Ground-based light curve follow-up validation observations of TESS object of interest TOI 5938.01

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Abstract

The intriguing field of exoplanets continuously amazes scientists around the world. The TESS mission intended to help discover new possible exoplanet candidates, but there is so much data it is difficult to deeply research each one. Our ground-based research intends to help with that problem by thoroughly analyzing our target TOI 5938.01. We plate-solved the observation data taken from GMU using Python code. We then used AstroImageJ to create a light curve and perform a NEB analysis. From here we interpreted our results from the NEB analysis, light curve plot and seeing profile with credible past data to conclude there is a transit. TOI 5938.01 provides a plethora of data concluding it is extremely likely it is an exoplanet.

1. Introduction

The possibility of another habitable planet has always been a fascination of mankind. From centuries in the past to the present and future, exoplanets have been hypothesized and suspected. Only recently have methods such as transits and spectroscopy proven exoplanets to exist. The TESS mission uses these methods along with others to search bright stars for any possible transits that could present candidates. To validate these candidates, the TIC is used to gather astronomical data that provides researchers and the public with useful information for identifying thousands of targets.[1] Since there are thousands of candidates with a broad amount of information, community aid is useful for denying or confirming data. Papers like Zheng & Plavchan[2] exhibit the importance of deep research into each target. Explaining and researching data that relates to the exoplanet can lead to astonishing discoveries, such as a habitable and resourceful planet. As mentioned in the above paper, there are few studies on this TOI. Previous research failed to complete a NEB search as well as the weather contributing to gaps in the data.[2]

Our follow-up studies hope to aid in the confirmation or additional information on TOI 5938.01 as we were able to do a NEB search. TOI 5938.01 has a Jupiter radius of 0.3501, its host star (TOI 5938) having a stellar radius (R_Sun) of 0.74. TOI 5938.01 has an orbital period of 2.260431± 0.0000131 days.[3] Our goal is to confirm whether the transit occurs on the expected star at the expected time, with the anticipated duration and depth.

In Section 2, we present our observations from TESS and the GMU 0.8m telescope. In Section 3, we present our analysis of the TESS light curve for TOI 5938.01 and our ground-based light curve analysis as well as our NEB analysis. In Section 4, we present our light curve and NEB analysis results. In Section 5 we discuss our results and compare, examine, and interpret additional research done on TOI 5938.01 with our own. In Section 6 we present our conclusions and potential future work.

2. Observations

In Section 2.1 we present the properties from the 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 GMU 0.8m telescope.

2.1 Exoplanet Candidate Properties

TOI 5938.01 has an assumed transit depth of 2680± 187.215ppm of an assumed transit duration of 2.098±0.342 hours. The assumed transit midpoint in days is 2459820.183153± 0.0019658. The predicted radius (R_Earth) is 3.92152± 0.365697. Its predicted insolation (Earth Flux) is 249.273. It has an assumed equilibrium temperature (K) of 1069.64-1106**.** Its host star, TOI 5938, has a predicted Teff (K) of 4452± 129.977. ITs assumed radius (R_Sun) is 0.742316± 0.0623242 and has a predicted mass (M_Sun) of 0.698± 0.08399. Its predicted density (g/cm3) is 2.406066± 0.71043 and has a predicted luminosity (L_Sun) of 0.1950264± 0.0112245.[3] Its predicted metallicity is -0.064± 0.08 and has a predicted surface gravity (log_10(cm/s^2)) of 4.5407400 +0.0766702 -0.1253920.[4] Furthermore, TOI 5938.01 has a master priority of 2 and a disposition of VPC+ (Validated Potential Candidate with additional supporting evidence), providing a reasonable speculation and anticipation of an evident exoplanet.

2.2 TESS Sector Light Curves

The TESS mission also produced a flux light curve for TOI 5938.01. Using the MAST Archive website[10], we gathered multiple light curves generated from TESS. Downloading all the files from MAST allowed us to open and view the light curve which shows multiple dates the target was observed. The light curves all have a transit at around 10.41-13.78 days.

