Received: 21 September 2023 | Revised: 24 November 2023 | Accepted: 14 January 2024

DOI: 10.1002/asna.20230128

Astronomische Nachrichten

ORIGINAL ARTICLE

Lessons from the apparent peculiar nature of the star TYC 6544-3483-1

Josep Martí[1] | **Pedro L. Luque-Escamilla**[2] | **Benito Marcote**[3] | **Daniel del Ser**[4,5] | **Gustavo E. Romero**[6,7] | **Cintia S. Peri**[2]

[1]Departamento de Física (EPSJ), Universidad de Jaén, Jaén, Spain

[2]Departamento de Ingeniería Mecánica y Minera (EPSJ), Universidad de Jaén, Jaén, Spain

[3]Joint Institute for VLBI ERIC, PD Dwingeloo, The Netherlands

[4]Observatori Fabra, Reial Acadèmia de Ciències i Arts de Barcelona, Barcelona, Spain

[5]Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Barcelona, Spain

[6]Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, La Plata, Argentina

[7]Instituto Argentino de Radioastronomía (CCT La Plata, CONICET; CICPBA; UNLP), Buenos Aires, Argentina

Correspondence
Josep Martí, Departamento de Física (EPSJ), Universidad de Jaén, Campus Las Lagunillas s/n, A3, E-23071 Jaén, Spain.
Email: jmarti@ujaen.es

Funding information
Consejo Nacional de Investigaciones Científicas y Técnicas, Grant/Award Number: PIP 0554; "María de Maeztu 2020–2023" award to the Institute of Cosmos Sciences, Grant/Award Number: CEX2019-000918-M; State Agency for Research of the Spanish Ministry of Science and Innovation, Grant/Award Numbers: PID2019-105510GB-C31AEI/10.13039/501100011033/, PID2019-105510GB-C32/AEI/10.13039/501100011033/; Consejería de Economía, Innovación, Ciencia y Empleo of Junta de Andalucía and FEDER funds, Grant/Award Number: FQM-322

Abstract

We report a radio and optical study of the star TYC 6544-3483-1 originally selected as a follow-up target in the course of our efforts to cross-identify Galactic high-energy sources. The star by itself finally turned out to be a very ordinary main-sequence star despite the initial expectations that apparently pointed to the contrary. We found that its, at first glance, exotic properties arise as a combined consequence of the limited angular resolution of the radio and optical databases being used. Our preliminary astrophysical interpretation was strongly hampered by the presence of unexpected optical variables inside both the photometric and background apertures. While such an ill-posed situation is not a frequent one, we believe that our experience is worth sharing with the community to raise a word of caution and help to avoid similar misleading results, especially when dealing with modern TESS data.

KEYWORDS

gamma rays: stars, stars: individual: TYC 6544-3483-1, techniques: photometric, techniques: interferometry

1 | INTRODUCTION

The identification of candidate counterparts to gamma-ray sources is an on-going task offering new opportunities for discovery whenever new gamma-ray catalogs are released. The recent publication of the latest *Fermi* 4FGL Point Source Catalog (Abdollahi et al. 2022) is an important milestone in this context. Although the gamma-ray sky is mostly dominated by extragalactic blazar sources, other populations of stellar gamma-ray emitters are also worth studying and searching for (Martí et al. 2013). A clear clue that betrays the possible connection of a stellar object with a gamma-ray source is the detection of non-thermal radio emission, by means of dedicated observations or catalog cross-identifications, implying a population of relativistic electrons (Martí et al. 2015; Martí & Luque-Escamilla 2021). If additional signs of binarity are found, then the suspicion becomes strengthened as prototypical stellar gamma-ray sources are often binary systems (Chernyakova & Malyshev 2020).

In this paper, we report a case of negative results of this observational methodology and the valuable lessons learned in the process that should hopefully illuminate future searches.

2 | SELECTION OF TYC 6544-3483-1 AS AN INTERESTING TARGET

This context outlined above is what originally attracted our attention to the star TYC 6544-3483-1 located inside the 95% confidence ellipse of the gamma-ray source 4FGL J0745.4−2447. Although a sound *Fermi* counterpart candidate was already pointed out in the 4FGL catalog, the quasar ICRF J074510.2-245143 (Immer et al. 2011), different observational facts presented below rendered TYC 6544-3483-1 worth of further additional investigation as an alternative feasible counterpart.

