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Using eclipsing binaries as a benchmark for the PLATO mission

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ABSTRACT

Eclipsing binaries allow for precise characterisation of stellar parameters: a use this Research Note applies in identifying targets in the LOPS2 field for calibration and further investigation by the PLATO mission. TESS and Gaia DR3 photometry of ten systems with little ellipsoidal effect and orbital periods $2.76 - 17.6$ days within LOPS2 were processed using `Lightkurve` and fitted using `jktebop`. Characterised parameters allowed for estimation of mass, age and absolute $G-$band magnitude, indicating most are solar-type, eight fulfil the PLATO P1 sample specification and ten are within the P5 criteria. Observed tidal effects and eccentricities are consistent with literature.

1. INTRODUCTION

The characterisation of eclipsing binaries (EB) is crucial in advancing our understanding of stellar structure and evolution. Light curve analysis allows for the detection of astronomical bodies due to various parameters being directly measurable (orbital periods, stellar masses, *etc.*).

PLATO, led by ESA, is designed to conduct precise and accurate photometry to detect transiting exoplanets in the habitable zone and conduct asteroseismology on pre-selected stars. For at least the first two years, PLATO will observe its southern field (LOPS2; Rauer et al. 2024). With this upcoming mission, a pre-selection of benchmark EBs is essential. Therefore, this project aims to identify EBs which fulfil the PLATO sample specification and act as benchmarks for observation.

The selection of optimal benchmark EB candidates requires high-cadence photometric datasets that can resolve short-period variability, distinguish between EBs and other periodic phenomena, and provide robust constraints on stellar parameters. Gaia DR3 epoch photometry provides precise multi-band flux measurements, enabling the characterisation of EB systems (Gaia Collaboration et al. 2023). This, alongside astrometric solutions, help constrain these parameters. However, low temporal resolution presents challenges in precise characterisation of orbital periods. Complementary to this, TESS provides high-cadence photometry across a wide region of sky, allowing for long-timescale EB observations. Notably, the 120 s cadence data from the SPOC pipeline, accessible via the MAST archive, allow for analyses of EBs using `jktebop` (Ricker et al. 2014).

Beyond this, additional characterisation is required. The catalogue from Prša et al. (2022), alongside TESS and Gaia DR3 data within the LOPS2 field, provides a framework for identifying EBs that align with the scientific objectives of the PLATO mission.

To further prioritise, samples P1, P2 and P5 are of interest to this Note. P2 and P1 are of absolute magnitudes V $\leq$ 8.8 mag and $\leq$ 11 mag respectively: the 'gold' standard, as they are bright enough for many planetary parameters (mass, density, *etc.*) to be measured, aligning with the overarching aim of the PLATO mission (identifying solar-type star with potentially habitable planets). P5 includes those $V \leq 13$ mag (both dwarfs and subgiants; Aerts et al. 2017).

2. METHODOLOGY

We assessed the efficacy of TESS and Gaia DR3 photometry in identifying benchmarks for observation by PLATO. We performed a two-stage survey using `Lightkurve` on a catalogue of EBs from Prša et al. (2022).

EBs with morphologies < 0.6 were pre-selected to exclude ellipsoidal variables. In the first stage, we examined the TESS light curves and selected EBs with high signal-to-noise ratios, narrow eclipses and minimal distortion. Orbital periods were estimated by phase-folding the light curves. For systems with long-period variations, we detrended the data by dividing the light curves by fitted polynomials. These detrended light curves were then processed using `jktebop` (task 3), and model light curves with residuals < 0.02 were generated.

