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I'm Not Dead Yet: Optical detection of the periodic variability at the white dwarf GD 394 with TESS

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ABSTRACT

We present observations obtained with the *Transiting Exoplanet Survey Satellite* (*TESS*) of the white dwarf GD 394. The space-based optical photometry demonstrates a 0.12 ± 0.01 per cent flux variation with a period of 1.146 ± 0.001 d, consistent with the 1.150 ± 0.003 d period variation detected in extreme ultraviolet observations from the *Extreme Ultraviolet Explorer* in the mid 1990s. Optical variation is a prediction of the metal accretion spot model proposed to explain that detection, although previous observations in the ultraviolet appear to rule out that hypothesis. We describe the analysis of the *TESS* lightcurve and measurement of the optical variation, and discuss the implications of our results for the various physical explanations put forward for the variability of GD 394.

1. INTRODUCTION

GD 394 is a hot, metal-polluted white dwarf that has presented challenges to astronomers since it's initial identification by Giclas et al. (1967). Indeed, both of the descriptions in the preceding sentence are unquantified: Estimates for the temperature vary from 33000–41000 K (Lajoie & Bergeron 2007; Barstow et al. 1996) and the measured metal abundances, accretions rates and species depends on the wavelength band and ionisation levels observed (Wilson et al. 2019). However, the most intriguing aspect of GD 394 is the detection by Christian et al. (1999) and Dupuis et al. (2000) of a sustained 25 per cent modulation of the extreme ultraviolet (EUV) flux with a period of 1.15 d, identified in observations made in 1992–1996 with multiple instruments onboard the *Extreme Ultraviolet Explorer* (*EUVE*) satellite. This phenomenon is thus far unique among white dwarfs, and was hypothesised to be due to opacity changes induced by a spot of accreting metals rotating in to and out of view with the white dwarf rotation. The spot hypothesis made two observable predictions: Firstly, the strength of the metal lines in the white dwarf spectrum should vary in phase with the EUV variation; secondly, there should be an anti-phase flux variation at optical wavelengths due to flux redistribution. Follow-up observations by Wilson et al. (2019) ruled out the first of these predictions, finding no change in the strength of the metal lines in eight phase-resolved *Hubble Space Telescope* (*HST*) far ultraviolet (FUV) spectra. They also searched SuperWASP photometry for optical variation, ruling out changes in flux $\gtrsim$ one per cent. Instead of a spot model, Wilson et al. (2019) favoured a circumstellar explanation such as a gas cloud generated by an evaporating but non-transiting planet (Haswell et al. 2012). Veras & Wolszczan (2019) suggested instead that an orbiting, iron rich planetesimal core could induce a magnetic flux tube connecting it to the white dwarf, heating the photosphere at the base of the tube.

Here, we present observations of GD 394 obtained using the *Transiting Exoplanet Survey Satellite* (*TESS*, Ricker et al. 2014) demonstrating that GD 394 is indeed varying in the optical with a period consistent with that of the EUV variation, but with an amplitude much smaller than in the EUV and below the SuperWASP detection limits.

2. OBSERVATIONS

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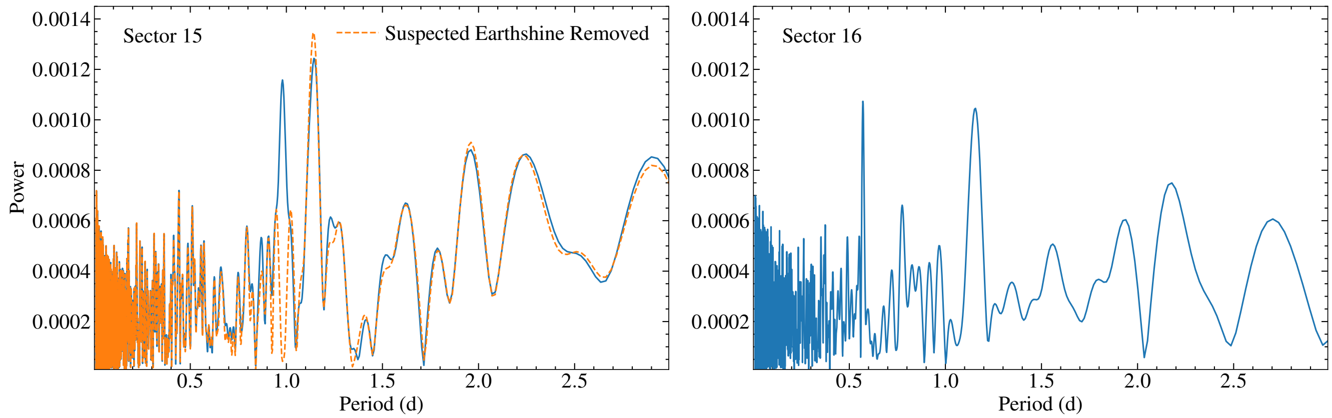

