Ground-based light curve follow-up validation observations of TESS object of interest TOI 3805.01

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Abstract

The discovery of exoplanets is slow to come, as an average of 25 exoplanets are discovered a year[6], wielding very intriguing results for the scientific community and the world. Currently, although plenty of exoplanets have appeared to be sighted, it is difficult to verify if an exoplanet is actually present due to other factors interfering with what we see, giving us a false positive. With data provided from George Mason University's observatory in addition to other virtually stored data, we can analyze the light output of our target, TOI 3805.01, and determine if an exoplanet is present. The data from GMU must be plate-solved via Python code first to filter out potentially bad data. Then, the new plate-solved data can be used for light curve generation, along with a NEB analysis. From the NEB analysis and the light-curve generated from our data, there is an indication of a potential NEB. Other evidence points towards the target TOI 3805.01 likely being a Hot Jupiter.

1 - Introduction

Many missions have been created and many more satellites deployed into space for exoplanet research, which is how we have discovered over 5,000 potential exoplanets. NASA's now-retired Kepler mission[11] and their current Transiting Exoplanet Surveying Satellite mission[12] (or TESS) has helped mankind pinpoint and validate various new exoplanets. TESS was launched April 18th of 2018 after the retirement of Kepler, as they ran out of fuel. TESS has been on a mission to discover new exoplanets for the past 6 years, and continues to do so.

Currently, there are much more potential exoplanets than confirmed or verified exoplanets, which is why this paper regarding TOI 3805.01 is important. There are no previous works or papers detailing TOI 3805.01, but only sciences and data stored online. In order for this to be validated, the data collected from the TESS mission needs to generate a light curve, and from there a transit needs to be identified. Seemingly no research appears to have been conducted on TOI 3805.01, so this study acts as a foundation that can be built upon to further enhance our understanding of this target and aims to further support future research done on this target in the future.

In this paper, we present information on TOI 3805.01, and include follow up observations. TOI 3805.01 has a Jupiter radius of 1.0837560±0.0745559. TOI 3805 has a stellar radius of 1.02 ±0.059. TOI 3805.01 has a period of 3.8960447 days.
In Section 2, we present observations made on TOI 3805.01 relating to physical properties in addition to collected data. In Section 3, we present the tools used throughout this entire process, and our analysis on the TESS light curve. In Section 4, we present the produced light curve in addition to the dmag vs RMS and Profile of the data. In Section 5, we interpret and analyze the results. In Section 6, we draw conclusions from the data given to us and present them for future work or reference.

2 - Observations

In Section 2.1, we present the properties of TESS TOI 3805.01 along with the exoplanet candidate properties, with that information being gathered from TESS input catalog, the *Gaia* mission, and other credible sources. In Section 2.2, we present the TESS sector light curves. In Section 2.3, we present a summary of the observational data collected with the George Mason University 0.8m telescope.

2.1 Exoplanet Candidate Properties

The predicted radius of TOI 3805 (R_{Sun}) is 1.2 ±0.059. The predicted mass (M_{Sun}) is 0.91 ±0.119. Metallicity (Fe/H) is at 0. The Stellar surface gravity [log10(cm/s2] is measured to be 4.3793 ±0.086. The effective temperature of the star ($Teff_{[K]}$) is 5295 ±131.783. The planetary equilibrium temperature (K) is 1190.41. The density (g/cm^3) is 1.2066. It has a period of 3.896 days. Transit duration is 2.15 ± 0.186 hours. The transit depth $[(R_p/R_{star})^2]$ is 1.334. TOI 3805.01 has a master priority of 3 and has a disposition of PC (Planet Candidate). We received this information from ExoMAST archives.

2.2 TESS Sector Light Curves

The TESS mission produced a flux light curve when collecting data for TOI 3805, with the sciences for the light curve stored in the MAST database. Downloading the sciences from that mission allowed us to create a light curve (Refer to Figure 4 for the light curve), which all have transit durations of around 2.150±0.186 hours.

