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High energy variability in η Carinae

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Abstract. One of the most outstanding stellar object in our Galaxy, η Carinae, a colliding wind binary (CWB) with the largest mass loss rate observed, presents a hard X-ray emission and is therefore a primary candidate to search for particle acceleration by probing its γ-ray emission. The gamma-ray spectral energy distribution of η Carinae features two distinct components. The first one can be understood by inverse Compton scattering of ultraviolet photons by electrons accelerated up to $\gamma \sim 10^4$. The second component is a hard gamma-ray tail detected above 20 GeV and displaying a variability along the orbit. We report on the latest Fermi/LAT results demonstrating that the hard gamma-ray component is indeed emitted by the binary system and that π^0-decay is the most likely source of that emission.

Key words. Cosmic-ray acceleration; colliding winds; η Carinae; Fermi/LAT; γ-rays; variability

1. Introduction

One century after the discovery of the cosmic-rays by V. Hess, their galactic origin is still unknown. Their sources must accelerate particles up to few PeV and account for a proton luminosity of few 10^{40}erg/s. Contrary to the primary charged galactic cosmic-rays which, deflected by magnetic fields, cannot be used to determine the nature of their sources, secondary produced γ-rays give insight on their site and mechanism of production. The *Fermi/LAT* telescope is currently the most sensitive observatory to conduct such research in the 0.1 to 100 GeV energy range.

Detections of cosmic-ray fluxes show high metallicities and feature abundances characteristic of OB associations with a mixing of ejecta from Solar (80%) and Wolf-Rayet (20%) type stars (Binns et al., 2008; Rauch et al., 2009), suggesting that their acceleration is related to stellar formation and massive stars. About 30 early-type stellar systems feature synchrotron radiation in the radio domain, a signature of electron acceleration (De Becker, 2007). Diffusive shock acceleration in stellar wind collisions (Benaglia & Romero, 2003), either in colliding wind binaries or OB associations, is the most likely acceleration process and a candidate for cosmic ray acceleration (Axford, 1981; Casse & Paul, 1982). Emission of γ-rays by hadrons accelerated in stellar wind collisions have however not yet been firmly identified. In this article, we report on the detection of a high energy γ-ray emission in *Fermi/LAT* data, in coincidence with the η Carinae CWB system, and on the confirmation of its association thanks to a variability at the highest energies.

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2. η Carinae binary system

η Carinae is one of the brightest and most massive stars of the Galaxy (Davidson & Humphreys, 1997; Hillier et al., 2001). Since few years now, it is widely believed that η Carinae is a binary system composed by a luminous blue variable (LBV) primary star, with the highest mass loss rate of the Galaxy, and an O or WR companion star. The system thus holds a powerful wind colliding region, which makes it a primary candidate to search for γ-ray detection. Some parameters of the two individual stars, as well as of the binary system are reported in Tab. 1.

Table 1. η Carinae binary system parameters

Parameter	Primary	Secondary
Star type	LBV	O or WR
$M(M_\odot)$	80-120	30
$\dot{M}(M_\odot yr^{-1})$	$10^{-4} - 10^{-3}$	10^{-5}
v_∞(km s^{-1})	500	3000
R ($R_\odot$)	100	20
Binary system		**Value**
Distance (kpc)		2.3
Eccentricity		0.9
Period (yr)		5.54
Semi-major axis (10^{12}m)		2.4
Periastron distance (10^{12}m)		0.25
Last periastron		2009/01/11

3. Study of the γ-ray emission with Fermi/LAT

The analysis of the 21 first months of *Fermi/LAT* data was previously reported in Farnier et al. (2011). A more accurate modeling of the surrounding γ-ray environment of η Carinae, including exponentially cut off power-law shape for pulsars, than the one used in the first year catalog of *Fermi/LAT* (1FGL, Abdo et al., 2010), was introduced. In this case, the γ-ray signal detected in *Fermi/LAT* data, from 0.2 to 100 GeV, was found to be fully consistent with the location of the binary system, in contrast with the 1FGL conclusion. The presence of the source is indisputable in *Fermi/LAT* data, with a significance of $\sim 53\sigma$. The spectral analysis, performed in a binned likelihood mode, clearly establishes a double component for η Carinae γ-ray emission. It can be modeled by the sum of an exponentially cut off power-law for the low energy component (LEC) (from 0.2 to 8 GeV) and a pure power-law for the high energy component (HEC) (from 10 to 100 GeV). The spectral parameters derived from the analysis are reported in Tab. 2.

