The Fermi LAT view of the colliding wind binaries.

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\section{INTRODUCTION}

Hot massive stars of early types have very strong stellar winds. In the specific case of Wolf-Rayet (WR) stars the mass loss rate could reach \(10^{-4} M_\odot \, \text{yr}^{-1}\) with terminal velocities > 1000 km s\(^{-1}\), wind kinetic power of these stars could exceed \(10^{37} \, \text{erg s}^{-1}\).

Massive binaries where both stars belong to early types and launch strong winds could be prominent sources of non-thermal radiation. Colliding supersonic winds produce strong shocks that could accelerate particles to ultrarelativistic energies, harnessing up to several percent of the total kinetic wind power (\textsuperscript{De Becker & Rauer} 2013). The acceleration takes place in a region where the energy density of the photon and magnetic fields is very high. This leads to a production of a strong non-thermal radiation via synchrotron and inverse Compton mechanisms (\textsuperscript{Eichler & Usoskin} 1994, \textsuperscript{Dougherty & Williams} 2000, \textsuperscript{Benaglia & Romero} 2003, \textsuperscript{Bednarek} 2005, \textsuperscript{Reimer et al.} 2005, \textsuperscript{Pittard & Dougherty} 2006, \textsuperscript{Reimer & Reimer} 2009, \textsuperscript{Reitberger et al.} 2014). Another contribution to the high energy (HE) part of the spectrum could arise due to the presence of accelerated hadrons that could interact with wind material, producing pions. Non-thermal synchrotron radiation from several of colliding wind binaries (CWBs) has already been discovered, in some cases interferometric observations reveal spatially extended region of the synchrotron emission (\textsuperscript{Dougherty et al.} 1996, \textsuperscript{Williams et al.} 1997).

No HE radiation from the CWBs has been observed besides truly exceptional \(\eta\) Car system (\textsuperscript{Tavani et al.} 2009; \textsuperscript{Bednarek & Pabich} 2011; \textsuperscript{Reitberger et al.} 2013) and previous searches in the HE domain produced only upper limits for other systems (\textsuperscript{Tatischeff et al.} 2004, \textsuperscript{Werner et al.} 2013). Seven most promising candidate systems were selected and analyzed using 2 years of the Fermi LAT data in (\textsuperscript{Werner et al.} 2013). In this paper we reanalyze this set using almost 7 years of data and the latest event reconstruction Pass 8. The rest of this paper is organized as follows: in section \texttt{B} the data and the method used are introduced, section \texttt{C} includes the results and their interpretation, the conclusions are presented in the section \texttt{D}.

\section{DATA AND METHOD}

A list of the most promising candidates for detection by the Fermi LAT was compiled in (\textsuperscript{Werner et al.} 2013), see Table\texttt{A} In this paper these candidates were reanalyzed using almost 7 years of new Pass 8 Fermi LAT data from 2008 August 4 to 2015 July 1. All events in the energy range 0.1-100 GeV within 15\(^{\circ}\) of the CWB positions belonging to the “SOURCE” class were selected and the recommended
Table 1. List of the candidate sources

| Name  | α, h m s | δ, d m s | l, ° | b, ° | Distance, kpc |
|-------|----------|----------|------|------|--------------|
| WR 11 | 08 09 32 | -47 20 12 | 262.80 | -07.69 | 0.34 |
| WR 70 | 15 29 45 | -58 34 51 | 322.34 | -1.81 | 1.9 |
| WR 125 | 19 28 16 | +19 33 21 | 54.44 | +1.06 | 3.1 |
| WR 137 | 20 14 32 | +36 39 40 | 74.33 | +1.10 | 2.4 |
| WR 140 | 20 20 28 | +43 51 16 | 80.93 | +4.18 | 1.7 |
| WR 146 | 20 35 47 | +41 22 45 | 80.56 | +0.44 | 1.2 |
| WR 147 | 20 36 44 | +40 21 08 | 79.85 | -0.31 | 0.65 |

Table 2. $TS$ of the candidate sources (simple power-law model).

| Name  | TS   |
|-------|------|
| WR 11 | 37.7 |
| WR 70 | 1.2  |
| WR 125 | 41.0 |
| WR 137 | 23.3 |
| WR 140 | 0.1  |
| WR 146 | 15.0 |
| WR 147 | 54.9 |

quality cut (zenith angle less than $90^\circ$) was applied. After that, binned likelihood analysis was performed using Fermi science tools version v10r0p5.

Implemented source models included the sources from the 3FGL catalogue [Fermi-LAT Collaboration 2015], the latest galactic interstellar emission model gll_iem_v06.fits, and the isotropic spectral template iso_P8R2_SOURCE_V6_v06.txt. Parameters of the sources inside the regions of interest (RoI) were allowed to change. Additional $\gamma$-ray sources from the 3FGL catalogue between $15^\circ$ and $25^\circ$ from the RoI centers were included with fixed parameters. The candidate sources were initially modelled with a simple power-law spectral model.