2.3 Observational Data

With George Mason University's 0.8 telescope, a total of 432 sciences were captured with a red filter with an exposure time of 85.000 seconds. After putting the sciences through the plate-solving program, the amount of sciences has been reduced to 229 plate-solved sciences. Other sciences were set aside due to sudden jumps from one place to another or not enough stars present in the data to be able to use it. There are 10 Flat exposures of 3.000s, in addition to 20 Dark exposures, 10 of 3.000s and 10 of 85.000s. The date of the observation is 2023-12-15. The start/end times are 18:40/6:20. The RA is 06:19:35.907 and the Dec is +42:18:49.00. Information can be found in Figure 5.

3 - Analysis

In Section 3.1, we present our tools used to analyze the TESS sector light curve(s) curves using AstroImageJ/ExoFASTv1/ExoFASTv2/Alnitak. In Section 3.2, we present our analysis of the ground-based light curve using AstroImageJ(AIJ). In Section 3.3, we present other analysis on other tools/plots generated alongside the main light curve.

3.1 Plate Solving/Reduction Tools

The instructions we used can be found in the Light Curve Tutorial document[1] and the Alnitak Tutorial document[13]. It is necessary to get a Astrometry ID[10] before moving on (the tutorial document covers the steps). The first step to analyzing the data is plate solving. Before plate solving, we would need to clean the collection of sciences from bad images, install packages that the plate solving program needs, and sort the file that needs to be plate solved. First, a manual inspection of each science was initiated to rid of any sciences with potential to skew the results. The bad sciences that were ridded of would appear to have a star jump from one place to another or have odd streaks in a couple images due to the telescope correcting their position (See Figure 6 for an example of a bad image). Next, other packages needed to be installed for the program to run. Using "pip install", astropy, astroquery, photutils, numpy, scipyx, barycorrpy, and Matplotlib. The last step needed to prepare for plate solving is separating all other content away from the main contents of the file, which should include the good sciences that need to be plate solved and data reduced in addition to 2 folders with darks and flats, each in their own respective folder. For plate solving, we used the Alnitak reduction code[5] that runs with versions of Python 3.6+. We are now able to upload all the good sciences to be plate solved and data reduced. After the program finishes running, it will create a separate folder containing the reduced and plate-solved sciences.

The reduced sciences can be uploaded to AIJ as an image sequence. Using RA/Dec, we can pinpoint the location of the star and create a 2.5' radius around it by right clicking the location of the star. Dragging the Gaia stars file over the image stack would plot reference stars near the target star. Once the window is right-clicked, or if the multi-aperture photometry button is clicked, it will run multi-aperture photometry. Once multi-aperture photometry finishes processing the Gaia stars, a measurement window would be created in a separate window. This measurement window would be used to create a light curve.

3.2 Ground Based Light Curve Analysis

After multi-aperture photometry has completed creating a measurement table, the MultiPlot tool could then be used to generate a light curve. A template to contain all kinds of data needs to be imported first, which was provided to us in a document with other detailed instructions[1]. In the

Multi-plot Main window, the ingress and egress values (0.47 and 0.57) can be typed into V. Marker 1 & 2 respectively. In the X-Scaling window, we set X to auto-scaling so the plot would automatically adjust itself to display all data in the X axis. Settings are changed accordingly, following a PDF guideline[2] of how light curve displays should be set in the Multi-Plot Y-data window. The Teff, Fe/H, and log(g) values from earlier are entered in a site[3] programmed to get the Linear LD u1 and the Quad LD u2 and those values are pasted in their respective place in the Data Set 2 Fit Settings window. In Multi-Plot Y-Data, enable the reference stars to show up on the plot and determine if the flux they display is too scattered to use or ok to use. If they are too scattered, uncheck that reference star on the Multi-Plot Reference Star Settings window if they were already checked. Once all settings are set, we can press the “Redraw Plot” button in the Multi-Main window to get a light curve model (See Figure 1 for the light curve).

3.3 Other Tools/Plot Analysis

Prior to using the Multi-Aperture Photometry tool, and right after dragging our Gaia stars on the science image stack, we would go to AIJ’s main menu and click “Plugins”. From there, click “Astronomy”. Then, near the bottom of the new menu will be a “Seeing Profile” button. This will generate the Seeing Profile window, generally used to determine the quality of the images taken and the radius of the target.

