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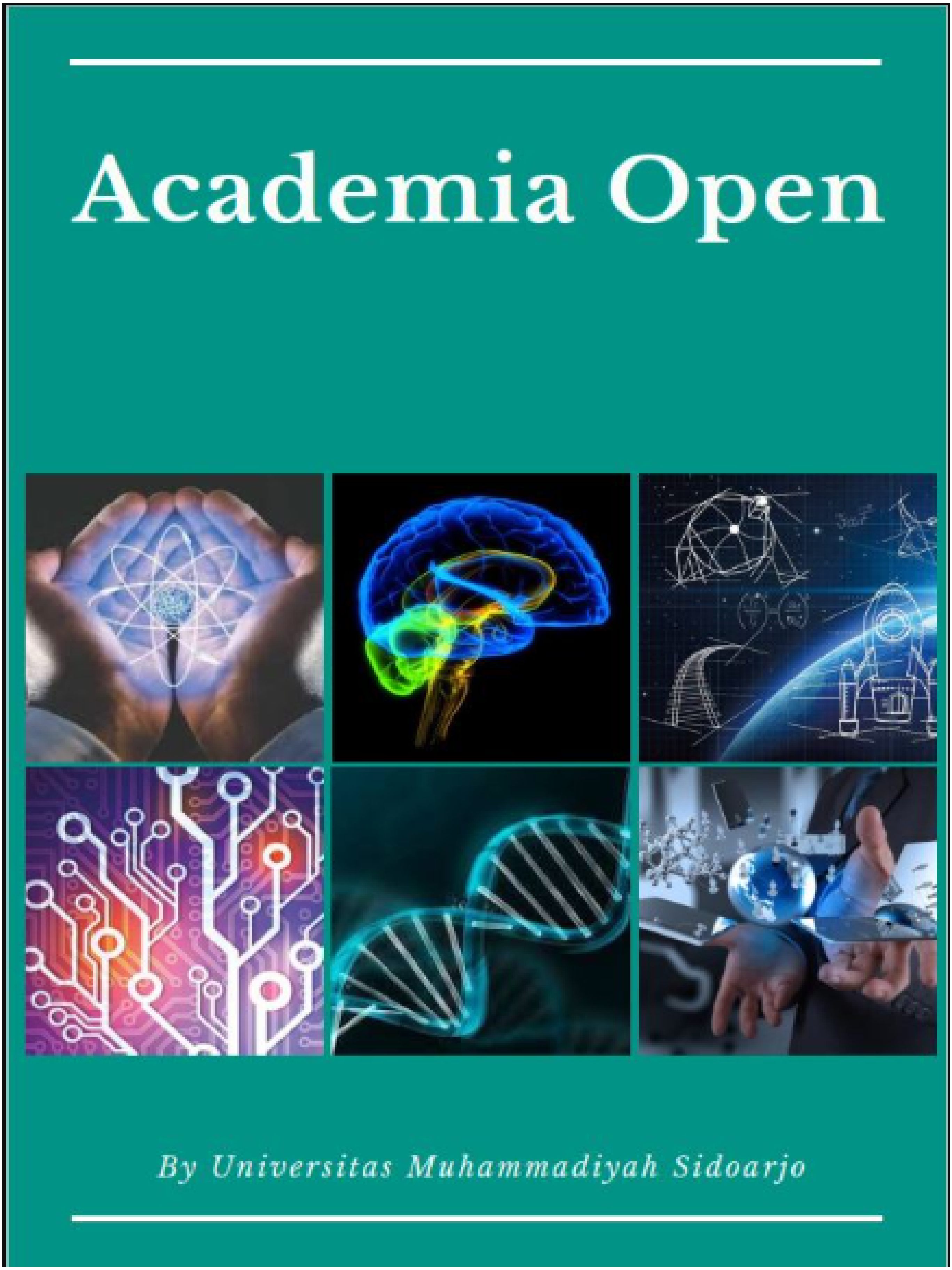