2.3 Observational Data

This data was collected with the George Mason University 0.8m telescope. There were a total of 208 science exposures of 70.000 seconds taken in the red filter. After plate-solving and reducing the images, the number of exposures decreased to 120. The 88 other exposures were left out of the research data due to graininess, large jumps in data, or streaks. The date of the observation of these exposures is 2023-06-15, starting at 22:20 and ending at 4:30. The RA of TOI 5938.01 was 20:15:38.12 and the DEC was +28:39:33.21.[5] There were a total of 12 flat exposures of 101.000 seconds in the red filter. There were a total of 12 dark exposures of 70.000 seconds and 10 dark exposures of 101.000 seconds.

3. Analysis

In Section 3.1 we present the tools used to analyze the TESS sector light curves using the Alnitak reduction code[6] and AstroImageJ[7]. In Section 3.2 we present our analysis of the ground-based light curve using AstroImageJ. In Section 3.3 we present our NEB analysis using AstroImageJ.

3.1 Analysis Tools

To create a light curve of TOI 5938.01, we plate-solved and reduced the exposures. For plate solving, we used the Alnitak reduction code[6] in Python 3.6+. Installing all the required packages using pip such as astropy, astroquery, photulis, numpy, scipyx, barycorrpy, and Matplotlib to be able to run the code. We then used the science images and data reduction code to start plate-solving. Once the images were plate-solved and data reduced, we imported them as a virtual stack into AstroImageJ.[7] We used the Aperture Photometry tool in AstroImageJ to create a seeing profile of TOI 5938.01. Using the RA/DEC to find the target star, we right clicked on it to place a circle with a radius of 2.5 around the target. We then used the Gaia stars.radec file[8] to view reference stars of TOI 5938.01. We used the multi-aperture photometry tool to place the apertures of the star, using the inner/outer radius annulus found in the seeing profile. Right clicking on the AstroImageJ[7] window allowed us to run differential photometry which lets us create a light curve. Doing so created a measurement table file storing data on each reduced image.

3.2 Ground-Based Light Curve Analysis

After the plot was created, we used the Multi-plot main, Data set 2 Fit Settings, Multi-plot Y data, and the Measurements table in AstroImageJ[7] to configure and modify the plot.[9] We entered the predicted ingress and egress times 0.7350 and 0.8225 into the "V.Marker 1" and "V.Marker 2" boxes. We used the EXOFAST Quadratic Limb Darkening website[4] to gather the values for Linear LD u1 and Quad LD u2. We AIRMASS detrended the rel_flux_T1 and shifted the residual data to better fit the graph. We then auto scaled the x range using the "Auto X-range" button in the Multi-plot main window.[7]

3.3 NEB Analysis

Using the Gaia file[8] prior to running multi-aperture photometry, we used the multi-plot main tool in AstroImageJ[7] to create NEB search reports and plots. In the “TFOP SG1 NEB Analysis Macro” window the predicted ingress and egress times were entered, along with the predicted target depth. We then chose the measurement table created in 3.1 along with a plate-solved image to generate multiple plots and a main dmagRMS plot. We then examined the plots for any outliers and unchecked them in the “Multi-plot Reference Star Settings.”

4. Results

In this section we present the results of the data obtained from the data reduction/plate-solving and differential photometry using the Alnitak code and AstroImageJ. Section 4.1 views the results of the seeing profile and apertures. Section 4.2 views the results of the light curve plot created. Section 4.3 views the results of the NEB analysis.

4.1 Results of Seeing Profile and Apertures

In **Figure 1**, the radius (26px) was the aperture size for the light curve. The inner radius is blocking the central light from the star and starts the background measurement annulus at 26px. The outer radius is the outer boundary of the annulus where background light from 45-67 pixels describes the region used for background measurement. The Half Width at Half Maximum (HWHM) is 8.46 pixels, providing a measure of the star’s image size aiding in finding the correct radii for apertures and background annuli.

4.2 Results of the Light Curve Plot

In **Figure 2**, the red data points (rel_flux_T1) represent the normalized AIRMASS detrended relative flux of the target. The red line is the transit model of the target. The black and green data points represent the reference stars C164 and C166.