TYC 6544-3483-1 was selected for in-depth study given that a non-thermal radio counterpart was suspected to be associated with it. Support for this claim is displayed in Figure 1 where the NRAO VLA Sky Survey (NVSS) radio contours (1.4-GHz, Condon et al. 1998) are overlapped onto the optical red plate of the Digitized Sky Survey (DSS).[1] The 9.6 ± 0.6 mJy compact radio source NVSS J074454-250522 position was coincident with TYC 6544-3483-1 within the NVSS astrometric error ($\pm 2''$). Moreover, it was also detected in images from the GMRT 150-MHz all-sky radio survey (Intema et al. 2017) at a flux density level of 33 ± 9 mJy. Assuming constant values, a negative spectral index of -0.6 ± 0.3 was estimated that pointed toward a nonthermal emission mechanism.

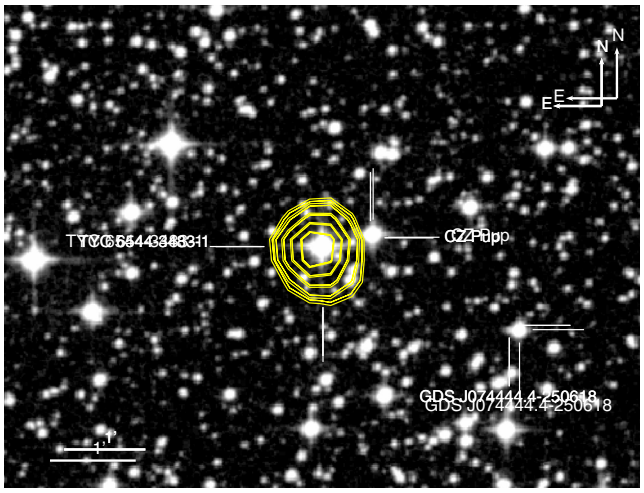

FIGURE 1 Field of view of TYC 6544-3483-1 in the red plate of the Palomar Digital Sky Survey with the other relevant stars in its vicinity (see Section 5). Yellow contours illustrate the radio emission according to the NVSS. The one arc-minute bottom left horizontal bar sets the angular scale. North is up and East is left. Two other stars (CZ Pup and ASASSN-V J074444.41-250618.7/ GDS_J0744444-250618) relevant in the Section 5 are also marked.

To pursue the exploration of TYC 6544-3483-1, we noticed that this star was included in different pointings of the Transiting Exoplanet Survey Satellite (TESS) corresponding to the sky sectors 07 and 34 of this space mission, observed during years 2019 and 2021, respectively. We downloaded and processed this data using the tools provided by the Lightkurve Collaboration (2018). The resulting optical light curves have a bandwidth of 600–1,000 nm overlapping with the Cousins I_C band centered at 786.5 nm. Their time resolution was excellent (10–20 min cadence) and each pointing lasted nearly four weeks. A plot of the TESS photometry is displayed in Figure 2. At first glance, the resulting light curve was strongly reminiscent of an eclipsing binary system and different periodogram algorithms suggested a 6.1669 day period, on which TESS data is phase-folded. Based on this evidence and the possible radio counterpart, TYC 6544-3483-1 appeared as a likely Algol-type eclipsing binary with promising follow-up perspectives.

Moreover, we additionally noticed the presence of repetitive small optical mini-flaring events superposed onto the TESS light curves (see again Figure 2). There were a total of four per cycle and their occurrence constantly drifted across the period phase. Their sharp appearance was also strongly reminiscent of self-lensing events observed in some binary systems (Kruse & Agol 2014).

[1] https://archive.eso.org/dss/dss .

