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Optical studies of γ-ray binaries and candidate systems

Josep Martí,[a,*] Pedro L. Luque-Escamilla,[b] Enrique Mestre,[a] Estrella Sánchez-Ayaso,[c] Josep M. Paredes,[d] Daniel del Ser[d,e] and Jorge Núñez[d,e]

[a] *Departamento de Física, Universidad de Jaén, Campus Las Lagunillas s/n, E-23071 Jaén, Spain*

[b] *Departamento de Ingeniería Mecánica y Minera, Universidad de Jaén, Campus Las Lagunillas s/n, E-23071 Jaén, Spain*

[c] *Departamento de Ciencias Integradas, Centro de Estudios Avanzados en Física, Matemática y Computación, Universidad de Huelva, E-21071 Huelva, Spain*

[d] *Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, IEEC-UB, Martí i Franquès 1, E-08028 Barcelona, Spain*

[e] *Observatori Fabra, Reial Acadèmia de Ciències i Arts de Barcelona, Rambla dels Estudis, 115, E-08002 Barcelona, Spain*

E-mail: jmarti@ujaen.es, peter@ujaen.es, estrella.sanchez@dci.uhu.es, jmparedes@ub.edu, danieldelser@ub.edu, jorge@fqa.ub.edu

Highly accurate photometry of the optical companion in γ-ray binary systems has the potential to enable the exploration of previously unknown phenomena. Here we report the discovery of repeated optical flares evolving on time scales of about one day in the optical light curve of the well known system LSI +61 303. Their amplitude does not exceed 0.01-0.02 magnitudes and, therefore, they are only within reach of space observatories such as the Transiting Exoplanet Survey Satellite (*TESS*) in the 600-1000 nm bandpass. We tentatively propose that these flaring events are shock-powered in nature as the compact object in LSI +61 303 interacts with the circumstellar envelope of its Be star companion. *TESS* results dealing with other systems (MWC 148, MWC 656 and HD3191) are also shortly addressed.

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[*] Speaker

1. Introduction

The topic of γ-ray binaries is at the forefront of high and very high energy astrophysics that has captivated astrophysicists specially in the last decade when revealing unexpected phenomenologies [1–3]. Remarkably, the spectral energy distribution of these objects culminates well beyond 1MeV and extends up to TeV energies. Their study is being made possible thanks to space-based observatories and other ground-based facilities, such as Cherenkov telescopes and air shower arrays. However, to understand these newly revealed properties one cannot neglect the parallel use of the classical tools in observational astrophysics at much lower energies. In particular, optical photometry and spectroscopy remain key for both multi-wavelength follow-up and putting constrains on the systems orbital and physical parameters. Moreover, some of these traditional observational methodologies are currently also feasible from orbiting telescopes with significantly improved capabilities.

In this contribution, we mainly focus on the discovery of new phenomena in an outstanding γ-ray binary thanks to the extremely accurate optical photometric data provided by the orbiting Transiting Exoplanet Survey Satellite (*TESS*) and its associated toolbox for light curve production [4]. The main object under study is the system LSI +61 303, well known for its 26.5 day orbitally modulated light curve across the whole electromagnetic spectrum from radio to γ-rays. Recently, it has been shown that the Be optical star in this system is accompanied by a a neutron star, and not a black hole, as revealed by the successful detection of radio pulsations using the FAST radio telescope [5]. We refer the reader to [6] and references therein for further system information and a detailed account on *TESS* results.

2. Studying LSI +61 303 with *TESS*

TESS observed the field of view of LSI +61 303 during its Sector 18 in November 2019. It is fortunate that the duration of its pointing practically matched the binary orbital period. This provided, for the first time, an almost uninterrupted optical (600-1000 nm) light curve of LSI +61 303 with time resolution better than half hour. We display it in Fig. 1 created using the *TESS* `lightkurve` package. A relative magnitude scale was preferred for reasons related to the historical photometry of LSI +61 303. We see that the gross trend matches well previous past observations [7, 8], but now the *TESS* light curve includes a richness of optical microflares evolving on time scales of about one day. Their amplitude typically amounts 0.01-0.02 magnitudes. The zoomed section of the light curve shown in Fig. 2 is well representative of this previously unknown behavior that the exquisite sensitivity of *TESS* renders visible.

