Ground-Based Light Curve Follow-Up Validation Observations of TESS Object of Interest TOI-3798.01

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Abstract

Exoplanets are planets that orbit stars other than our sun. There are several methods for detecting them, of which the transit method is the most common. The goal of this paper is to use the data collected from George Mason University's (GMU's) ground-based 0.8m telescope to provide a follow-up validation of the existence of candidate exoplanet TOI-3798.01 using the transit method, which the Transiting Exoplanet Survey Satellite (TESS) discovered from space also using the transit method. We used AstroImageJ to create a light curve using GMU's telescope data. We also created a nearby eclising binary (NEB) table to check for the presence of NEBs, which could have led to a false positive detection of TOI-3798.01. We were unable to reach a definitive conclusion on whether TOI-3798.01 exists for three reasons: usable data was only available starting partway through the transit, the data was significantly scattered, and none of the stars within a 2.5" radius of TOI-3798 passed the NEB check. This means that future work such as using the transit method again with enough usable data, or a verification using another method such as the radial velocity method, is necessary to confirm the existence of TOI-3798.01.

1. Introduction

There are currently 5741 confirmed exoplanets (Caltech, n.d.a). The first two were discovered in 1992 by observing pulsar timing variations (Wenz, 2019). Since then, a large number of telescopes, both ground-based and space-based, have been used to detect exoplanets. These exoplanets can be classified as gas giants, Neptunian, super-Earth, and terrestrial based on their sizes (NASA, n.d.a). Some of the telescopes used for detecting exoplanets include the Hubble Telescope, the Spitzer Space Telescope, the Kepler Telescope, and the TESS Telescope (ESA, 2018).

There are several methods for detecting exoplanets, of which the most common is the transit method. The transit method works because a star's brightness dips when an exoplanet passes between it and the Earth. Telescopes gather light-intensity data from the stars that they are observing, which is then used to produce light curves that show any dips in brightness, leading to the detection and characterization of exoplanets (NASA, n.d.). TESS, in particular, uses this method. In order for an exoplanet that TESS observes to be confirmed, it must be verified by ground-based observatories (Brennan, n.d.).

That is where this paper comes into play: it discusses the steps used to validate the existence of the exoplanet TOI-3798.01, which TESS discovered from space, using GMU's telescope. This planet has been previously observed by ground-based telescopes since it was first discovered by TESS, but there have been no papers published about it (ExoFOP, n.d.). In this paper, we present a follow-up observation of TOI-3798.01. The goal of this paper is to investigate whether the transit occurs at the expected time, with the expected duration and depth, and thereby to validate the existence of TOI-3798.01.

In Section 2, we will look at TOI-3798.01 data from TESS and GMU. In Section 3, we will summarize the processing performed on the GMU data. In Sections 4 and 5, we will present and discuss our results. Finally, in Section 6, we will present our conclusions and recommend future work.

2. Observations

In Section 2.1, we will look at the properties of TOI-3798.01 and its star based on TESS data published on the NASA Exoplanet Archive (owned by Caltech). In Section 2.2, we will look at the TESS light curve of the target star, and in Section 2.3, we will discuss the light-curve data collected by GMU's telescope.

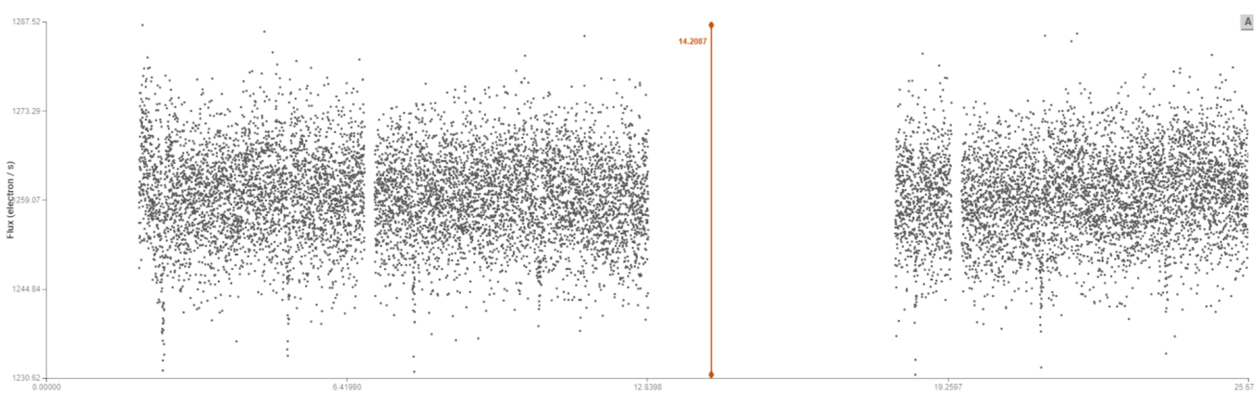
2.1 Candidate Planet and Stellar Parameters