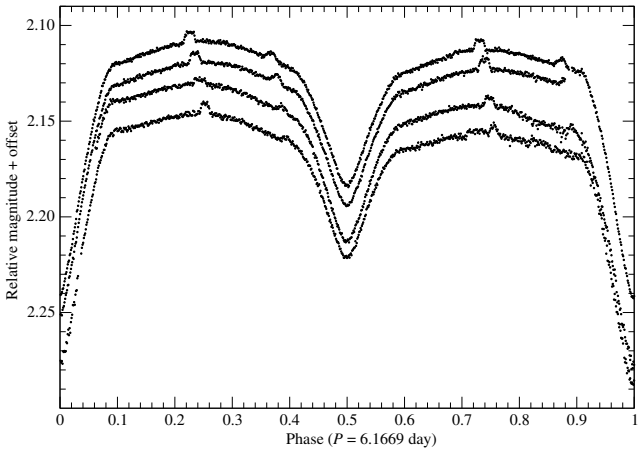

FIGURE 2 Apparent result of performing aperture photometry on the TYC 6544-3483-1 position using TESS data folded on a 6.1669 day period. Four almost complete cycles are shown. No additional corrections beyond the subtraction of scattered light have been applied. Notice the repeating four mini-flares best visible in the top light curve.

Overall, the observed facts resulted in very puzzling and stimulated further observational studies.

3 | RADIO OBSERVATIONS

The first step to assess the peculiar nature of TYC 6544-3483-1 was to obtain a sub-arcsecond accurate radio position of NVSS J074454-250522 to check its apparent coincidence with the star. For this purpose, we carried out a Very Long Baseline Interferometry (VLBI) using the antennae of the European VLBI Network (EVN), under proposal code EM168. The observations were conducted in two blocks, of 3 h each, scheduled on the March 6 and 11, 2023. The frequency setup was centered at 1.67 GHz (18 cm wavelength) with four subbands of 32 MHz each (32 channels per subband). The integration time of visibilities was 2 s. The sources J0745+1011 and J0745-2451 were used as fringe finder and phase calibrator, respectively. The EVN data were calibrated following standard procedures in AIPS (Greisen 2003). The a priori amplitude calibration and flagging were applied from the tables generated by the EVN Pipeline. We then manually corrected for the ionospheric contribution, instrumental delay, fringe fit, and bandpass calibration. A round of imaging and self-calibration were performed in the phase calibrator source using the Caltech VLBI Analysis Program DIFMAP. These solutions were then transferred to the target source to improve the calibration, and we finally imaged the source.

The EVN map revealed that NVSS J074454-250522 actually consists of two resolved components separated

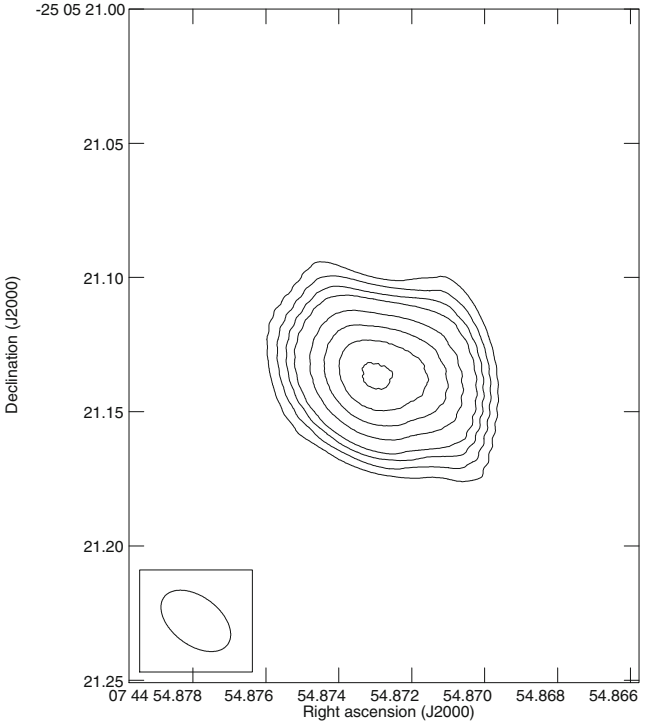

FIGURE 3 VLBI map of the main component of NVSS J074454-250522 as it appears at the 18 cm wavelength. It was obtained with natural weight and a *uv* taper of 5 Mλ. Contours shown correspond to −4, 4,5, 6, 8, 10, 12, and 14 times 9.6 μJy beam^{-1}, the rms noise. The bottom left ellipse illustrates the synthesized beam of 18 × 30 milli-arcsecond^2, with position angle of 53°.

