Ground-Based Light Curve Follow Up Validation Observations of TESS Object of Interest 5907.01

Colin Sardilli, Dr. Peter Plavchan[1]

[1] Department of Physics and Astronomy, 4400 University Drive MS 3F3, George Mason University, Fairfax, VA 22030, USA

Abstract

The Transiting Exoplanet Survey Satellite (TESS) observes large parts of the sky and creates candidate exoplanets called TESS Objects of Interest (TOIs). TOIs need to be validated with other telescopes and exoplanet observation methods.[2] The goal of this research effort was to validate the existence of TOI-5907.01 as well as its orbital characteristics. Data from the 0.8 meter telescope at the George Mason University Fairfax Campus was used in the investigation. Data was collected on 2023/7/10 and 2023/7/11 local using the telescope. 228 science images, 10 science darks, 10 flat darks, and 10 flat fields were collected. AstroImageJ was used to remove bad frames, reduce the data, perform aperture photometry, create a light curve, and perform a nearby eclipsing binary (NEB) check.[3] Unfortunately, we were not able to observe a detection. Our transit depth was within our model RMS and only twice that of our transit depth uncertainty. In addition, our NEB check was inconclusive due to data that was too noisy.

1. Introduction

As of July 31st, 2024, over 5,000 exoplanets have been confirmed, over 4,000 discovered with the transit method.[4] The transit method involves measuring a decrease in the brightness of a star, indicating a passing planet.[5] The first exoplanet detected by the transit method was HD 209458b, a known Hot Jupiter. This was observed with a 4 inch consumer telescope in the parking lot of a store (Plavchan 2024). The Kepler Space Telescope was the first spacecraft specifically designed to look for exoplanets via the transit method.[6] Now, the Transiting Exoplanet Survey Satellite (TESS) observes large portions of the sky to look for exoplanet candidates. These exoplanet candidates need follow-up observation in order to be confirmed.[2] Much of this research is carried out by ground-based telescopes all over the world such as the 0.8m Ritchey-Chrétien at the George Mason University Fairfax Campus.

Due to TESS's ability to survey large parts of the sky, it has created thousands of candidate exoplanets. As of July 31th, 2024, 7,203 candidates have been observed by TESS.[7] These need to be validated in order to be further researched. One example of validation of an exoplanet is titled "A sub-Neptune transiting the young field star HD 18599 at 40 pc" (De Leon et al. 2022). The participants in this paper used ground-based photometry from the InfraRed Survey Facility, the Las Cumbres Observatory, the Perth Exoplanet Survey Telescope, and the Next Generation Transit Survey in order to validate the candidate TOI-179 (De Leon et al. 2022).

---

[2] https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/transiting-exoplanet-survey-satellite-tess
[3] https://www.astro.louisville.edu/software/astroimagej/
[4] https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html
[5] https://science.nasa.gov/exoplanets/whats-a-transit/
[6] https://science.nasa.gov/mission/kepler/
[7] https://exoplanetarchive.ipac.caltech.edu/

In this paper, we present follow-up observations of TESS Object of Interest (TOI) 5907.01. The right ascension of this object is 21h00m52.77s, the declination is +17d06m59.1s. It has an orbital period of 0.66 Earth days, a radius of 8.31 R_Earth, and orbits a 12th magnitude star at a distance from Earth of 456.74 parsecs.[8] Our goal was to determine whether a transit of the star would occur at the expected time, with the expected depth and duration.

In Section 2, we present our observations of TOI-5907.01. In Section 3, we present our analysis of the collected data. In Section 4, we present our results. In Section 5, we discuss those results. In Section 6, we make conclusions and recommend future work.

2. Observations

In Section 2.1, we present TOI 5907.01, its properties, as well as those of its host star. In Section 2.2, we present follow up observation data from the 0.8m telescope at the George Mason University Fairfax Campus.

2.1. TOI 5907.01, or Tess Input Catalog (TIC) 387318486, is located at RA 21h00m52.77s, and DEC +17d06m59.1s, at a distance of 456.641±7.1535 parsecs. It has a radius of 8.31454±2.06084 R_Earth and an orbital period of 0.6583175±0.0000797 Earth Days. It has a transit duration of 0.796±0.417 hours and a transit depth of 3740±2376.25 PPM. It has an equilibrium temperature of 1963K. The host star has a magnitude of 12.4411±0.007, a stellar effective temperature of 5766±124.5K, and a stellar radius of 1.08±0.05 R_Sun, meaning it is similar in size to our Sun. The TOI was created on 2022/11/08.[8]

2.2. Data was collected between 21:46 on 2023/7/10 and 4:42 on 2023/7/11 local. 228 science frames were collected each with an exposure time of 80 seconds. 10 flat fields were taken with an exposure time of 2.5 seconds. 10 science darks and 10 flat darks were also collected. The data was collected by Dr. Peter Plavchan and Schar Students. The observation was conducted with a Red filter in order to help combat severe light pollution. The object was at 66 degrees in altitude at the predicted ingress time of 3:39 local and at 61 degrees at the predicted egress time of 4:27 local. The transit was predicted to last 48 minutes. The predicted transit depth was 3.7 ppt.

[8] https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=TOI

3. Analysis

In Section 3.1, we present AstroImageJ, the tool used to analyze our dataset. In Section 3.2, we present our analysis of the ground-based light curve created by the 0.8m telescope at the George Mason University Fairfax campus.