In the second stage, we compared the TESS light curves with corresponding Gaia data, selecting EBs with primary and secondary eclipses in the $G-$, $BP-$ and $RP-$bands. We used the parameters from the TESS analysis to fit Gaia model light curves, accounting for differences in reference time. Limb darkening coefficients ($h1$, $h2$) for the Gaia data were calculated, assuming effective temperatures $5000-8000$ K, zero metallicity, microturbulent velocity 2 km s^{-1}, and logarithmic surface gravity 4 cm s^{-2}. These values were used to generate the power-2 limb darkening parameters interpolated from Claret, A. & Southworth, J. (2022). $h1$ and $h2$ values were computed using equations (14) and (15) from Southworth (2023). Uncertainties in the Gaia model parameters were derived using Monte Carlo simulations (task 8, `jktebop`).

The output scale factors and flux ratios from task 8 were used to estimate the primary and secondary apparent magnitudes, from which the corresponding colour indices ($BP-RP$) and $G-$band absolute magnitudes were calculated. Parallax, extinction, and colour excess values were obtained from Gaia Collaboration et al. (2023). Systems with limited data were assumed to have zero extinction and colour excess. Finally, we estimated stellar masses by interpolating our results with Mamajek (2022). Our ten best-characterised EBs are presented on a CMD (Figure 1).

3. RESULTS

The selected EBs have orbital periods 2.76 – 17.6 days, with primary masses 0.9 – 2 $M_{\odot}$, secondary masses 0.6 – 1.9 $M_{\odot}$, and effective temperatures 6100 – 11000 K. These properties make them suitable as benchmark EBs.

Shorter orbital periods show evidence of tidal interaction, leading to a potentially circular orbit, confirming theoretical predictions (Justesen & Albrecht 2021). EBs of orbital periods 3 – 8 days have secondary eclipses occurring at phase 0.5, aligning with this paper. TIC201497357, with an orbital period < 3 days, and TIC7695666 and TIC78568736 with periods > 8 days required eccentricity parameters to be fitted to minimise residuals. Aligning with Justesen & Albrecht (2021), EBs with extreme separations have higher eccentricities.

Soydugan et al. (2006) estimated TIC201497357 is located within the instability strip, identifying it as an ALGOL-type EB. The absolute parameters were not determined, so its exact placement within the strip is not confirmed. This Research Note provides the necessary parameters for a reassessment of its potential pulsational variability and classification.

Figure 1 shows a CMD, identifying the position of the studied EBs. This allows for comparison with the PLATO sample specifications. TIC279087522 has a high mass for both primary and secondary stars (2$M_{\odot}$ and 1.9 $M_{\odot}$, respectively). Although the absolute magnitude of the EB ($V \sim 9.88$ mag) is within P1 criteria, the stars are not solar-like and therefore of low priority to PLATO.

The secondary component of TIC78568736 had a significant error due to the flux contributing 10% and low Gaia coverage at the eclipses, significantly different from the other EBs. However, the primary contribution to the eccentric EB has mass $\sim 1 M_{\odot}$ and absolute magnitude $V \sim 10.89$ mag (fulfilling the P1 sample criteria). This primary component is classified as a K-type main-sequence star, suitable for detection and analysis by PLATO. We note TIC279087522 may have underestimated uncertainties due to similarly low Gaia coverage in eclipses (reversing their locations on the CMD).

Based on analyses, eight EBs are within the PLATO P1 sample specification, while all ten fulfil the P5 criteria. The EBs have absolute magnitudes 8.4 – 11.5 mag, and thus all are suitable for detection by PLATO. However, while most are positioned on the main sequence, the required star masses should be $\sim 1 M_{\odot}$ to be considered a priority target for PLATO (Rauer et al. 2024). TIC279087522 and the primary component of TIC201497357 have masses significantly above this (2 $M_{\odot}$ and 1.9 $M_{\odot}$; and 1.8 $M_{\odot}$ respectively), making both systems lower priority targets for PLATO observations.

