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The 2020 periastron of η Carinae at high-energies

Guillem Martí-Devesa[a,*] **and Olaf Reimer**[a]

[a] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria*

E-mail: guillem.marti-devesa@uibk.ac.at

Colliding-wind binaries are massive stellar systems featuring strong, interacting stellar winds. The resulting shocks may act as effective particle accelerators, making them good candidates for detection at high energies. However, only the massive binary η Carinae (with an orbital period of $\sim$ 5.5 years) has been firmly identified as a γ-ray source. A second system, γ^2 Velorum, was found positionally coincident with a γ-ray signal, with solid evidence of orbital variability along its orbit. Thus massive binaries are a promising, emerging class of high-energy emitters.
However, the origin of the non-thermal emission in η Carinae is still unclear, with both leptonic and hadronic scenarios currently under discussion. Moreover, γ-ray fluxes differ between the two periastrons previously observed by the Fermi Large Area Telescope (*Fermi* LAT). Here we report the analysis of the 2020 periastron, together with a complete analysis of more than two orbits, allowing the first orbit-to-orbit variability study of η Carinae at GeV energies.

We discuss these results in the context of previous hard X-ray (*NuSTAR*) and very-high-energy (H.E.S.S.) observational results. This new analysis provides highly valuable information for the radiative scenarios and the conditions of the wind-collision region.

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)
4-8 July 2022
Barcelona, Spain

*Speaker

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1. Introduction

Binaries are particularly suitable systems to study shocks under variable, periodical conditions – therefore providing conditions for particle acceleration different to those of supernova remnants or pulsar wind nebulae. An emerging class of these binaries is colliding-wind binaries (CWBs): two massive stars with powerful stellar winds [1]. Those strong winds will interact, forming a two-sided bow-shocked wind collision region (WCR) whose conditions change along the orbit [2]. Particle acceleration can occur there via diffusive shock acceleration (DSA), with cosmic rays eventually reaching up to TeV energies and leading to high-energy radiation [3–5].

However, only two CWBs have been detected in γ-rays: η Carinae [6] and γ^2 Velorum [7]. Despite notorious efforts, CWBs with significant synchrotron radio emission have been elusive to detection with γ-ray observatories [see e.g. 8, 9]. These upper limits reported in the past imply considerably low efficiencies for γ-ray emission (e.g. via the Inverse Compton (IC) process) in classical CWBs. Therefore, the best target source to understand the ideal conditions for efficient γ ray emission in CWBs is η Carinae itself.

The intensively studied η Carinae is a CWB with a primary Luminous Blue Variable (LBV) star with $M_{\eta Car_A} \sim 90\,\mathrm{M}_\odot$ at least with an O or Wolf Rayet (WR) star companion with $M_{\eta Car_B} \sim 30-50$ $\mathrm{M}_\odot$ [10]. Interestingly, η Carinae is surrounded by the Homunculus Nebula, which was the result of a large mass ejection (40 $\mathrm{M}_\odot$) in the mid 19th century, suggesting episodic variability. The central binary system has a period of $P \sim 2024$ days [periastron at $T_0 = 50799.3$ MJD, 11], in a highly eccentric orbit ($e \sim 0.9$).

Synchrotron emission from the source is undetected, likely due to the high opacity of the stellar winds, while it has a confirmed non-thermal X-ray [12] and GeV-TeV γ-ray [6, 13] components. Previous studies above 100 MeV with *Fermi* LAT have established that η Carinae displays two distinct components above (High Energy; HE) and below (Low Energy; LE) 10 GeV. Despite the consensus that the HE component has a hadronic origin, at LE the situation is unclear: both leptonic [14] and hadronic [15] scenarios are still under discussion. The work presented here aims to contribute to such discussion and shed light onto the nature of both components – for more details, see [9].

2. *Fermi*-LAT analysis

In this work we used data of the Large Area Telescope (LAT), the main instrument on board the *Fermi Gamma-ray Space Telescope* [16]. It performs an all-sky survey in the energy range between 30 MeV to more than 100 GeV. The main analysis presented here was performed using data taken from 2008 August 4 to 2020 May 29, while an updated light-curve is obtained using observations up to 2022 June 27. For this purpose, we employed *Fermitools-1.2.23* on P8R3 data. Fluxes are obtained performing a binned maximum likelihood fit with `fermipy 0.19`. We used the 4FGL DR2 catalogue (`gll_psc_v23`) for our source model [17], while the diffuse emission was assessed using 'gll_iem_v07.fits' and 'iso_P8R3_SOURCE_V2_v1.txt' for the Galactic and isotropic components, respectively. The significance of the detection of all sources in the region of interest was assessed with the test statistic $TS = -2\ \ln\left(L_{\max,0}/L_{\max,1}\right)$, where $L_{\max,0}$ is log-