TOI-3798.01 has a surface temperature of 1316.534 ºK, a radius 12.225 times the Earth's, an orbital period of 2.680 Earth days, and an insolation flux of 709.985 Earth fluxes (Caltech, n.d.b). It is located 488.429 parsecs (1593.042 light years) away from Earth (Caltech, n.d.b). It has a right ascension of 08h16m27.58s and a declination of +47d01m19.16s (Caltech, n.d.b). Its transit lasts for 2.029 hours, has a midpoint at 2459604.437 days, and has a depth of 0.986% (Caltech, n.d.b).

2.2 TESS Light Curve

Figure 1.

TESS Light Curve for TOI-3798



2.3 GMU Observatory Data

TOI-3798.01 was observed from GMU's telescope using a R filter from 11:04 PM on 2024-02-05 to 1:05 AM on 2024-02-06 (spanning the entire transit). The ingress of the planet was at 11:29 PM on 2024-02-05 and the egress was at 1:03 AM on 2024-02-06. A total of 257 exposures were taken, of which 227 were sciences, 20 were darks, and 10 were flats. The sciences and science darks each had an exposure time of 85 seconds, while the flat darks and flats each had an exposure time of 3 seconds.

3. Analysis

In Section 3.1, we look at the tools that were used to analyze the GMU light curve for TOI-3798 using AstroImageJ. In Section 3.2, we present our analysis of this ground-based light curve using AstroImageJ.

3.1 AstroImageJ Analysis Tools

After installing AstroImageJ, we visually inspected each of the 227 sciences for issues such as streaking, condensation on the camera, and no stars being visible. At this point, we had to discard 14 of them due to no stars being visible or extra light on the camera obstructing visibility. We then performed dark subtraction and flat division to create a master dark and a master flat. Then, we data-reduced the sciences on a custom server and used the nova.astrometry.net server to plate-solve them.

Next, we performed aperture photometry and generated a seeing profile, which showed an aperture-photometry radius of 21 arcseconds and inner and outer background annulus radii of 36 and 54 arcseconds, respectively, as seen in Figure 3. We then cleared the overlay.

After that, we placed a 2.5” circle around our target star in the image stack window. Next, we uploaded our Gaia stars .radec file, which was used for the generation of our NEB table (shown in Figure 5). Then, we placed the apertures on our plate-solved image. AstroImageJ created the measurement table necessary to make a light curve.

3.2 Light Curve Analysis

We downloaded the AstroImageJ template plot configuration[3] and opened that through AstroImageJ. We then entered TOI-3798.01's transit-specific settings and planet-specific settings. After that, we plotted Sky/Pixel_T1, Width_T1, AIRMASS, tot_C_cnts, X(FITS)_T1, and Y(FITS)_T1. We also checked the "Page Rel" boxes and adjusted the scale, shift, and color values to match with those prescribed in the "TFOP SG1 Guidelines"[4]. Then, we reviewed each reference star's flux individually and chose the two that were the best because they showed little scattering, were straight, were close to the target star, and didn't overlap with other data. We un-clicked the other reference stars and made sure that the predicted ingress and egress lines were aligned. In addition, we checked the detrend parameters one at a time and found that the ones that improved the data were AIRMASS, Sky/Pixel_T1, and X(FITS)_T1, so we left those checked and un-checked the others. The resulting light curve is seen in Figure 2. Finally, we generated the dmagRMS-plot, which is seen in Figure 4.

