# Ground-based Light Curve Follow-up Validation Observations of TESS Object of Interest TOI 5612.01

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**Abstract:**

Several studies in astronomy have focused on exoplanet analysis; however, many exoplanet candidates still remain to be confirmed. This study aims to discover if the Transiting Exoplanet Survey Satellite (TESS) Object of Interest 5612.01 is an exoplanet transit or if it is a false positive caused by an event such as a near eclipsing binary. This analysis ensures the accuracy of the transit discovered by TESS as it provides a secondary source of confirmation for the data discovered by TESS as well as deeper analysis on specific aspects of the transit such as if other stars may have affected the transit due to them experiencing separate astrological events. Using observations from George Mason University's observatory as well as AstroImageJ and NASA reference materials, this study generated plate-solved images, Near Eclipsing Binary (NEB) analysis, and a light curve. Using the statistical methods of root mean squared analysis and the bayesian information criterion, a model of the transit was generated through this data. However, no result was found due to error in the data set, likely caused by cloud cover or light pollution. This paper provides a demonstration of the flaws of the data set, showing that TOI 5612.01 requires reanalysis and offers commentary on conditions that should be avoided for future analysis of this exoplanet.

## 1. Introduction:

Over 5,000 exoplanets have been discovered since 1992 (Brennan) when the first two exoplanets were discovered: Poltergeist and Phobetor (Wolszczan and Frail). These 5,000 exoplanets are categorized into four main categories: gas giants, neptunians, super-earths, and terrestrials (“Overview”). The most common category is the super-earth which is a planet larger than Earth but lighter than ice giants such as Neptune (Haghighipour 403-438). However even with all of the planets that have been analyzed enough to be categorized, there are still thousands more signals of potential exoplanets.  These exoplanets require analysis to see if they truly exist or are merely false positives. These planets are detected by transit photometry, in which the orbits of the planets are analyzed by seeing when they block vision of the light from the star. This works because during a planetary transit, the light emitted by the star is blocked by a planet, allowing for satellites and telescopes to detect a change in the light output (Deeg and Alonso). Due to its requirements being just a series of images, this method was used by NASA with both the Kepler Space Telescope (“Kepler / K2”) and the Transiting Exoplanet Survey Satellite (TESS). TESS specifically works through the use of ultra wide cameras to be able to cover a substantial amount of the sky at any one time.  With this unique ability to detect so much of the sky at once, TESS has been able and continues to detect a massive quantity of potential exoplanets through the method of transit photometry (NASA). However, due to the wide field of view TESS can detect false positives due to stars being so close together that they are grouped as the same light source. This can occur as a result of events like eclipsing binaries, in which stars pass in front of each other (Latham). It is as a result of events like these that the TESS follow up program exists, using TESS as a way to find potential exoplanets and subjecting these candidates to further analysis through the use of ground based transit photometry. This follows the same process as the TESS photometry but in a more targeted manner with the goal of confirming that the detected candidate is not a false positive.

This object of detecting false positives through ground based transit photometry is a highly tested methodology and thus a wealth of research was available to demonstrate its validity. No research has been published on TESS Object of Interest (TOI) 5612.01 before but data exists for planets with a similar radius, specifically around 8 R_Earths. Examples of these include TOI 5704, which was found to be a hot Mini-Neptune (Mistry 21); TOI 3353.01, which was initially considered to be a possible near eclipsing binary (Mantovan) but later found to be a Neptunian planet within a multiple planet system (Hord); and TOI 1260 b, which was found to be a sub-Neptune in a multi planet system (Lam).

This paper attempts to detect if TOI 5612.01 is a false positive due to an eclipsing binary as well as follow up the TESS observations in an attempt to acquire more precise data on the transit time and depth through ground based transit photometry. The authors hypothesize that TOI 5612.01 is not a false positive and that its transit time is between 0.627 and 0.745 due to the TESS data indicating this as the most likely possibility. Ultimately, errors found to be inherent in the data set made it so that no result could be confirmed or denied.