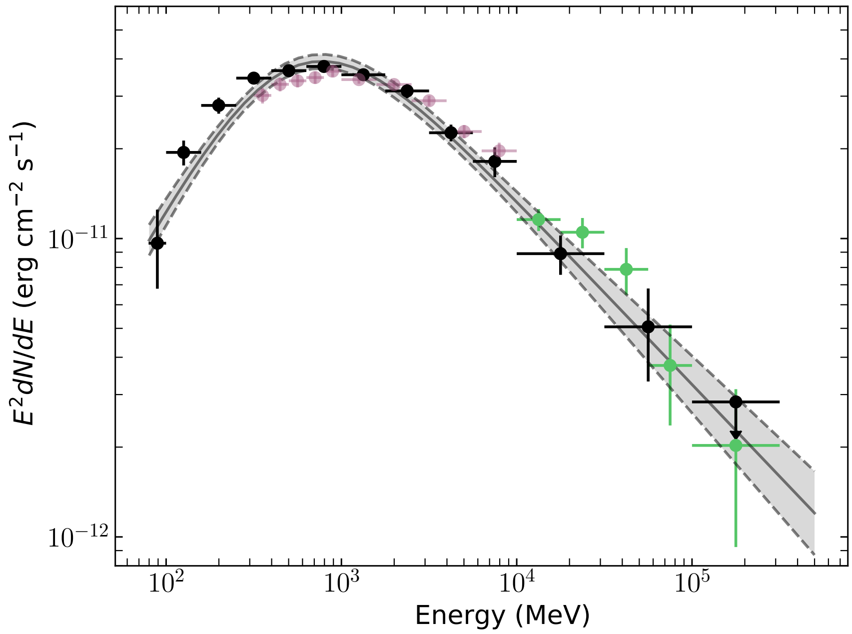

Figure 1: Spectral energy distribution for η Carinae using the LE (violet), HE (green) and PSF3 (black) datasets. The black line represents the smoothly-broken power law fit, with the 1σ uncertainty shown in grey. Upper limits are displayed at 95% confidence level.

likelihood value for the null hypothesis and $L_{\max,1}$ the log-likelihood for the complete model. The larger the value of the TS, the less likely is $L_{\max,0}$.

Since the point-spread function (PSF) of the LAT is highly energy dependent (from $\sim 5°$ at 100 MeV to 0.1° above 10 GeV) while η Carinae shows two clearly distinct components at different energies, we have optimized our analyses by using different cuts on our dataset (see details in Appendix A of [9]). We split our data below and above 10 GeV (but still using the `FRONT+BACK` event type, evtype = 3, for both). We will refer to these as the LE and HE analyses. Furthermore, since the large PSF at lower energies could result in source confusion in the Galactic plane and the contamination of our target, we produced a comparison dataset where we only selected the ensemble quartile with the highest quality in the reconstructed direction (hereafter PSF3, evtype=32[1]). Moreover, we iteratively search for new sources in our different datasets to account for possible excesses of γ-rays not included in the 4FGL-DR2 model. The results from these analyses are used to produce the different spectral energy distributions (Figure 1) and light curves (Figures 2 and **??**) discussed in the following.

3. Interpretation

The dedicated PSF3 analysis of the broad, orbitally-averaged γ-ray spectrum of η Carinae shows smoothly-broken power law shape (Figure 1), fitted with the function

[1]Event types are described in https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html