by a few arc-seconds, hereafter designated as A and B. This separation is a large angle in a VLBI context to produce a full clean map. In Figure 3, we display a contour plot of the brightest A component that was detected with an excellent signal-to-noise ratio. With a total flux density 792 ± 19 μJy beam^{-1}, NVSS J074454-250522-A is located at J2000.0 coordinates $07^h44^m54.87273^s \pm 0.8$ mas and $-25°05'21.1360'' \pm 1.6$ mas. Its angular size is 49 ± 1 mas. Concerning NVSS J074454-250522-B (not shown here), it does not have a well definite core. With a total flux density 588 ± 53 μJy beam^{-1}, its centroid is located at $07^h44^m54.3663^s \pm 6$ mas and $-25°05'17.522'' \pm 3$ mas. Its angular size is 149 ± 22 mas. Errors given combine both statistic, systematic, calibrator position and phase referencing uncertainties. Angular sizes are as measured by fitting a circular Gaussian component.

4 | OPTICAL SPECTROSCOPIC OBSERVATIONS

To complete our observational study, a low-resolution ($\lambda/\Delta\lambda \sim 10^3$) spectrum of TYC 6544-3483-1 was obtained

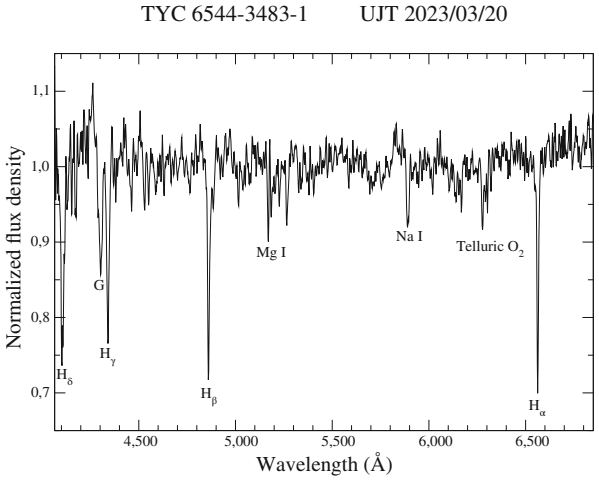

FIGURE 4 Optical spectrum of TYC 6544-3483-1 as observed with the University of Jaén telescope. The continuum has been normalized to unity and the most relevant absorption spectral features are identified.

in March 20, 2023. We used a commercial LISA spectrograph attached to the 41 cm University of Jaén telescope (UJT). This is an educational facility located on the outskirts of the Spanish city of Jaén, and occasionally used for research purposes involving bright targets as in this work (Martí et al. 2017). The instrument resolving power and wavelength coverage (including 4,000–7,000 Å) enables a first spectral classification and search for the emission line features exhibited by most peculiar star systems (X-ray binaries, cataclysmic variables, WR stars …). The final UJT spectrum is shown in Figure 4. It resulted from a total of eight exposures of 5 min each median-combined to get rid of cosmic ray impacts. Data reduction followed the standard procedure of bias and dark current removal, flat field correction, and wavelength calibration (using a Ne-Ar lamp). Different tasks of the IRAF package were used for these purposes as well as for the spectrum extraction and analysis.

The resulting Figure 4 spectrum is dominated by narrow absorption features that correspond to the Balmer series (Hα, Hβ, Hγ, and Hδ). In addition, it also exhibits a clear absorption next to Hδ consistent with the so-called G-band (4,299–4,313 Å), a feature related to CN molecules. This is commonly seen in F-type stars later than F3 (Kaler 1989). A visual comparison with an extended stellar library suggests an F5V type as the most plausible spectral classification, whose expected effective temperature is about 6,700 K. This is also consistent with the available optical photometry by Høg et al. (2000) ($B = 10.72 \pm 0.04$, $V = 10.30 \pm 0.04$ and $B - V = 0.42 \pm 0.06$). Given the Gaia parallax, that points to a nearby 0.34 kpc distance, both the absolute magnitude and color point to a mid-F-type star observed under very low extinction ($A_V \leq 0.1$ mag).