3.1. AstroImageJ (AIJ) is a software package used to analyze astronomical images for research and is capable of opening and analyzing .fits format images, reducing them, plate solving them, and performing aperture photometry in order to construct a light curve.[9]

3.2. First, the collected science images were opened in AIJ for a visual inspection in a virtual stack. Of the 228 science images, 16 were not able to be used. Unreasonable vignetting was an issue in 10 images, satellite streaks was an issue in 5 images, and inaccurate tracking was an issue in 1 image. Less than 6 of these frames were taken during the transit. 212 usable science images were left. Next, the science images were reduced. A master flat file was created by dark subtracting the flat darks from the flat field images. Then, the science images were reduced by subtracting by the science darks and dividing by the master flat. The images were then plate solved. Next, the reduced science images were imported into AIJ in a virtual stack, and a seeing profile was created for the images using the aperture photometry tool in AIJ.[9] A Gaia file was also applied to the virtual stack.[10] Next, the multi aperture photometry tool was used to place apertures. Aperture size was according to the seeing profile. AIJ auto compared stars and chose reference stars.[9] 3 of these reference stars had to be deleted due to drift in the field throughout the course of the imaging session, which left these stars out of the telescope's field of view in the latter part of the imaging session. From this, multi aperture photometry was performed and a plot was generated.[8] A template file was provided by astrodennis.[11] The predicted ingress and egress time was input into the Multi Plot Main page in which an auto x-range and custom y-range were used. The Data Set 2 Fit page was used to tune the model to fit the transit. The detrend parameters AIRMASS, Sky/Pixel_T1, and tot_C_cnts were used. The Multi Plot Y Data page was used to position and scale the data within the plot for proper presentation. An NEB Check was then performed and a Dmag vs. RMS plot was created.[9]

[9] https://www.astro.louisville.edu/software/astroimagej/

[10] https://www.esa.int/Science_Exploration/Space_Science/Gaia

[11] https://astrodennis.com/

4. Results

In Section 4, we present 8 figures.