## 2. Observations

### 2.1 TESS Data

The TESS found that the planet candidate TOI 5612.01 had a transit that lasted approximately 2.809 hours, with a transit depth of 7550 ppm (7.5 ppt). This indicated a radius of approximately 7.98 R_Earth (0.712 R_Jupiter). In addition to this, the TESS data found an orbital period of 7.13 days (ExoFOP). Given all of this data, TOI 5612.01 was labeled a planet candidate and deemed worthy of further analysis.

### 2.2 George Mason University Observatory Data

The data used in this paper was collected by George Mason University's University. Data collection occurred on February 20th 2024, starting at 19:35 and ending at 5:55 on February 21st 2024. This observation attempted to capture the planet which had a predicted ingress time of 21:56 and a predicted egress time of 0:44. This data was collected using a red (R) filter and a 90 second exposure time, as well as a 3.5 second exposure time for flats. Within this data there were moments in which the telescope's perspective jumped and the location of the stars in the images taken changed. While this could be a source of error, it was mainly corrected in plate solving and detrending since the reference stars used were always visible. Additionally, some images had to be deleted due to interference in view or streaking of stars. These data points were removed. However, since some data points occurred during the transit this introduces a potential source of error in the results of this paper, but given that the majority of the transit was captured and the errors in data were sporadic, the data can still be analyzed.

## 3. Methods

### 3.l Data Reduction

The data was separated into three categories: darks, flats, and sciences. The darks are images that capture the thermal noise that may corrupt the image. The flats are images that capture issues with the telescope such as imperfect and defective pixels. The sciences are images that contain the data that is actually being evaluated. In order to make these sciences contain useful data they must be properly corrected.

AstroImageJ's CCD Data Processor Tool (*AstroImageJ*) was used for this process of data correction. Using the build function, the darks were merged together to create a master dark so that only one image would have to be applied to future corrections. This process was done twice, in order to create a master dark for both the flat and the sciences. A master flat was then created in the same manner, merging the flats together using the build function. Additionally, the master dark with the exposure time of the flats was enabled so that any thermal error would be corrected. Finally, enabling the master dark with the same exposure as the sciences and the master flat, the sciences were corrected.

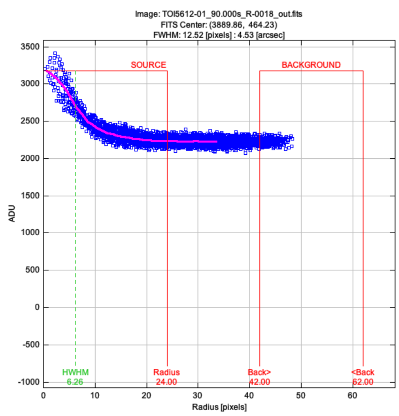
### 3.2 Plate Solving

Plate solving is the process of detecting where the telescope is pointing in the sky. This process gives the coordinates for the stars that the telescope identifies. For this, the AstroImageJ CCD Data Processor was used as well as an API from nova.astronomy.net ("Nova Astronomy"). The settings used were a radius of 30 pixels, a filter radius of 2 pixels, a noise tolerance of 0.5 StdDev, a max stars of 50, a plate scale of 0.35 arcsec/pix, a tolerance of 0.05 arcsec/pix, and a radius of 20 arcmin.

### 3.3 Aperture Photometry

AstroImageJ was used to import an image sequence of the plate-solved sciences. Using the coordinates found by TESS, the target star was located. Using AstroImageJ's Seeing Profile, a Seeing Profile was generated (Figure 1), showing that the target star had a radius of 24 pixels, an inner radius of 42 pixels, and an outer radius of 62 pixels.

AstroImageJ's Aperture Photometry Tool was then used to create a 2.5' radius circle around the target. A Gaia stars .radec file was used to find all of the stars within that 2.5' radius in order to search for any near eclipsing binaries that may corrupt the data. AstroImageJ's Multi Aperture Photometry feature was then used in order to look at the relative flux of the stars over all images in the set (Figure 2). With the target stars in the radius and the reference stars used for comparison, the data was found and collected in a table.



