How to make a LATTE

by Nora Eisner

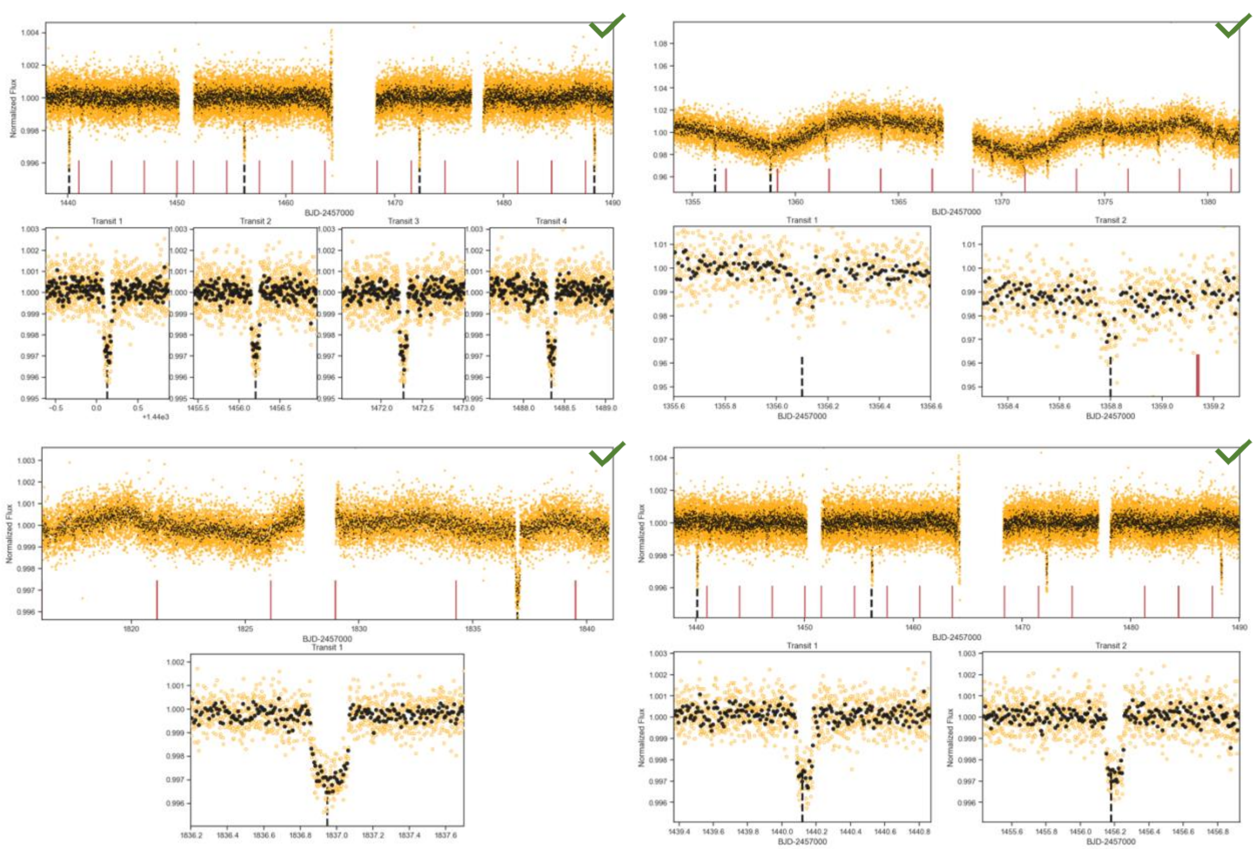
The LATTE diagnostic plots can be used to look at promising TESS planet-candidates in order to help distinguish between planetary signals and various false positive scenarios. Below is an outline of what to look for in each plot and how to use LATTE reports to identify promising planetary candidates. Look out or examples of good planet candidates: ✓, and bad planet candidates: ✗.

Figure 1: Full LC

This first plot shows the full lightcurve (LC) of the target. The orange points show all the data (two-minute cadence) and the black points show binned data (the average flux over 7 data points). The transit events are shown by the black dashed lines. The red lines show the times of the momentum dumps, which occur around every 2-2.5 days and typically last for a couple of hours. Momentum dumps can result in spurious signals in the LC, and the transit-like events should therefore not coincide with these.

This plot is also useful for ruling out eclipsing binaries (EBs) – two stars orbiting around one another. Dips caused by EBs are usually deeper, more V-shaped and the odd and even transits have different depths.

These four example LCs show dips that are periodic (or single), U-shaped and not very deep, making them excellent planet candidate.



Eclipsing binaries, as shown below, can be recognised by 1) different odd an even transit depths 2) V-shaped transit signal 3) deep transits and 4) different spacing between eclipses (these are due to eccentric eclipsing binaries).