Figure 1. Periodograms of the lightcurves from each *TESS* observing Sector. The dashed orange line shows the periodogram of the Sector 15 lightcurve where the probably spurious ≈ 0.98 d signal has been removed, leaving strong signals at ≈ 1.15 d in each Sector. The narrow signal in Sector 16 at ≈ 0.57 d is a P/2 alias. **Do we need this figure? Appendix?**

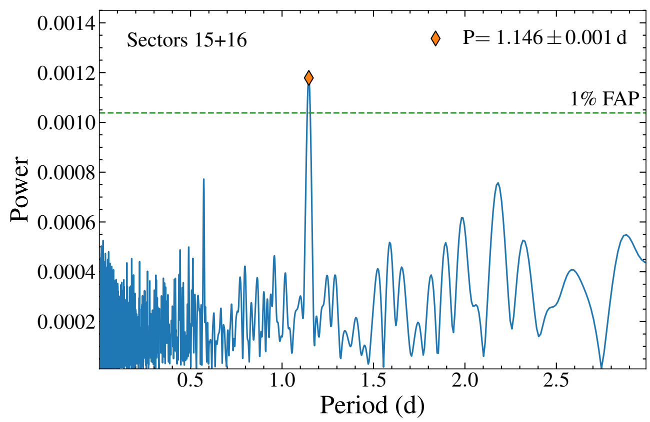

Figure 2. Periodogram of the combined Sector 15 and Sector 16 lightcurve, with a significant peak at the $\approx$1.15 d period originally detected in the EUV. The calculated 1% False Alarm Probability is shown by green dashed line.

GD 394 was observed by *TESS* in Camera 2 for 52 days in Sectors 15 and 16 (2019 August 15–2019-October-06), with three roughly one-day gaps at spacecraft perigee[1]. Data was returned with a two minute cadence as requested in proposals G022077, G022028 and G022017, and processed using the Pre-Search Data Conditioning Pipeline (PDC, Stumpe et al. 2012) to remove common known instrumental trends.

We initially analysed the lightcurves from each Sector separately. The two lightcurves were retrieved from MAST[2], points marked with a quality flag were removed, and the flux normalised by dividing it by a two-order polynomial fit. We generated Lomb-Scargle periodograms using the `Lightkurve` package (Lightkurve Collaboration, 2018), shown in Figure 1. A $\approx$ 1.15 d period is clearly detected in each Sector, providing the first confirmation of the *EUVE* detection beyond the extreme ultraviolet. The Sector 15 periodogram contains a second peak at $p = 0.979 \pm 0.002$ d. As this does not appear in the Sector 16 data and is very close to one sidereal day, we suspect that this is due to background contamination from Earthshine. We divided out a sinusoidal fit to the data at the spurious period, and recomputed the periodogram to confirm that the signal was successfully removed (orange dashed line in Figure 1). The Earthshine-removed Sector 15 lightcurve was then combined with the Sector 16 lightcurve to perform the remainder of this analysis.