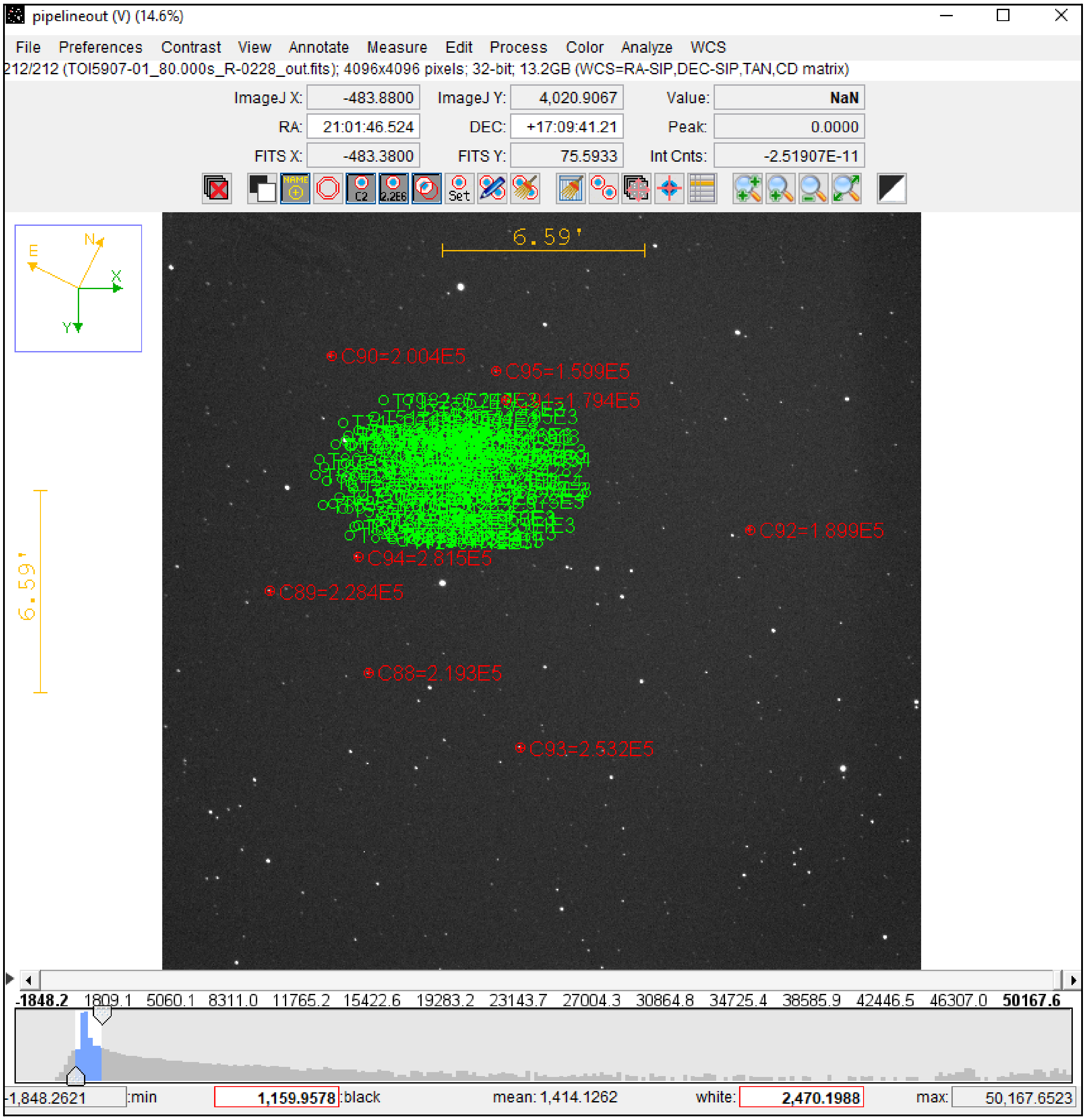

Figure 1: Plate Solved Image with Apertures Placed

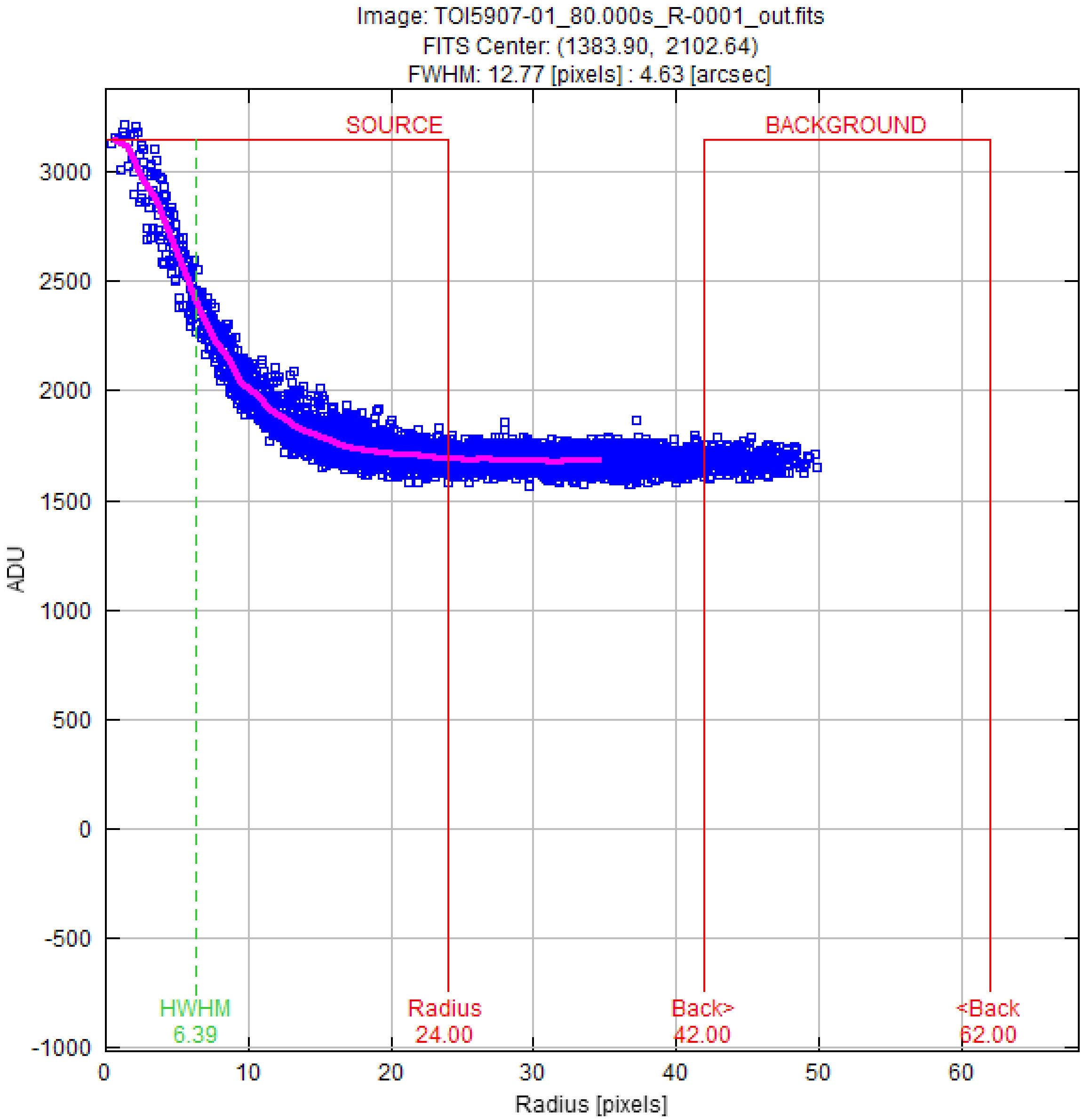

Figure 2: Seeing Profile