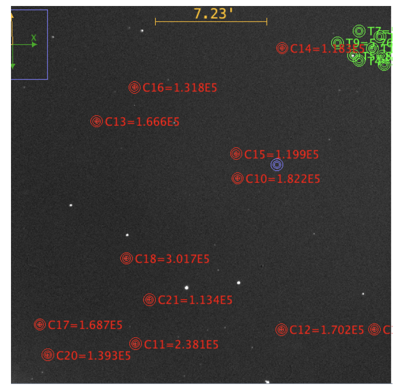




Figure 1: A Seeing Profile of TOI 5612.01 Figure 2: Aperture Photometry of TOI 5612.01

**3.4 Depth of Magnitude vs Root Mean Squared Analysis**

In order to assure that none of the stars were near eclipsing binaries (NEBs) the AstroImageJ feature of the TFOP SG1 NEB Analysis Macro was used. This analysis was used to determine if any stars had a transit that could be explained by an eclipsing binary. This analysis used a depth of 7.5 ppt and a radius of 2.5 arcmin. It checked T1, T2, T3, T4, T5, T6, T7, T8, and T9.

**3.5 Light Curve Creation**

The table created with aperture photometry was put into AstroImageJ's MultiPlot Tool using the Read MeasurementTable Tool. The plot was set to automatically scale its x and y axis with the data in the table. A line of fit was created to demonstrate the transit, using the host star's Linear Limb Darkening Coefficient of 0.5956 and Quadratic Limb Darkening Coefficient of 0.1327 (Eastman), both derived using the star's Teff of 4701.06, log(g) of 4.43, and metallicity of 0.124 (ExoFOP). This created parameters of the line of fit.

The data of the Sky/Pixel_T1, Width_T1, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1 were all used as data points with page relative transformations of a scale of 15 and shift of -42.

Additionally, AIRMASS was used with page relative transformations of a scale of -15 and a shift of -42. All of these were recorded with the intention of showing areas that may cause variability in the data due to shifts in the telescope's location, the conditions around the telescope, or other factors. The scales were determined based on TFOP SG1 Guidelines (Conti).

The data was then detrended in order to minimize the complexity of the fit, focusing on lowering the root mean square (RMS) value. Another variable used to detrend was the Bayesian Information Criterion (BIC), which was used to detect if the fit was getting too complex and thus additional detrending was not worthwhile as it would make the model less accurate to the reality of the data points. The initial reference stars chosen were C10, C13, C14, C15, C17, and C18 as that was the grouping that provided the lowest RMS. Y(FITS)_T1 was chosen as it reduced BIC from 622.9 to 560.42. C11 was then selected as a reference star as it substantially lowered the RMS.