After clearing all bad reference stars from the Multiplot Reference Star Settings window, continue to multi-plot main. Under files, find “Create NEB search papers and plots”. Then, enter settings in the new pop up window following the instructions document[1] in addition to recorded depth and ingress/egress, if not provided already. It will also request measurements generated in step 3.1, in addition to a science image associated with the measurement. This process will generate the dmagRMS plot. This plot is generally used to determine if any eclipsing binaries are close enough to the target star, and if they may alter the results drastically.

4 - Results

This section discusses the properties of the materials generated from AIJ. Section 4.1 presents the light curve. Section 4.2 presents the generated Profile from the Gaia stars back in step 3.3. Section 4.3 presents the dmag vs RMS plot, also received in step 3.3.

4.1 Light Curve plot Analysis

Referencing Figure 1, the red line of this plot represents the transit model of TOI 3805.01. The red data points represent our normalized Airmass detrended with transit fit. There are 2 reference stars present, with the black data points representing reference star C55 and the green points representing C66.

4.2 Seeing Profile Analysis

The aperture size for the light curve has a radius of 21px. The 21px radius is considered the inner radius, while the outer radius is measured to be around 36-54px. The Half-Width at Half-Measurement (HWHM) is measured to be at 7.14px.

4.3 dmag vs RMS plot Analysis

Most stars lie in a cluster near the cleared boundary, represented in a curve made of green points. Some stars are seen far away from the boundaries, but follow the general shape it shows. There are only 2 stars left of the target star, showing low dmag but also low RMS. A couple of stars are plotted near the target star to the right, displaying little dmag and medium RMS. Most stars are plotted around 2-4 dmag, and 250-100 RMS.

5 - Discussions

In Section 5.1, we will discuss and interpret the results displayed by the light curve. Section 5.2 will be discussing the Profile of the data. Section 5.3 will be discussing the dmag vs RMS plot. 5.4 will be discussing the instance of this target showing signs of being a false-positive. 5.5 will be discussing the potential for this target to be something other than just an exoplanet.

5.1 Light Curve Discussion

Observing Fig.1, plenty of data is missing from our plot within ingress/egress. However, lots of information and conclusions can still be drawn from this. The red data plots display a fluctuation of light near the end of the predicted egress, while a clearer dimming fluctuation happens after the egress. The red line shows a slight dip between the ingress and egress. A transit may have occurred in the current predicted ingress/egress, but it is difficult to confirm due to the data that has been removed during the plate-solving process and data reduction step mentioned in Section 3.1. However, clear signs of a transit happening afterward the predicted egress is apparent. Noise data might not be recommended to be taken into consideration due to “Sky/Pixel” (Yellow point data) displaying faulty results. Reference stars C55 and C56 display a low amount of RMS and a somewhat low dmag, according to the dmag vs. RMS plot, and land on the “Likely Cleared Boundary”, making them good reference stars to use in the light curve plot as they can decrease data and system errors and increase plot accuracy. It is also difficult to confirm if the data reduction processes for detrending were effective, as either the predicted ingress/egress were off or the the data present during the current ingress/egress cannot be used because they are considered bad images.

5.2 Profile Discussion

Observing Fig.2, It is expected that as the radius increases that the ADU decreases. The data provided does not show much change happening as radius increases. The HWHM is 7.14px, and the lower the value the higher the quality of images taken. This is ideally the kind of data quality we want.

5.3 dmag vs. RMS Discussion

Observing Fig.3, we can observe that there is a cluster main cluster of stars around, inside, and outside the boundaries. Plenty of stars are also seen scattered very far from the boundaries, but they should not pose much of a problem as they are far enough away where they will not affect the data drastically. The stars clustered near the bottom middle area have medium-high dmag. The lower the dmag the dimmer the stars are, so those stars will not affect the possibility of the transit being caused by a non-eclipsing binary (NEB). However, there are plenty of stars on the middle-bottom of the plot that have medium-low dmag and are close to the target star. The closer other stars are to the target star (and the greater the distance between them and the Likely Cleared Boundary is), the greater the possibility that NEB occurred.

5.4 Potential False Positive Discussion

Mentioned in 5.3, the more stars closer to the target star, the greater the possibility that a NEB occurred. Plenty of stars are not too far off from the target star. This potentially could be a false positive, as a NEB could have been detected. This doesn't immediately declare a false positive, however, as it would be better to compare this data with others and it would be beneficial if another NEB analysis is conducted before coming to any conclusions.