Table 2. γ-ray spectral parameters of η Carinae CWB. (*All energies are in GeV.* $F_{0.2}^{100}$ *corresponds to the integrated flux from 0.2 to 100 GeV.*)

Parameter	LEC (0.2<E<8)	HEC (10<E<100)
Significance (σ)	47	8.5
Spectral index	1.69 ± 0.12	1.85 ± 0.25
Cut off energy	1.8 ± 0.5	-
$F_{0.2}^{100}$ (10^{-7}ph $cm^{-2}s^{-1}$)	1.52	0.41

4. Temporal variability

η Carinae displays a strong variability near periastron at different wavelengths: radio (Duncan & White, 2003), millimetre (mm; Abraham et al. 2005), optical (Damineli, 1996; Damineli et al., 2000), near-infrared (near-IR; Whitelock et al. 1994, 2004; Damineli 1996), and X-ray (Corcoran, 2005). In the hard X-ray domain however, the emission is consistent with a steady source (Leyder et al., 2010).

In γ-rays, a two days flaring episode was reported by *AGILE*[1] (Tavani et al., 2009) but was not confirmed by the analysis of *Fermi/LAT* data. Moreover, the γ-ray flux observed from the CWB region is consistent with a steady emission for the energy range between 0.2-8 GeV.

At higher energies however, there is a strong indication of variability of the γ-ray

[1] With an integrated flux reaching $F_{0.1} = (270 \pm 65) \times 10^{-8}$ph $cm^{-2}s^{-1}$ above 0.1 GeV.

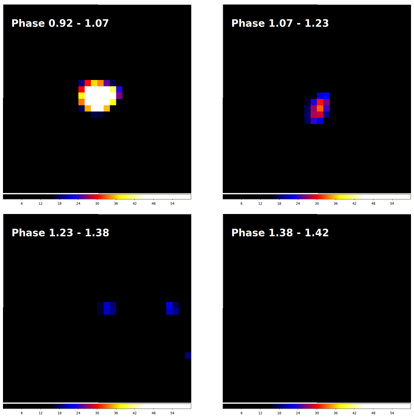

Fig. 1. From left to right and top to bottom: TS (significance^2) maps corresponding to the intervals defined in the left image. (*NB: the same color scale is used for all significance maps.*)

emissivity, correlated with the orbital separation of the two stars. Fig. 1 displays, for the four phase intervals described in Tab. 3, the Test Statistic (TS) maps, equivalent to the square of the significance, obtained for energies above 10 GeV. The complete data set corresponds to the 30 first months of *Fermi/LAT* observations. The duration of the first three intervals is identical (44 weeks) and was chosen so that the first one symmetrically encompasses the periastron passage. From these images, it is clear that the hard γ-ray tail is fading when the distance between the two stars increases.

The integrated fluxes, extrapolated over the entire energy range (0.2-100 GeV), obtained for the four different intervals are reported in Tab. 3, for both γ-ray components. For this time binning, the emissivity of the LEC is, within the statistical uncertainties, compatible with a steady emission. The HEC fluxes on the other hand vary significantly. As the flux of the HEC decreases with time and the latest interval is shorter, we were only able to derive a 95%C.L. upper-limit.