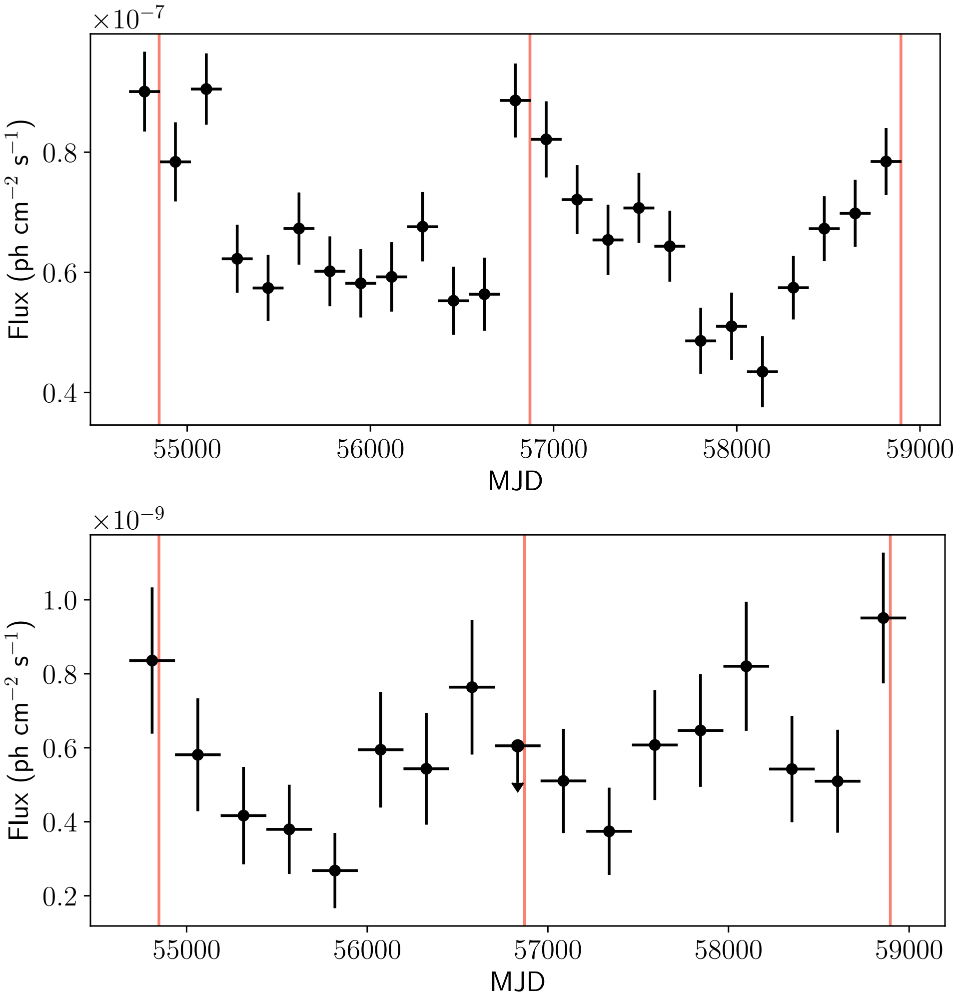

Figure 2: *Top:* Light curve of η Carinae using the LE dataset (300 MeV – 10 GeV), with 12 bins per orbit (168.67 days per bin). *Bottom:* Light curve of η Carinae using the HE dataset (10 GeV – 500 GeV), with 8 bins per orbit (253.0 days per bin). The vertical red lines represent the periastron passages of 2009, 2014, and 2020. At least 5σ are required per detection in each bin, otherwise a 2σ upper limit is displayed.

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\mathrm{GeV}}\right)^{-\Gamma_1} \left[1 + \left(\frac{E}{E_b}\right)^{\frac{\Gamma_2 - \Gamma_1}{\delta}}\right]^{-\delta} \tag{1}$$

where $\delta = 1.05 \pm 0.22$ is a curvature parameter, $\Gamma_1 = 2.64 \pm 0.09$ and $\Gamma_2 = 1.19 \pm 0.06$ (also consistent with [18]) are the spectral indexes above and below the pivot energy $E_b = 0.50 \pm 0.08$ GeV, and the best fit integrated energy flux is $(11.0 \pm 0.5) \times 10^{-5}$ erg cm^{-2} s^{-1}. Dedicated fits on the LE and HE datasets display compatible results. We note that the spectral index below E_b is slightly larger than expected for the π^0-bump expected in the hadronic scenario [15], but prevents a smooth IC component extrapolated from the non-thermal X-ray power law [12].

In terms of variability, the LE component has been peaking consistently during periastron for the last three passages (January 2009, August 2014, and February 2020; Figure 2), reaching similar

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flux levels and without displaying significant spectral variability. Furthermore, no flares are seen close to periastron with *Fermi* LAT [9]. This contrasts with the HE component reaching up to > 100 GeV, which has a more complex behaviour. The flux during the 2014 periastron was smaller [19], and we find that the light curve peaks more than 6 months before the periastron itself. Approaching the 2020 periastron, the light curve did not diminish as much the flux towards apastron and peaked again at periastron, thus displaying orbit-to-orbit variability.

These differences between the phenomenology observed in the LE and HE components support the idea that the populations of particles behind both components are indeed distinct, and suggest that the particles are accelerated at different locations. This could be both sides of the shock (see e.g. [15]) or other spatial distributions along the wings of the WCR.

4. Summary

We find evidence of orbit-to-orbit variability in the HE component of η Carinae using *Fermi*-LAT data, showing phenomenological evidence of the distinct behaviour of the underlying two populations of particles in the system. However, the spectral shape of the LE component does not show preference for a hadronic (i.e. no low-energy cut-off or π^0-bump) or leptonic origin (i.e. no smooth connection with the non-thermal X-rays) even with a dedicated analysis using PSF quality-cut selections.

Consequently, η Carinae is still a surprising system at high energies. Future monitoring of the source and dedicated modelling will allow a more precise characterisation of the particle populations that lead to the observed LE and HE components.

Acknowledgements

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515.

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