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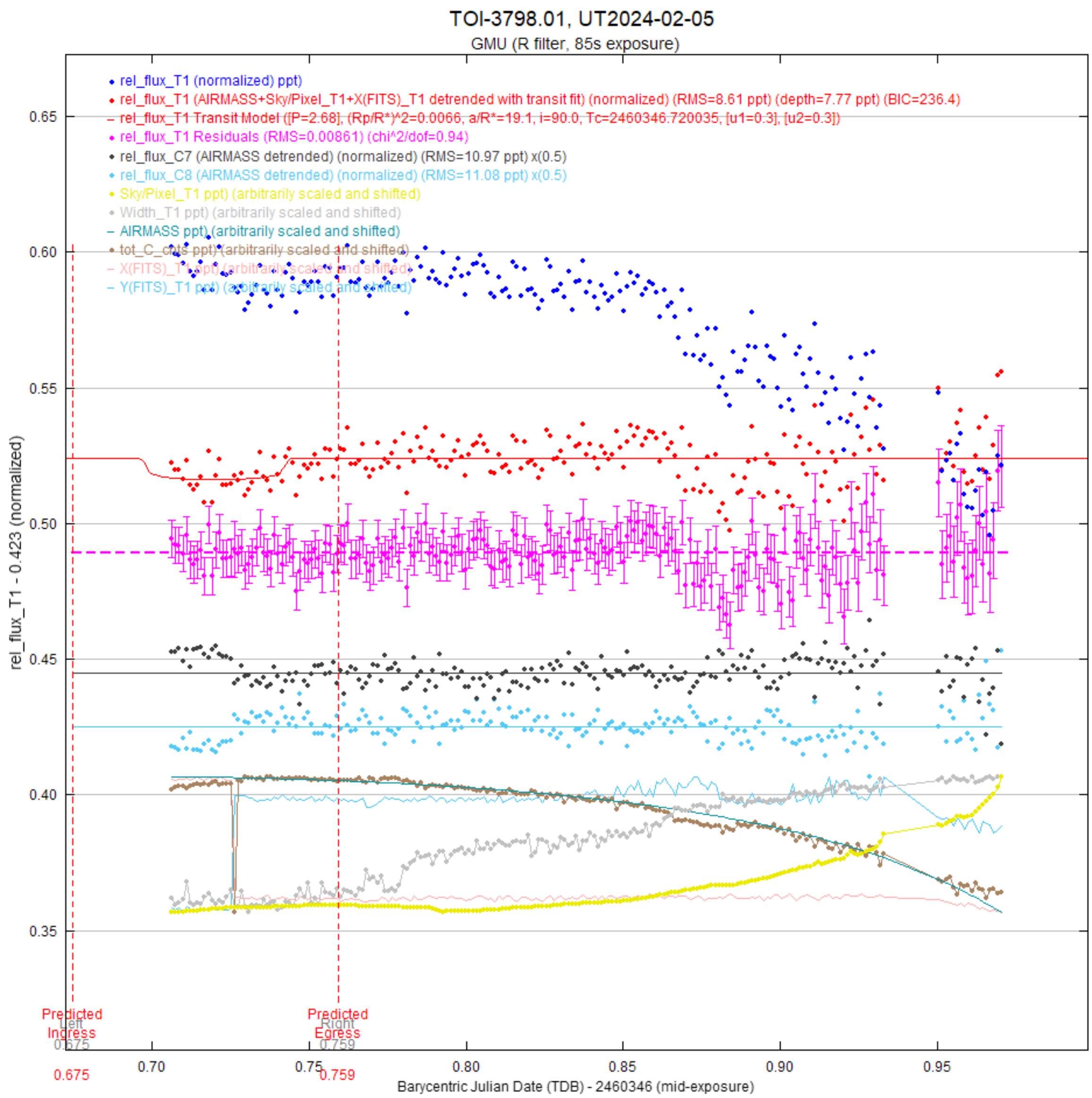
[3] www.astrodennis.com/Template.zip

[4] https://astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf

4. Results

Figure 2.