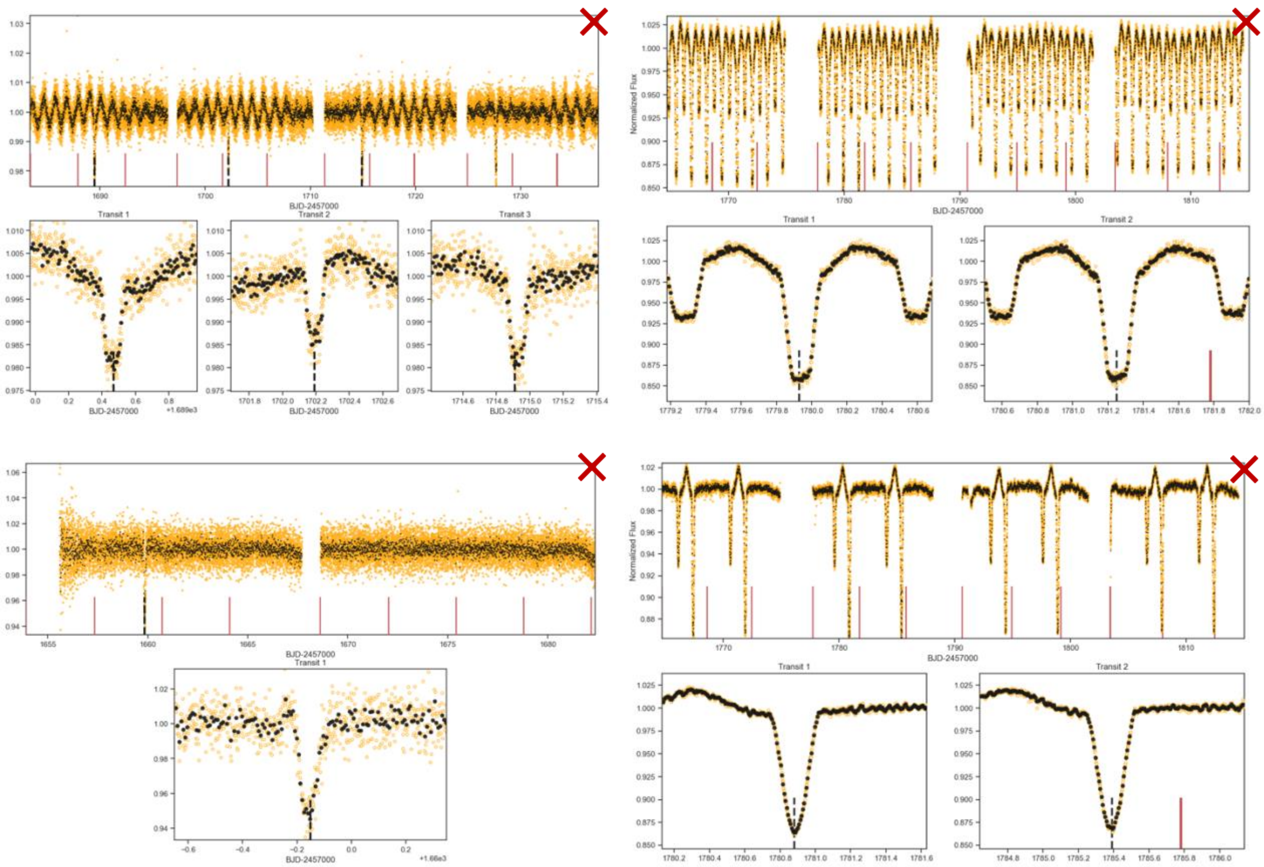


Table 1: Stellar parameters

There is a lot of information packed into Table 1. First, you can check whether the target was already flagged as TCE (Threshold Crossing Event) or as a TOI (Tess Object of Interest). If it is a TOI it is being followed up by the TESS team. TCE (Threshold Crossing Event), on the other hand, are not being followed up by TESS team. These are targets that have been flagged but were ruled out as planet candidates as they failed one or more of their vetting tests. There is a link to these reports in the table (see figure below).

The table also presents you with stellar parameters. One of the most important number in this table is the stellar radius as this can help you distinguish between planetary signals and eclipsing binary signals. You can calculate an approximate planet radius using the following equation:

$$R_{planet} = R_{star} \times \sqrt{transit\ depth}$$

Where R is the radius. If you plug the numbers into the equation – the stellar radius is given in the table and the transit depth can be read straight off figure - you will get the planet radius in terms of the radius of the sun, so divide it by 0.0091577 to convert it into a size in terms of Earth Radii (a much more useful measure).

Earth-size: $R_p < 1.25\ R_E$
super-Earth size: $1.25\ R_E < R_p < 2\ R_E$
Neptune-size: $2\ R_E$, $< R_p < 6\ R_E$
Jupiter-size: $6\ R_E < R_p < 15\ R_E$
(reference: https://arxiv.org/pdf/1102.0541.pdf)

If the resulting planet radius is larger than this, the signal is most likely caused by an eclipsing binary.

