Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ28325

Transit Timing and Occultation Depth Variability of 55 Cancri e: Evidence for Volcanic and Atmospheric Activities

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Abstract. 55 Cancri e (55 Cnc e), a super-Earth with an orbiting period of 0.73 days, is very close to its host star 55 Cancri. The surface of this planet is supposed to be covered with hot lava. To verify the potential transit and occultation variation patterns of 55 Cnc e,TESS data were obtained and analyzed using the Lightkurve package built in Python program. By data cleaning, transit searching, and validation, light-flux curves were obtained and shown in respective figures. The measured transit times did not reveal any departure from periodicity, and the measured occultation depths showed only statistically marginal evidence for variability. The light curve data of 2020 year (sector 21), 2021 year (sector 44 and 46), and 2023 year (sector 76) were obtained, and the corresponding occultation depths were analyzed and presented. The transit time analysis indicates a strong linear trend with an upper limit on the rate of change of the period 3.7×10^{-2} seconds/year, and the small value suggests that the exoplanet's orbit is stable and Keplerian, and no clear orbital decay is observed. The occultation variation pattern is observed to be chaotic, and the variation of which is possibly caused by volcanic and atmospheric activities.

Keywords: 55 Cancri e, super-Earth, transit, occultation, atmosphere, volcanic activity

1. Introduction

1.1. Background

55 Cnc e is a super-Earth with a radius of 1.88 Earth radius ($R_{\oplus}$) and a mass of 7.99 Earth masses ($M_{\oplus}$) [1]. It was initially detected by McArthur et al. [2] using Hobby-Eberly Telescope. However, the detected signal was misinterpreted, and an incorrect orbital period was assigned. Only after the transits were detected by Winn et al. [3] was the true period confirmed to be 0.73 days. Due to its extreme proximity to 55 Cancri, 55 Cnc e has a surface temperature of approximately 1,958 K [4].

Recent studies on 55 Cnc e radiation and brightness [3] have revealed unusual signal patterns from the planet: the hemisphere-averaged brightness of the planet's dayside exhibits a variability over different periods. This unusual pattern of signal may refer to a special mode of planet 55 Cnc e.

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Demory et al. [5], for example, even reported a (300±31)% difference in 55 Cnc e occultation depth between 2012 and 2013.

Meier Valdes et al. [6] made another step on studying the optical light of 55 Cnc e. With data from the Transiting Exoplanet Survey Satellite (TESS), this study confirmed that the occultation also appears in the optical range and the mean occultation depth was observed as $(13.0\pm2.1)\times10^{-6}$, with observed range -9.6×10^{-6} to 36.6×10^{-6}. This result shows significant variability in the flux. Sulis et al. [7] studied the reflected light signals of 55 Cnc e and found that the amplitude and shape of reflected light signals changed significantly without periodicity. Moreover, since this planet has intense surface volcanic activities, the surface reflective index is expected to be low. Combining with the instability of reflected light signals, this study excluded the possibility that the variability was caused by reflected light, but the actual reason for this phenomenon remains unclear.

One possibility is that 55 Cnc e is experiencing orbital decay, since the distance between this planet and the host star is very close. In our project, the TESS data were examined to check whether each consecutive transit is at a consistent time. If each consecutive transit is at a consistent time, the orbital trajectory of this planet would be constant, and the orbital decay could be excluded.

Another possibility is that this planet has an atmosphere, and that weather conditions affect the planet's brightness. Our project aims to verify this phenomenon by analyzing additional TESS data and working toward a clearer explanation of the phenomenon. Our discussion focuses on whether different weather patterns on 55 Cnc e could be responsible for the observed variability.

1.2. Method

In our project, numerous data from TESS were obtained, and created light curves of 55 Cnc e system. Necessary modifications were executed on the light curve, including normalization, removing long-time trends, removing outliers and not-a-number data. By using Lightkurve package, the program was able to finish these processes. Some modified light curves were designed to be the output for verification and further study.