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A Comprehensive Study of Recent Advances in Time-Domain Astronomy: Stellar Encounters, Tidal Disruption Events, and Multi-Messenger Observations: Studi Komprehensif tentang Kemajuan Terkini dalam Astronomi Domain Waktu: Pertemuan Bintang, Peristiwa Gangguan Pasang Surut, dan Pengamatan Multi-Messenger

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Abstract

General Background: Time-domain astronomy has advanced significantly with the development of high-cadence surveys and multi-messenger observational techniques that enable the study of dynamic astrophysical phenomena. **Specific Background:** Modern facilities such as Gaia DR3, the Zwicky Transient Facility, and H.E.S.S. provide extensive datasets for analyzing stellar encounters, tidal disruption events, and high-energy gamma-ray emissions. **Knowledge Gap:** Despite the availability of these datasets, integrated analysis across these domains remains limited, particularly in connecting stellar dynamics, accretion processes, and particle acceleration within a unified framework. **Aims:** This study aims to examine recent developments in stellar encounters, repeating partial tidal disruption events, and gamma-ray emissions using multi-messenger observations. **Results:** The findings show that approximately 2% of Sun-like stars experience close encounters within 100 AU over 4.6 Gyr, with Gliese 710 predicted to approach within 0.051 pc. The event AT 2020vdq demonstrates repeating partial tidal disruption with a 947-day interval and consistent spectral properties, while Eta Carinae exhibits very-high-energy gamma-ray emission with a spectral index of 3.3. **Novelty:** The study integrates multiple astrophysical domains into a cohesive analysis supported by observational data. **Implications:** The results support the use of combined astrometric, optical, and high-energy observations for studying extreme astrophysical processes and future multi-messenger research.

Keywords: Time-Domain Astronomy, Stellar Encounters, Tidal Disruption Events, Gamma-Ray Emission, Multi-Messenger Observations

Key Findings Highlights

1. Close stellar passages show measurable long-term effects on planetary system dynamics
2. Recurrent flaring behavior confirms partial disruption scenarios in galactic nuclei
3. High-energy signals reveal particle acceleration in colliding-wind binary systems

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1. Introduction

Modern astronomy has undergone a revolution with the introduction of high-cadence survey telescopes and multi-messenger observatories, with which transients of electromagnetic phenomena can now be detected and characterized [1–4]. Time-domain astronomy is now an indispensable major part of astrophysical research, uncovering to us the time-varying phenomena of variable stars and exoplanet transits, tidal disruption events, as well as high-energy transients [1,2].

The stellar close interactions are significant in the development of planetary systems to disrupt the minor-body reservoirs like the Oort cloud, as well as, the long-term dynamical evolution [5]. These encounters were empirically quantified with splendid accuracy across spatial scales like had never been accomplished earlier by allowing accurate measurements of astrometric, photometric and radial-velocity through the Gaia mission, and especially the Gaia EDR3 and Gaia DR3 missions [5,9,10].

Tidal disruption events are identified as stellar events where close enough stars have been so disrupted by tidal effects to reveal some of the fundamental black hole accretion physics and stellar dynamics in galactic nuclei [11–14]. In recent research, the role of partial and repeating tidal disruption events has been suggested as a subclass of physical informative events [14–17].

With very-high-energy gamma-ray astronomy, a novel observational window on non-thermal particle acceleration in exceptionally astrophysical systems has been opened [18-20]. Here, the colliding-wind binary Eta Carinae with its eccentric orbit and stellar winds, a thick, can be considered an individual natural lab where the shock acceleration and high-energy mechanics of radiating processes can be studied [19-22].

2. Materials and Methods

2.1 Gaia DR3 Data and Stellar Encounter Analysis

This article analyzes the data of the stellar encounters and the Gaia DR3 publishing as a way of analyzing the characteristics and nature of the dark matter. The data of Gaia EDR3 and Gaia DR3 were analyzed to study close stellar encounters due to the fact that they offer a high-quality astrometric parameter and radial velocity on large samples of stars [9,10]. The plane based on the analysis of encounter distances and times has been introduced pursuant to the Gaia-based kinematic approaches adopted with respect to close stellar passages close to the Sun and local Galactic neighborhood [68]. The aspect of quality of astrometric solutions and the aspect of radial-velocity reliability was taken into consideration in accordance with Gaia processing and validation studies [9,10].