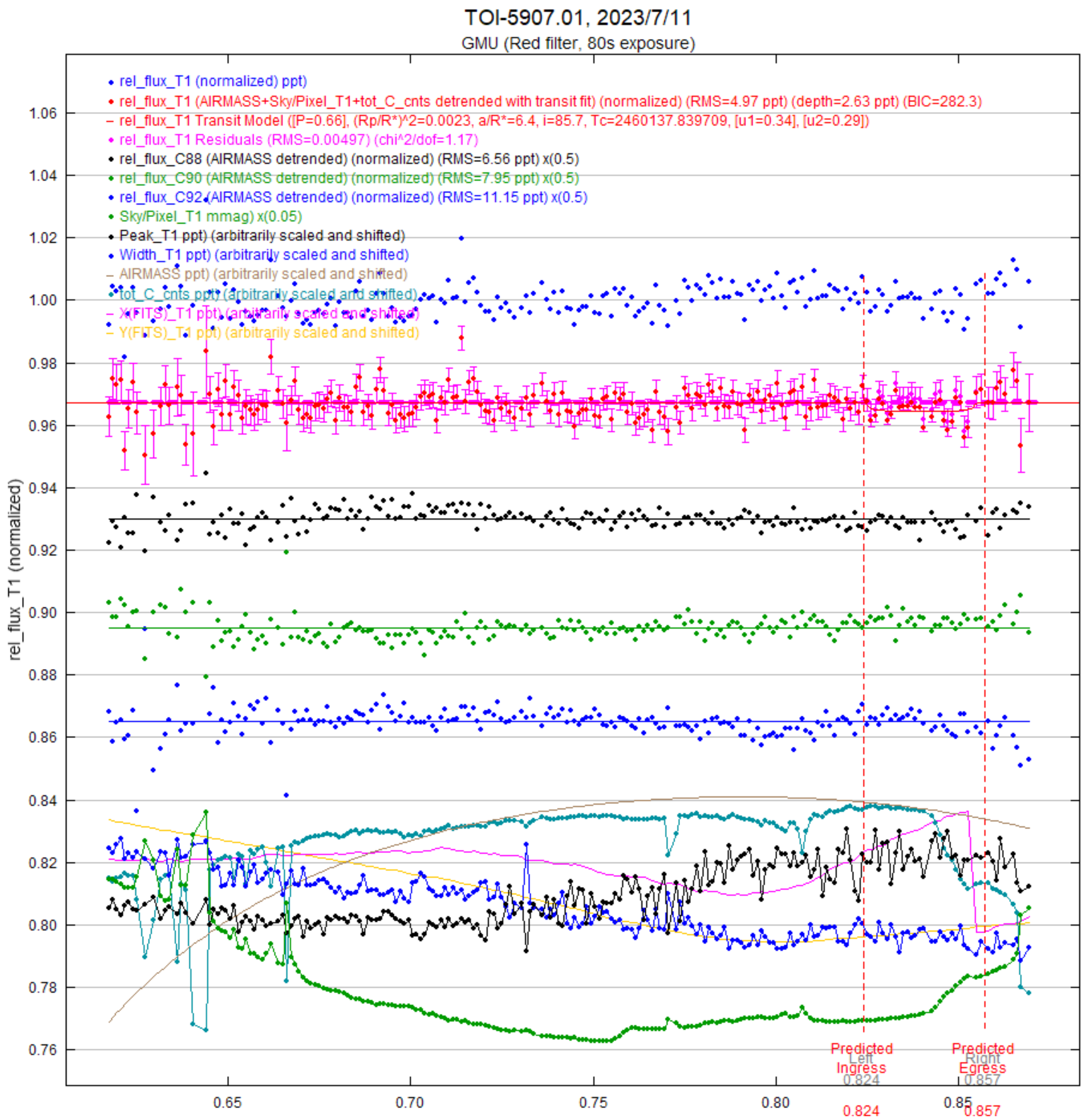

Figure 3: Target Star Flux, Reference Star Flux and Trend Plot. X-axis is Barycentric Julian Date (TDB). The date was 2460136 (mid-exposure).