## 4. Results

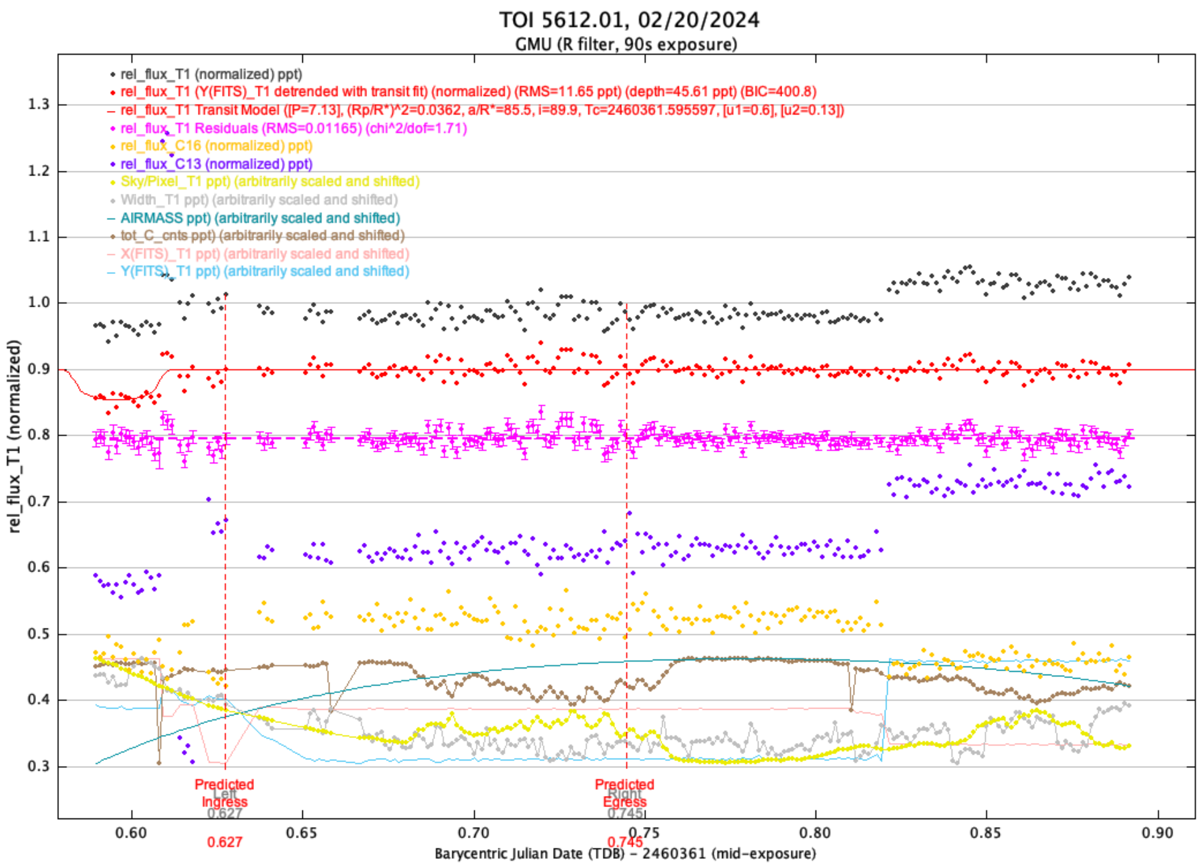



Figure 3: Light Curve of TOI 5612.01

No transit was detected within the predicted ingress or egress times. However the data did show a partial transit from 0.5814 to 0.6115. This transit had a depth of 48.25 ppt and a duration of 42 minutes and 57 seconds. (Figure 3)