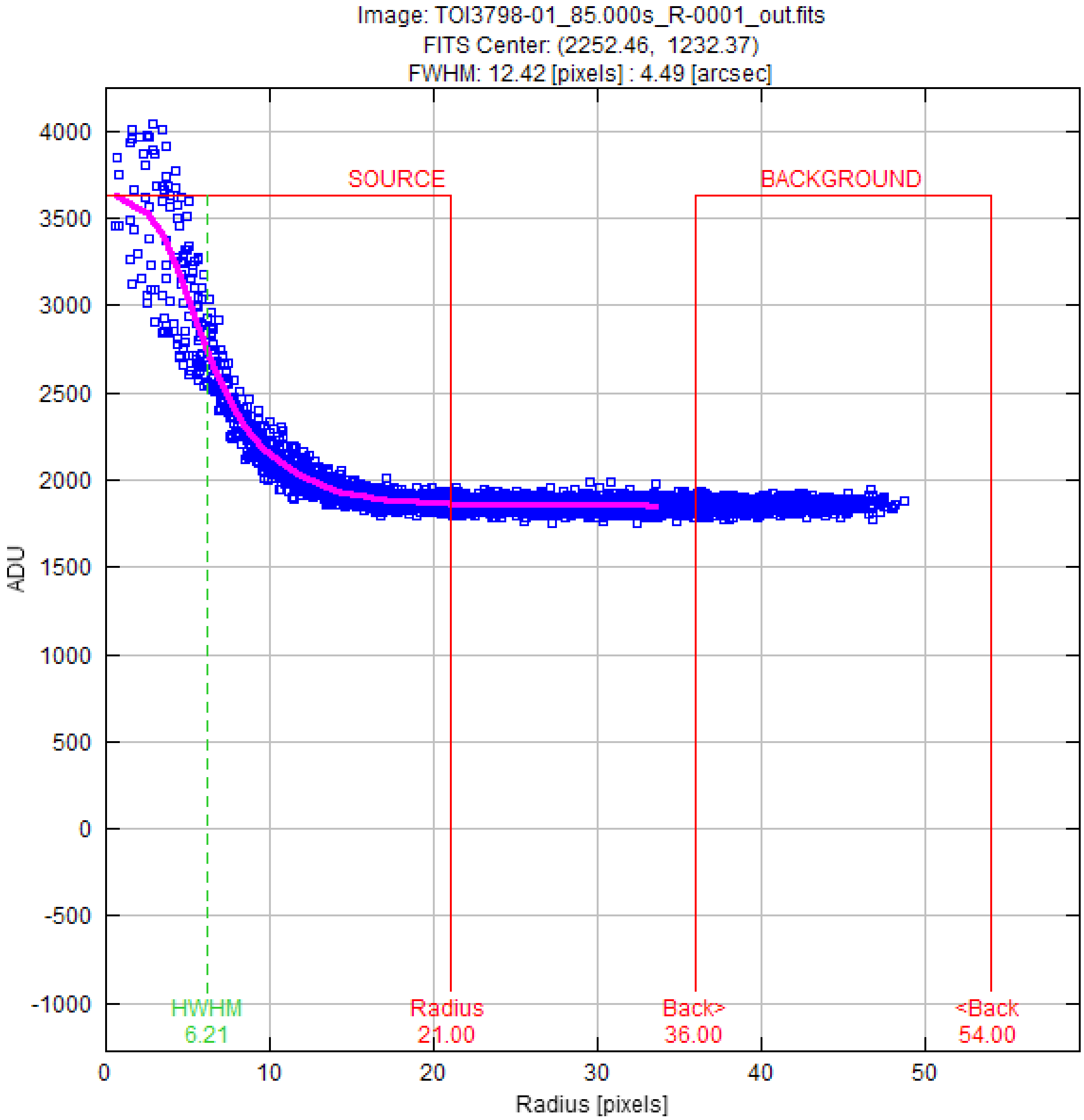
Ground-Based Light Curve for TOI-3798 and Selected Reference Stars



Note. The detrending parameters applied are AIRMASS, Sky/Pixel_T1, and X(FITS)_T1. The RMS value of the detrended target star is 8.61 parts per thousand and the observed depth of the transit is 7.77 parts per thousand.

Figure 3.