4.3 Results of the NEB Analysis

In **Figure 3**, there are few stars that lie on or near the cleared/likely cleared boundary. These close stars also have lower RMS than the stars that lay further out. There are several stars further and higher in RMS/dmag than the target star. There are no stars in the upper left hand of the graph with high RMS and low dmag.

5. Discussion

In Section 5.1 we interpret our results from our light curve plot. In Section 5.2 we interpret our results from the Seeing Profile. In Section 5.3 we interpret our results from our NEB analysis. In Section 5.4 we examine, compare, and interpret our results to multiple other credible sources research on TOI 5938.01.

5.1 Interpreting Light Curve Plot Results

Based on the light curve plot (**Figure 2**), there is an exceptionally low RMS/ppt value in our rel_flux_T1 (normalized) value. This is a promising sign as low RMS indicates a better fit between the observed data and the model. Low ppt value expresses slight change in brightness, possibly a small planet and/or shallow transit depth. The rel_flux_T1 Transit Model (red line) precisely follows the rel_flux_T1 AIRMASS detrended transit-flitted flux data points, hinting that the observed data and transit model are correlative. The rel_flux_T1 residuals also have an extremely low RMS of 0.05062, indicating very small deviations from the model. This shows how well the transit model fits the observed data after accounting for noise and systematics. Examining the plot, we can see the residuals are exceptionally low. The Sky/Pixel_T1 data (yellow line) shows the sky background/pixel noise of RMS 89.15ppt, concluding lots of noise which is common for background measurements. The Width_T1 (grey line) represents the PSF during observations that can affect the accuracy of the flux measurements. Reference stars such as rel_flux_C164 and rel_flux_C166 are being used to account for systematic errors and improve the accuracy of the star's light curve. They both have a higher RMS indicating high scatter. The RMS of 5.92ppt (rel_flux_T1 AIRMASS detrended) expresses effective detrending. Even though the Sky/Pixel, AIRMS, Width, and tot_C_cents RMS values are considered on the higher side, they seem to smoothen around the predicted transit time, suggesting the data reduction and detrending processes were effective.

5.2 Interpreting the Seeing Profile Results

Based on the seeing profile created in AstroImageJ (**Figure 1**), the ADU Drop-off flux decreases as the radius increases from the center of the star, which is expected. The HWHM (used to characterize image quality) value of 8.46 is moderately low, suggesting a higher image quality. This is ideal to get the most out of our data.

5.3 Interpreting the NEB Analysis

Based on the NEB analysis performed (**Figure 3**), a moderate number of nearby stars are in (or close to) the likely cleared boundary (magenta line) and the cleared boundary (green line). This indicates several possible contaminating stars have been cleared and checked. The stars with higher RMS values that are outside the cleared boundaries are far enough from the target star that it is unlikely they affect the data/curve. Most of these stars also have a high differential magnitude (dmag) indicating they are much dimmer than the target star, suggesting even more evidence for the signal to not be a false-positive. There are also no possible contaminating stars in the upper left hand of the graph with high RMS and low dmag. This removes the clear confirmation of the signal purely being a NEB. Although there are stars with high RMS that are far out from the target star, our analysis found them to not be cleared due to the flux being too low. They are not definitively classified as false positives; therefore, further analysis is needed to compare the NEB results to other data to get a better understanding. Though this does not also conclude there is not a real signal/transit. Comparing our data to past research will aid us in this uncertainty.

