

Solving the Mystery of Extreme Light Variability in the Massive Eccentric System MACHO 80.7443.1718

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Abstract

The evolution of massive stars is heavily influenced by their binarity, and the massive eccentric binary system MACHO 80.7443.1718 (ExtEV) serves as a prime example. This study explores whether the light variability of ExtEV, observed near the periastron during its 32.8-day orbit, can be explained by a wind–wind collision (WWC) model and reviews other potential explanations. Using broadband photometry, TESS data, ground-based *UBV* time-series photometry, and high-resolution spectroscopy, we analysed the system’s parameters. We ruled out the presence of a Keplerian disk and periodic Roche-lobe overflow. Our analysis suggests the primary component has a radius of about $30R_{\odot}$, luminosity of $\sim 6.6 \times 10^5 L_{\odot}$, and mass between 25 and $45 M_{\odot}$, with a high wind mass-loss rate of $4.5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, likely enhanced by tidal interactions, rotation, and tidally excited oscillations. We successfully modelled ExtEV’s light curve, identifying atmospheric eclipse and light scattering in the WWC cone as key contributors. The system’s mass-loss rate exceeds theoretical predictions, indicating that ExtEV is in a rare evolutionary phase, offering insights into enhanced mass loss in massive binary systems.

Keywords: close binary systems, early-type stars, emission-line stars, massive stars, mass-loss, MACHO 80.7443.1718

1. Introduction

Most massive stars reside in binary and multiple systems (e.g., Vanbeveren et al., 1998; Sana et al., 2012; Duchêne and Kraus, 2013). The presence of a relatively close companion can affect the mass loss rate (MLR) due to line-driven stellar wind (e.g., MacLeod and Loeb,

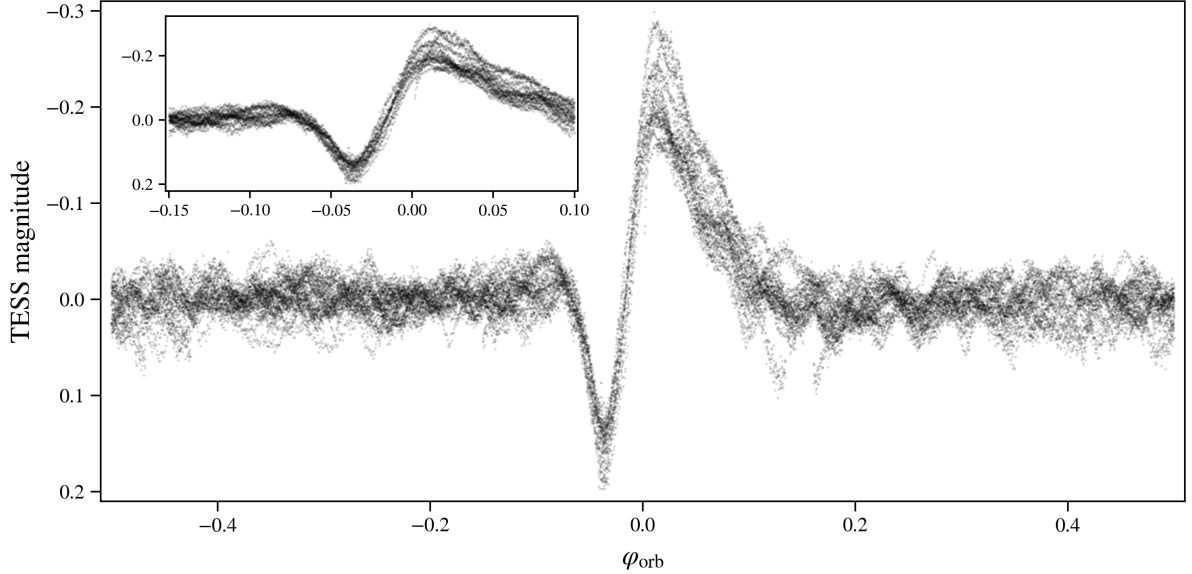


Figure 1: TESS near-infrared light curve of ExtEV phased with the orbital period of 32.83016 d. Orbital phase $\varphi_{\text{orb}} = 0$ corresponds to the time of the periastron passage. The inset shows the light curve near the periastron passage. Stochastic light variations and TEOs can be seen over the entire range of orbital phases.

