LATTE: Lightcurve Analysis Tool for Transiting Exoplanets

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Summary

NASA's Transiting Exoplanet Survey Satellite (*TESS*, Ricker et al., 2015) is the first nearly all-sky space-based exoplanet search mission. During the nominal two year primary mission alone, *TESS* will monitor over 80 per cent of the sky with the prime objective of discovering transiting exoplanets around 200,000 pre-selected bright nearby stars, which are being monitored every two minutes. In addition to these short-cadence observations, *TESS* is obtaining Full Frame Images (FFIs) every thirty minutes, which include brightness measurements of millions of additional stars.

Unlike its predecessor *Kepler* (Borucki et al., 2010), *TESS* uses very large pixels, meaning that astrophysical false positives (e.g. where the signal of a target is contaminated by a faint eclipsing binary) are expected to be common. Many false positive scenarios can be ruled out from detailed examination of the *TESS* data using standard diagnostic tests.

LATTE is an open source Python package that performs these standard diagnostic tests to help identify, vet and characterise signals in the *TESS* lightcurves in order to weed out instrumental and astrophysical false positives. The program is designed to allow for a fast, in depth analysis of targets that have already been identified as promising candidates by the main *TESS* pipelines or via alternative methods such as citizen science (e.g., Fischer et al., 2012; Christiansen et al., 2018; Eisner et al., 2020). The implemented diagnostic tests are similar to the 'Data Validation' steps performed by the Science Processing Operations Center (SPOC; Jenkins et al., 2016) pipeline for the short-cadence data, and by the quick-look pipeline (QLP; Huang et al. (2019)) for the long-cadence data. However, while the SPOC pipeline tests are performed on a selection of two-minute cadence *TESS* targets only, LATTE allows for the analysis of any *TESS* target with a valid TIC ID (Stassun et al., 2019), including both the two-minute and thirty-minute cadence targets.

Other tools that are often used to extract and vet TESS lightcurves include the open source packages *Lightkurve* (Cardoso et al., 2018) and *eleanor* (Feinstein et al., 2019), for the short and long-cadence data respectively. These tools can perform similar diagnostic tests to the ones provided by LATTE, however, LATTE differs in that it does not require any interaction with Python coding. Instead, LATTE allows for an interactive diagnostic analysis via a Graphical User Interface (GUI) and summarizes multiple diagnostic tests in an efficient and automated manner.

LATTE

The standard vetting tests performed by LATTE provide a useful tool for both researchers and students. Furthermore, LATTE was developed with the growing exoplanet citizen science

community (e.g., Fischer et al., 2012; Christiansen et al., 2018; Eisner et al., 2020) in mind and thus all interactions with the code are done via a user-friendly interface, requiring minimal experience in Python programming.