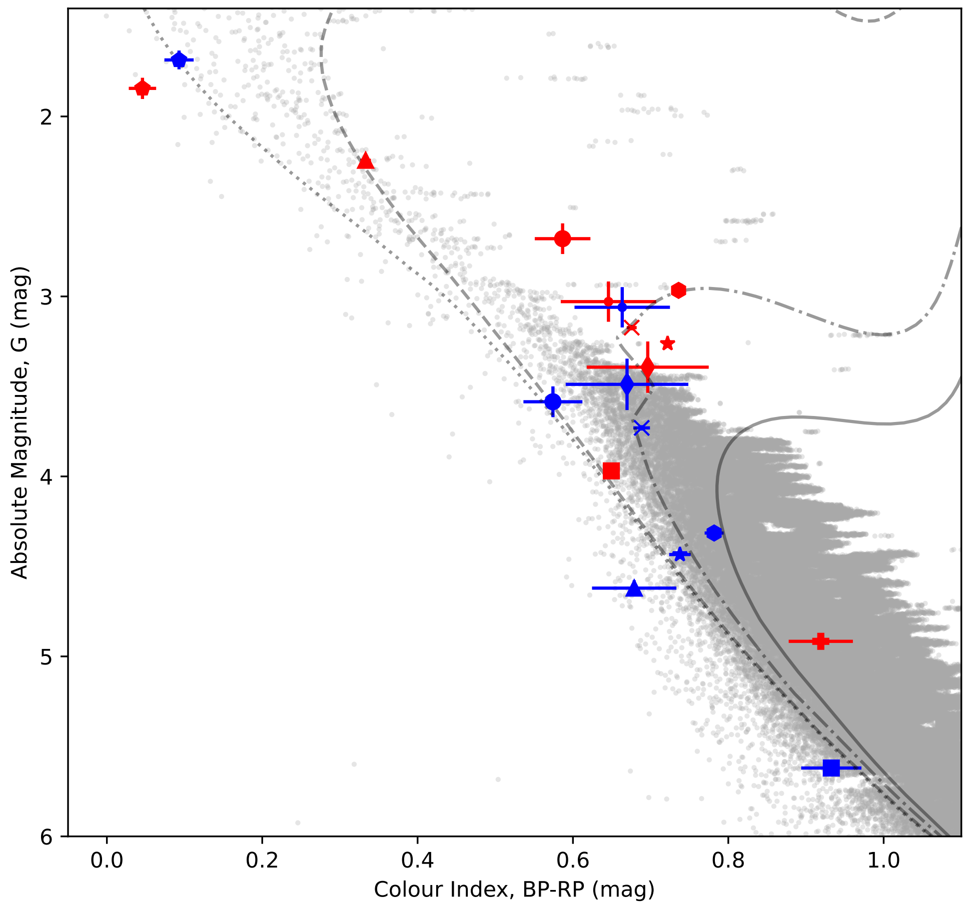

Figure 1. The two colours, red and blue, represent primary and secondary components respectively. These symbols represent EBs: TIC279087522 (⬟), TIC30122338 (●), TIC7695666 (×), TIC66602813 (■), TIC63579446 (★), TIC201497357 (▲), TIC349480507 (·), TIC349059354 (◆), TIC78568736 (+; secondary outside figure boundaries), TIC80556181 (⬢). Isochrones from Dotter (2016); Choi et al. (2016); Paxton et al. (2018) represent stellar ages 0.5 – 10 Gyr from left to right. Main sequence stars (grey) are from Gaia Collaboration et al. (2018)

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4. CONCLUSION

This project was successful in finding multiple benchmark candidates for calibration of PLATO which are consistent with the parameters set by the mission, fulfilling the aim. Our best candidates are TIC7695666, TIC349480507 and TIC80556181. These exhibit properties $\sim 1\ M_{\odot}$ and $V < 11$ mag. We therefore recommend these stars for further study.

Facilities: MAST (TESS), Gaia (DR3)

Software: `jktebop` v43 (Southworth 2013), `Lightcurve` v2.5.0 (Lightkurve Collaboration et al. 2018)

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