A wavelet periodicity analysis above 0.5 Hz frequencies was conducted using a Morlet mother wavelet with wavenumber 8. As a result, the recurrent visual impression from Figs. 1 and 2 was confirmed by the spectrograms (not shown here). Yet, the periodicity scheme seems to be evolving along the LSI +61 303 orbital phase as a sort of quasi-periodic oscillation. In this way, optical microflares develop $\sim$ 10 % faster in the vicinity of periastron while their frequency diminishes close to apastron [6].

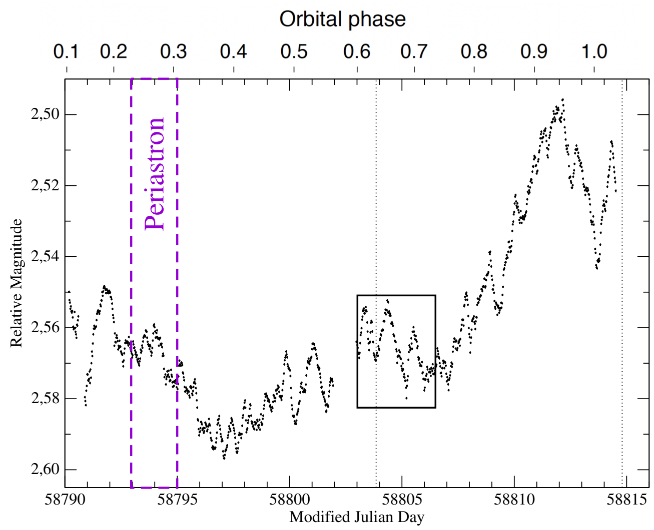

Figure 1: *TESS* light curve of LSI +61 303 covering a full orbital period during November 2019 as adapted from [6]. The region of periastron passage is marked by the dashed violet rectangle. There is another rectangle in black continuous line displayed as an enlarged view in Fig. 2. Vertical thin dashed lines mark the times when optical spectroscopy was acquired.

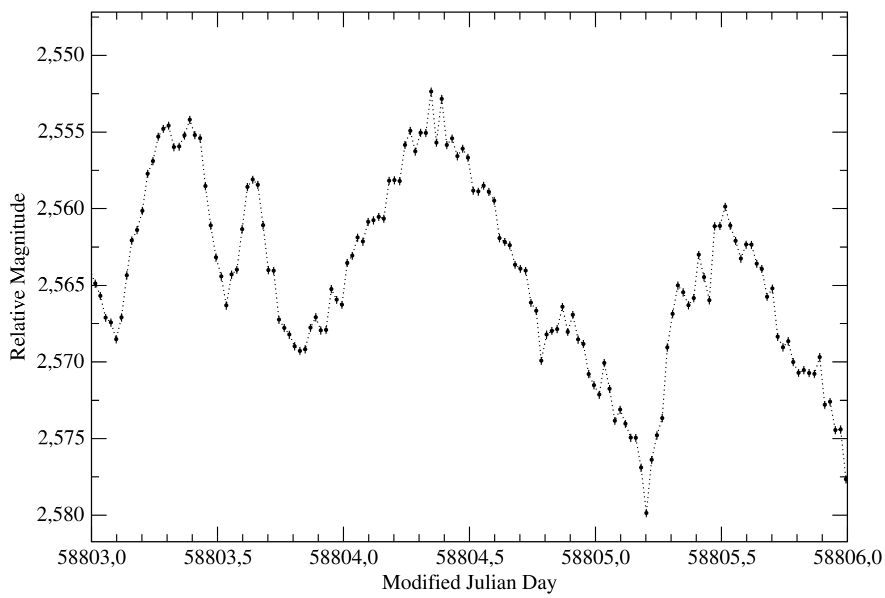

Figure 2: Detailed and representative view of fast optical variability in LSI +61 303 as observed with *TESS*. Error bars are practically of the same size as the plotted points.