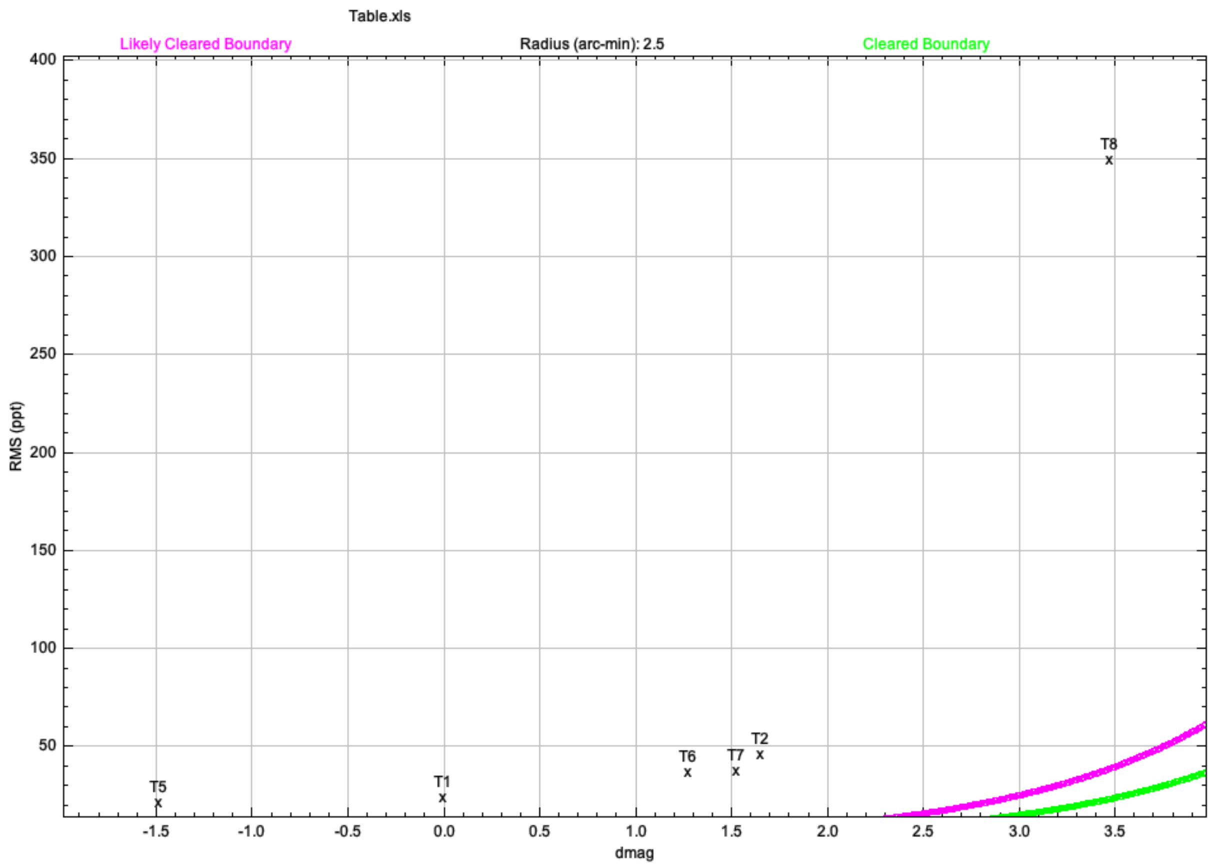



Figure 4: DMag vs RMS Analysis

All stars tested were potential NEBs. Stars T3, T4, and T9 were marked as not cleared - flux too low. Stars T1, T2, T5, T6, T7, and T8 were marked as not cleared (Figure 4).

## 5. Analysis

### 5.1 Interpretation

This data is unable to show if TOI 5612.01 is a false positive or if it is a legitimate transit. The transit that was found by the analysis had a depth of 48.25 ppt which means that it has a percent error of approximately 543% when compared to the TESS findings. The duration of 42 minutes and 57 seconds gives it a percent error of approximately 71% compared to the TESS findings. The ingress and egress times were also substantially different from the predictions from TESS. This all demonstrates that the transit found in the graph is clearly not the transit found by

TESS. Due to the RMS of 11.65 ppt and a BIC of 400.31, this is highly unlikely to be an actual transit, and when this high uncertainty is taken in conjunction with its massive error compared to the TESS findings, it can be dismissed as a sign of error in the data.

The lack of transit within the predicted time cannot be extrapolated to any further meaning due to the high statistical uncertainty. The RMS value of 11.65 ppt is greater than the predicted depth of 7.5 ppt which means that the statistical uncertainty of the data is enough to block the transit from appearing on the graph. Due to this, no conclusion can be drawn from the lack of transit within the predicted times.

It also cannot be concluded that the transit shown was caused by an NEB. While no star cleared the NEB check, they all had a very high RMS as shown in [INSERT NAME OF TABLE]. The dmag vs RMS plot also depicts a clear curve for the stars, even though they are above the line of being cleared as NEBs, which is emblematic of data that was interfered with, as no star stands out as a substantial outlier. This means that while the transit could potentially be an NEB, there is no clear indication of a specific NEB and thus no conclusions can be drawn.

