Contrib. Astron. Obs. Skalnaté Pleso **54/2**, 228 – 233, (2024)
https://doi.org/10.31577/caosp.2024.54.2.228

Eclipse timing variations of evolved eclipsing binaries: potential targets for meter-sized telescopes in the light of TESS observations

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Received: November 6, 2023; Accepted: December 8, 2023

Abstract. Evolved eclipsing binaries, featuring a white dwarf or a subdwarf companion on relatively short orbital periods of a few hours, exhibit interesting characteristics in their eclipse timing variations (ETV), analysis of which brings several advantages. Firstly, their small total masses enable us to detect substellar mass objects by observing the light-time effect, due to a subtle wobbling of the binary system around the barycenter. Additionally, the short orbital periods of these binaries allow for the accumulation of a large dataset comprising numerous observations, facilitating rigorous analysis and enhancing statistical significance. Moreover, their minima profiles have symmetric V-shapes in most cases, which decrease the uncertainties in the measurements of minima timings. In this study, we collect and analyze all available photometric data from the Transiting Exoplanet Survey Satellite (TESS), using observation cadences of both 20 and 120 seconds for such systems identified by various surveys. Our sample includes more than 60 evolved eclipsing binaries, whose primaries are either white dwarf or subdwarf companions. By calculating mid-eclipse timings, we construct detailed ETV diagrams and apply the Lomb-Scargle period analysis to determine the amplitudes and periods of their ETVs.

Key words: binaries: eclipsing – methods: data analysis – planetary systems

1. Introduction

The Eclipse Timing Variation (ETV) method is a well-known and useful tool for detecting additional objects within a binary system. This method relies on analyzing the cyclic variations in eclipse times, which are caused by the radial component of the binary's orbit around the barycenter, influenced by the presence of one or more additional objects.

The emergence of the eclipse signal with varying distances to observers induces the light-time effect (LiTE), also known as the Roemer delay. In many cases, the precision of timing data and the relatively simple system complexity, such as a small number of bodies and large orbital separations, allow for the use of elliptical orbit models (Keplerian orbits) to sufficiently model ETVs with LiTE. However, as photometric precision increases, perturbations between the bodies necessitate the use of Newtonian approaches to precisely determine the orbital properties of such systems. It's important to note that other cyclic ETV-causing mechanisms, like the magnetic activity cycles of late-type companions, can produce signals that mimic those of additional objects.

The ETV method has detected numerous substellar mass circumbinary objects (Baştürk et al., 2023). However, the history of ETV searches for substellar objects includes both successful detections and rejections. The lack of independent confirmation methods has contributed to the variability in these ETV analyses. Long-period ETV modulations make comprehensive radial velocity follow-ups challenging and significantly reduce transit probabilities. Orbital stability tests for systems with multiple circumbinary candidate objects are currently the most practical tools for confirmation purposes.

Eclipsing binaries with circumbinary substellar mass objects detected using the ETV method share common characteristics. They typically fall into two categories: HW Virginis-like binaries with a subdwarf OB (sdOB) primary star and a low-mass main sequence companion, or cataclysmic binaries with a white dwarf primary and a main sequence companion. These systems generally have a total mass of less than one solar mass, which is crucial for detecting the wobbling induced by substellar mass objects. Their short orbital periods enable frequent eclipse observations, while their eclipse light curves often feature prominent V-shaped eclipses, facilitating precise determination of eclipse mid-times. The presence of a common envelope in previous evolutionary stages may be a key factor in these binaries hosting circumbinary planets (Zorotovic & Schreiber, 2013).

Baştürk et al. (2023) revealed that many multiplanet ETV systems lack stable orbital configurations. Several potential reasons for this issue include: i) The cyclic ETV modulations have long periods spanning years or decades, requiring extended observations and thorough analysis, which are often lacking. ii) Modeling of the ETV tends to result in positive eccentricity parameters, increasing the likelihood of close encounters or even orbit crossings. iii) In some cases, other ETV mechanisms may not have been correctly implemented.