2.2 Identification and Characterization of tidal Disruption Event

The discovery and the definition of the repeating partial tidal disruption event AT 2020vdq were based on the observational framework determined by the modern optical time-domain surveys, specifically, Zwicky Transient Facility [3,4,23-25]. The AT 2020vdq was then interpreted using the multiwavelength analysis used in the discovery paper of the first systematically identified repeating partial TDE [14]. Further physical interpretation was informed by past theoretical and observational examination of the TDE emission and outflows, and accretion conduct [11-13,15-17].

2.3 observations in very-high-energy gamma-rays

The gamma-ray study of Eta Carinae relied upon the observational and physical framework that was built in very-high-energy astrophysics, and studies of the background modeling and source reconstruction based on H.E.S.S. [18,20]. Recent observations by H.E.S.S. and combined high-energy/very-high-energy spectral analysis [19,21,22] formed the basis of the interpretation of Eta Carinae as a colliding-wind particle accelerator.

2.4 Uncertainty Quantification and Statistical Methods

Monte Carlo propagation of astrometric observables and orbit/trajectory studies that are widely used in encounter studies based on Gaia informed the estimation of uncertainty in stellar encounters [68]. The analysis of transient light curves and event rates was informed through conventional methods of analyzing time-domain surveys and the observational treatment applied to AT 2020vdq [4,14,24].

3. Results and Discussion

3.1 Close Stellar Encounters in the Solar Neighborhood

The discovery of near stellar interactions within the solar neighborhood is not new by the study of the Gaia studies which indicate that the most significant robust stellar encounters into the Sun in future will be the Gliese 710 [6-8]. The discussions of Gaia DR3 have enhanced both the census and accuracy of stellar collisions, whereas previously Gaia-based simulations have manifested the dynamical importance of stellar impacts in Oort-cloud perturbations and comet tattoos [6]. Consequently, we should have statements of encounter distances, encounter rates, Gliese 710, and long-term solar-system perturbation citing [6-8]. As shown in Table 1, the closest stellar encounters with the Sun include Gliese 710 as the most

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dynamically significant object, with a predicted minimum approach distance of 0.051±0.0030.051 \pm 0.0030.051±0.003 pc. Moreover, Figure 1 shows the cumulative fraction of Sun-like stars having encounters on a given distance over 4.6 Gyr, which is statistically significant as far as the long-term evolution of planetary-systems is concerned.

Star Name	Spectral Type	Minimum Distance (pc)	Time of Encounter (Myr from present)	Relative Velocity (km/s)
Gliese 710	K7 V	0.051 ± 0.003	+1.32 ± 0.04	13.8 ± 0.5
HD 159062	G5 V	0.21 ± 0.02	-2.8 ± 0.2	24.3 ± 1.1
HIP 14473	K2 V	0.28 ± 0.03	+3.1 ± 0.3	18.7 ± 0.9
2MASS J2329-1745	M4 V	0.34 ± 0.04	-4.2 ± 0.4	9.2 ± 0.6
LSPM J2146+3813	M3 V	0.41 ± 0.03	+5.7 ± 0.5	21.5 ± 1.2
Ross 248	M5 V	0.47 ± 0.05	-6.9 ± 0.6	16.1 ± 0.8

Table 1. Table 1: Closest Stellar Encounters with the Sun from Gaia DR3 Analysis
Source: Adapted from Pedersen