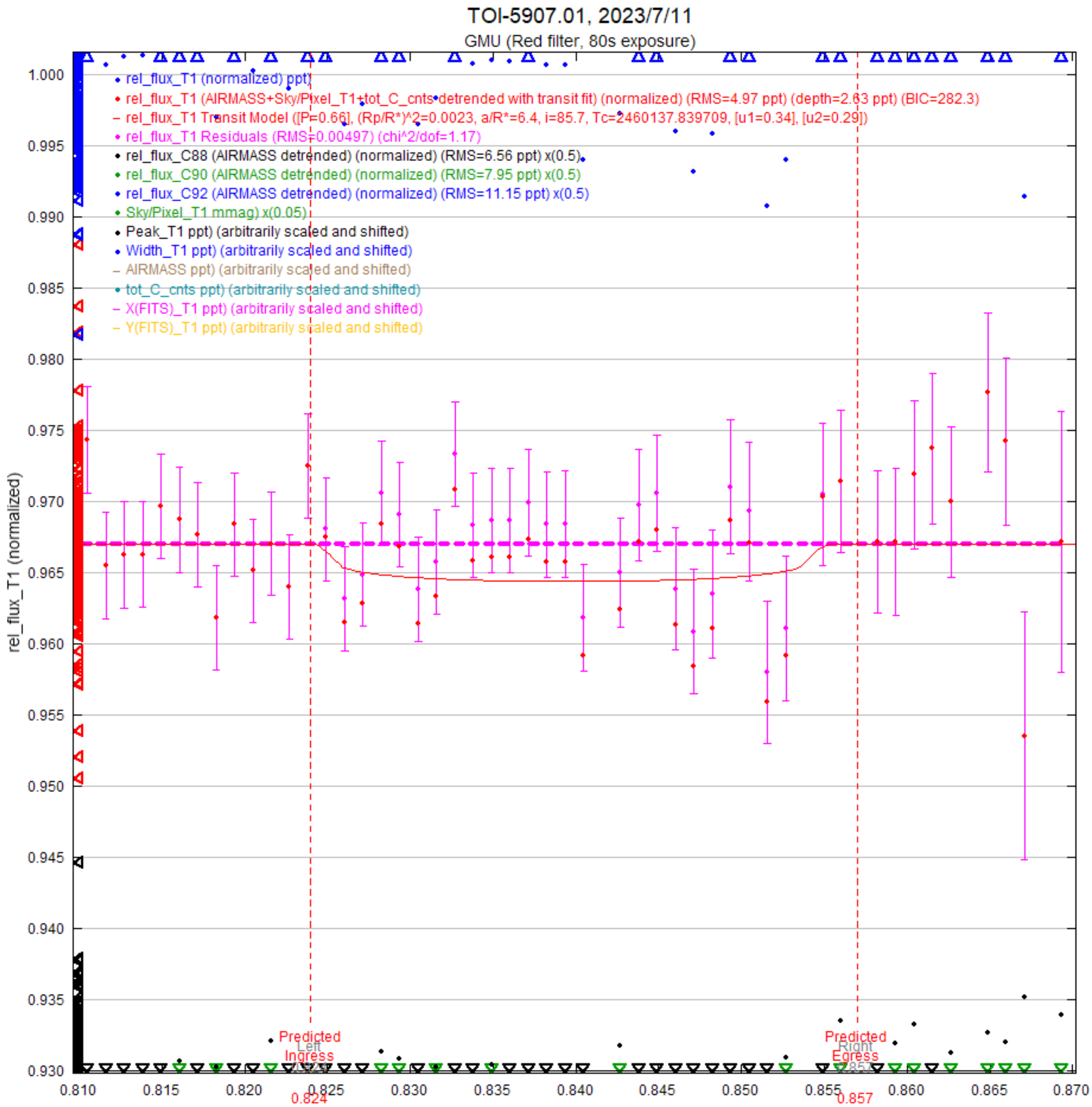

Figure 4: Transit Detail

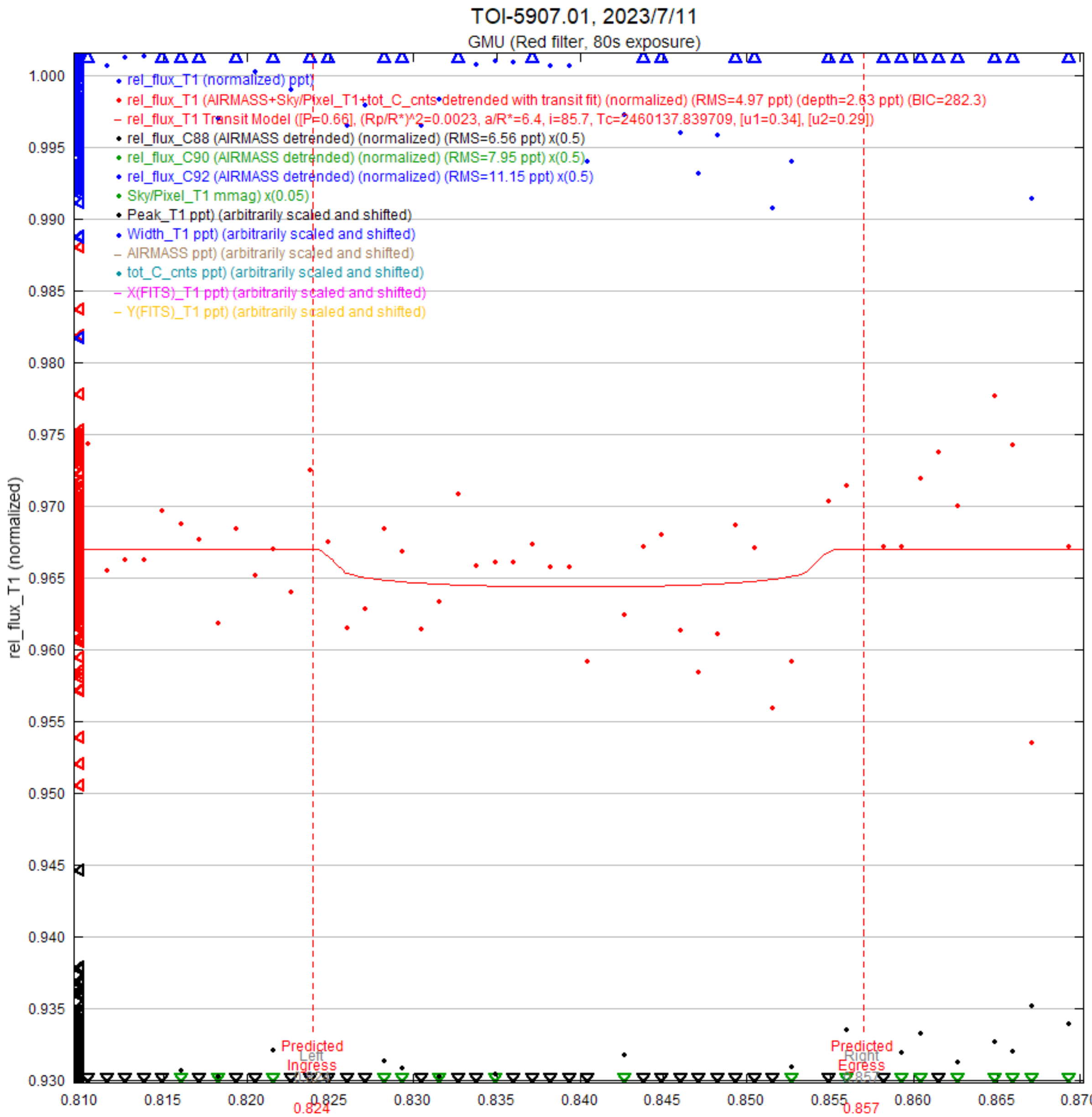

Figure 5: Transit Detail without Residuals