Target Properties

Parameter	Value	Unit
TIC ID	202490797	
RA	229.7138	degrees
Dec	63.1545	degrees
Radius	2.9229	Solar Radii
Tess Mag	8.2230	Mag
Teff	7457	Kelvin
Sectors	14, 15, 16, 21, 22, 23 *	
TCE	Yes **	
TOI	-	

Table 1. Stellar properties of TIC 202490797. * List of the sectors in which the target will be has been observed. ** Click here for the TCE report.

This field is empty so this is not a TOI

Click on this to see the TCE report generated by the SPOC pipeline

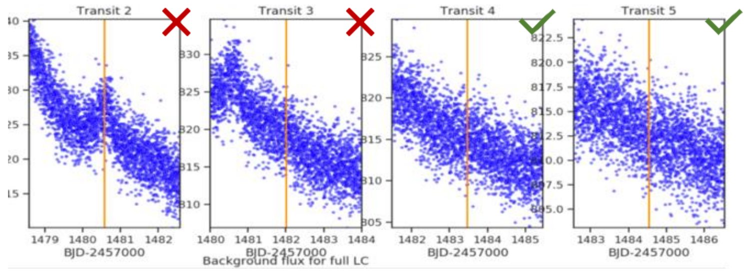
Click on the TIC number to see the TFOP page for this target

Figure 2: Background Flux

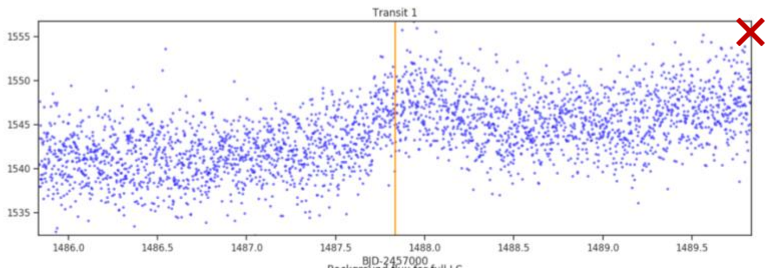
Figure 2 of the DV report shows the background flux as a function of time, where the time of the transit-like event is marked by an orange vertical line.

The background flux of TESS varies greatly over the course of the 27.8 observational window. This is partly because TESS is in an eccentric orbit around the Earth and in a 2:1 resonance with the Moon, meaning that the amount of reflected Earth-light and moonlight hitting the TESS cameras changes over time. This is not a concern here as the TESS pipeline largely removes this effect.

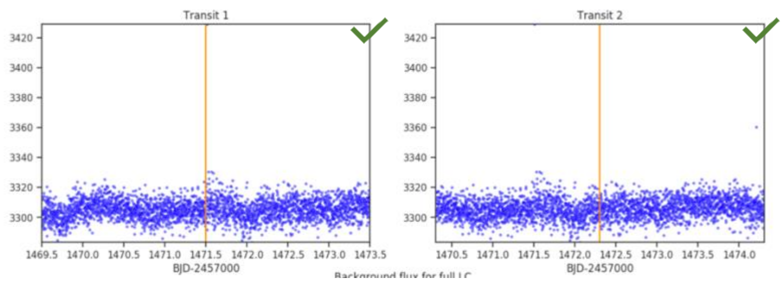
A sudden change in the background flux, possibly caused by a passing solar system object, however, can introduce spurious signals into the LC which can be mistaken for transit signals. We therefore look at the background plots to ensure that there are no 'spikes' at the time of the transit-like events.



The second and third images show that the marked events fall at the time of (or very close to) a small spike in the background event. This means that the dip that was seen in the LC was most likely due to the background.



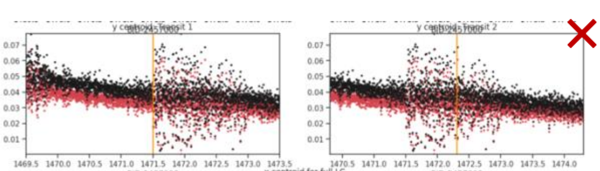
This another example of a bump in the background at the time of the marked transit-like event and this candidate can therefore be ruled out as a planet candidate.



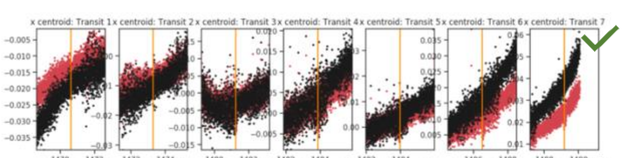
This is an example where the background flux looks.

Figure 3: Centroid positions

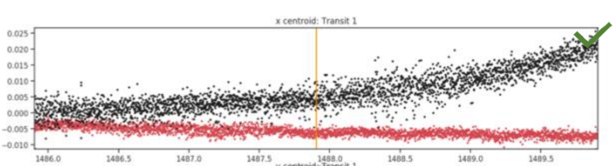
Figure 3 shows the stability of TESS throughout the observations by monitoring the x and y position of the brightest point in the aperture as a function of time. Just like for the background diagnostic, a sudden spike or lots of variability at the time of the event is a sign that the dip was caused by systematics.