5.4 Comparing and Interpreting Results

Due to other research[10] studying different methods more extensively, such as high contrast imaging and gamma rays, it is useful to compare and combine our results to complete a full analysis of TOI 5938.01. In **Figure 4,** the top left plots green vertical lines represent possible transits, and the blue triangles represent transit events. The consistent detection of dips at regular intervals shows a repeating event, suggesting a planet orbiting the star sometimes blocking its light. The second plot, the phase folded light curve, folds the light curve on the planet's orbital period (2.26 days) to align transit events on top of each other showcasing their consistency. The black data points show clear periodic dimming, hinting at the detection of a planet. The third plot provides a closer zoomed-in view at the transit. This plot confirms the depth of the transit as well as the shape of the light curve during it. Since it is consistent in transit shape and depth, it strongly suggests a planetary transit as that data is not likely to be caused by stellar variability. The fourth plot, depth and significance of transit, the primary depth is 495ppm indicating how much the star's brightness dimmed during the transit. The centroid offset plot confirms no significant offset, meaning the transit signal is centered on the target star. This confirms the source of the transit. In **Figure 5,** there is normalized flux showing clear data of each transit over time. **Figure 6** shows the star field and neighboring stars of our host TOI 5938[11]. This high-contrast (Hcont) image does not present any obvious close companions that may create a false positive. The consistency of these transit events across different observation periods shows a periodic nature to the transits, further confirming to be a planet. Due to weather conditions and a relatively small number of plate-solved images, the NEB analysis we did could be faulty. In this case, **Figure 7** shows the NEB analysis done by John Kielkopf[12]. This allows a more accurate conclusion to be made. Looking at the plot shows multiple stars that are now being cleared/likely cleared that were not before. The outliers such as T121 and T183 have high RMS further out from the target star. This yet again applies that it is not likely for the transit to be caused by a NEB. This data aligns with the data we collected with the GMU telescope. We captured multiple transits in the light curve and our data plotted illustrating the depth and ingress/egress lines up to that of TESS and other past observations.

6. Conclusions

Due to the overwhelming amount of data collected from not only our research but others, it is strongly implied that TOI 5938.01 is indeed an exoplanet. Our light curve confirms multiple transits aligning with the summary reports data from the MAST Archive. The transit time and other planetary data also align with that of the TESS[3] data. High-contrast imaging and NEB analysis suggest a low possibility of the signal being from a NEB or a being a false positive. A possible follow-up to enhance the data would be one more detailed NEB analysis to have more confidence in the transit signals' existence.