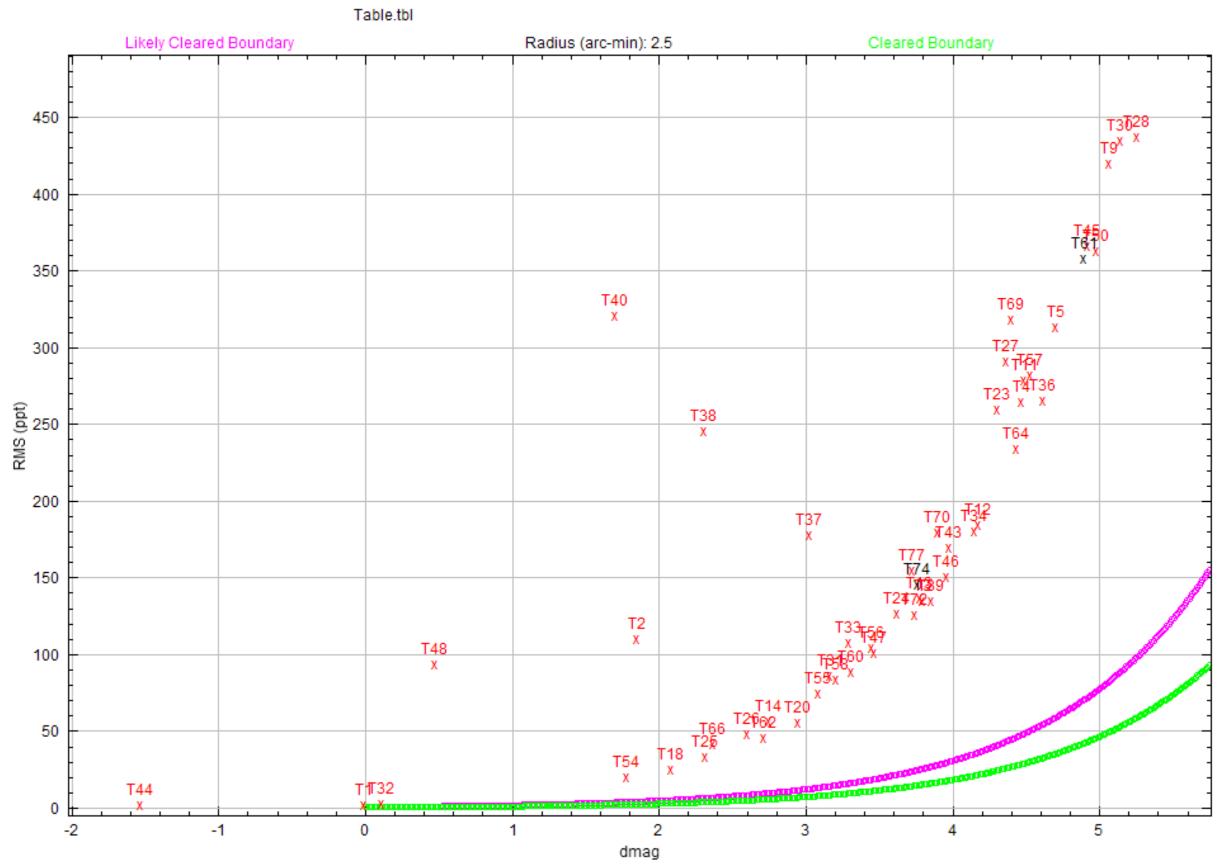

Figure 6: Dmag vs. RMS Plot. Dmag is plotted on X-axis, RMS on Y-axis with the unit parts per thousand.