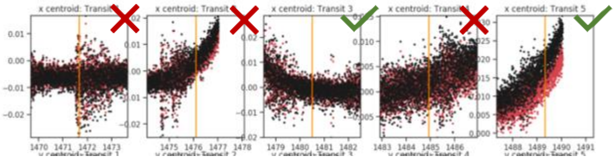
The increase in scatter around the time of the transit means that the event is likely due to systematics and these events can be discarded.



Even though these centroids vary a lot, there are not significant spikes at the time of the events.



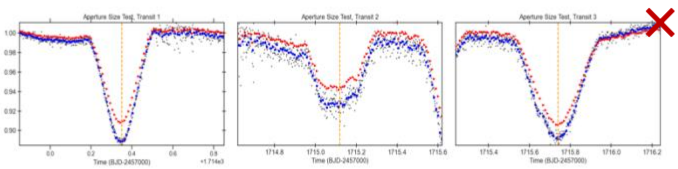
In this example the red and the black lines deviate from one another but they are both 'smooth' around the time of the transit-like event.



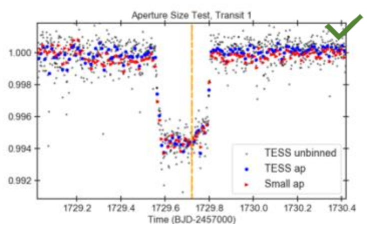
Some of these look slightly problematic whilst others are fine.

Figure 4: Aperture Size

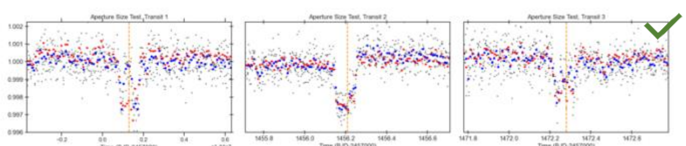
Figure 4 shows the LC extracted using various different aperture sizes. If a transit is due to a planet passing in front of a star, the transit shape and depth should remain constant with different apertures. If the shape does change for different extraction aperture sizes, for example if the transit is shallower with a smaller extraction aperture, the transit-like event is likely caused by a reflection in the ‘halo’ of the star (known as a halo-effect) and is therefore not due to a planet transiting. Make sure to look at figure 5, which shows the apertures used to extract the two LCs, along side of these.



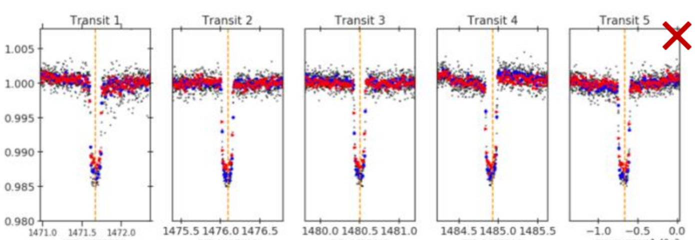
This example clearly shows that the smaller aperture (red) results in a smaller transit depth than with the TESS pipeline defined aperture. This shows that this is a halo effect caused by an eclipsing binary



This a an example of a transit-event where the transit shape and depth is the same with both apertures making it a good planet candidate.



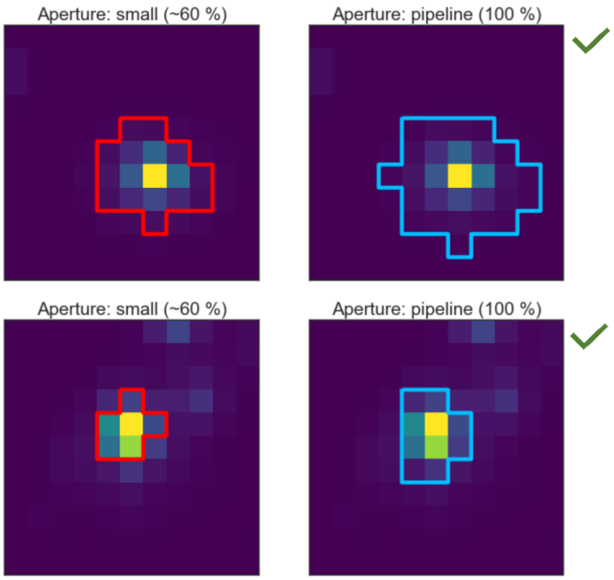
This is another example of a good planet transit.