2020) or induce high-amplitude tidally excited oscillations (TEOs; e.g., Fuller, 2017). In particular, the intensity of stellar wind has fundamental implications for the evolutionary track of a massive star (e.g., Smith, 2014; Vink, 2022; Björklund et al., 2023). Unfortunately, there are still many uncertainties regarding theoretical predictions of MLRs in massive stars due to their clumped, radiation-driven winds, especially when they leave the main sequence and become blue supergiants (BSGs; e.g., Gormaz-Matamala et al., 2023). Therefore, any opportunity to observe massive binary systems during the ongoing process of envelope stripping due to mass transfer or stellar wind enhanced by the presence of a companion is particularly valuable for verifying theoretical studies. In this context, MACHO 80.7443.1718 is of particular interest.

MACHO 80.7443.1718 (ExtEV, which stands for “extreme eccentric variable”) is an eccentric and massive binary (or even triple hierarchical) system with an orbital period of approximately 33 d, located in the LMC (Jayasinghe et al., 2021). The primary component of this system is a BSG of spectral type B0 Iae, while the secondary component is likely an O-type dwarf. ExtEV is a unique object for at least two reasons. Firstly, its light curve (without photospheric eclipses) exhibits an exceptionally large range of flux changes near periastron (~ 0.4 mag; Fig. 1), which initially led Jayasinghe et al. (2019) to reclassify the object as an “extreme heartbeat star”. However, it quickly became apparent that it could not be the case as the model of ellipsoidal variability failed to reproduce the photometric amplitude of ExtEV. The actual source of ExtEV’s variability became intriguing enough for the system to be featured in a dedicated publication in *Nature Astronomy* (MacLeod and Loeb, 2023). The authors suggest that the system experiences periodic Roche-lobe overflow (RLOF) near the periastron,

accompanied by the nonlinear tidal wave breaking on the surface of the primary component (MacLeod et al., 2022). However, this model suffers from numerous assumptions and approximations, making it questionable (Kořaczek-Szymański et al., 2024). The second distinguishing feature of ExtEV is the presence of high-amplitude TEOs. It is also the first system where relatively sudden and strong changes in the amplitude of TEOs have been detected (Kořaczek-Szymański et al., 2022). Therefore, we revised the existing models of ExtEV variability and proposed another solution, based on the new spectroscopic and photometric data collected by us (Kořaczek-Szymański et al., 2024). This article is a short summary of the extensive analysis that we describe in detail in the aforementioned paper.