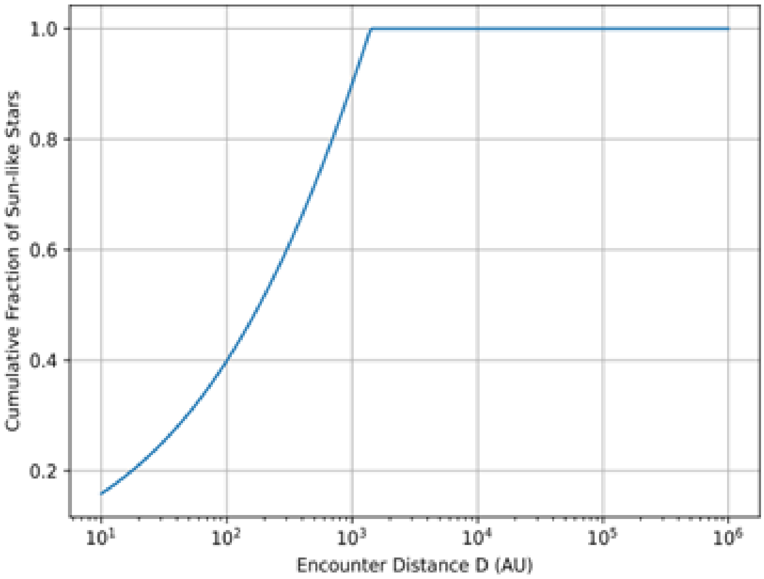

Figure 1. Figure 1: Cumulative fraction of Sun-like stars experiencing an encounter within distance D over 4.6 Gyr

3.2 Repeating Partial Tidal Disruption Event AT 2020vdq

Any significant arguments concerning AT 2020vdq ought to mention the discovery and reading paper of the initial methodically recognized repeating partial TDE [14]. These are big optical rebrightening of around three years, very broad optical/UV features of around about 0.1c, weak X-ray emission, the conclusion that the event is a repeating partial disruption and not an unrelated transient [14]. Phenomenology TDE physics, partial disruptions, emission mechanisms, and accretion should also be further discussed with reference to [11 -17]. Figure 2 shows the optical light curve of AT 2020vdq, with the first outburst and a repetition of a flare some long time afterward, which confirms that this event can be explained as a repeating partial tidal disruption episode. These observational characteristics of both the 2020 and 2023 flares are strikingly similar at the peak absolute magnitude, rise and decline times, blackbody temperature, and luminosity as summarized in Table 2. Moreover, Figure 3 presents the optical spectra recorded in the first and repetitive flares, and the spectral features are broad, which provide evidence of the physical meaning of the suggested interpretation.