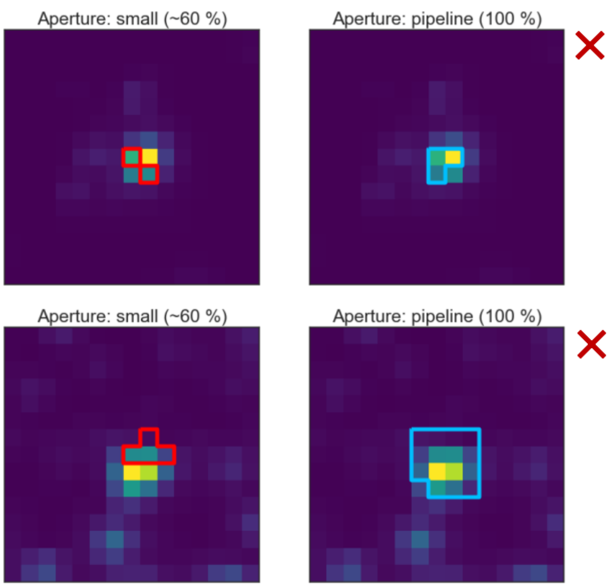
In this example can see that the red dips are slightly shallower than the blue dips, suggesting that this could be due to a background eclipsing binary (a nearby binary star).

Figure 5: aperture masks

Differences in the transit depth and shape of the two different lightcurves may be indicative of the transit-like events resulting from a blended eclipsing binary, however, a sub-optimal mask selection can lead to the mis-interpretation of a moving signal. You should therefore ensure that the masks that are being used are both on target and that their sizes and shapes make sense.



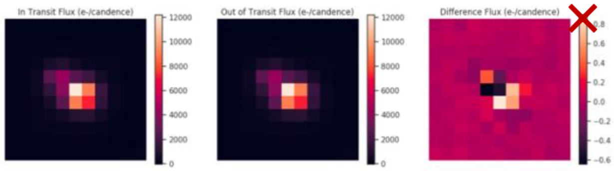
For both of these cases the two apertures are centred on target (depicted by the brightest pixel) meaning that the aperture size test should work well and give an indication of whether the signal is caused by a transiting planet.



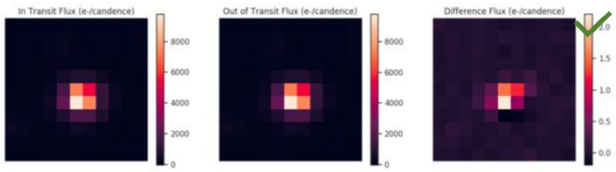
For these two cases, the apertures move and the brightest pixels are not enclosed within the solid lines for both aperture sizes. You should therefore be cautious when interpreting the aperture size test.

Figure 6: In and out of transit average flux

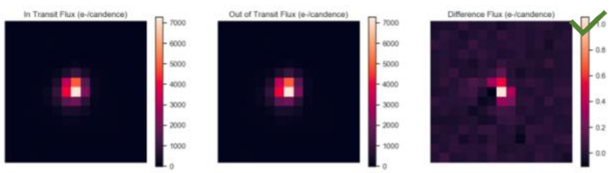
Next, we compare the average flux during the transit-like event to the average flux outside of the transit like event. The left most image is the average flux during the time of the transit-event, the middle image the average out-of-transit flux and the right image the difference between the two. It is the right image that we are primarily looking at to see whether it differs from the other two. If the average flux in the right image changes, for example if the brightest pixel moves to a different region, then this suggests that the variation in brightness is caused by an object other than the star of interest e.g. due to a background eclipsing binary.



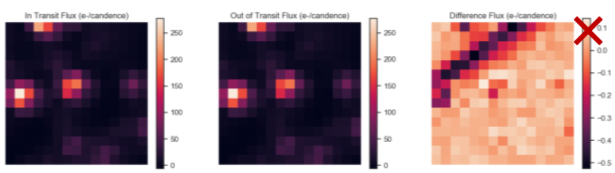
In this example the brightest pixel has moved, this is not a good sign. However, also take note of the scale, the difference in flux across the image is very small (compared to the next example).



This looks good – the brightest pixel is the same in and out of transit, showing that the target that we are observing is causing the dip in the lightcurve.



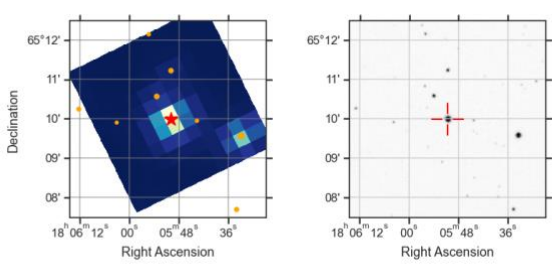
This is also an example of a good candidates as the brightest pixel doesn't move.



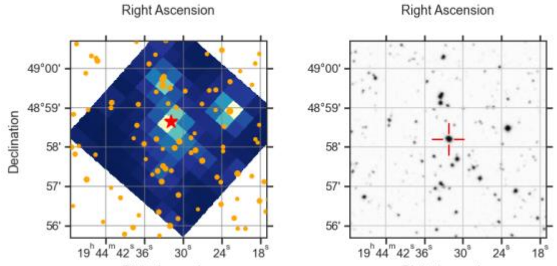
A streak through the image, like in this example, shows that a an object (probably an asteroid) passed thorough the frame at the time of the transits resulting in the dip in the lightcurve. These can be rule out.