[1] See *TESS* Data Release Notes at http://archive.stsci.edu/tess/tess_drn.html

[2] https://archive.stsci.edu/

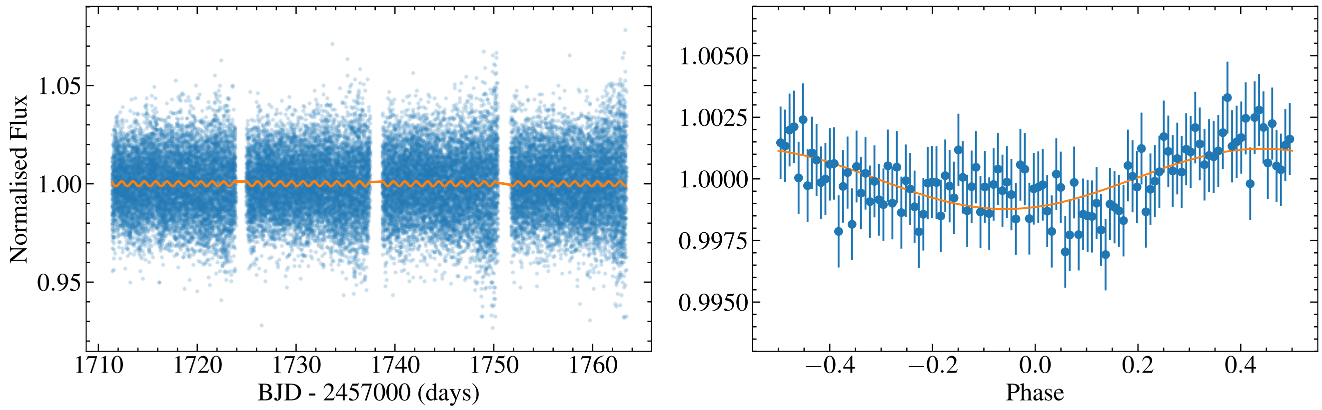

Figure 3. Left: Unbinned, two sector *TESS* lightcurve of GD 394 showing the sine fit used to measure the period. The enhanced scatter at the end of each segement of the lightcurve is due to increased background Earthshine as the spacecraft approaches perigee. Right: The lightcurve folded onto the measured 1.146 d period and binned by a factor of 300 (i.e. to a cadence of 10 h) for clarity. A sinusoidal fit to the folded, unbinned lightcurve returns an amplitude of $= 0.12 \pm 0.01$ per cent.

Figure 2 shows the `Lightkurve` periodogram of the combined two-sector lightcurve, with a clear peak at P≈1.15 d. To check that this was not due to random noise, we calculated the false alarm probability (FAP) using a variation of the method used in Hermes et al. (2017); Bell et al. (2019): specifically, we generated 10000 fake lightcurves using the time axis from the combined lightcurve and drawing each flux point from a normal distribution with a mean = 1 and 1 sigma defined as the normalised flux error. A periodogram was taken for each fake lightcurve, and we defined our one per cent FAP as the power below which the maximum power in 99 per cent of our fake lightcurves fell. The green dashed line in Figure 2 shows the 1 per cent FAP, clearly demonstrating that there is a less than one per cent chance that our detected signal is due to noise. To measure the period precisely we fit a sinusoidal curve to the entire lightcurve using the peak measured from the periodogram as an initial guess, returning a final period of $P = 1.146 \pm 0.001$ d (Figure 3, left). Finally, we folded the lightcurve onto our measured period and fitted it with a sinusoidal curve, returning an amplitude of $A = 0.12 \pm 0.01$ per cent (Figure 3, right). We note that this fit should only be taken as an approximate value for the amplitude as the true variation may have a more complex behaviour than a simple sine wave, for example the spot model fit to the *EUVE* data by Dupuis et al. (2000), but fitting a more complex model to the *TESS* is impractical given the small amplitude of the signal **unless someone has a spot model lying around?**.

3. DISCUSSION AND CONCLUSION

The $P = 1.146 \pm 0.001$ d period variation of GD 394 in the *TESS* lightcurve is (just) within 1 sigma of the 1.150 ± 0.003 d period measured in the *EUVE* data by Dupuis et al. (2000). The variation in the two wavebands therefore almost certainly have the same origin, and there is no strong evidence for period evolution in the roughly 24 years between the observations. On the other hand, the optical amplitude of 0.12 ± 0.01 per cent is much smaller than the ≈25 per cent variation in the EUV.

The *TESS* observations support the prediction made by Dupuis et al. (2000) that, if the EUV variation is due to opacity changes caused by a spot of metals, an anti-phase variation in the optical would be produced by flux redistribution. However, the metal spot model was ruled out by the non-detection of changes in the metal absorption line strengths by Wilson et al. (2019). It is possible that the spot has a variable opacity, appearing strongly at the time of the *EUVE* observations, fading by the time of the 2015 *HST* observations but returning in time to be observed with *TESS* (with the period fixed by the white dwarf rotation period) but this may be too strong an appeal to coincidence, especially considering that the 2015 *HST* spectra were consistent with *HST* spectra obtained in 1992 by Shipman et al. (1995).