7. Tables and Figures

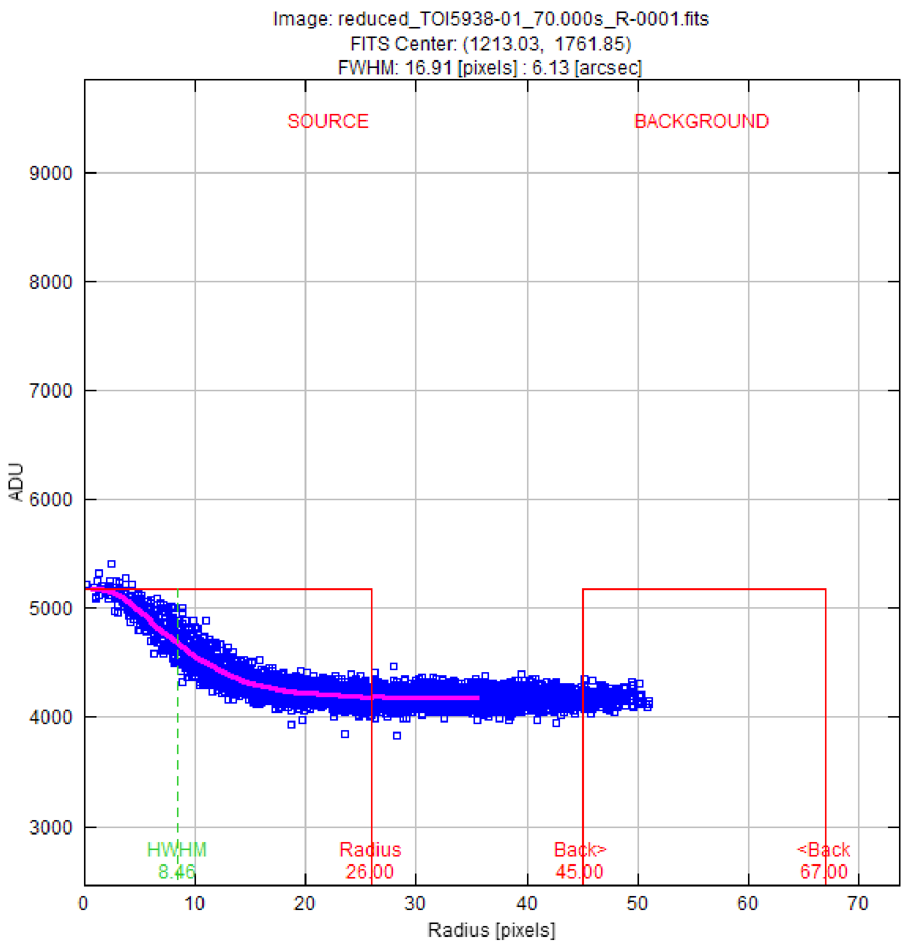

Figure 1. Seeing Profile obtained from Aperture Photometry (AstroImageJ)[7]

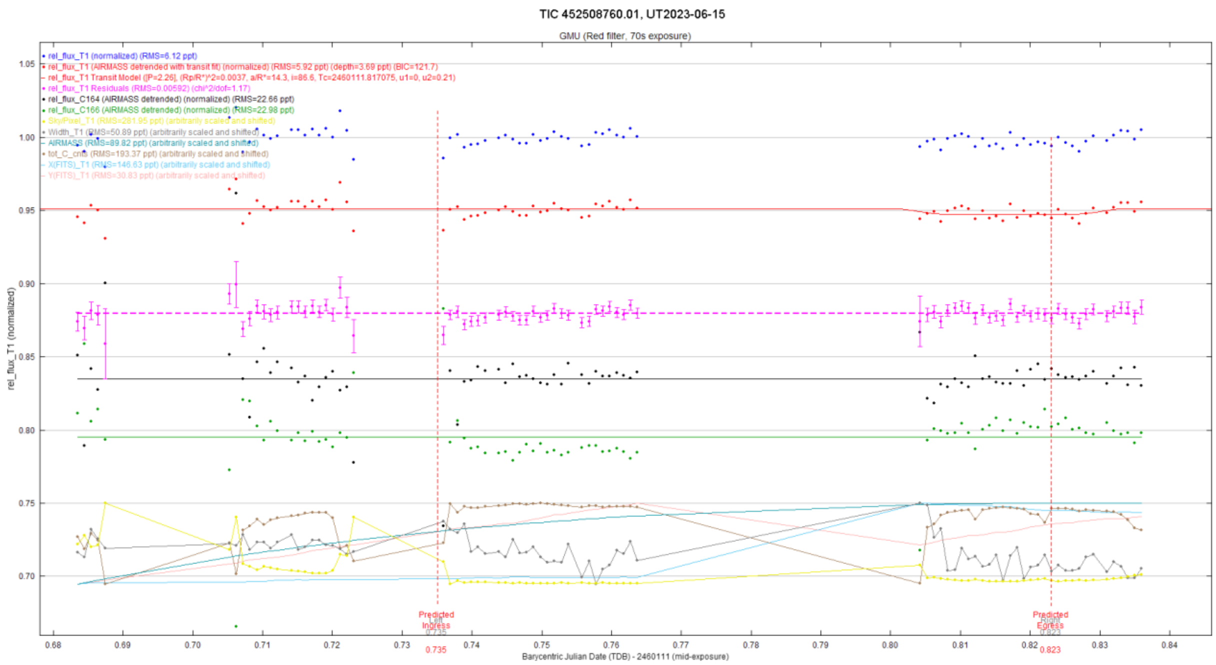

Figure 2. Transit light curve obtained from multi-aperture photometry (AstroImageJ)[7]