5.5 Type Of Exoplanet Discussion

This will be a short discussion subsection. Referring to Figure 5, TOI 3805.01 is observed to have a Teff of 5295 [K] and a radius of 1.0207 [R_{suns}]. Hot Jupiters have temperatures of over 5000 Kelvin and radii between 0.8-1.5, so this would classify TOI 3805.01 as a Hot Jupiter.

6 - Conclusion and Further Work

A confirmed transit has appeared on the Light Curve plot, as seen in Figure 1 and talked about in Section 5.1. However, this transit did not show up at the predicted times, most likely due to outdated data being collected in regards to time. Despite that, it is highly likely an exoplanet is present as most of the data matches up with data gathered by TESS, stored on the MAST archive[4] and other sources. TOI 3805.01 appears to be a Hot Jupiter, based on the Teff [K] and Radius [R_{suns}] seen in Figure 5.

In the future, since the false-positive verification method in step 5.4 has not been verified and confirmed in the most efficient manner, doing a false-positive check by other reliable means would be ideal to validate the candidate exoplanet's existence in addition to conducting another analysis. In addition to that, some data presented here may display odd values (Referring to Figure 1, the yellow "Sky/pixel" data plots display very drastic measurements which is not supposed to happen). Something else to do in the future is to try and start from the raw sciences again, complete the plate-solving process, and generate another light curve again, as it would perhaps wield clearer results. All the data for TOI 3805.01 was run on a somewhat unreliable hardware system, which consumed a lot of time when we attempted to download necessary programs or process images, sciences, and data.

7 - Figures and Tables

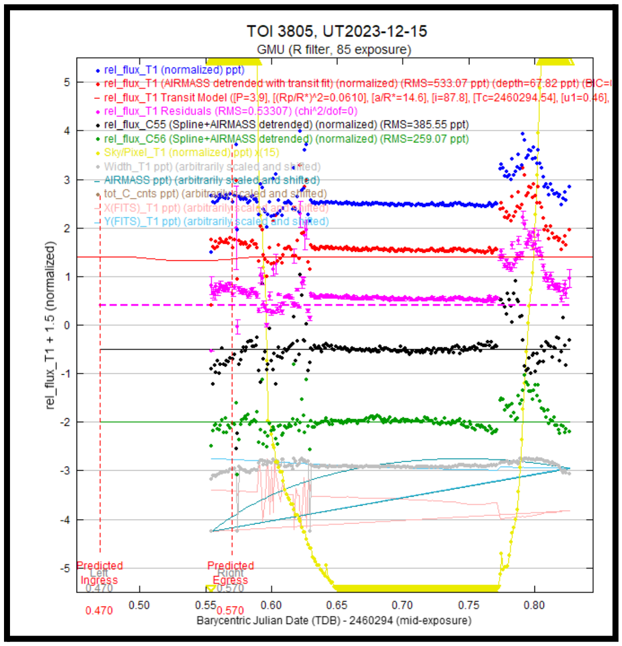


Fig 1: Light Curve Plot, generated in AIJ

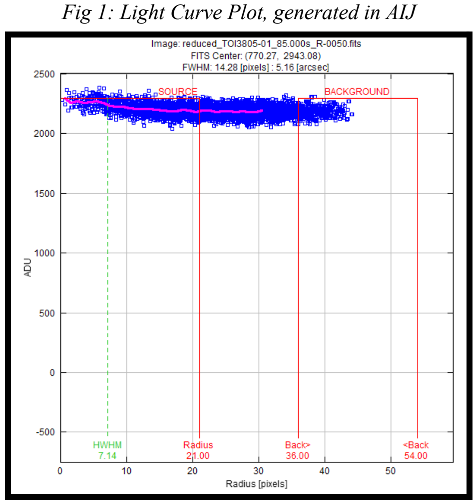


Fig 2: Seeing Profile Plot

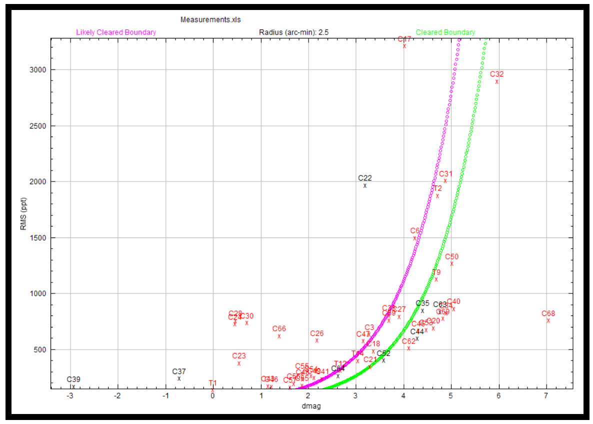


Fig 3: dmag vs. RMS plot.