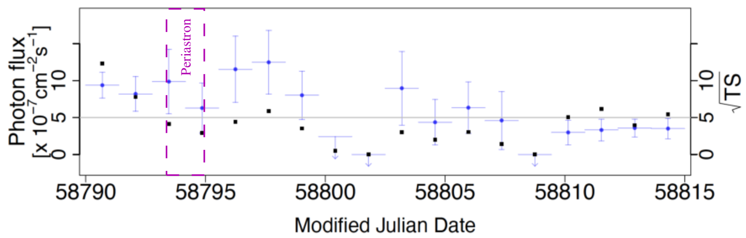

Figure 3: Light curve of LSI +61 303 contemporaneous with the *TESS* observations as observed with the *Fermi* LAT (blue points). Time bins used correspond to 32.9 hours. Error bars are statistical only. The periastron region is also marked by a dashed violet rectangle. Black points indicate the detection significance in the right side scale.

3. Contemporaneous LSI +61 303 optical spectroscopy and γ-ray observations

By chance, the authors obtained low-resolution optical spectral of LSI +61 303 in coincidence with the *TESS* pointing using a LISA spectrograph attached to the 0.4 m University of Jaén telescope (UJT). The observations dates were 16 and 27 November 2019. The Hα emission line appeared with a nearly constant equivalent width of about -14 Å. This is a significantly high value suggestive of a well-developed circumstellar envelope of the Be companion star [9].

In parallel, we used the continuous γ-ray monitoring provided by the *Fermi* Large Area Telescope (LAT) [P8R3, 10, 11] in an attempt to search for possible counterparts of the mini-flare events. The selected time interval better overlapping with the *TESS* observations corresponds to 494995769 - 652762170 seconds in *Fermi* mission time. The region of interest used had a radius of 15° centered around the LSI +61 303 position corresponding to the *Fermi* source 4FGL J0240.5+6113. Further details about the LAT dat analysis using a joint likelihood approach with a broken power-law model can be found in [6]. The final result is the light curve displayed in Fig.3. Here, strong care was applied to choose a time binning that provided a 5σ detection across the orbital phases. Unfortunately, fullfilling this requirement prevented us from using a binning interval shorter than 33 h. Therefore, by no means the *Fermi* light curve could be extracted with a time resolution comparable to that of *TESS*. Yet, on the merged data LSI +61 303 was detected with high confidence and with spectral parameters compatible with our previous knowledge of the source.

4. A tentative scenario for LSI +61 303

By analogy with semi-analytic models of nova shocks [12, 13], we tentatively propose that the LSI +61 303 microflares could arise from shocks created while the neutron star companion interacts with the Be circumstellar envelope across the orbital period. This should be specially true for an enriched Be circumstellar envelope as optical spectroscopy indicates during the *TESS* pointing. If this is the case, then one would expect the optical flaring emission should be accompanied by concurrent and γ-ray flaring events. As we estimate in [6]. their expected γ-ray luminosity is $L_\gamma \sim 6.3 \times 10^{32}$ erg s^{-1} equivalent to an energy flux of 7.6×10^{-13} erg cm^{-2} s^{-1} averaged over the LAT passband at an assumed 2.6 kpc distance. While the *Fermi* sensitivity does not allow us to directly check their existence, alternative evidence could perhaps be obtained at lower energies, such as X-rays. However, we point out here that we still ignore if the *TESS* microflares are always a common phenomenon in LSI +61 303 as they have been only observed during a single orbit.

5. *TESS* light curves of other γ-ray binaries

Other binaries relevant in high-energy astrophysics have been targeted by *TESS*. The almost uninterrupted monitoring often allows to confirm their binary nature when a clear orbital period emerges from the light curve. The case of the candidate γ-ray binary HD 3191 is a good example of this capability [14]. *TESS* also enables to disentangle the orbital variability from the rotational period of the optical companion. Moreover, when combined with high-resolution optical spectroscopy of the emission lines formed in circumstellar envelopes of Be systems, it becomes possible to estimate different stellar parameters such as the projected rotational velocity, stellar radius and inclination of the star rotation axis. So far this approach has been applied to MWC 148 and MWC 656 [15].