Upon execution, `LATTE` prompts the user to enter the TIC ID (Stassun et al., 2019) of a target star, as well as the observational sector(s) to analyse. The corresponding data are then downloaded directly from the Mikulski Archive for Space Telescopes (MAST, http://archive.stsci.edu/tess/) and displayed in a GUI, as shown in Figure 1. The user is asked to identify the times of the transit-like events by directly clicking on the lightcurve plots and recording the transit-times using the 'Add time' button. Additional settings, such as whether to run a Box-Least-Squares (BLS) algorithm that searches for periodic signals in the lightcurve, can be selected within the GUI (see left side of Figure 1). Once the times of one or more transit-like events have been identified the program automatically downloads and handles the *TESS* data to provide standard exoplanet diagnostic plots and statistics.
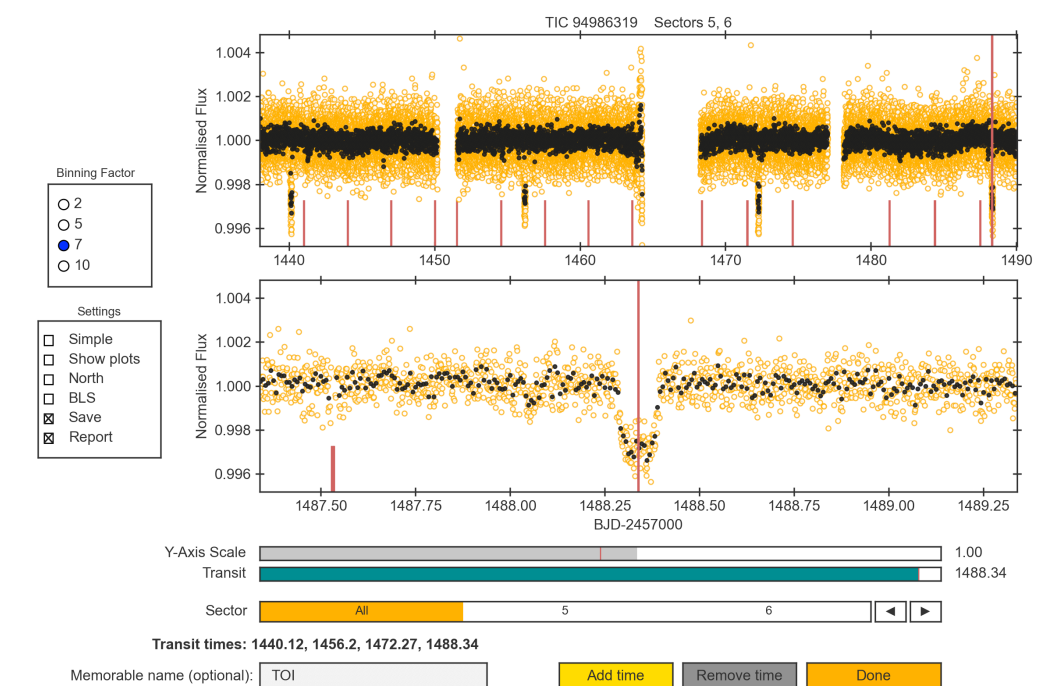
Figure 1: User-interface displaying the whole lightcurve (top panel) and a zoom-in of the data around the selected transit-time (bottom panel) as indicated by the vertical red line. The selected time can be changed by clicking on either one of the two lightcurve plots. Times are stored and removed with the 'Add time' and 'Remove time' buttons respectively. Further program options are shown to the left of the lightcurve plots: '*Simple*' for a quick analysis that doesn't require the Target Pixel Files (TPFs); '*Show plots*' to display the plots as they are being produced; '*North*' to reproject the TPF plots due north; '*BLS*' to run a Box-Least-Squares algorithm to search for periodic signals; '*Save*' to store the files locally (selected by default); and '*Report*' to create a PDF summary report (selected by default). There is also an option to change the binning of the displayed full lighcurve.

Different Modes

Standard mode

By default `LATTE` runs in *standard mode* using the pre-selected short-cadence *TESS* data and lightcurves that were extracted and detrended by the Science Processing Operations Center (SPOC, Jenkins et al., 2016) pipeline. The *Lightkurve* package (Cardoso et al., 2018) is used to extract raw lightcurves from the Target Pixel Files.

FFI mode

The *FFI mode*, which can be selected with a check-box at the time when the TIC ID is entered, downloads the FFI *TESS* data using *TESScut* (Brasseur, Phillip, Fleming, Mullally, & White, 2019). The data are then detrended using the *Astropy PCA* module (Astropy Collaboration et al., 2018) and an iterative non-linear filter (Aigrain & Irwin, 2004) to estimate and subtract residual systematics. Unlike the two-minute cadence *TESS* targets, the FFI targets have no pre-identified optimal apertures. The user is, therefore, prompted to manually identifying two different sized photometric extraction apertures by interacting with a GUI, which displays the average flux per pixel around the target (see Figure 2). The apertures are chosen by clicking on the desired pixels, where the lighter coloured pixels represent higher flux. The two lightcurves, extracted using the chosen 'large' and 'small' apertures, are simultaneously displayed. Alternatively, the user can opt to have the two apertures selected automatically using a threshold flux value where the apertures are centred on the coordinates of the target star.
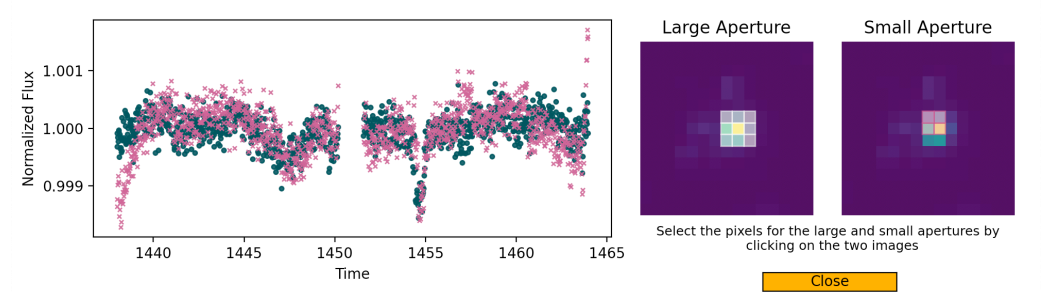
Figure 2: The FFI interface which allows the user to manually select the pixels for two separate apertures (right), where the lighter coloured pixels correspond to a higher flux. The resultant lightcurves, extracted with the larger (teal green circles) and a smaller (pink crosses) apertures, are displayed on the left.