5 | DISCUSSION

The key finding of our TYC 6544-3483-1 follow-up study is the lack of coincidence with none of A and B components of NVSS J074454-250522. Given the ±0.01 mas accurate optical position of the star[2] from the third *Gaia* Data Release,[3] its offset from the two radio components is a significant arc of about several arc-seconds for both A and B. Therefore, the optical-radio overlap suggested by Figure 1 must be considered a mere line-of-sight effect. This negative result prompted us to consider with strong care the other hints of TYC 6544-3483-1 peculiarity, in particular the photometric ones.

A later in-depth investigation of the literature, unexpectedly revealed a previously cataloged eclipsing binary in the TYC 6544-3483-1 field of view, known as CZ Pup (Wood & Forbes 1963), with orbital period almost identical to the period apparently present in the light curve of Figure 2. This fact quickly raised, a posteriori, an alarm pointing to possible contamination of the TESS light curve of TYC 6544-3483-1. The close location of the polluting star is marked in Figure 1. Even if only one or a few edge pixels of the TESS photometric aperture were affected by the weak CZ Pup signal, this turned out to be sufficient to introduce a contaminating periodic modulation wrongly attributed to TYC 6544-3483-1. This unwanted effect unavoidably occurred despite TYC 6544-3483-1 dominated the counts inside the aperture. The large size of TESS pixels (21 arc-seconds) can certainly cause this kind of problem and strong caution is needed when interpreting the light curves with blended objects. This concern has been also pointed out by other authors in the recent literature (Pedersen & Bell 2023).

Concerning the apparent mini-flaring events present in Figure 2, we have also searched for a possible contamination origin that makes it unnecessary to invoke other exotic phenomena initially considered, such as lensing effects. And indeed a contaminating culprit was finally found thanks to the All-Sky Automated Survey for Supernovae (ASAS-SN) (Jayasinghe et al. 2020; Shappee et al. 2014), namely the star ASASSN-V J074444.41-250618.7/GDS_J0744444-250618 currently classified as an eclipsing binary. Using the ASAS-SN photometry, we estimated its most likely period to be 3.1108 d, with two minima whose timing coincides with the apparent mini-flares of TYC 6544-3483-1. Although the ASAS-SN object was outside the TESS Full Frame Image used (see its location in the bottom left side of Figure 1), part of its flux managed to leak towards at least one edge

[2] 116.2275026111792, −25.088836626280095 in degrees.
[3] https://gea.esac.esa.int/archive/ .

pixel inside the region used to evaluate the background. When removing it, the signal of the two eclipsing minima translated into unreal flaring excesses.

Comparable background and/or photometric aperture problems have been reported in the past. For instance, seeing fluctuations may translate into fake optical microvariability of quasars if the aperture is not correctly chosen (Cellone et al. 2000). Spurious effects on gamma-ray light curves can also be potentially related to the Moon sidereal period (Abdo et al. 2015).

Taking all previous considerations into account, it clearly appears that TYC 6544-3483-1 is nothing else but an ordinary main sequence star since all the evidences for peculiar phenomena vanished after a careful inspection of the observed data. This statement is further supported by the UJT low-resolution spectrum shown in Section 4, where no emission lines but only normal absorption features consistent with an F-type star are present. No peculiar behavior is seen from this star, not even signs of chromospheric activity. Consequently, the quasar ICRF J074510.2-245143 remains as the only reliable candidate counterpart to the gamma-ray source 4FGL J0745.4-2447.

6 | CONCLUSIONS

The star TYC 6544-3483-1 has finally been revealed to be a standard stellar object, thus confirming the previous quasar counterpart candidacy to 4FGL J0745.4-2447. However, the most relevant outcome of this work is the lesson learned about the dangers of misinterpretation of subtle effects in otherwise high-quality photometric databases. The limitation of angular resolution, mainly at optical but also at radio wavelengths, has been at the origin of the problem in our case. In particular, crowded variable objects in the same field of view can lead to confusing results if not properly accounted for by identifying and excluding the affected pixels. TESS light curves are especially prone to this problem and disentangling the true individual light curves can then become a very painful task. The source cross-identification purposes, that originally motivated this work, require full awareness of this real possibility in future work.