Figure 7: nearby stars

The plot on the left shows the location of the target star (red star symbol) as well as nearby stars (orange circles) overlaid on an average brightness of the target pixel file around the candidate. The size of the orange circles correspond to the magnitude of the star (where a larger circle depicts a brighter star). The plot on the right shows the SDSS (Sloan Digital Sky Survey) image of the surrounding field, where the red cross shows the position of the target star. These figures are good to see whether there are any bright stars very close to the target, as these could be the cause for the event. We do not generally rule out candidates based on this analysis, but it is good to be aware of nearby star especially if they become candidates for follow-up observations, as very crowded fields makes follow-up much more difficult, or even impossible.



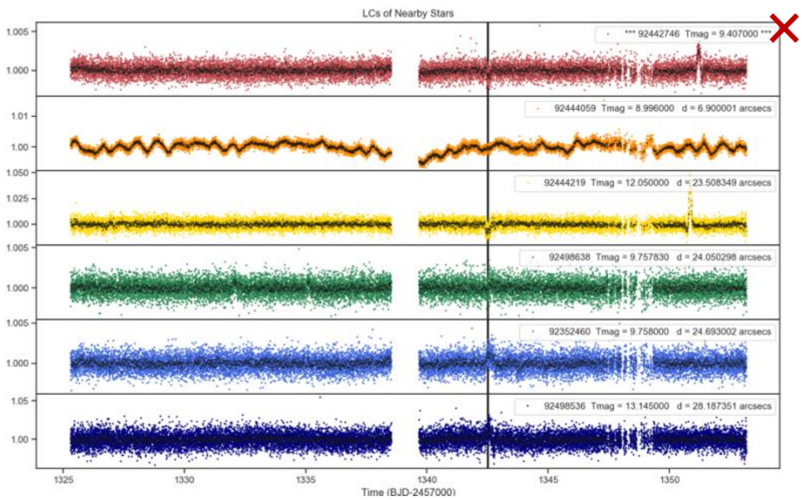
This is a nice an example of an empty field.



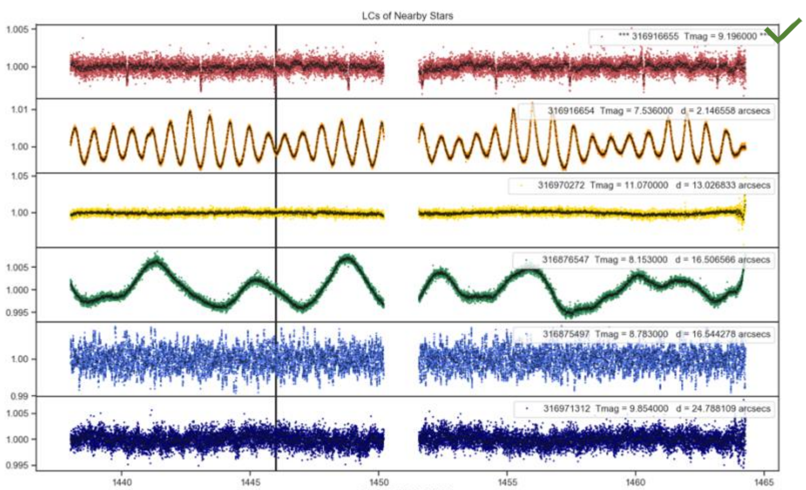
This is an example of a very crowded field.

Figure 8: LCs of nearby stars

Lightcurves of the five two-minute cadence stars closest to the selected target. A similar dip in the LCs of nearby stars at the same time as the transit-like event, suggests that a different star, or a background event is responsible for the signal. The vertical black lines indicate the times of the marked transit-like events. Note that these stars do *not* correspond to the closest stars shown in figure 7. This is because this figure only shows lightcurves of stars that were observed by TESS every 2-minutes.



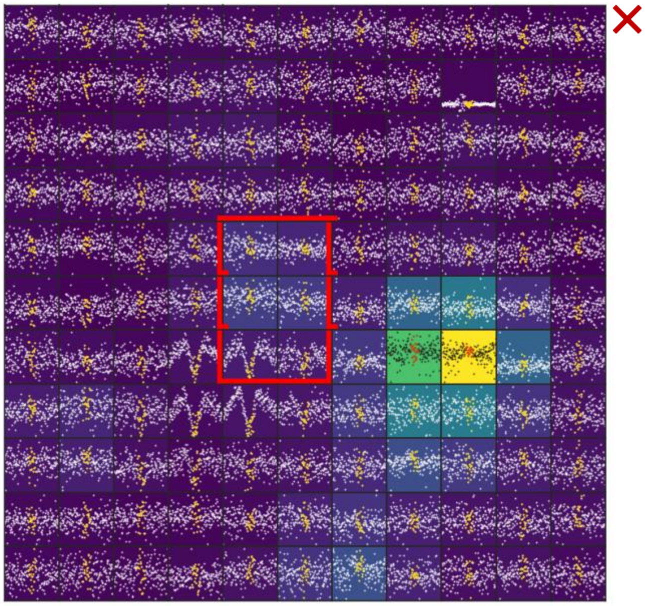
In this example the you can see that all of the lightcurves show a dip or a spike at the time of the marked event (black line). This suggests that the event is most likely caused by a background event.