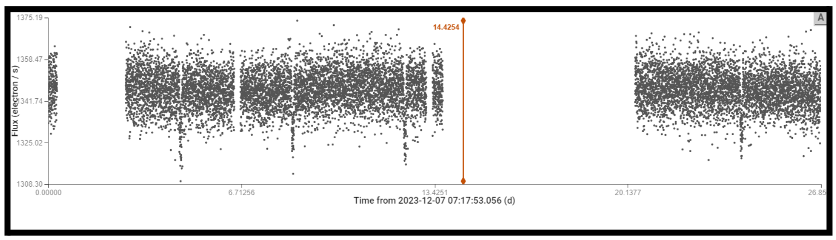
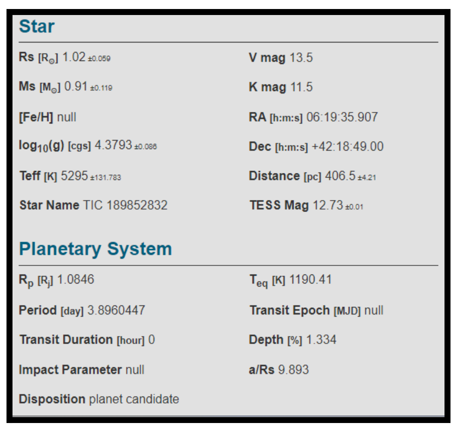


Fig 4: LCviz in MAST: Data from MAST (obtained by TESS) was put through a light curve generating software and displays transits in addition to times observed.



Star

Rs [$R_\odot$] 1.02 ±0.059	**V mag** 13.5
Ms [$M_\odot$] 0.91 ±0.119	**K mag** 11.5
[Fe/H] null	**RA** [h:m:s] 06:19:35.907
log$_{10}$(g) [cgs] 4.3793 ±0.086	**Dec** [h:m:s] +42:18:49.00
Teff [K] 5295 ±131.783	**Distance** [pc] 406.5 ±4.21
Star Name TIC 189852832	**TESS Mag** 12.73 ±0.01

Planetary System

R_p [R_j] 1.0846	T_{eq} [K] 1190.41
Period [day] 3.8960447	**Transit Epoch** [MJD] null
Transit Duration [hour] 0	**Depth** [%] 1.334
Impact Parameter null	**a/Rs** 9.893
Disposition planet candidate	

Fig 5: Target star properties. Data found on exo.MAST.

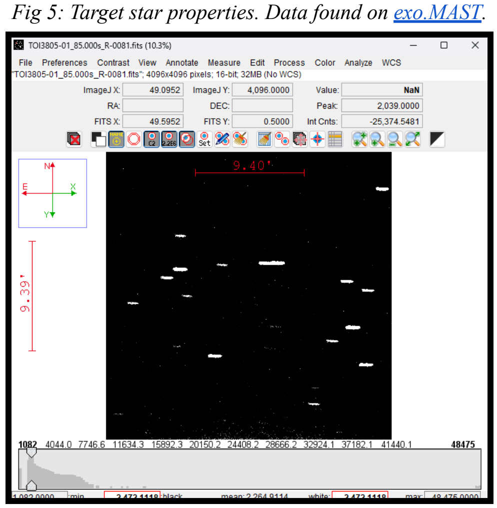


Fig 6: Example of a "Bad Science"

8 - Acknowledgements

I would like to thank Dr.Plavchan and the GMU NASA Data Processing Internship staff (Kevin Collins, Owen Alfaro, S Falgiano) for providing us with program materials, detailed instruction, access to data, immense and extended support, and for their unwavering patience when we encounter various issues.

9 - References

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