**5.2 Work in a Larger Context**

Possible reasons why no definitive conclusions can be drawn from this study include cloud cover, light pollution, and low quality images at the time of the transit. Cloud cover was a slight issue on the day that the data was collected as even though the night was mostly clear, the preceding morning and evening was cloudy (World Weather) and the night of February 21st (World Weather), which observations ran into, was mostly cloudy. This could have served as the source of error that led to the data being inadequate and implies that any future data collected on TOI 5612.01 should be conducted under conditions that have a substantially lower cloud cover than the minimally operable amount as it has shown to be difficult to detect with even a minor cloud cover. Additionally, light pollution may have caused the inadequacies in the data. George Mason University's Observatory has been noted to have a substantial amount of light pollution (Plavchan and Powers) and while this light pollution does not undermine its typical operational procedures, it may be beneficial for research on TOI 5612.01 to be conducted in an observatory with substantially lower light pollution as the NEB curve is emblematic of data that is artificially brightened by a great deal of light pollution, implying that the conditions demonstrated by this data could be caused by light pollution and thus it should be minimized.

Additionally, some images from around the time of transit showed signs of satellite interference or did not include views of the stars. If the transit had a shorter duration than that found by TESS, that may have been a substantive interruption instead of the minor one that it would be if the predicted values held true. Due to this, any future research will need to ensure that the data collected at the beginning of the transit is of a usable quality as to ensure that the same issue does not occur again. Finally, this paper recommends a longer exposure time be used for future analysis of TOI 5612.01. A longer exposure time allows for a lower signal to noise ratio which would provide a greater degree of certainty of the relative flux of the surrounding stars (Daigle). Since the uncertainty was extremely high for the stars that could have been NEBs, a longer exposure time would allow for the surrounding star's status as near eclipsing binaries to be formally confirmed or denied without the high degree of uncertainty shown by the current dataset. A final source of error came from the jump in Y_FITS shown in the data. This required a Y_FITS detrending in order for the fit to be accurate. While it was partially corrected in this manner, this hindered the study’s freedom in generating the best possible fit in the data.

## 6. Conclusion

This study represents a preliminary step in the process of confirming the planetary nature of the transit found in TOI 5612.01. The study found that TOI 5612.01 cannot be determined to be either a legitimate exoplanet transit or a false positive. The light curve that was found did not indicate any transit within the predicted times and the transit that did appear was likely to be an artifact of the data being highly inaccurate. The NEB check suffered from this same issue, as no star was able to be cleared but a standard curve still emerged, not giving any information as to what star, if any, actually caused an NEB event. Future papers will need to analyze a similar data set to find if the transit was caused by an NEB while following the modifications suggested above. In order to complete this, light pollution and cloud cover must be minimized, the start of the transit should be kept especially free of data interferences, and a longer exposure time should be used.

Works Cited

*AstroImageJ*. 5, University of Louisville, 2021.

Brennan, Pat. "Cosmic Milestone: NASA Confirms 5000 Exoplanets." *NASA Science*, 21 March 2022, https://science.nasa.gov/universe/exoplanets/cosmic-milestone-nasa-confirms-5000-exoplanets/. Accessed 11 August 2024.

Conti, Dennis M. "TFOP SG1 Guidelines." *TFOP SG1 Observation Guidelines Revision 6.4 September 4, 2020 Dennis M. Conti email: dennis@astrodennis.com Introduction*, 4 September 2020, https://astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf. Accessed 31 July 2024.

Daigle, Olivier. "Astronomical imaging with EMCCDs using long exposures." *SPIE*, vol. 9154, 2014. *SPIE*, https://doi.org/10.1117/12.2056617. Accessed 31 July 2024.

Deeg, Hans J., and Roi Alonso. "Transit Photometry as an Exoplanet Discovery Method." *arxiv*, 2018. *arxiv*, https://doi.org/10.48550/arXiv.1803.07867. Accessed 31 July 2024.

Eastman, Jason. "EXOFAST - Quadratic Limb Darkening." *Astroutils*, Ohio State University, 20 July 2016, https://astroutils.astronomy.osu.edu/exofast/limbdark.shtml. Accessed 31 July 2024.

