still held a careful eye investigation on the lightcurves with a scale of 5 days each to check if there are interesting increasing or decreasing trends in the 4 lightcurves we chose, as we described in Section 2.1. And we did find some transit-like patterns like on the time period 2458600 to 2458605 BTJD days as shown in Fig.4. We had removed some obvious steep increase that indicate the flares, and plotted a best fit transit function to the lightcurve. Though it seems like a transits very much, especially compared to our injected transits, its pattern violate some geometric property of the transits: its not symmetry and the declination didn't show precipitous declination. And we regretfully rule out these data as they more seem like to be some bad data with mysterious pattern, probably because the events occurred near the beginning of each TESS spacecraft orbit where data are likely to be unreliable. Nonetheless, if its really a transits but interfered by the flares, we are unable to tell. And after removing the outliers out of the range we set in the first step when we were processing our data, there are some reminded lightcurve trends that are similar to transits, and we plotted some of these periods in Fig.5. Just as we described in our former example, although they are transits-like, they are not very significant with only negligible magnitudes when we fit them to the function of transits. We ruled out all of them by analyzing the geometric pattern of each and lay doubts on those data at the starting or ending points of the lightcurves. And in our data processing, we minus all these intervals as bad data from our lightcurves. So in brief we ruled out all of them, but since our judgment relied on the perfect model of transits, it is hard to say that a transits won't have similar patterns in reality.

To eliminate the potential uncertainty in our data analysis, we suggest more complex and advanced mathematical and computer methods like Gaussn Process should be applied to the lightcurves, to get more objective determination of candidate transits, instead of the observation by people that may lead to individual subjectivity. And more specific handling to the flares will be favored to give a cleaner lightcurve to have a better display for the transits. When we tried to remove the outliers, our limit is 0.98 to 1.0015, which is a very board range of interval, as the maximum possible depth of transits is 0.0175 magnitude of flux. (by Proxima Centauri c, the largest of the three), though it won't remove the potential transits of the known companions, it will be impossible for us to investigate some giant planets possible around Proxima Centauri. Moreover, our BLS graph is only in the range of 0.3 to 16 days, which means we are also blind to large period transits, including that for Proxima Centauri c.

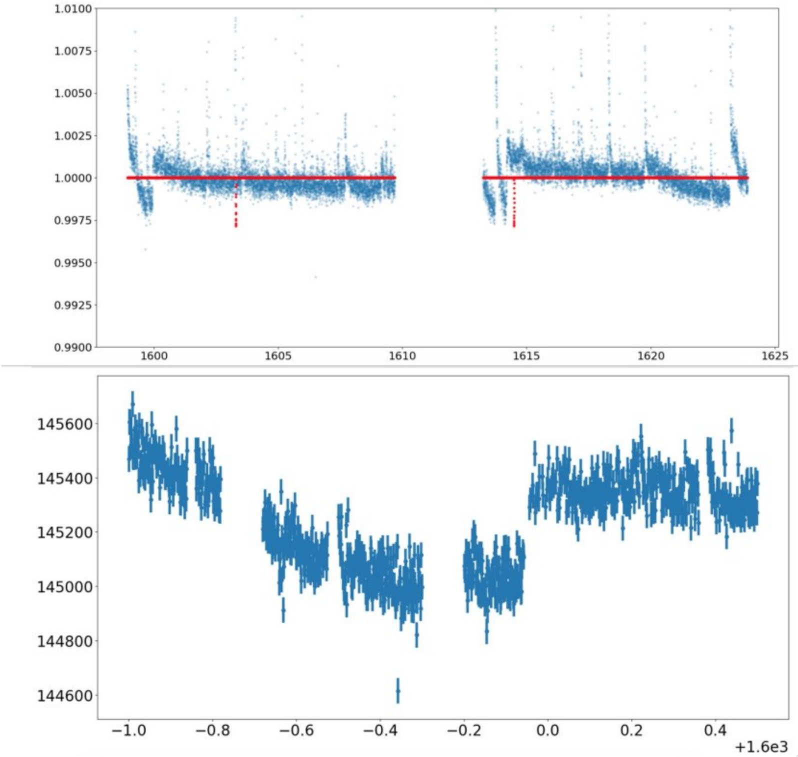

Figure 4: The first is lightcurve compared with simulated signals (printed red). The second is the lightcurve on time period 2458600 to 2458605 BTJD days

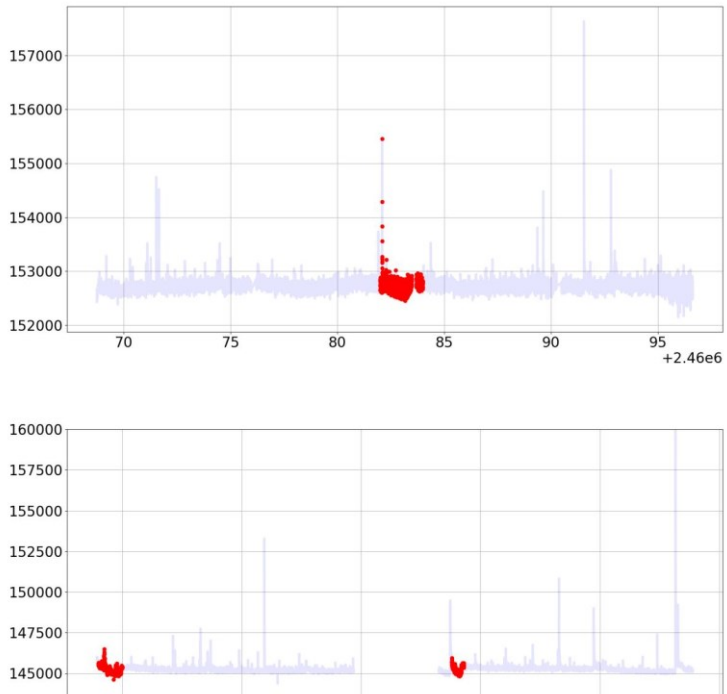

Figure 5: Some region where indicate a transit trend

5. Conclusion

In this study, we focused on analyzing four distinct lightcurves of our target, Proxima Centauri, utilizing computer-aided processes such as normalization, outlier removal, and flattening to enhance their suitability for BLS analysis. Despite our efforts, no significant peaks emerged at the reported periods of Proxima Centauri b, c, and d, though neighboring regions displayed BLS power peaks.

To assess our data's investigative capabilities, we inserted simulated transits, varied the b value, and generated multiple simulated signals. Among these, we identified the highest precision reading, which fell below the theoretical transit magnitude of Centauri's companions. And in total 4 interval with pattern similar to transits were ruled out. In conclusion, we are unable to confirm the existence of transits in Proxima Centauri.

Statement of work

Xinyao Liu complete the writing of 'methodology' 'discussion' 'conclusion' section. Furthermore, Liu modified other sections base on the writing of our teammates and organized all the sections up. Also, Liu took charge of organizing the figures, table and references used in our study.

Xinqing Hao finished the writing part of 'result'. Also, with Liu, I used Python to find the graph of Proxima Centauri, making it easier to understand. Then, we processed the image to form the transit curve, which is used in the passage.

Yuzhu Sun is responsible for the writing of 'abstract' and 'introduction. By summarizing the process and result of observing Proxima Centauri, she concluded the research into a paragraph. Furthermore, Sun searched the history and value of researching Proxima Centauri and included it into the 'introduction' part.

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