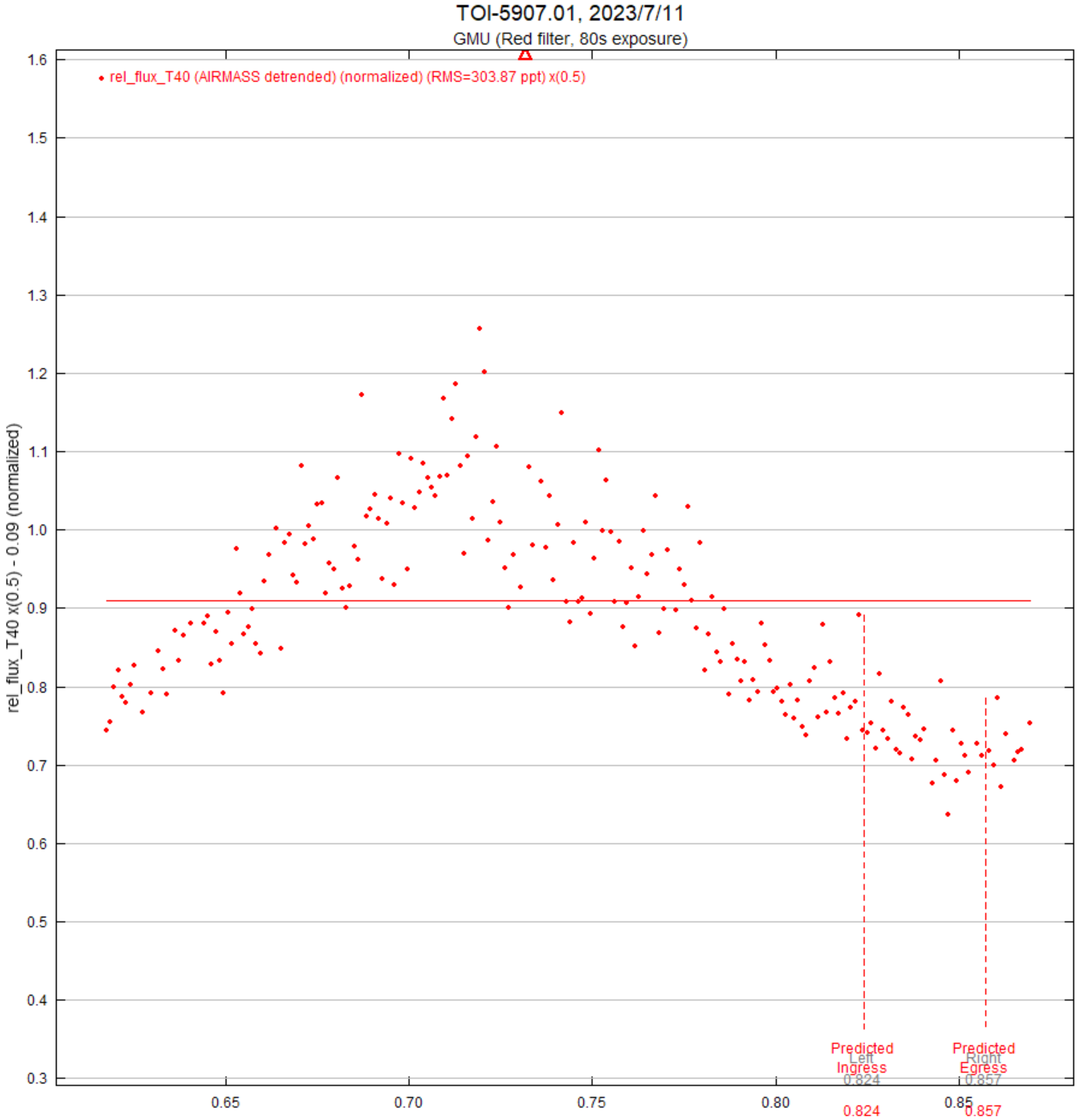

Figure 7: Light Curve of Aperture T40

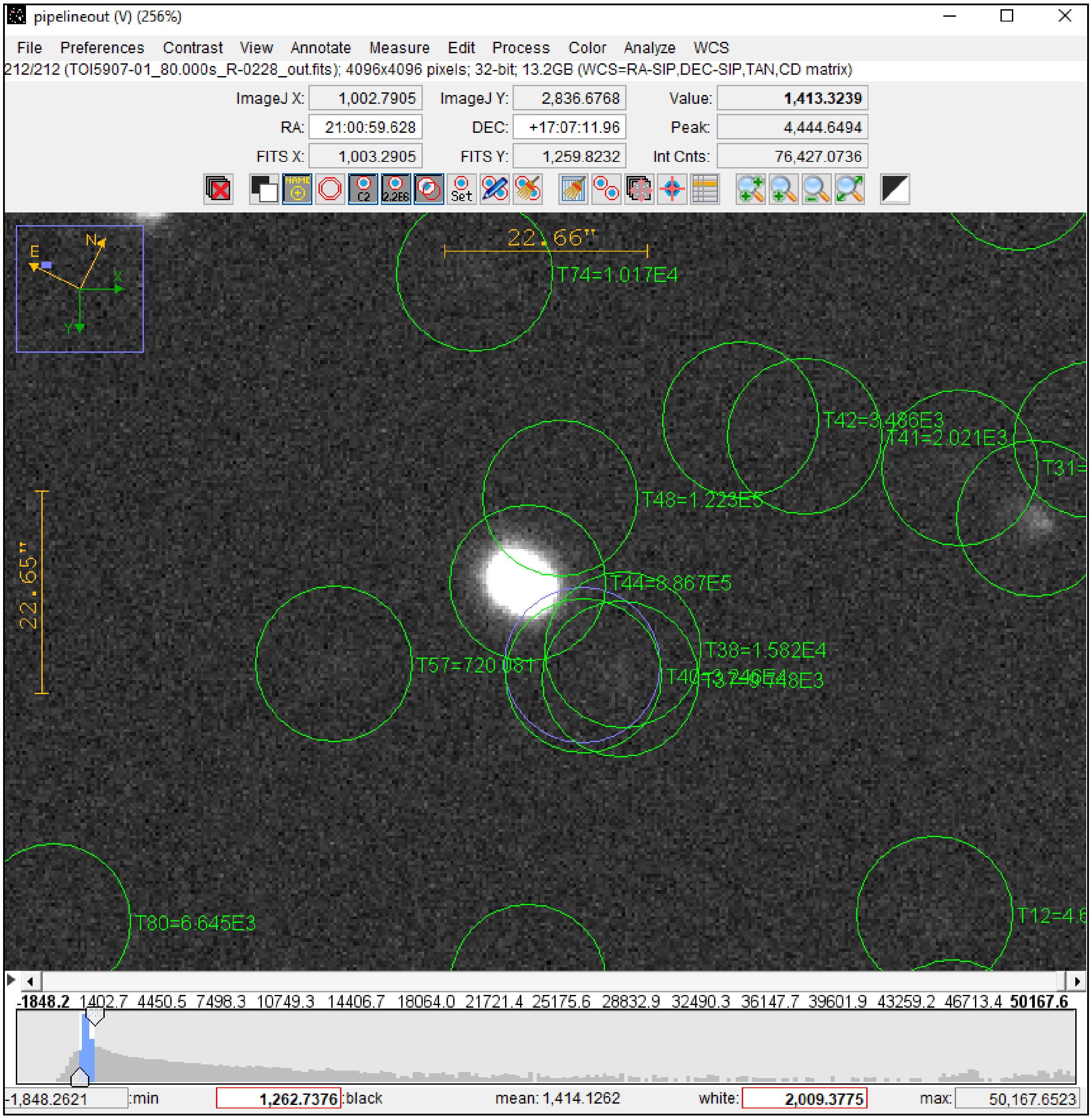

Figure 8: Aperture T40

5. Discussion

In Section 5.1, we present our interpretation of the light curve plot. In Section 5.2, we present our interpretation of the Dmag vs. RMS plot.

5.1. When zooming in on the light curve plot, there is a traditional transit shape exhibited in the model as shown in Figures 3, 4, and 5. The reduced Chi^2 of the transit model was 1.174. This Chi^2 value is close to 1, suggesting a good model fit. The Chi^2 value was 239.4073 and there were 204 degrees of freedom. The RMS of the model was 4.97 ppt. The uncertainty in the transit depth was 0.96 ppt. The measured transit had a depth of 2.63 ppt. This is 1.07 ppt less than the predicted transit depth of 3.7 ppt. This could be caused by the planet being smaller or further away from its host star than previously thought. The predicted ingress time was 3:39 local, while the observed ingress time was 3:47 local. The predicted egress time was 4:27 local, while the observed egress time was 4:31 local. The transit started 8 minutes later than expected and finished 4 minutes later than expected. This means the transit was also 4 minutes shorter than expected at a time of 44 minutes instead of the predicted 48 minutes. Unfortunately, this cannot be considered a detection. First, the transit depth is within the RMS of 4.97 and only twice the transit depth uncertainty of 0.96 ppt. This is not strong enough evidence to conclude a transit. In addition, when looking at the tot_C_cnts trend graph, it is clear the total counts dropped off in the second half of the transit, suggesting clouds interfered with the observation. There is also not sufficient control data past the egress of the transit due to the time of night the transit occurred (early in the morning).

5.2. Finally, When looking at the Dmag vs. RMS plot (Figure 6), the majority of stars are present on one curve, suggesting their flux didn't change significantly throughout the imaging session. However, their RMS is too high to conclusively rule them out. There are also a few outliers such as T40. This aperture has very high RMS in relation to other stars of similar brightness. The RMS is high because of large changes in flux over the imaging session as evident in the light curve for T40 (Figure 7). When looking at aperture T40 in the image (Figure 8), there isn't even a star within it, meaning the measured flux changes came purely from background brightness changes throughout the night. Again, this results in an inconclusive NEB Check.