AUTHOR CONTRIBUTIONS

TYC 6544-3483-1 was initially identified as a potentially interesting object by J.M. and P.L.L.E. The rest of co-authors actively contributed to acquire and/or interpret the observational results. All authors engaged in the manuscript's final discussion.

ACKNOWLEDGMENTS

This work was mainly supported by grant PID2019-105510GB-C32/AEI/10.13039/501100011033/ from the State Agency for Research of the Spanish Ministry of Science and Innovation. We also acknowledge support by Consejería de Economía, Innovación, Ciencia y Empleo of Junta de Andalucía as research group FQM-322, as well as FEDER funds. B.M., D.d.S., and G.E.R. acknowledge financial support through the Unit of Excellence "María de Maeztu 2020–2023" award to the Institute of Cosmos Sciences (CEX2019-000918-M). G.E.R. also acknowledges financial support from the State Agency for Research of the Spanish Ministry of Science and Innovation under grant PID2019-105510GB-C31AEI/10.13039/501100011033/) and additional support from PIP 0554 (CONICET). The EVN is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. Scientific results from data presented in this publication are derived from the following EVN project code: EM168.

CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest.

ORCID

Josep Martí https://orcid.org/0000-0001-5302-0660

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2015, *ApJ*, *799*(2), 143.

Abdollahi, S., Acero, F., Baldini, L., et al. 2022, *Astrophys. J. Suppl.*, *260*(2), 53.

Cellone, S. A., Romero, G. E., & Combi, J. A. 2000, *Astron. J.*, *119*(4), 1534.

Chernyakova, M., & Malyshev, D. 2020, Gamma-ray binaries. In Multifrequency Behaviour of High Energy Cosmic Sources - XIII. 3-8 June 2019. Palermo p. 45.

Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *Astron. J.*, *115*(5), 1693.

Greisen, E. W. 2003, AIPS, the VLA, and the VLBA. in: *Information Handling in Astronomy - Historical Vistas, Astrophysics and Space Science Library*, ed. A. Heck, Vol. *285*, Springer (Dordrecht). https://doi.org/10.1007/0-306-48080-8_7

Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, *Astron. Astrophys.*, *355*, L27.

Immer, K., Brunthaler, A., Reid, M. J., et al. 2011, *Astrophys. J. Suppl.*, *194*(2), 25.

Intema, H. T., Jagannathan, P., Mooley, K. P., & Frail, D. A. 2017, *Astron. Astrophys.*, *598*, A78.

Jayasinghe, T., Stanek, K. Z., Kochanek, C. S., et al. 2020, *Mon. Notice R. Astron. Soc.*, *491*(1), 13.

Kaler, J. B. 1989, Stars and their spectra. an introduction to spectral sequence.

Kruse, E., & Agol, E. 2014, *Science*, *344*(6181), 275.

Lightkurve Collaboration 2018, Lightkurve: Kepler and TESS time series analysis in Python., Astrophysics Source Code Library, record ascl:1812.013.

Martí, J., & Luque-Escamilla, P. L. 2021, *Universe*, *7*(7), 214.

Martí, J., Sanchez-Ayaso, E., Luque-Escamilla, P., et al. 2013, *Eur. Phys. J. Web Conf.*, *61*, 3002.
Martí, J., Luque-Escamilla, P. L., Casares, J., et al. 2015, *Astrophys. Space Sci.*, *356*(2), 277.
Martí, J., Luque-Escamilla, P. L., & García-Hernández, M. T. 2017, *Bulg. Astron. J.*, *26*, 91.
Pedersen, M. G., & Bell, K. J. 2023, *Astron. J.*, *165*(6), 239.
Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, *Astrophys.J.*, *788*(1), 48.
Wood, B. D., & Forbes, J. E. 1963, *Astron. J.*, *68*, 257.

AUTHOR BIOGRAPHY

Josep Martí Full professor of astronomy and astrophysics at the University of Jaén (Spain) since 2010. His research is mainly devoted to multi-wavelength observational studies of Galactic high and very high-energy sources.

How to cite this article: Martí, J., Luque-Escamilla, P. L., Marcote, B., del Ser, D., Romero, G. E., & Peri, C. S. 2024, *Astron. Nachr.*, e20230128. https://doi.org/10.1002/asna.20230128