In 2023, TESS captured 55 Cnc e (TIC 332064670) during sector 72. These data, including data from previous sectors, were gained from Science Processing Operations Center (SPOC) (Jenkins et al. [8]) by LightKurve. The above mentioned data can be compared with previous data (2020, 2021).

Firstly, all data of TESS sectors were collected in each year. Python package called Lightkurve [9] was adopted to download the data, remove bad data points, and conduct analysis. Data in each group were folded in order to maximize the trend. Our team used Mandel & Agol method [10] to create an approximate line for light curve in each year. The occultation best-fit lines in each year were then put together. Three graphs of separated years and one graph of folded three years were generated. If the variation occur, there will be a difference among three best-fit line occultation patterns.

Similarly, all data from TESS sectors were also collected and downloaded in each year by using the functions mention above and calculate the time of transit by fitting the Mandel & Agol method [10] to obtain the parameters of each transit, which includes the transit time. Then by plotting the transit time with the cycle, the resulting graph should be a linear trend. The program can verify this by checking the residual graph of the linear line with the actual data. If the residual seems to have a pattern, it is then highly likely that the transit time isn't constant, meaning it is experiencing orbital decay.

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2. Result

Figure 2.1 presents three light curves and best-fit lines in three years. The occultation patterns are very weak in all cases. Fig. 2.1.a shows the light curve of 2020 year (sector 21), with an occultation depth of $(15.0 \pm 4.5) \times 10^{-6}$. Figure 2.1.b shows the light curve of 2021 year (sector 44 and 46), with an occultation depth of $(8.5 \pm 1.3) \times 10^{-6}$. Figure 2.1.c shows the light curve of 2023 year(sector 76), with an occultation depth of $(1.2 \pm 2.4) \times 10^{-5}$.

Furthermore, the depth of occultation in each sub-sectors were measured. TESS obtained 7 sub-sectors of data from 2020 to 2023, so these measurements contain 7 trials. The data are listed in Table 1, and the best-fit line of data in Table 1 is graphed as shown in Fig. 2.

Table 1. Occultation depths of 7 sub-sectors from 2020 to 2023 by TESS

index	occultation depth	standard error
1	1.46×10^{-5}	4.50×10^{-6}
2	1.22×10^{-5}	4.02×10^{-6}
3	1.17×10^{-5}	2.63×10^{-6}
4	1.02×10^{-5}	5.02×10^{-6}
5	1.28×10^{-6}	3.76×10^{-6}
6	3.50×10^{-6}	2.52×10^{-6}
7	1.02×10^{-5}	2.63×10^{-6}

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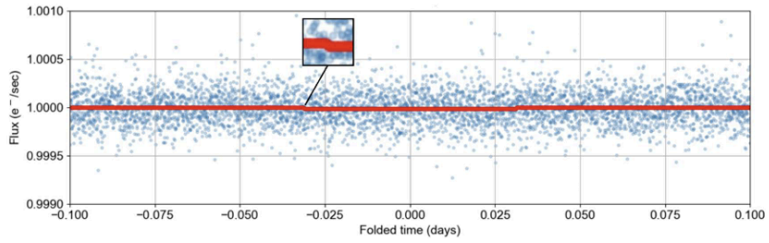
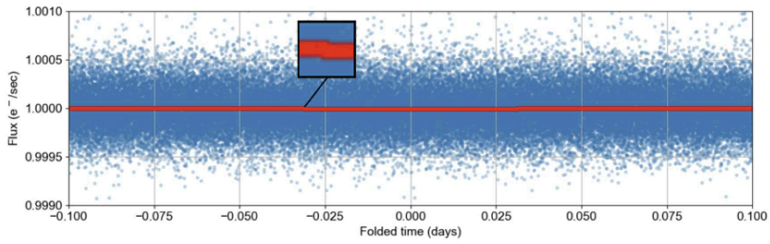
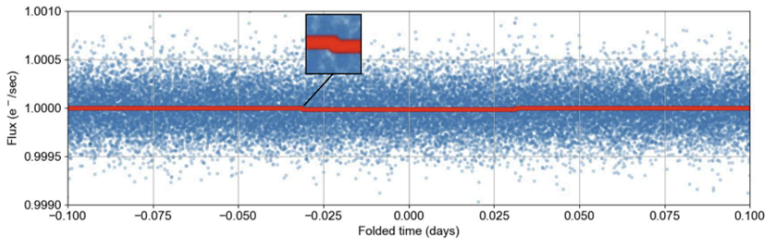