This research undertakes an initial exploration of a thorough ETV search to identify potential timing modulations of eclipsing binaries. We introduce our research project and present preliminary results based on TESS observations. Our main objective in this study is to detect potential short-period ETV modulations within the TESS data. Following this, we aim to amalgamate timing data from TESS with existing ground and space-based timings, creating a comprehensive ETV dataset. This dataset will serve as a valuable resource for conducting timing analyses on a variety of eclipsing binary systems.

Table 1. Gaia G brightness values, number of TESS sectors with 120-second and 20-second exposures, number of mid-eclipse timings calculated for each exposure, and their corresponding uncertainties. The first group is HW Vir-like systems and the second one is cataclysmic variables. [1]Full identifier is ATO J294.7689+11.1822

System	G Mag	Sectors 120 s	Sectors 20 s	Timings 120 s - 20 s	σ_{120s} (s)	σ_{20s} (s)
DD CrB	12.9	3	2	580 366	2.61	2.65
HW Vir	10.6	1	1	380 374	6.57	0.72
NY Vir	13.4	3	2	1116 749	2.91	1.72
AA Dor	11.1	29	17	4727 2985	4.44	2.26
V1828 Aql	13.2	1	1	223 190	8.59	4.74
CHSS 3072	14.3	1	0	101 0	5.55	-
HS 0705+6700	14.6	3	2	1252 714	5.01	11.63
Kepler-451	12.1	4	0	1166 0	10.18	-
HS 2231+2441	14.2	1	1	342 249	25.61	7.98
PN A66 46	15.0	3	2	251 196	22.68	6.04
UCAC4 489-038954	15.2	1	0	495 0	26.37	-
TIC 455206965	15.2	3	2	1093 721	35.56	25.63
ATO J294.7+11.1[1]	14.9	1	1	97 133	94.17	19.05
TIC 467187065	15.8	8	6	4318 3370	43.39	17.41
V588 Vir	13.8	1	0	51 0	97.65	-
RW Tri	13.2	1	0	248 0	8.07	-
V1315 Aql	14.3	1	0	231 0	7.16	-
TIC 240872692	15.1	3	1	461 236	16.22	13.34
V363 Aur	14.1	2	0	272 0	17.96	-
UZ For	16.6	1	0	411 0	43.53	-
TIC 271137877	16.9	1	0	217 0	24.48	-
V870 Lyr	15.9	4	0	744 0	25.06	-
V1776 Cyg	16.5	5	0	1276 0	55.73	-

2. ETV analysis of evolved eclipsing binaries

We selected a subgroup of evolved eclipsing binaries from a larger pool of 68 similar systems (see Table 1) for which TESS data was available. Our objective was to construct ETV diagrams and identify periodic patterns within their TESS data. To achieve this, we obtained both 120-second and 20-second exposure TESS data for each system through the Space Telescope Science Institute's (STScI) Mikulski Archive for Space Telescopes (MAST)[1]. The data underwent quality flag filtering, and any evident outliers were removed. We applied second-degree polynomial detrending to continuous observation sections within each sector and normalized the data to their respective median flux levels.

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

To generate ETV diagrams, we initially computed mid-eclipse times using the well-established Kwee & van Woerden method (Kwee & van Woerden, 1956), focusing solely on the primary eclipses. We concurrently updated the linear ephemeris for each system while also eliminating outliers from the ETV diagrams. By combining timings from all available sectors, we produced the final ETV diagrams for each evolved eclipsing binary. The ETV scatter is generally smaller for HW Virginis-like binaries in comparison to cataclysmic variables, primarily due to the symmetrical eclipse features of HW Virginis-like systems. Notably, we observed that the scatter tends to be smaller for systems with 120-second exposures and brighter systems, aligning with our expectations.

To identify periodic patterns in the ETV diagrams, we employed the Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982) on the ETVs from 120-second exposures using our custom Python script. The script is based on relevant functions from the ASTROPY package (Astropy Collaboration et al., 2013, 2018, 2022). For each periodogram, we determined the periods corresponding to the highest Lomb-Scargle power and calculated their associated amplitude and false alarm probability (FAP), which are listed in Table 2.