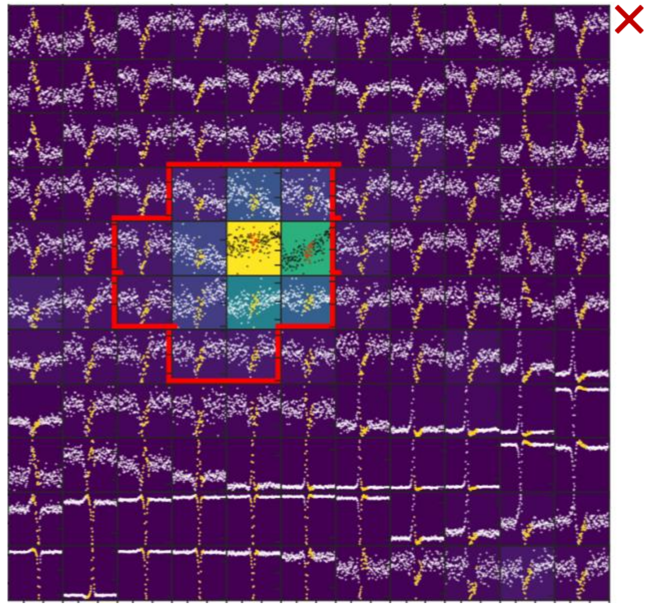
This example shows that, even though the nearby stars are very variable, none of them have a signal that occurs at the same frequency as the transit-like events seen in the lightcurve of the target star (top panel).

Figure 9: Pixel level lightcurve plot

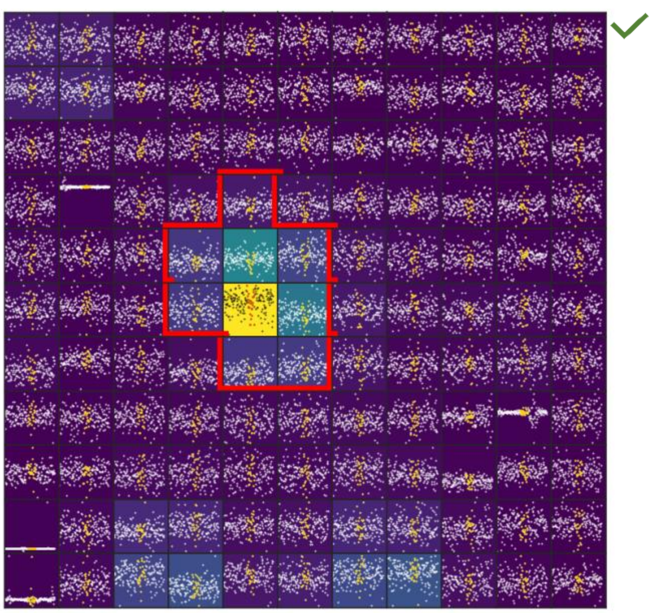
A plot showing lightcurves extracted for each individual pixel around the target. With this plot we want to check that the dip/transit occurs on target, and does not originate from elsewhere in the image. Each individual plot is very small so it might be very hard to see the transit event, especially if it is shallow. The red and yellow data points highlight the centre of the marked transit-event. The validation report will only show you this plot for the first marked transit, but the others are saved in the same folder where the report is saved so you can look through all of them if you please.



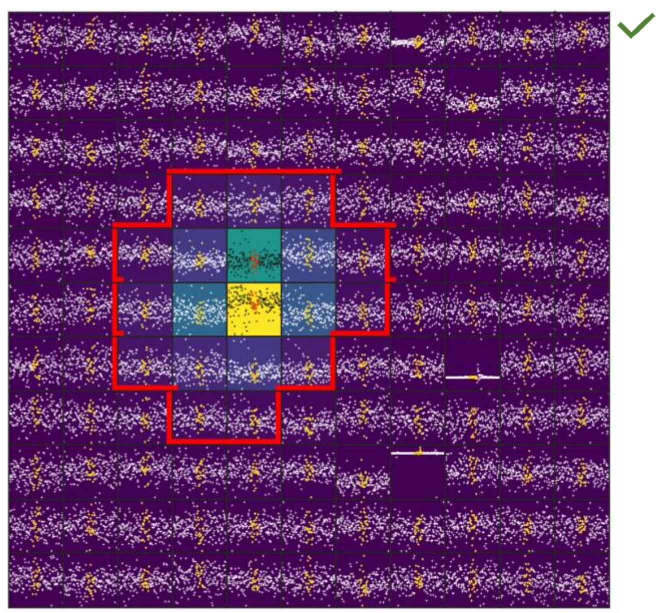
In this figure you can see that the eclipses are very prominent in the pixels just outside of the extraction aperture (solid red line). This suggests that the eclipses are due to a background eclipsing binary.