(a) 2020



(b) 2021



(c) 2023

Figure 1. Light curves and best-fit lines in year 2020, 2021, and 2023. The occultation depths showed only statistically marginal evidence for variability (folded)

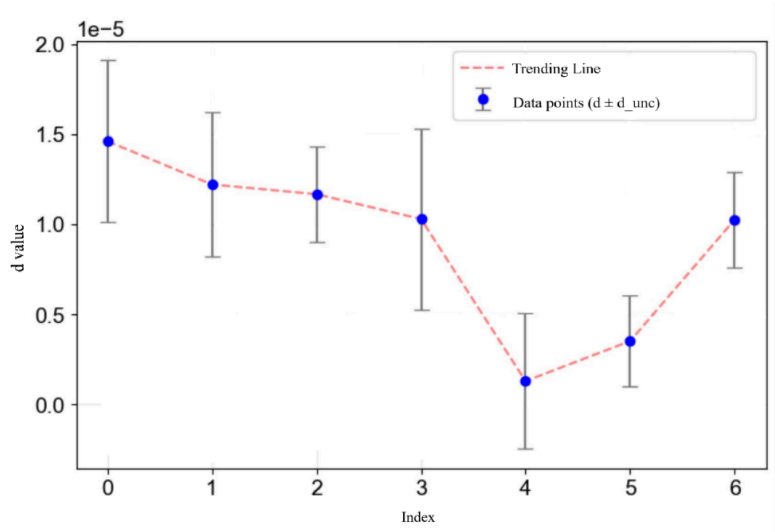


Figure 2. Best-fit line of occultation depths of 7 sub-sectors from 2020 to 2023 by TESS data. The d value represents the measured depth of the transit ($\times 10^{-5}$)

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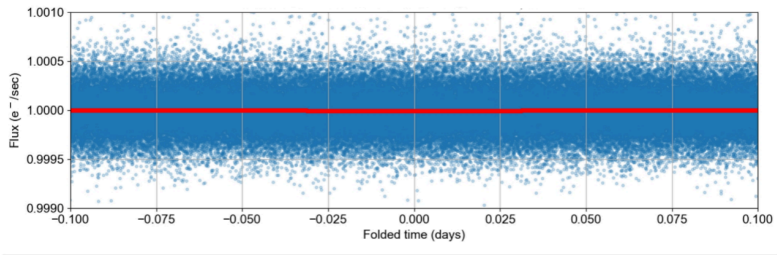

Figure 3. Combined light curve and best-fit line in three years (folded)

Table 2. Annual cycle counts and their corresponding calculated transit time midpoints with associated measurement uncertainties. TC value is the calculated central time of a transit event expressed in Julian Day Number

Index	Cycle	TC value	Uncertainty
1	-680	1869.96	3.85×10^{-2}
2	-679	1870.69	5.10×10^{-3}
3	-678	1871.43	1.72×10^{-3}
4	-677	1872.17	1.70×10^{-3}
5	-676	1872.90	1.68×10^{-3}
…	…	…	…
121	1237	3281.91	2.22×10^{-4}
122	1238	3282.65	2.72×10^{-4}
123	1239	3283.39	3.80×10^{-4}
124	1240	3284.12	3.81×10^{-4}
125	1241	3284.85	3.85×10^{-2}