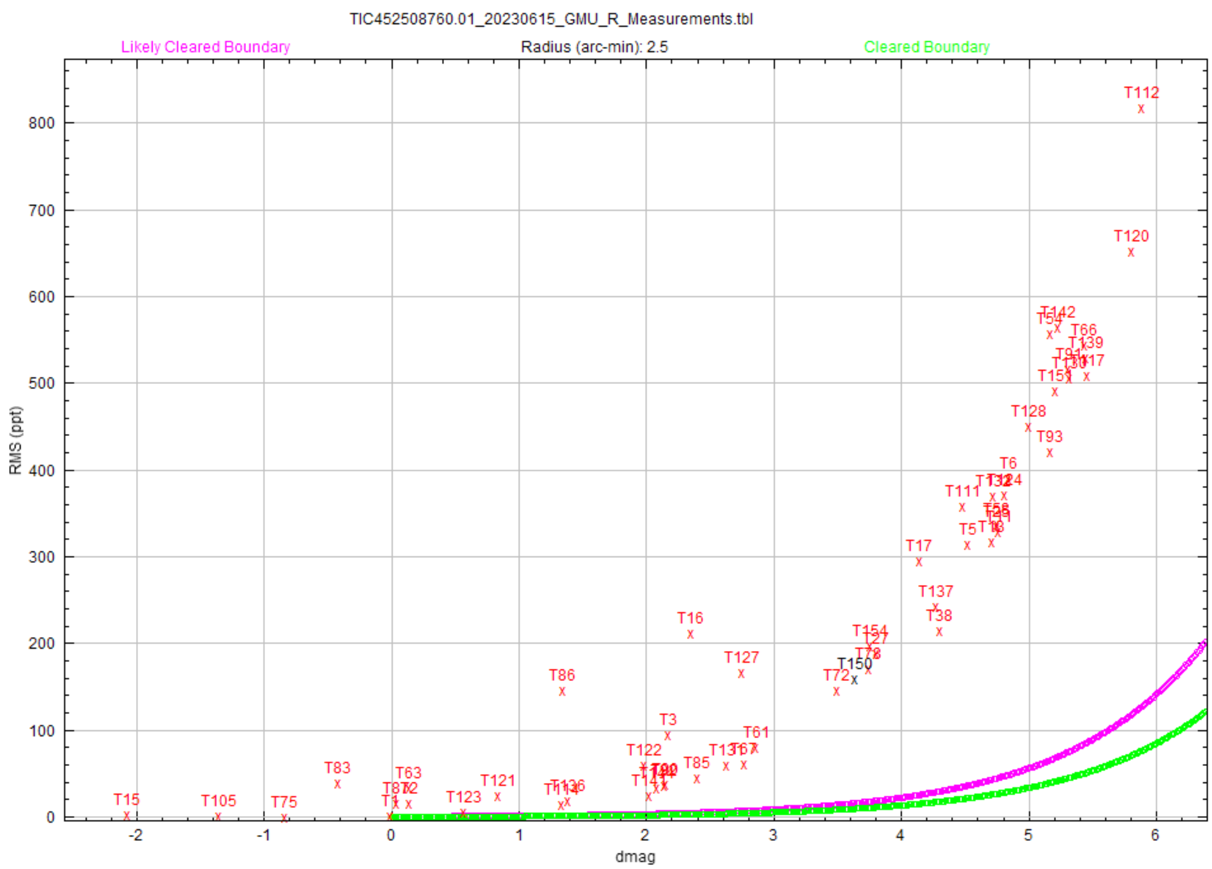

Figure 3. NEB analysis results (AstroImageJ)[7]