ExoFOP. "TOI Documentation." *ExoFOP*, https://exofop.ipac.caltech.edu/tess/view_toi.php. Accessed 31 July 2024.

"Exoplanets, worlds beyond the Solar System." *The Planetary Society*, https://www.planetary.org/worlds/exoplanets. Accessed 31 July 2024.

Haghighipour, Nader. “Super-Earths: a new class of planetary bodies.” *Taylor and Francis Contemporary Physics*, vol. 52, no. 5, 2011, pp. 403-438. *Taylor and Francis Online*, https://doi.org/10.1080/00107514.2011.598370. Accessed 31 July 2024.

Hord, Benjamin J. “Identification of the Top TESS Objects of Interest for Atmospheric Characterization of Transiting Exoplanets with JWST.” *The Astronomical Journal*, vol. 167, no. 5, 2024, p. 33. *IOP*, 10.3847/1538-3881/ad3068. Accessed 31 July 2024.

“Kepler / K2.” *NASA Science*, https://science.nasa.gov/mission/kepler/. Accessed 31 July 2024.

Lam, Kristine W F. “Discovery of TOI-1260d and the characterisation of the multi-planet system.” *Monthly Notices of the Royal Astrological Society*, vol. 519, no. 1, 2022, pp. 1437-1451. *Oxford Academic*, https://doi.org/10.1093/mnras/stac3639. Accessed 31 July 2024.

Latham, David W. “Discovery of a Transiting Planet and Eight Eclipsing Binaries in HATNet Field G205.” *The Astrophysical Journal*, vol. 704, no. 2, 2009. *IOP Science*, 10.1088/0004-637X/704/2/1107. Accessed 31 July 2024.

Mantovan, Giacomo. “Validation of TESS exoplanet candidates orbiting solar analogues in the all-sky PLATO input catalogue.” *Monthly Notices of the Royal Astrological Society*, vol. 516, 2022, pp. 4432-4447. *MINRAS*, https://academic.oup.com/mnras/article/516/3/4432/6692879. Accessed 31 July 2024.

Mistry, Priyashkumar. “VaTEST. II. Statistical Validation of 11 TESS-detected Exoplanets Orbiting K-type Stars.” *The Astronomical Journal*, vol. 166, no. 1, 2023, p. 21. *ads*, 10.3847/1538-3881/acd548. Accessed 31 July 2024.

NASA. "The TESS Science Writer's Guide." *NASA*, 2017, https://www.nasa.gov/wp-content/uploads/2016/07/tesssciencewritersguidedraft23.pdf?emrc=94a59b. Accessed 31 July 2024.

Nasiir, and Johnathan. *Schar Data Sets*. George Mason University Astro Scholars Program, 20 February 2024. Accessed 31 July 2024.

"Nova Astronomy." *Nova Astrometry*, https://nova.astrometry.net/. Accessed 31 July 2024.

"Overview." *NASA Science*, https://science.nasa.gov/exoplanets/planet-types/. Accessed 31 July 2024.

Plavchan, Peter, and Laura Powers. "The night sky is in jeopardy, and it is up to us to fix it." *George Mason University College of Science*, 22 April 2022, https://science.gmu.edu/news/night-sky-jeopardy-and-it-us-fix-it. Accessed 31 July 2024.

Wolszczan, Aleksander, and Dale Frail. "A planetary system around the millisecond pulsar PSR1257 + 12." *Nature*, vol. 355, 1992, pp. 145-147. *Nature*, https://doi.org/10.1038/355145a0. Accessed 31 July 2024.

World Weather. "Weather in Fairfax, February 20." *World Weather*, 20 February 2024, https://world-weather.info/forecast/usa/washington_1/20-february/. Accessed 31 July 2024.

World Weather. "Weather in Fairfax, February 21." *World Weather*, 20 February 2024, https://world-weather.info/forecast/usa/fairfax/21-february/. Accessed 31 July 2024.