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A Ghost in the Toast: TESS Background Light Produces a False 'Transit' across τ Ceti

Nora L. Eisner,[1] Benjamin J. S. Pope,[2,3,4] Suzanne Aigrain,[1] Oscar Barragán,[1] Timothy R. White,[5,6] Chelsea X. Huang,[7,8] Chris Lintott,[1] and Andrey Volkov[9]

[1]Oxford Astrophysics, Denys Wilkinson Building, University of Oxford, OX1 3RH, Oxford, UK
[2]Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA
[3]Center for Data Science, New York University, 60 Fifth Ave, New York, NY 10011, USA
[4]NASA Sagan Fellow
[5]Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia
[6]Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
[7]Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[8]Juan Carlos Torres Fellow
[9]Citizen Scientist, Zooniverse c/o Oxford Astrophysics, Denys Wilkinson Building, University of Oxford, OX1 3RH, Oxford, UK

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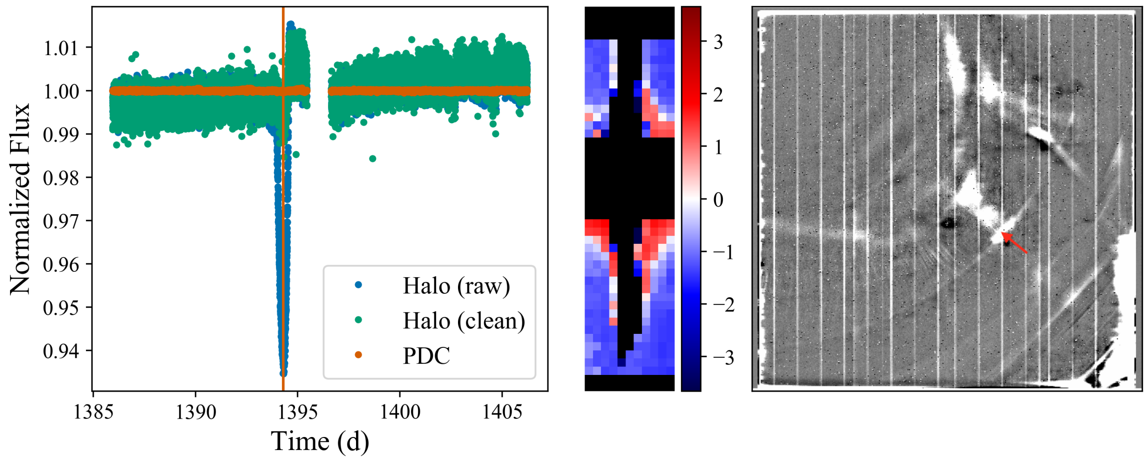
The space-based Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) provides 2-min-cadence photometry of tens of thousands of stars across the sky. The vast majority of transit events are discovered via the main TESS pipelines, nevertheless humans have been shown to be able to detect by eye certain types of transit that the major pipelines miss (Schwamb et al. 2013), including long-period planets and transits across active stars (e.g., Fischer et al. 2012). The citizen science project Planet Hunters TESS (PHT) engages thousand of volunteers in identifying transit events in TESS lightcurves that are otherwise missed by automated pipelines (Eisner et al. 2019).

The G8 dwarf τ Ceti is the second-closest star system visible to the naked eye ($V = 3.50$) at a distance of $\sim$3.65 pc, which, from radial velocity studies, is believed to host a system of planets with periods from 14-640 days and masses of $\sim$ a few $M_\oplus$(e.g., Feng et al. 2017). It was observed by TESS in Sector 3 with a large aperture containing its whole bleed column and a large unsaturated halo.

The lightcurve of TIC 419015728 (τ Ceti) was brought to our attention by PHT volunteers triggering further investigation. Because τ Ceti is so saturated in TESS, we use the halo photometry code `halophot` (White et al. 2017; Pope et al. 2019) to produce a lightcurve from pixels in the unsaturated halo surrounding the saturated core. A transit-like event is detected at very high precision around TJD 1394.3. Both lightcurves are displayed in Figure 1a. The weightmap (Figure 1b) assigned to the pixels by `halophot` resembles the deep TESS PSF shape as expected. In comparison to the PDC data, however the transit in the halo lightcurve is higher signal-to-noise, but much deeper. The absolute normalization of halo lightcurves of saturated stars is comparable to that of the PDC lightcurves (Pope et al. 2019), and this is the first sign that the signal may be spurious.

The TESS field is contaminated by background light from Earthshine (Luger et al. 2019), which is modulated by the rotation of the Earth and by the eccentric orbit of TESS. This background has a rounded-square 'toast' shape, crossed by rapidly-varying caustics, and is strongest near perigee, in this case just before mid-Sector (TESS Sector 3 Data Release Notes, Figure 2). The τ Ceti transit-like event occurs just before the mid-Sector perigee, suggesting that Earthshine may be the origin of this signal. Furthermore, the TPF 'background' lightcurve used in the PDC lightcurve extraction shows a dip $\sim$7 h after the midpoint of the transit-like event. To investigate the background spatial variation, we extracted background lightcurves from the 2-min cadence TPFs on the same camera as τ Ceti and found similar dips around the time of our transit-like event. We therefore infer that mis-calibration of the spatial variation of the background light may be the origin of this signal.

Corresponding author: Nora L. Eisner @EisnerNora
nora.eisner@physics.ox.ac.uk



(a) (b) (c)

Figure 1. (a): PDC (orange) and `halophot` lightcurves with and without (green and blue) background correction of τ Ceti, with the epoch of the transit-like event highlighted with an orange vertical line. (b): `halophot` weight map of τ Ceti 'raw' reduction, with colorbar in log-scale; these follow the expected shape of the unsaturated halo. The map for the 'clean' reduction is similar. (c): Difference image of the FFI around the transit-like event, with τ Ceti highlighted with a red arrow. The star's location coincides with a bright spot on a moving arc of Earthshine.

Next, we inspect individual pixel time series in the τ Ceti pipeline TPF: above the mid-axis of the TPF, they go up during 'transit' and below they go down. Other bright stars also exhibit a 'jump' towards the top of the field of view and 'dip' toward the bottom. The pixel cutouts are elongated in this axis, meaning that if the true background is spatially-varying, but a constant background is subtracted, an asymmetric pattern will contaminate the pixels across the field of view. When we apply a spatial quadratic, instead of a constant background light map, we find that the apparent `halophot` transit depth is significantly reduced (Figure 1, 'clean' lightcurve). The lack of proper background subtraction can, therefore, result in the introduction of features that resemble transit-like signals.

In order to further investigate the global structure of this spatially-varying background light, we compute a difference image using the non-background-corrected 30-minute Full Frame Images (FFIs), by directly subtracting the FFI at midpoint of the transit-like event from a median-stacked reference FFI composed from 40 "good" FFIs (those not near any momentum dumps or images with high background values). A localized sharp scattered light pattern is apparent at the location of τ Ceti (Figure 1c).

We conclude that the transit-like event seen in both PDC and `halophot` lightcurves of τ Ceti is spurious, caused by Earthshine. This has significant consequences for validating transits detected in TESS: across a large photometric aperture, either more-sophisticated spatially-varying background models, or careful inspection of difference imaging, must be used to validate any proposed planetary signal. Precise calibration of the background light is therefore essential for studying bright stars in TESS either by simple aperture photometry or the halo method.

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