6. Conclusions and perspectives

γ-ray binaries with luminous counterparts are among the multi-disciplinary domains of modern astrophysics benefited from optical *TESS* monitoring capabilities. The discovery of repeating microflares in LSI +61 303 (beyond reach of ground-based photometry) and the opening of other approaches for stellar parameter determination support this statement. The authors look forward to *TESS* covering the whole celestial sphere so that many other systems could be studied in this way.

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References

[1] G. Dubus, *Gamma-ray binaries and related systems*, *A&A Rev.* **21** (2013) 64 [1307.7083].

[2] J.M. Paredes and P. Bordas, *Phenomenology of gamma-ray emitting binaries*, *Rendiconti Lincei. Scienze Fisiche e Naturali* **30** (2019) 107 [1902.09898].

[3] M. Chernyakova, D. Malyshev, A. Paizis, N. La Palombara, M. Balbo, R. Walter et al., *Overview of non-transient γ-ray binaries and prospects for the Cherenkov Telescope Array*, *A&A* **631** (2019) A177 [1909.11018].

[4] Lightkurve Collaboration, J.V.d.M. Cardoso, C. Hedges, M. Gully-Santiago, N. Saunders, A.M. Cody et al., "Lightkurve: Kepler and TESS time series analysis in Python." Astrophysics Source Code Library, Dec., 2018.

[5] S.-S. Weng, L. Qian, B.-J. Wang, D.F. Torres, A. Papitto, P. Jiang et al., *Radio pulsations from a neutron star within the gamma-ray binary LS I +61° 303*, *Nature Astronomy* (2022) [2203.09423].

[6] E. Mestre, E. Sánchez-Ayaso, P.L. Luque-Escamilla, J. Martí, J.M. Paredes, D. del Ser et al., *Optical microflares in LS I +61 303 and the search for their multiwavelength counterpart*, *A&A* **662** (2022) A27 [2205.05380].

[7] J.M. Paredes and F. Figueras, *Detection of optical variability of LSI +61 303.*, *A&A* **154** (1986) L30.

[8] H. Mendelson and T. Mazeh, *Discovery of a 26.5 day optical periodicity of LSI +61 303.*, *MNRAS* **239** (1989) 733.

[9] R. Zamanov, J. Martí, K. Stoyanov, A. Borissova and N.A. Tomov, *Connection between orbital modulation of Hα and gamma-rays in the Be/X-ray binary LS I+61°303*, *A&A* **561** (2014) L2 [1311.7618].

[10] Fermi-LAT collaboration in *Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential*, 3, 2013 [1303.3514].

[11] P. Bruel, T.H. Burnett, S.W. Digel, G. Johannesson, N. Omodei and M. Wood, *Fermi-lat improved pass 8 event selection*, 2018.

[12] E. Steinberg and B.D. Metzger, *The multidimensional structure of radiative shocks: suppressed thermal X-rays and relativistic ion acceleration*, *MNRAS* **479** (2018) 687 [1805.03223].

[13] E. Aydi, K.V. Sokolovsky, L. Chomiuk, E. Steinberg, K.L. Li, I. Vurm et al., *Direct evidence for shock-powered optical emission in a nova*, *Nature Astronomy* **4** (2020) 776 [2004.05562].

[14] J. Martí, P.L. Luque-Escamilla, E. Sánchez-Ayaso and J.M. Paredes, *Orbital and sub-orbital period determination of the candidate high-mass X-ray binary HD 3191*, *A&A* **651** (2021) A1 [2105.03189].

[15] R.K. Zamanov, K.A. Stoyanov, J. Mart, V.D. Marchev and Y.M. Nikolov, *Radius, rotational period, and inclination of the Be stars in the Be/gamma ray binaries MWC 148 and MWC 656*, *Astronomische Nachrichten* **342** (2021) 531 [2102.01971].

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