In Table 2, collected and the time of transit were compared with the cycle number. 125 of transits, along with their respective transit time and uncertainties were collected. In figure 4 the data were plotted into a scatter plot. When the program fitted a linear function to the data by using the lmfit function in Python, we calculated and plotted out the residual in order to determine whether the data is linear. In Figure 5, a plot showcasing the residual of the linear function we just fitted, it is obvious to see that the data are scattered random around 0, which indicates that it is most likely a linear model with no orbital decay. The root mean squared error value of 6.009×10^{-5} indicates a perfect linear fit of the transit time function.

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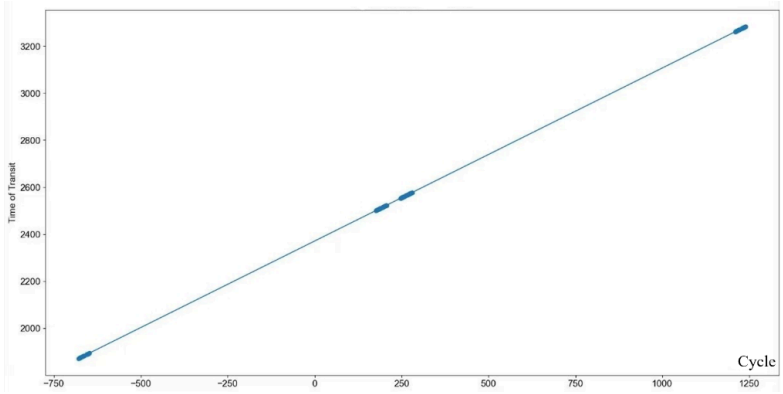

Figure 4. Transit time versus cycle. A perfect linear fit indicates stable time of transit

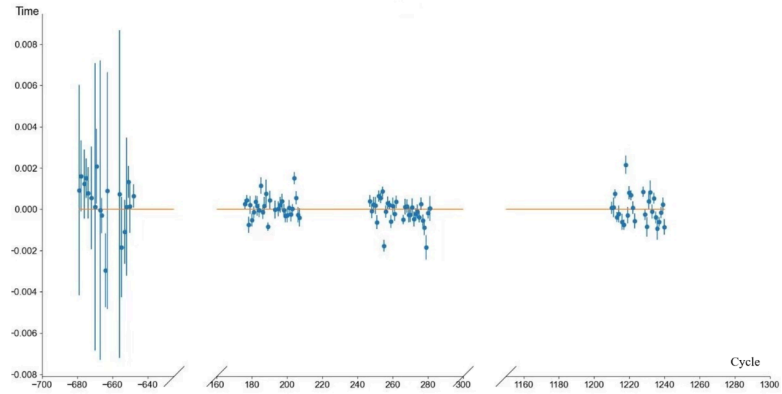

Figure 5. Residual of transit time predicted by the linear function versus cycle

3. Discussion

3.1. Analysis

The data of occultation depths showed only statistically marginal evidence for variability, which is consistent with the result of the project of Brice Olivier et. al. [5] which used Mandel & Agol method. The results of occultation depths in our project are also consistent with values measured by Meier Valdés et. al. [6], where the measured occultation depth is reported as $(18.6 \pm 2.9) \times 10^{-6}$ for all available TESS sectors (27, 29, 43, 44, 46, and 57) combined and analyzed together.

From occultation patterns, minor variations can be observed among years and sectors. Figure 1 and Figure 2 show visible differences in each period of planet 55 Cnc e: there is a noticeable difference between numbers 5-6. This phenomenon accords with the research of Meier Valdés et. al. [6], and also matches our initial prediction. The differences suggest that the light flux of 55 Cnc e varies slightly with no periodicity. Moreover, this occultation variation pattern is chaotic and does not follow any clear order, which raises questions for further study. In addition, the transit timing analysis indicated a linear relationship between a cycle number and transit timing, which means that the 55 Cnc e is not experiencing orbital decay.