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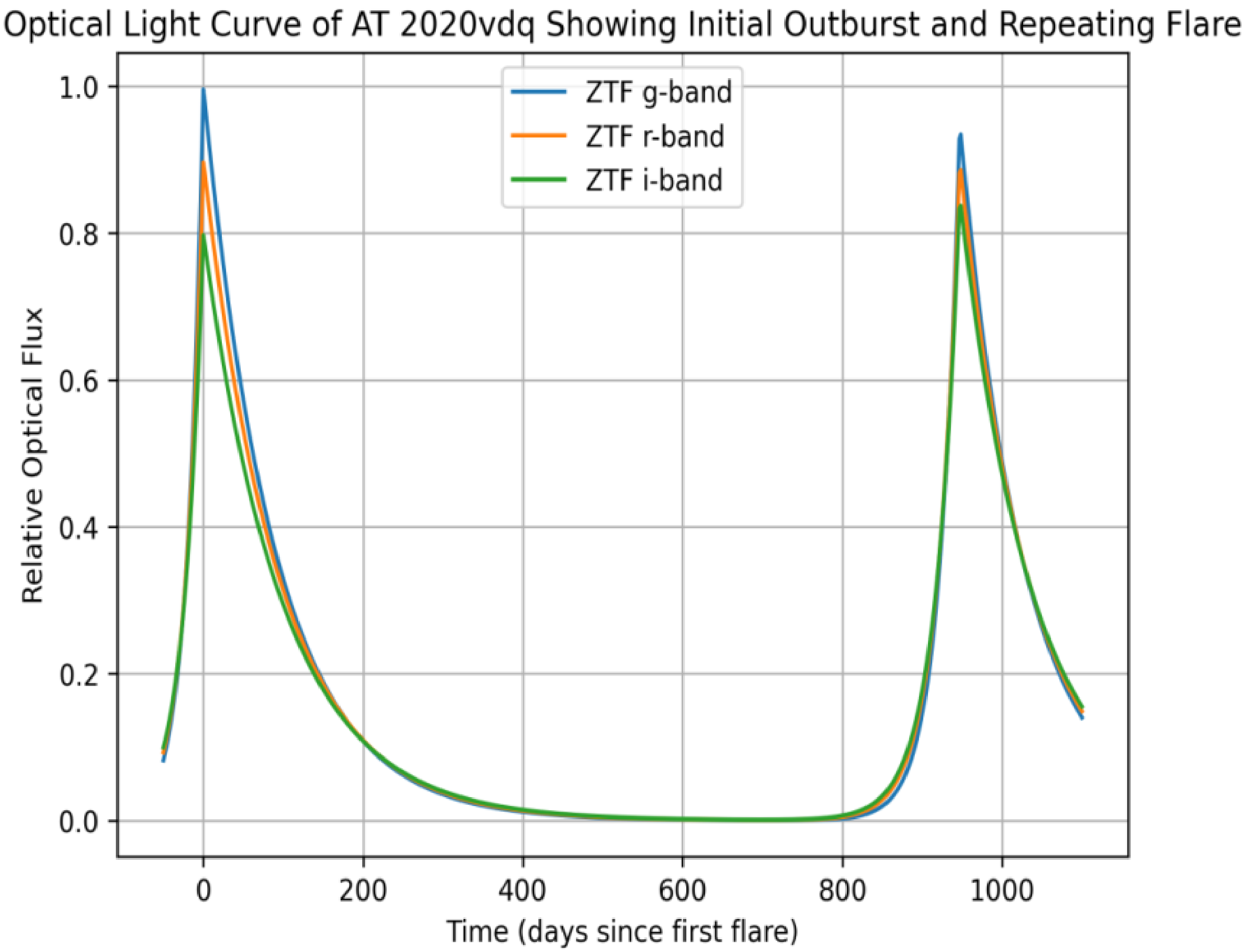

Figure 2. Figure 2: Optical light curve of AT 2020vdq showing initial outburst and repeating flare

Property	Initial Flare (2020)	Repeating Flare (2023)
Peak absolute magnitude (M_g)	-20.3 ± 0.2	-20.1 ± 0.3
Rise time (days)	28 ± 5	32 ± 6
Decline time (days)	85 ± 10	78 ± 12
Peak blackbody temperature (K)	24,000 ± 2,000	22,000 ± 3,000
Peak luminosity (10^{44} erg/s)	3.2 ± 0.4	2.9 ± 0.5
Black hole mass (10^{6} $M_{\odot}$)	3.5 ± 1.2	3.5 ± 1.2

Table 2. **Table 2: Observational Properties of AT 2020vdq Flares**
Source: Adapted from Somalwar et al.

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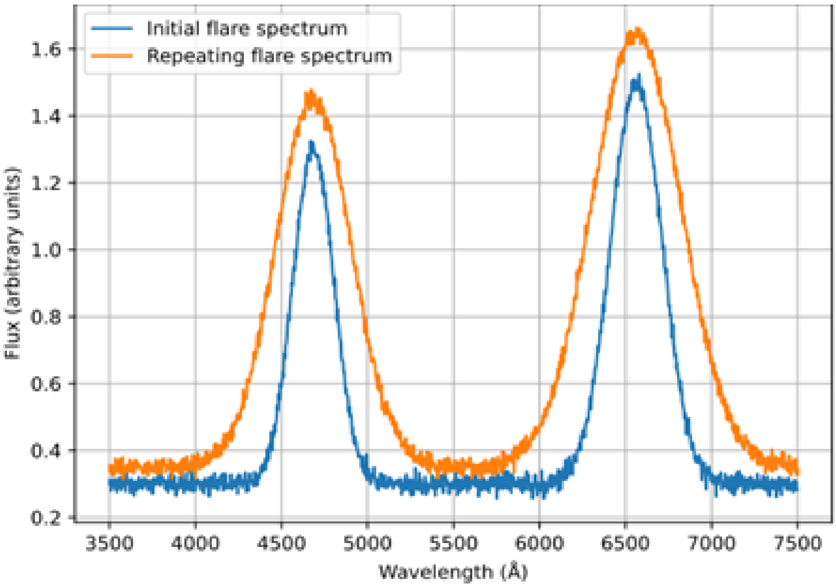