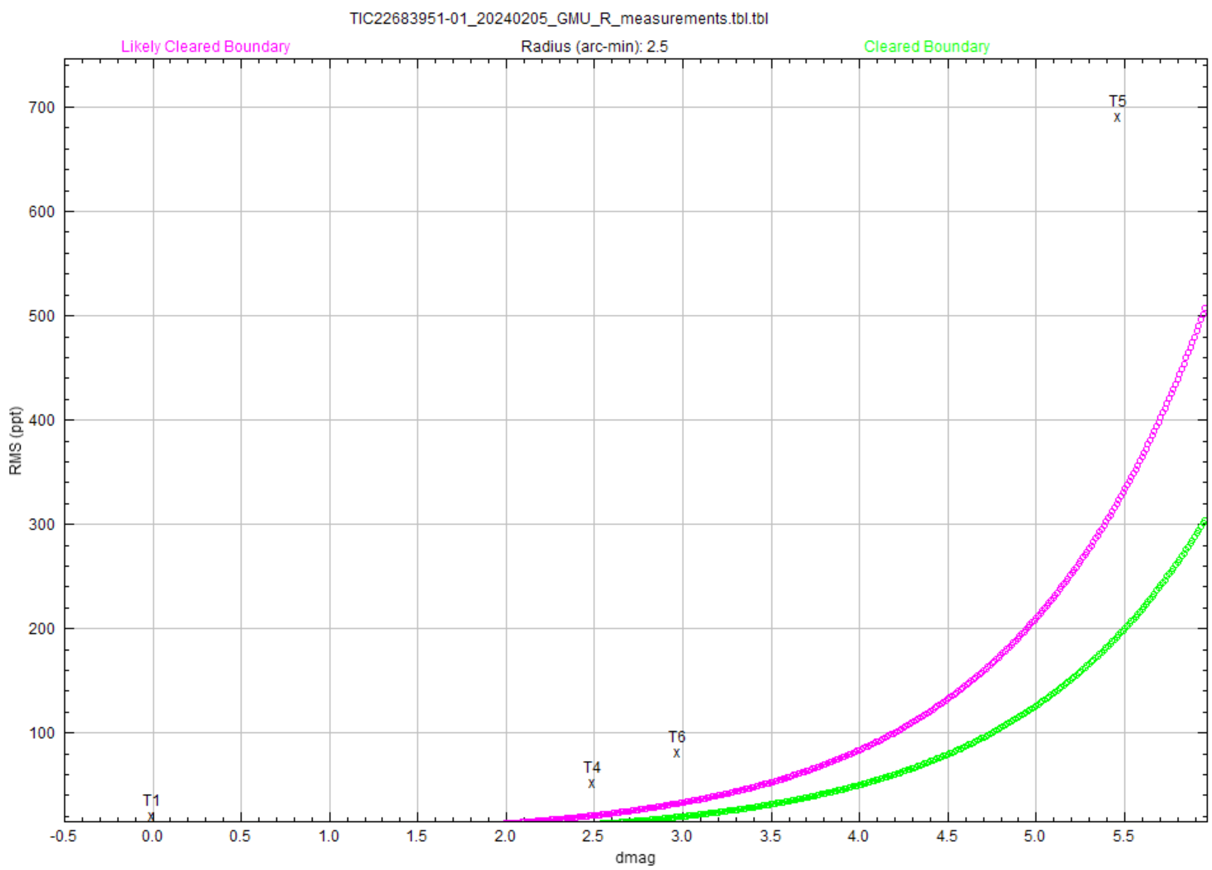
Seeing Profile for TOI-3798



Note. The aperture-photometry radius is 21 arcseconds and the inner and outer background annulus radii are 36 and 54 arcseconds, respectively.

Figure 4.

DmagRMS-Plot for TOI-3798



Note. All of the stars within a 2.5" radius of TOI-3798 that were bright enough to be visible in the dmagRMS-plot are to the left of the "likely cleared boundary", indicating that they are not cleared.

Figure 5.