According to the newest TESS data (2023 year, sector 72) and James Webb Space Telescope (JWST) (Patel et. al. [11]), the data captured by the space telescope also prove the variation of occultation pattern. This result suggested that there is also a variation in 55 Cnc e system. Previous research has provided different explanations. Some have already been excluded. For example, Sulis

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et al. [7] ruled out the possibility that reflection is the main cause. Because this variation is irregular and without any rule, therefore the variation tends to be caused by a chaotic system.

Patel et. al. [11] used JWST to detect the temperature of surface of 55 Cnc e. The detected temperature is lower than the predicted temperature of a completely exposed rocky surface. Based on this, they concluded that 55 Cnc e likely has an atmosphere or an atmosphere-like structure. If such atmosphere exists, it is possible that the atmosphere-associated weather pattern exists, which may affect the atmosphere and surface structure. The influences on surface and atmosphere may significantly affect the flux and brightness of planet 55 Cnc e, which also modifies the occultation depth. Furthermore, the weather pattern also agrees with the chaotic occultation, making this theory more plausible.

3.2. Hypothesis

Based on the literature and data analysis in previous sections, this study suggests that large-scale surface activities on 55 Cnc e, such as volcanism and atmospheric variability, play the major role on the variability of occultation depths.

As discussed before, 55 Cnc e has a radius of $1.88R_{\oplus}$ and a mass of $7.99\ M_{\oplus}$[1]. The theoretical escape speed is calculated as:

$$v = \sqrt{\frac{2GM}{R}} = 23,049\ \mathrm{m/s}$$

Due to its extreme proximity to 55 Cnc, along with the fact that 55 Cnc e is tidally locked to its host star, the surface temperature is estimated to be approximately 1,958 K [4]. The theoretical root mean square speed is calculated as:

$[c] = \sqrt{\frac{3kT}{m}} = 1746 m/s$, which is significantly smaller than the escape speed.

Therefore, the 55 Cnc e has the ability to hold very thick atmosphere. With violent and frequent volcanic and atmospheric activities, volcanic ash is transported through the atmosphere, leading to a change in transparency. This contributes to the variance of occultation depths among different years. Moreover, due to its extreme proximity to the host star, strong “solar wind”, which is the continuous, supersonic flow of charged particles primarily composed of protons and electrons, blows the atmosphere of 55 Cnc e and may lead to significant change of the atmospheric depth, and therefore causes the chaotic variations of occultation depths.

To verify the above hypothesis, more data of occultation depths at different wavelengths (such as infrared and microwave) are necessary, and further studies need to be conducted.

4. Conclusion

This study focused on the transit patterns and occultation depths of 55 Cnc e from 2020 to 2023. The transit times and occultation depths of 55 Cnc e were obtained and analyzed using the Lightkurve package built in Python program, and plots were drawn for better visualization. The relation of transit time versus cycle was found to be approximately linear. The occultation depth variations were chaotic, with no significant pattern found. It is possible that the change of patterns is caused by the violent and frequent volcanic and atmospheric activities on 55 Cnc e.

Further research can focus on collecting more data at different wavelengths (such as infrared and microwave) from different space telescopes. The spectroscopy analysis can be adopted to identify

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the elements of the atmosphere on 55 Cnc e. Tracking change in elements distribution could become an important direction for research when the space telescope technology gets advanced. Additionally, future research will contribute more data to analyze in order to find a clearer trend in the planet's orbital time. It is possible that 55 Cnc e is experiencing orbital decay, but only on a much smaller scale.

Acknowledgement

We are grateful to our professor, teaching assistants, our family members, and those who provided us help. Our professor Joshua Winn gives us valuable instructions. These helps contribute our success. All of our team members have made indelible contributions to our project. The contributions of all team members to the project were roughly the same.

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