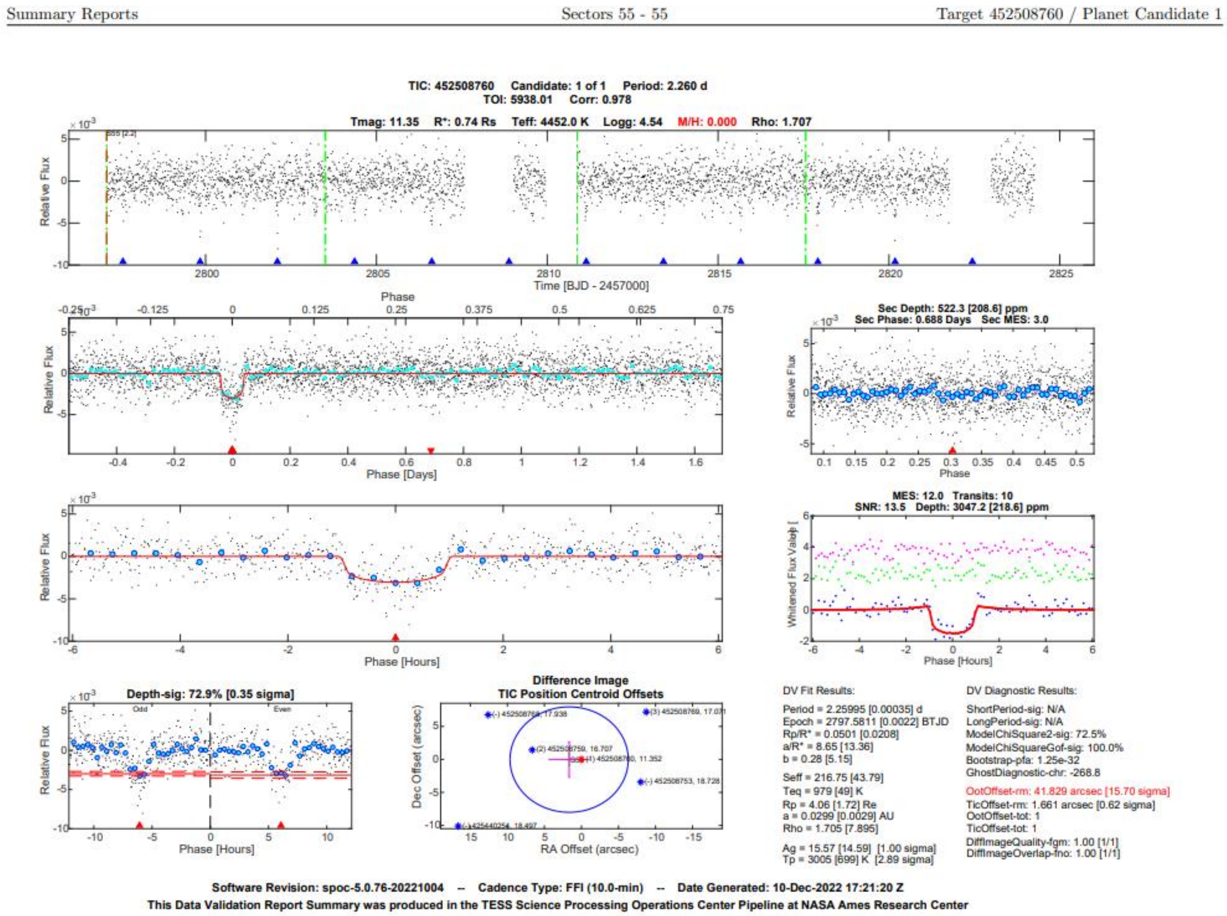

Figure 4. Summary Reports of TOI 5938.01 (MAST Archive)[10]

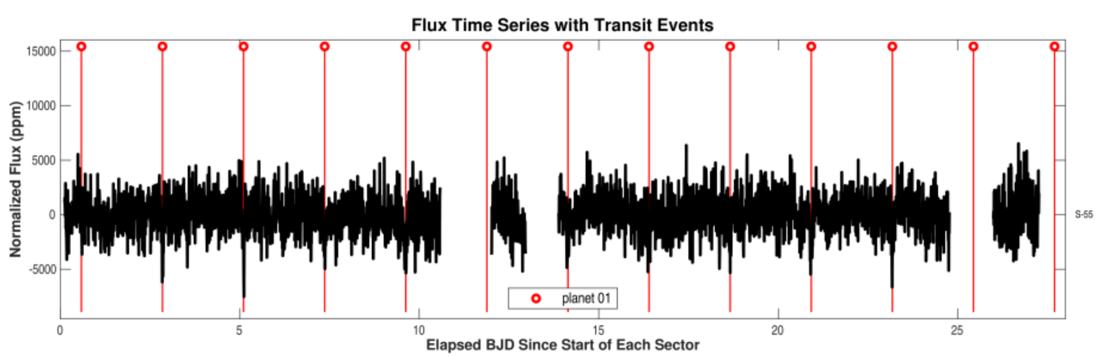

Figure 5. Flux Time Series with Transit Events (MAST Archive)[10]