Table 3. γ-ray emissivity. (* *corresponds to a 95%C.L. upper-limit.*)

	$F_{0.2}^{100}(10^{-7}\mathrm{ph\,cm^{-2}s^{-1}})$	
Orbital phase	LEC	HEC
0.92-1.07	1.63 ± 0.10	0.31 ± 0.05
1.07-1.23	1.69 ± 0.09	0.19 ± 0.04
1.23-1.38	1.66 ± 0.08	0.14 ± 0.04
1.38-1.42	1.71 ± 0.16	0.1*

5. Modeling of the system

Colliding wind binaries, such as η Carinae, are likely to produce high energy electrons and protons through diffusive shock acceleration. In such a system, the main cooling mechanism is inverse Compton scattering on the intense UV radiation field of the stars for electrons and interaction with the dense wind material for the accelerated protons. In both cases, energetic γ-rays are produced. The power law distribution of the γ-rays resulting from the high energy electrons cooling is expected to have an exponential cut off at $\gamma_{max} \sim 1$ GeV, fairly independent of the orbital position in the dipole approximation (Farnier et al., 2011), for a magnetic field of ~50 G at the surface of the primary star. Proportional to the mechanical energy arriving in the shock fronts, the γ-ray intensity of such a component is not expected to vary strongly along the orbit. On the contrary, the intensity of the high energy γ-ray component arising from proton-proton interactions is linked to the matter density in the post-shock region, were the particles are trapped by the magnetic field. Far from the stars, the interaction time scale of the protons remains significant when compared to the diffusion time scale whereas close and at periastron passage, the wind becomes very dense and the protons interact before diffusing and produce γ-rays through decay of neutral pions. The γ-ray emissivity of this component is therefore expected to vary with the density, similarly to the thermal X-ray emission. The double spectral component observed in *Fermi/LAT* energy range and the difference of behaviour of these two components with time, suggest that the γ-ray emission observed in η Carinae arises from two different origins. The non-thermal spectral energy distribution (SED) observed in direction of the system, displayed on Fig. 2, can be reproduced by a model consisting of two cut-off power law distributions for the electrons and the interacting protons. The magnetic field and the electron energy distribution were adjusted to match the upper limit on the radio synchrotron emission, derived from the minimal thermal emission detected with *ATCA* (Duncan & White, 2003), and to match the inverse Compton continuum determined by *INTEGRAL* and *Fermi*. The slope and cutoff energy of the interacting proton energy distribution were fixed to 2.25 and 10^4, respectively, the same values as found for electrons. and its normalization was fitted to match the high-energy gamma-ray tail using π^0-decay (Kelner et al., 2006).

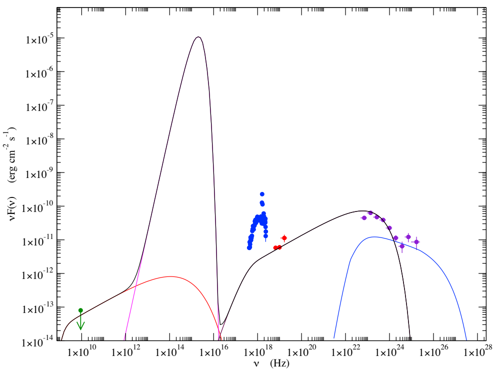

Fig. 2. η Carinae SED including *ATCA* upper limit (green), *BeppoSAX/MECS* (blue), *INTEGRAL/ISGRI* (red) and *Fermi/LAT* (purple) data. From low to high energies are shown the synchrotron, stellar emission, inverse Compton and π^0-decay spectral components.

6. Conclusion

The detection of the variation of the hard γ-ray tail of η Carinae, correlated with the orbital separation of the two stars, confirms our previous association of the γ-ray signal with the colliding wind zone. The variation of this component alone, coupled with γ-ray spectrum features also strengthen our hypothesis of two population particles accelerated within the colliding wind zone. In case *Fermi/LAT* continues to operate in 2014, a new rise of the high energy component is expected to be observed during a few weeks around periastron passage, allowing a deeper understanding of this complex object.

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