NEB Table for TOI-3798

Star	Separation from target	PA (deg.)	Uncorr. dmag	RMS(ppt)	NEBdepth(ppt)	NEBdepth/RMS	Disposition
T2	1'08"	247	6.937	1459.79	N/A	N/A	***Not Cleared-flux too low***
T3	1'30"	109	6.059	743.75	N/A	N/A	***Not Cleared-flux too low***
T4	1'33"	82	2.496	56.66	62.9	1.1	***Not Cleared***
T5	1'32"	167	5.467	696.38	970.4	1.4	***Not Cleared***
T6	2'14"	67	2.973	85.79	97.5	1.1	***Not Cleared***

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Possible dispositions of the star being the source of the target predicted depth:
   Likely cleared (NEBdepth/RMS is between 3 and 5)
   Cleared (NEBdepth/RMS is >= 5)
   Cleared-too faint (NEBdepth >= 1000ppt)
   ***Not Cleared-flux too low*** (weighted average of Source-Sky counts per aperture pixel < 2)
   ***Not Cleared*** (none of the above conditions are met)

Summary count of dispositions:
         0 Likely cleared
         0 Cleared
         0 Cleared-too faint
         2 ***Not Cleared-flux too low***
         3 ***Not Cleared***
```

Note. The NEB table indicates that none of the stars within a 2.5" radius of TOI-3798 were cleared.

5. Discussion

In Section 5.1, we interpret our results from the light curve analysis and from the NEB table. In Section 5.2, we compare TOI-3798.01 with a confirmed TESS exoplanet.

5.1 Interpretation of Results

The weather was fine for the most part when the sciences were taken. In the light curve, a slight dip in the data is visible between the ingress and egress times, hinting at the detection of a transit. AstroImageJ fitted a transit line here, indicating that the transit occurred in the predicted window. Also, the predicted transit depth was 10.0 parts per thousand and the observed transit depth was 7.77 parts per thousand. These values are relatively close to each other, hinting that the transit is viable. However, usable data was only available starting partway through the transit, so it is difficult to draw an accurate conclusion from this. There is a possibility that the 14 sciences that were unusable due to having no stars or reduced visibility were part of this time frame. In addition, when we performed a NEB check on TOI-3798 and generated the NEB table shown in Figure 5, none of the stars within a 2.5” radius of TOI-3798 were cleared, because either their NEBdepths were too low or their apertures did not have enough flux to measure a reasonable dmag. This means that there is a possibility that the detection was a false positive due to the presence of a NEB. Also, the RMS value of the detrended target star was 8.61 parts per thousand, which is relatively high, meaning that there is significant scattering of the data. This significant scattering of data indicates that the light curve was not very reliable. Due to the aforementioned reasons, the data is inconclusive.

5.2 Comparison with Confirmed Exoplanet

TOI-3798.01 has a radius 12.225 times that of the Earth’s or 1.091 times that of Jupiter’s (Caltech, n.d.b). A confirmed exoplanet, TOI-5232.01, also has a similar radius of 12.78 Earth radii or 1.140 Jupiter radii and is classified as a hot Jupiter, which is a type of gas giant (Schulte et al., 2024). TOI-5232.01 has an equilibrium temperature of 1772.0 ^{o}K (Schulte et al., 2024), while TOI-3798.01 has an equilibrium temperature of 1316 ^{o}K (Caltech, n.d.b), which is somewhat similar. This means that TOI-3798.01 would likely be classified as a hot Jupiter if confirmed, though further measurements such as to get its density and its distance from its star would be necessary for this.

6. Conclusions and Future Work

We used AstroImageJ to analyze the ground-based light curve for TOI-3798 based on data taken from GMU’s telescope to determine whether the candidate exoplanet TOI-3798.01 exists.

We were unable to come to a conclusion because usable data was only available starting partway through the transit, we were not able to rule out any of the nearby stars as possible NEBs, and there was significant scattering of the data (leading to an unreliable light curve). Due to these reasons, the data is inconclusive and candidate exoplanet TOI-3798.01 may not exist.

In order for TOI-3798.01 to be validated, future work must be performed. If using the transit method again, usable light-intensity data would need to be gathered for TOI-3798 starting from before the predicted ingress time. Alternatively, another method of exoplanet detection could be employed, such as the radial velocity method that measures the Doppler effect on stars as they move due to their orbiting planets (The Planetary Society, 2002).

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