We are left requiring a mechanism that will generate flux variations of 25 per cent in the EUV, 0.12 per cent in the optical, and $\lesssim 1$ per cent in the FUV (the upper limit placed by lightcurves extracted from the time-tagged *HST* spectroscopy by Wilson et al. (2019). The suggestion by Veras & Wolszczan (2019) that the variation is due to a hot spot at the base of a magnetic flux tube may fit these criteria, as a sufficiently hot spot could provide the required amplitude in the EUV, with the flux quickly dropping away in the Rayleigh–Jeans to the low levels observed at longer wavelengths. However, this would require spot temperatures of $\gtrsim 10^5$ K, and thus far no magnetic field has been detected in high-resolution spectroscopy of GD 394 (Dupuis et al. 2000; Wilson et al. 2019). The generation of a flux tube requires an orbiting metal-rich planetary fragment which may be radio-loud, and thus radio observations can be used to test this model (Veras & Wolszczan 2019).

Hmm...this is consistent with the EUV variation having higher amplitude at shorter wavelengths. Would show up nicely in the Chandra obs as well...

The various explanations for the flux variations at GD 394 could be tested by searching for phase differences between the two wavebands: Out of phase variation would favour a spot; in phase variation would point to a circumstellar cause. In practice, phasing up the *EUVE* and *TESS* observations is impossible given the decades-long gap between them, so new, simultaneous EUV and high-precision optical observations are required, although this will be challenging given current observing facilities. **Cheops?**

In conclusion, we have re-detected the periodic variation of the white dwarf GD 394 with *TESS*, providing an optical counterpart to the original EUV detection over two decades ago. The white dwarf is varying in the optical with a period of 1.146 ± 0.001 d and an amplitude of 0.12 ± 0.01 per cent. Our detection demonstrates that GD 394 is still variable despite the null results of Wilson et al. (2019), but a physical explanation for this activity remains elusive.

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Software: Astropy (Astropy Collaboration, 2013), Lightkurve (Lightkurve Collaboration, 2018)

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Barstow, M. A., Holberg, J. B., Hubeny, I., et al. 1996, 279, 1120

Bell, K. J., Córsico, A. H., Bischoff-Kim, A., et al. 2019, arXiv e-prints, arXiv:1910.04180. https://arxiv.org/abs/1910.04180

Christian, D. J., Craig, N., Cahill, W., Roberts, B., & Malina, R. F. 1999, AJ, 117, 2466, doi: 10.1086/300847

Dupuis, J., Chayer, P., Vennes, S., Christian, D. J., & Kruk, J. W. 2000, 537, 977, doi: 10.1086/309079

Giclas, H. L., Burnham, R., & Thomas, N. G. 1967, Lowell Observatory Bulletin, 7, 49

Haswell, C. A., Fossati, L., Ayres, T., et al. 2012, ApJ, 760, 79, doi: 10.1088/0004-637X/760/1/79

Hermes, J. J., Gänsicke, B. T., Kawaler, S. D., et al. 2017, ApJS, 232, 23, doi: 10.3847/1538-4365/aa8bb5

Lajoie, C., & Bergeron, P. 2007, 667, 1126, doi: 10.1086/520926

Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, Lightkurve: Kepler and TESS time series analysis in Python, Astrophysics Source Code Library. http://ascl.net/1812.013

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9143, Proc. SPIE, 914320, doi: 10.1117/12.2063489

Shipman, H. L., Provencal, J., Roby, S. W., et al. 1995, 109, 1220

Stumpe, M. C., Smith, J. C., Van Cleve, J. E., et al. 2012, PASP, 124, 985, doi: 10.1086/667698

Veras, D., & Wolszczan, A. 2019, MNRAS, 488, 153, doi: 10.1093/mnras/stz1721

Wilson, D. J., Gänsicke, B. T., Koester, D., et al. 2019, MNRAS, 483, 2941, doi: 10.1093/mnras/sty3218