2. Key Properties of the ExtEV System and its Primary Component

Using the Las Cumbres Observatory Global Telescope (LCOGT) light curves of ExtEV in the Johnson U , B , and V passbands, we conclude that the peak-to-peak amplitude and the shape of the ExtEV’s light curve seem to be independent of wavelength over a broad range from near-ultraviolet to near-infrared (IR). The spectral energy distribution (SED) of ExtEV reveals a significant IR excess, especially in the mid-IR bands (WISE W3 and W4 filters). Although the IR properties of ExtEV suggest an increased mass loss rate in the system, they do not align with the typical characteristics of B[e] SGs, as no emission lines like [O I] lines (which are typical of the Be phenomenon; Lamers et al., 1998) were detected in our SALT High-Resolution Spectrograph (SALT/HRS) spectra. Our SED modeling indicates that the primary component has a radius of approximately $30R_{\odot}$ and a luminosity of about $\log(L/L_{\odot}) \approx 5.82$ with an additional attenuation around 2760 \AA of unknown origin. Determining the initial and current mass of the primary component is challenging due to the impact of rotation and mass loss on its evolution, but simulations we performed with the MESA software (Paxton et al., 2011; Jermyn et al., 2023) suggest the zero-age main-sequence mass likely falls between 27 and $55M_{\odot}$, with a present mass between 25 and $45M_{\odot}$. The evolutionary status of the primary component is difficult to define. It is either in the hydrogen or helium core-burning phase. We also derived spectroscopic parameters of the primary’s orbit by combining archival radial-velocity data with those from SALT/HRS spectra, obtaining a more precise mass function of $f(M) = (0.74 \pm 0.05)M_{\odot}$ and identifying significant changes in the systemic velocity of ExtEV, suggesting that it may be a hierarchical triple system. Our analysis shows that assuming the $H\alpha$ and $H\beta$ emission features arise from a hypothetical Keplerian disk around the primary component leads to a disk location that would strongly interact with the secondary’s orbit. Furthermore, the primary component likely maintains a detached geometry during periastron passage, with a rotation period of about 8 days, consistent with pseudo-synchronous rotation. The light curve of ExtEV can be explained by a superposition of an atmospheric eclipse of the secondary by the primary’s intense stellar wind and excess emission from scattered light on the dense structures of the WWC cone. Using the theoretical model of atmospheric eclipses developed by Lamontagne et al. (1996) and later modified by Shenar et al. (2021), we determined the orbital inclination of ExtEV to be approximately 66° and the wind mass-loss rate from the primary component as large as $4.5 \times 10^{-5}M_{\odot} \text{ yr}^{-1}$. The results of this modelling are depicted in Fig. 2.