We identified two distinct groups within our results. The first group comprises three systems: HW Virginis, NY Virginis, and V1776 Cyg. Their associated false alarm probability (FAP) values are effectively zero, suggesting potential periodic variations in the ETV diagrams based on TESS data. For HW Virginis and NY Virginis, we compared the ETV diagrams between 120-second and 20-second exposures. The periodic variation observed in 120-second exposures disappears in the 20-second ETV diagram of HW Virginis, indicating that the periodicity is a result of the 120-second TESS exposure times. Conversely, for NY Virginis, the periodicity remains consistent in the 20-second exposures, which we attribute to pulsations of the primary sdB component within the eclipsing binary. These pulsations have detectable amplitudes, even in ground-based observations, as demonstrated in a prior study by Vučković et al. (2007). We have deferred assessing the source of periodicity in V1776 Cyg due to the absence of 20-second exposures, leaving it for further investigation.

The second group exhibits periodicities extending beyond a single TESS sector, and the associated false alarm probability (FAP) values for these periodicities are notably high (FAP > 0.2). These systems include HS 0705+6700 and Kepler-451. We phase-folded the ETV diagrams for these systems using the periods with the highest Lomb-Scargle power. In the case of HS 0705+6700, the phase-folded ETV lacks coverage for almost half of the phase. For Kepler-451, although the period we found is somewhat close to that of the innermost planet ($P_d = 43\ d$) detected by Esmer et al. (2022), however, the amplitude is significantly higher than expected for such an object. The periodicities observed in these cases may result from jitter caused by pulsations of the primary star or stellar spots on the secondary star, phenomena expected in these types of eclipsing binaries. Additionally, the sampling of TESS may introduce jitter at a detectable level in their ETVs. However, a comprehensive explanation for these

Table 2. Periods, amplitudes, and false alarm probabilities (FAP) of the ETV data calculated by Lomb-Scargle periodograms for our target subgroup.

System	LS Period (d)	Amplitude (sec)	FAP
DD CrB	6.408	1.30	0.94
HW Vir	3.884	4.85	10^{-38}
NY Vir	4.309	1.93	10^{-7}
AA Dor	3.146	0.52	1.00
V1828 Aql	2.005	3.73	1.00
CHSS 3072	2.311	6.30	0.31
HS 0705+6700	61.345	7.81	0.49
Kepler-451	33.671	8.68	0.21
HS 2231+2441	2.200	10.11	1.00
PN A66 46	2.112	15.73	0.89
UCAC4 489-038954	2.351	10.85	1.00
TIC 455206965	5.294	10.88	1.00
ATO J294.7+11.1	5.767	61.34	1.00
TIC 467187065	4.562	22.25	1.00
V588 Vir	2.751	3749.80	0.38
RW Tri	5.607	12.84	1.00
V1315 Aql	6.96	13.94	1.00
TIC 240872692	3.203	12.47	1.00
V363 Aur	7.175	30.15	0.96
UZ For	2.382	16.37	1.00
TIC 271137877	8.651	26.69	1.00
V870 Lyr	4.092	24.66	0.76
V1776 Cyg	6.520	87.33	10^{-8}

periodicities in their ETVs is yet to be provided and remains a subject for future studies.

3. Summary

With this study, our primary goal is to search for potential short-period ETV modulations within the TESS data. We intend to expand our ETV datasets for these systems by incorporating both ground-based and space-based timing calculations. The TESS photometry, in particular, will play a crucial role in binary modeling, which we aim to apply to a majority of the evolved eclipsing binaries on our target list.

This study serves as a preliminary ETV search for our list of evolved eclipsing binaries. We have compiled this list as part of a comprehensive ETV research project, where we aim to detect circumbinary substellar mass objects around evolved binaries. Our objectives include testing the validity of previous ETV solutions, updating them as necessary, building population statistics for hosts and substellar companions, creating a comprehensive ETV catalog, and contributing to the research field by developing the required software tools.

Acknowledgements. We gratefully acknowledge the support by The Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Project 122F358. We also extend our gratitude to the SOC and LOC of the conference, *Observing techniques, instrumentation and science for metre-class telescopes III* for their financial support. We appreciate the valuable discussions with fellow conference attendees.

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