6. Conclusion and Future Work

Throughout the research effort, we were able to produce a seeing profile, light curve plot, and a NEB Check. Unfortunately, we have to conclude a non-detection. Clouds most likely interfered with observation of the transit, the model RMS was too high, and we did not have enough control data past the transit. Our NEB check was inconclusive as well, and many of the Gaia stars didn't even show up in our field.

Much needs to be done in order to validate TOI-5907.01 as an exoplanet. First, a conclusive NEB check should be carried out. A larger telescope and/or longer exposures will need to be used for this as our data was too noisy to reveal many of the Gaia stars. In addition, a Bayesian Statistical Analysis should be performed. Other methods besides the transit method should also be used to validate this exoplanet. Performing Radial Velocity and Spectroscopy measurements would all be useful in confirming the existence of TOI-5907.01 as an exoplanet.

References

Conti, Dennis. (2016). *Exoplanet Observing by Amateur Astronomers*. Astrodennis. Accessed August 4 2024, https://astrodennis.com/

De Leon, J.P. et al. (2022). *A sub-Neptune transiting the young field star HD 18599 at 40 pc.* Arxiv.

(n.d.). *Exoplanet and Candidate Statistics.* NASA Exoplanet Archive. Accessed August 2 2024, https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

(n.d.). *Gaia ESA's billion star surveyor.* The European Space Agency. Accessed August 2 2024, https://www.esa.int/Science_Exploration/Space_Science/Gaia

(n.d.). *Kepler / K2.* NASA. Accessed August 2 2024, https://science.nasa.gov/mission/kepler/

(n.d.). *TESS Project Candidates.* NASA Exoplanet Archive. Accessed August 2 2024, https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=TOI

(n.d.). *Transiting Exoplanet Survey Satellite (TESS).* Center For Astrophysics Harvard & Smithsonian. Accessed August 2 2024, https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/transiting-exoplanet-survey-satellite-tess

(n.d.). *What's a transit?*. NASA. Accessed August 2 2024, https://science.nasa.gov/exoplanets/whats-a-transit/

Plavchan. P. (2024). Five-Week Young Astro-Scholars Internship: Astronomy Data Analysis and Space Research for NASA Missions, Lecture 5 [PowerPoint presentation].

(2021, August 5). AstroImageJ ImageJ for Astronomy. Accessed August 2 2024, https://www.astro.louisville.edu/software/astroimagej/