Diagnostic tests

Summary of the `LATTE` diagnostic tests:

- **Momentum Dumps.** A plot highlighting the times of the *TESS* reaction wheel momentum dumps to ensure that the times of the transit-like events do not coincide with times of increased systematics due to the satellite unloading built up photon pressure.

- **Target Properties Table.** A table that summarizes the properties of the target star, including the stellar radius, effective temperature, TESS magnitude, and the galactic coordinates. The table also lists all of the *TESS* sectors in which the target will be observed. Additionally, it indicates whether the target has been flagged as a Target Threshold Crossing Event (TCE) or as a Tess Object of Interest (TOI) by the SPOC pipeline, with links to the corresponding validation reports as well as a link to the Exo-FOP page that contains additional stellar information (Akeson & Christiansen, 2019).

- **Background Flux.** A plot to verify that the transit-like dips in the lightcurve are not caused by background events such as asteroids passing through the field of view.

- **x and y centroid positions.** A plot showing the CCD column and row local position of the target's flux-weighted centroid, and the CCD column and row motion which considers differential velocity aberration (DVA), pointing drift, and thermal effects.

- **Aperture size test.** A plot showing the lightcurves extracted with two different aperture sizes. In the *FFI mode* the two different aperture sizes can be selected manually (see above), while in the *standard mode* the SPOC pipeline defined aperture, and an aperture that is 40% smaller, are used. 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, we caution that a sub-optimal mask selection can lead to the mis-interpretation of a moving signal. The data are extracted from the Target Pixel Files (TPFs) and are neither detrended nor corrected for systematics.

- **Pixel-level centroid analysis.** A plot showing the average in-transit and average out-of-transit flux as well as the difference between the two. A change in spatial distribution of the flux suggests that the transit-like event is caused by a blend with a background eclipsing binary. The data are extracted from the TPFs and corrected for systematic effects using Principal Component Analysis (e.g., Stumpe et al., 2012).

- **Nearby companion stars.** A plot showing the location of nearby stars brighter than *TESS* magnitude 17 as queried from the Gaia Data Release 2 catalog (Gaia Collaboration et al., 2018) and the DSS2 red field of view around the target star. The sizes of the markers indicate the positions of the Gaia stars relate to the magnitude of each companion. The *Astropy reproject* module (Astropy Collaboration et al., 2018) was used to align the plots such that north points towards the top of the page.

- **Nearest neighbour lightcurves** (not available in *FFI mode*). Lightcurves of the five two-minute cadence stars closest to the selected target. The occurrence of similar transit-like events in nearby lightcurves may suggest that the signal is caused by a background event or a blended eclipsing binary.

- **Pixel level lightcurves.** A plot showing lightcurves extracted for each individual pixel around the target. The data are extracted from the TPFs and detrended using a third order spline fit.

- **Box-Least-Squares fit.** A plot showing the results from two BLS searches. The data are corrected for residual systematics using an iterative non-linear filter (Aigrain & Irwin, 2004) prior to being searched for periodic signals using the *Astropy BLS* module (Astropy Collaboration et al., 2018). The intitial BLS search 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 signals.

All of the results are summarized in a pdf report.

Input target list

In order to efficiently generate diagnostic plots for multiple targets without having to interactively enter the target TIC IDs, LATTE can be executed with an input file that lists the TIC IDs, the times of the transit-like events, and the observational sectors to consider (if known). In the cases where the times of the transit events or the sectors have not been entered, the user is prompted to enter these manually via the GUI, as described above. For longer target lists the code can also be parallelized (see https://github.com/noraeisner/LATTE for an example.)

Installation and command line execution

LATTE is developed publicly through a GitHub repository, which provides the user with example input and output files, as well as the opportunity to highlight arising issues with the code.

The main aspects of the code have been tested using the *unittest* package. `LATTE` can be installed either directly from the GitHub repository or via the pip command on PyPi (https://pypi.org/project/tessLATTE/).

Once installed, the program is easily executed via the command line (e.g. python3 -m LATTE). Further command line options, such as to run the code with an input target list, can be entered in order to execute the code with more advanced settings. For further information on these options please see the documentation provided on the GitHub page. The first time that the code is executed, the user is prompted to enter a local path that directs to a location on the user's computer where the data and output files will be stored. We also note that on the initial run `LATTE` automatically downloads text files that are required for the program run, which may take a couple of minutes to complete.

Future

The next release will allow for the option to model the transit-like events using the open source package *Pyaneti* (Barragán, Gandolfi, & Antoniciello, 2019) which uses a Bayesian approach with an MCMC sampling to determine the parameters of the best-fit.

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