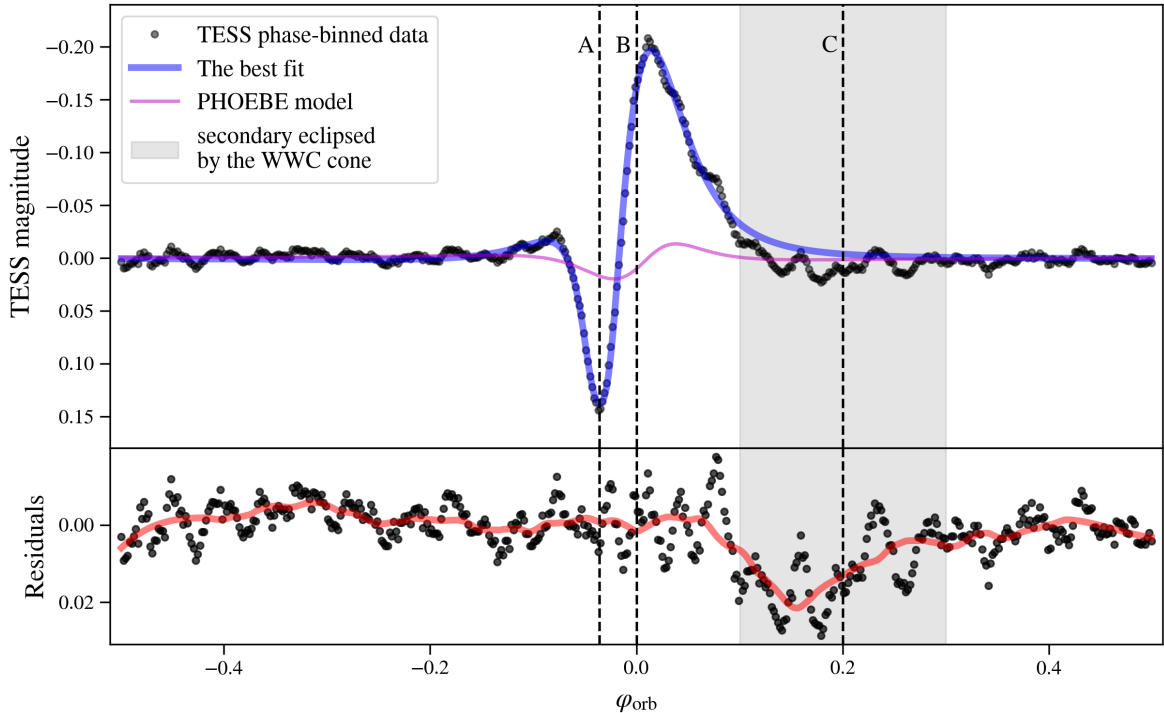


Figure 2: Plot summarizing the fit of our analytical variability model to the TESS light curve of ExtEV. The *top panel* shows the TESS light curve binned in the orbital phase (black dots) with the best-fit model (blue curve) superimposed. The pink line corresponds to the variability model generated with PHOEBE software (Prša et al., 2016). Vertical dashed lines labelled “A,” “B,” and “C” mark the orbital phase of superior conjunction, periastron passage, and inferior conjunction, respectively. The vertical shaded region marks the range of orbital phases where we expect the secondary component to be partially obscured by the WWC cone. The *bottom panel* shows the residuals from the best fit and their smoothed version (red curve). The zero phase corresponds to the time of periastron passage.

3. Summary and Conclusions

ExtEV is not a B[e] SG because its several key properties differ significantly from those of B[e] SGs, hence its extreme brightness changes cannot be explained by a disk surrounding the primary component. It is also unlikely that the light variability in ExtEV is caused by extreme tidal distortion and subsequent nonlinear breaking of tidal waves on the surface of the primary component. The system most likely does not experience RLOF at periastron, as the rotation rate of the primary component is at most half of that assumed in the MacLeod and Loeb (2023) models. Additionally, the light curve of ExtEV exhibits a similar shape and peak-to-peak amplitude in the Johnson *UBV* and TESS passbands, ruling out extreme tidal distortions and associated gravitational darkening, which would result in heterochromatic effects in the light curve. The ellipsoidal distortion appears to play only a secondary role in shaping the light curve of ExtEV, suggesting that it is not an extreme case of a “heartbeat star.”

According to our study, ExtEV may be in fact a unique WWC binary system in which a considerable mass loss by the primary component ($4.5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$) causes a remarkably large range of light variability. The combination of atmospheric eclipse with excess emission from the WWC cone can satisfactorily explain the amplitude and shape of the light curve, which previous models were unable to do. According to our scenario, the double-peaked emission observed in the $H\alpha$ and $H\beta$ lines should be interpreted as originating from the WWC recombination zone and the primary's stellar wind itself. The MLR of the primary component we obtained is two orders of magnitude greater than the theory predicts. We can suspect that the wind of the central BSG is tidally and rotationally enhanced, possibly with some additional interaction with TEOs. In this scenario, ExtEV is an extremely rare example of a massive binary system during a short but dramatic stage in its evolution, when the proximity of a massive companion leads to a sudden stripping of the primary's envelope without the need for RLOF. Thus we conclude that ExtEV can serve as an excellent laboratory for studying the mechanisms of wind enhancement in massive stars and predicting the impact of this enhancement on their evolution.

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Author contributions

PKS was responsible for the majority of the conceptual work, data analysis, modelling, and preparation of the manuscript. PŁ developed a simplified model of emission in the $H\alpha$ and $H\beta$ lines, assuming it originates from a Keplerian disk around the primary component of ExtEV.

PŁ also extracted differential photometry for ExtEV based on the data from LCOGT. AP was responsible for critically evaluating the results obtained by PKS and PŁ. He also actively participated in preparing the manuscript and responding to the reviews. TR provided normalised spectra from the SALT/HRS instrument. DM conducted an independent quality assessment of the photometry provided by PŁ.

Conflicts of interest

The authors declare no conflict of interest.

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