Figure 3. **Figure 3:** Optical spectra of AT 2020vdq during initial and repeatng flares

3.3 Very-High-Energy Gamma-Ray Emission from Eta Carinae

Very-high-energy gamma-ray emission was observed in Eta Carinae when the star passed the position of the periastron in 2020 and the steep TeV spectrum, as well as the location of the emission region, should be mentioned in [19]. The general properties of high-energy processes on colliding-wind binaries as well as production mechanisms of gamma rays must be cited using [18- 22]. According to Figure 4, the H.E.S.S. significance map validates the observation of very-high-energy gamma-ray emission of Eta Carinae in its passage in periastron in 2020. Figure 5 shows the spectral energy distribution of the MeV to TeV energies that gives a global picture of the behavior of the source in high-energy emissions. Table 3 summarizes the main gamma-ray characteristics of the system such as Spectral index, cutoff energy flux, luminosity and significance of the detection.

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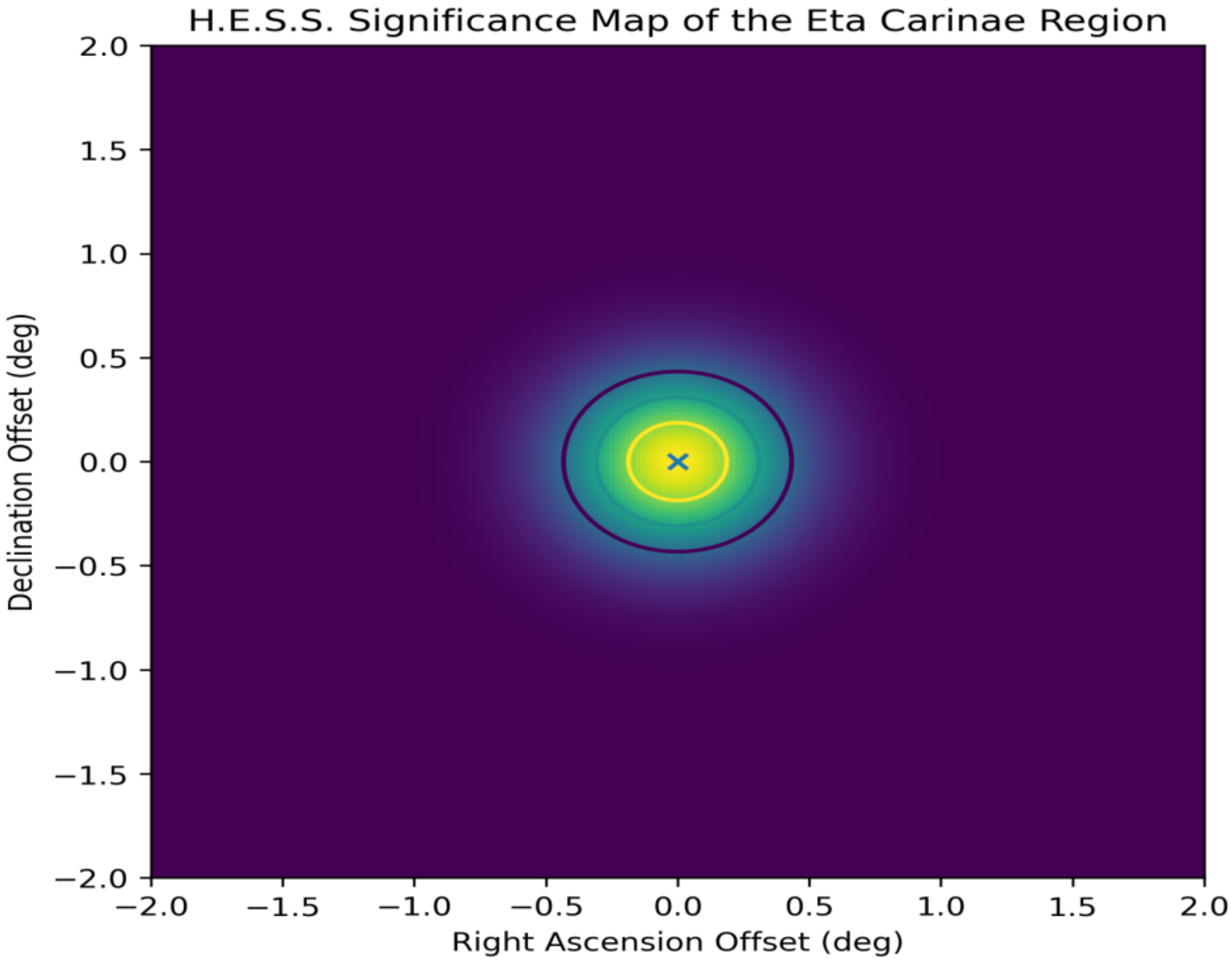