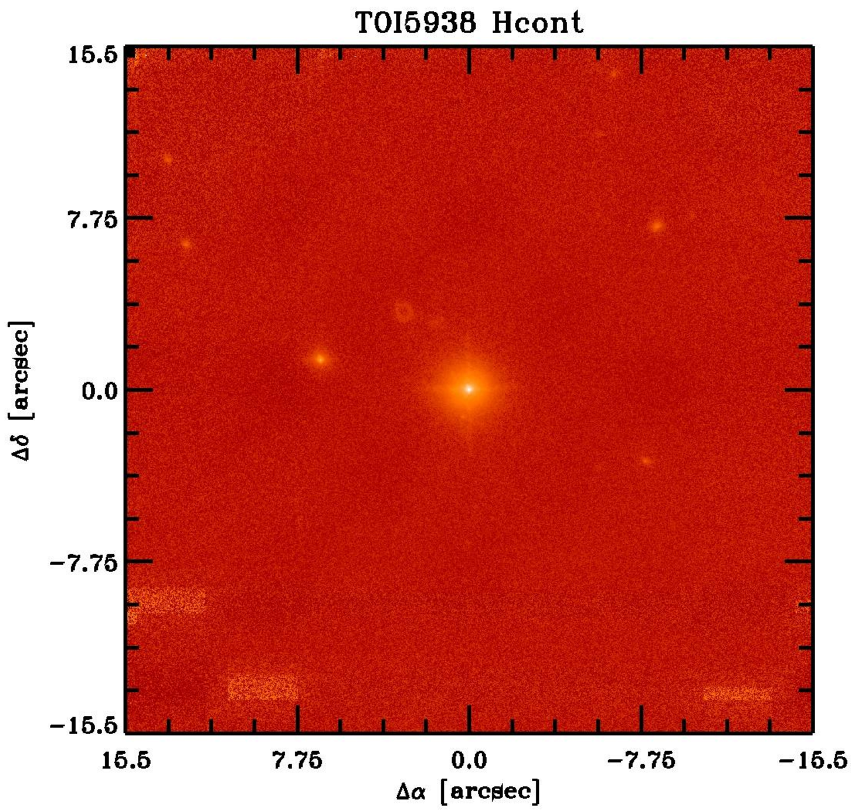

Figure 6. High-contrast Imaging (Hcont by David Ciardi)[11]

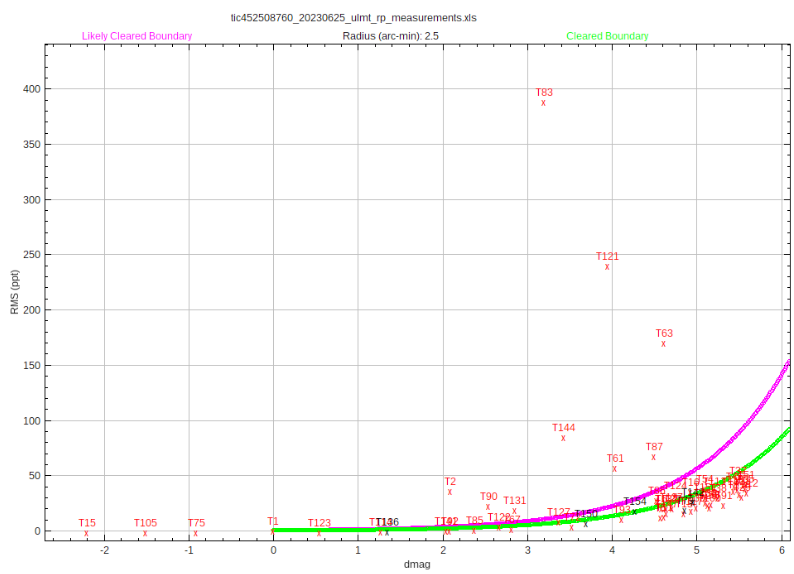

Figure 7. NEB Analysis (John Kielkopf)[12]

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9. References

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