In this figure you can see that there is a signal in all pixels at the time of the transit like event – some are spikes and some are dips. This is most likely due to a solar system object, such as an asteroid, passing through the field of view.



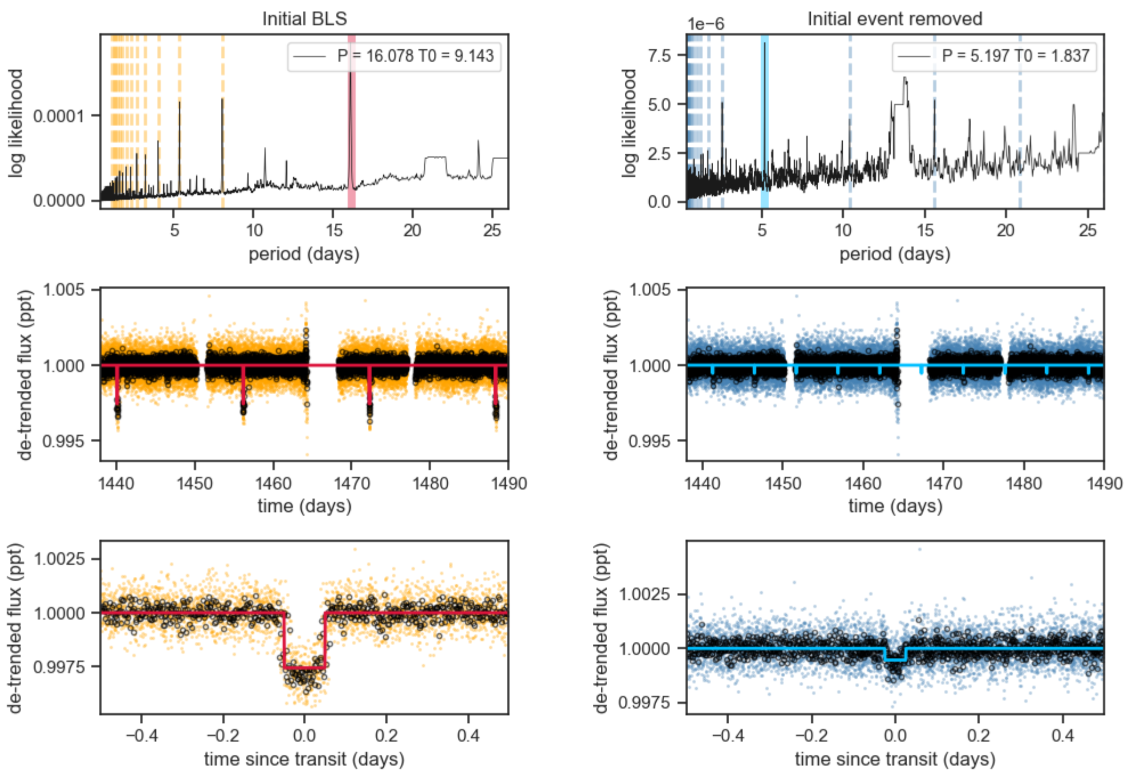
In this figure the transit-like event is very difficult to see, however, we also can't see a strong signal in any of the surrounding pixels, so this is a 'good' example.



Same as figure to the left. There are a couple of pixels that have very flat LCs, this is due to some outliers which change the scale of that individual plot. Don't worry about these, especially when they are outside of the extraction aperture.

Figure 10: BLS (optional)

Plots showing the results from two BLS searches, which look for periodic signals in the data. The initial BLS search (left: orange data) identifies the times of the highest detected signal-to-noise event and removes these data from the lightcurve. A second search is then carried out in order to search for additional periodic signal (right: blue).



The above example shows that the BLS search found a periodic signal that repeats around every ~16.1 days. The bottom panel of this plot shows the phase folded lightcurve (all the dips lined up). These dips were then removed from the LC and the algorithm run again, as shown on the right. This shows that an additional, shallower signal may be present within the data, with a period of ~5.2 days.

What Next?

1. If the candidate passes all the test it becomes what we like to call a ‘high priority candidate’.
2. At this point it is useful to model to the transit-event to refine the planet parameters and to gain a better understanding of the possible planet radius. This modelling will be available in the next LATTE release.
3. If you are not a researcher and find a candidate that passes all of these test, you can contact Nora Eisner via email and we will see if we can follow the target up further.

Words/abbreviations

LC: Lightcurve

TOI (Tess Object of Interest): targets that the TESS pipeline flagged as very likely to have a planetary candidate.

TCE (Threshold Crossing Event): targets that the TESS pipeline flagged initially but that were never promoted to TOI status (these are often promising candidates as the pipeline is quite quick at ruling out candidates).

Candidates: Potentially a planet but not yet confirmed. Even once they pass all the CTC test they remain 'candidates' until we can follow them up with further observations.

High Priority Candidates: Transit like events that passed all of our tests up until this point and are ready to be followed up using ground based telescopes.