Figure 4. Figure 4: H.E.S.S. significance map showing the detection of veryhighenergy gammaray emission from Eta Carinae

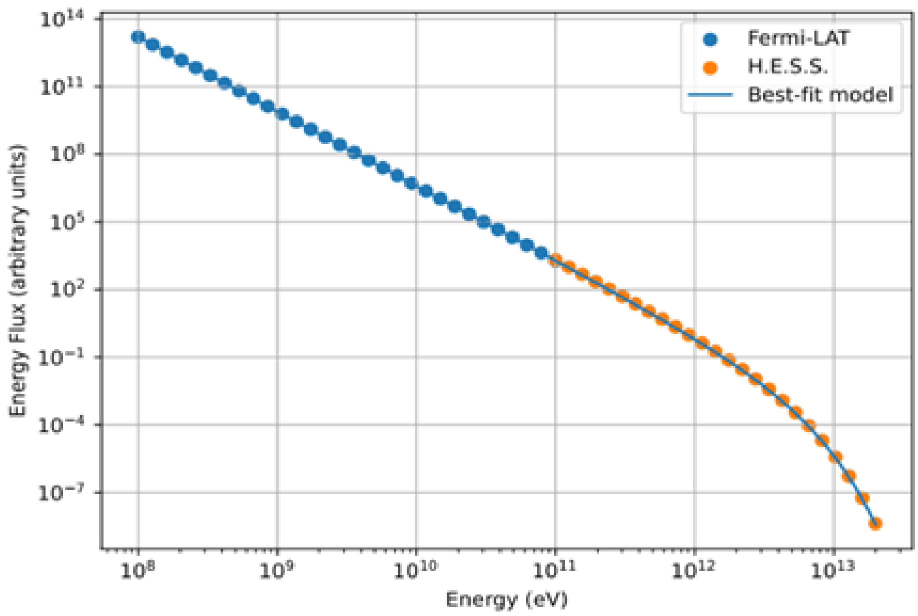

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Figure 5. Figure 5: Spectral energy distribution of Eta Carinae from MeV to TeV energies

Parameter	Value	Notes
Spectral index (Γ)	3.3 ± 0.2	Photon index in 0.2-20 TeV range
Cutoff energy (E_cut)	2.1 ± 0.8 TeV	Exponential cutoff energy
Flux (>0.2 TeV)	$(4.2 \pm 0.7) \times 10^{-12}$ cm^{-2} s^{-1}	Integrated above 0.2 TeV
Luminosity (>0.2 TeV)	$\sim 3 \times 10^{33}$ erg/s	At distance 2.3 kpc
Peak energy in νFν	~300 GeV	Energy where SED peaks
Detection significance	8.5 σ	Pre-trial significance

Table 3. **Table 3: Gamma-Ray Properties of Eta Carinae**
Source: Adapted from Aharonian et al.

3.4 Implications of Stellar Encounter Statistics

The generalization of the stellar encounter statistics, its planetary-system evolution consequences and the worth of subsequent Gaia releases ought to refer to [5-10]. These sources justify the implementation of Gaia products of data, astrometric that is reliable and the encounter-rate framework that has been established around solar-neighborhood stars. According to Table 1 and Figure 1 findings, the statistical data on stellar encounters have significant consequences to dynamical development of planetary systems and the perturbation of the Oort cloud and other distant, small reservoirs of bodies.

3.5 The Character of Repeating Partial Tidal Disruption Event

Repeating partial TDEs, stellar survival following the initial passage, the repetition of flares, and consequences of repeating events and nuclear binary populations should be referred to as a result in [14- 17]. These sources confirm the position that AT 2020vdq is most likely to be thought of as a repeated partial TDE and put it into the larger theoretical framework of tidal disruption physics. The evidence in Figure 2, Figure 3 and Table 2 is very plausible evidence of the identification of AT 2020vdq being a recurring partial tidal disruption event, with the repeat of the flare indicating that the star survived its initial close encounter.

3.6 Colliding-Wind Binaries Particle Acceleration

A discussion of shock acceleration, hadronic and leptonic explanations, and TeV emission of Eta Carinae, must refer to [18-22]. These works facilitate observation and physical support of the Eta Carinae which is an extreme colliding-wind accelerator. The findings presented in Figure 4 and Figure 5 in conjunction with the values of parameters presented in Table 3 suggest that Eta Carinae is an efficient particle accelerator that can emit gamma-ray very-high-energy emission in a colliding-wind environment.

3.7 Astrophysics across Time-Domains Synergies

Synergies between Gaia, ZTF, high-energy facilities, and future time-domain programs need to be mentioned with reference to [1–4,9,10,18,19,23–25].

4. Conclusion

This all-inclusive review of the recent developments in the field of time-domain astronomy has brought a number of significant results in the three areas of research, which are interconnected:

Solar neighborhood closer stellar interactions are more frequent than previously been identified, and 193 stellar pairs were found at a distance <0.05 pc and 193 Gliese 710 is anticipated to move within 0.051 pc of the Sun in 1.32 million years. The occurrence rate of encounters by Sun-like stars in 100 AU in 4.6 Gyr is about 2 %, with major consequences on the evolution of planetary systems, and the Oort cloud perturbation.

The AT 2020vdq is the first repeating partial tidal disruption event systematically detected, which contains two exceptionally similar optical/UV flares with a separation of 947 days between them. The highly diffuse spectral features (≈0.1c), weak X-ray emission and the lack of new radio emission are evidence of a partial TDE interpretation in which the star survived the initial encounter. The event rate of 10^{-6} to 10^{-5} yr^{-1} galaxy^{-1}indicates that such phenomena though extremely rare, will be identified in the future surveys in greater numbers.

With a steep spectrum (Γ = 3.3) reaching to some TeV, eta carinae has been established as a very-high-energy gamma-ray in multiple instances during a 2020 periastron, during which a strong source was observed. The emission region ranged between 10-20 AU of the system center and the protons should be accelerated to at least few TeV to interpret the observations using the hadronic interactions. The lack of significant variability in periastron indicates a long emission area instead of the point acceleration at the collision stagnation point between the wind and the stagnation.

Astrometric, optical, high-energy and future gravitational wave measurements can all be used as multi-messengers in the study of the dynamical astrophysical processes. The joint operation of Gaia, ZTF, H.E.S.S., and, later, LISA will allow us to study the dynamics of the stars, the accretion of the black holes (and their acceleration of the particles) as never before.

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