3 RESULTS AND DISCUSSION

The results are presented in the Table 2. It could be seen that three candidates: WR 11, WR 125, and WR 147 have significance exceeding threshold $TS = 25$ and the significance for the WR 37 system is hovering around this threshold ($TS = 23.7$). However, these sources reside close to the galactic plane where the $\gamma$-ray background is especially strong. In case of its imperfect modelling the likelihood analysis could possibly produce unrealistic results. In order to check the validity of detections, $TS$ maps of the immediate neighborhoods were calculated using the gttsmap tool. Unfortunately, in all cases except the WR 11, there were several hotspots in $< 0.5^\circ$ radius with the significance larger than that of the “sources” (see for illustration WR 147, Fig. 1). That is not the case for WR 11, where there is a clear maximum of $TS$ residing very close to the CWB (less than $0.05^\circ$) (see Fig. 2). Thus it can be concluded that the source spatially coinciding with this system is genuine.

Results of the fit with a simple power-law model for this source, from now on dubbed WR 11, gives a $TS = 37.7$ and a spectral index $\Gamma = 2.16 \pm 0.2$. However, the spectrum of the source is considerably curved (Fig. 3), and the fits with more elaborated spectral models fare a bit better: $TS = 41.5$ for a log-parabola model and $TS = 44.3$ for a broken power-law model. Nevertheless, they all fail to fully reproduce the spectral shape: there is a hard tail at the energies larger than $10$ GeV. Overall spectral shape is very close to the one of $\eta$ Car during its periastron passage [Reitberger et al. 2013].

The WR11 ($\gamma^2$ Vel, WC8+O7.5) at a distance $d = 340$ pc is the closest to us Wolf-Rayet binary. The components have small separation ($0.8 - 1.6$ au), and the orbital period is short, $P = 78.53$ days [North et al. 2007]. The orbital eccentricity is non-negligible, $e = 0.33$. The relevant physical parameters are presented in the Table 3. Total kinetic wind
power $L_w = 5.8 \times 10^{36} \text{ erg s}^{-1}$ is dominated by the contribution from the Wolf-Rayet component. A fraction of the total kinetic power that is dissipated in the wind collision zone is $L_{\text{cwz}}$, which could be estimated from a purely geometrical reasoning and it is equal to the wind momentum ratio $\eta$ (De Becker & Raucl [2013]):

$$\eta = \frac{M_\text{O} v_\infty^2}{M_{\text{WR}} v_{\text{WR}}^2} = 0.04,$$

$$(1)$$

The detected $\gamma$-ray source is rather weak: the flux in the HE range (0.1 -100 GeV) from the WR 11 is $(1.8 \pm 0.6) \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$, and the energy flux $E_{\gamma} v_{\gamma} = (2.7 \pm 0.5) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. At the adopted distance $d = 340$ pc this gives a luminosity $L = (3.7 \pm 0.7) \times 10^{31} \text{ erg s}^{-1}$ or $\sim 6 \times 10^{-6}$ fraction of total kinetic wind power $L_w = 5.8 \times 10^{36} \text{ erg s}^{-1}$ and $\sim 1.6 \times 10^{-4}$ fraction of the wind power that flows into the wind collision zone.

The mechanism of the emission is uncertain, though the latest simulations imply that the hadronic processes dominate when the binary separation is small, like in the case of WR 11 ($\sim 10^{13}$ cm) (Reitberger et al. 2014). On the other hand these simulations predict almost flat spectrum around $E = 100$ MeV for the hadronic mechanism and that could be in mild tension with the observations (see Fig. 3). Future observations, including ones in the extended energy range ($< 100$ MeV and $> 100$ GeV), will allow to clarify this issue.

If the emission is leptonic in origin then it is possible to estimate the magnetic field strength in the collision wind zone: the ratio of the magnetic field energy density $\epsilon_B$ to the seed photon field density $\epsilon_{ph}$ is equal to the ratio of the $\gamma$-ray luminosity to the non-thermal radio luminosity (Tatischeff et al. 2004):

$$\epsilon_B/\epsilon_{ph} = L_{\text{non-thermal}}/L_\gamma \equiv K = 2.2 \times 10^{-4},$$

where $L_{\text{O}} = 1.1 \times 10^{39} \text{ erg s}^{-1}$ is the O-type star luminosity, $r_\text{O} = \sqrt{\frac{L_{\text{O}}}{\epsilon_{ph}}}$ is the distance from the star to the collision zone which is a fraction of the total separation $r = 0.8$ au. Magnetic field of this magnitude could be expected when the collision zone is located at such a small distance from the O-type star with a surface field of $\sim 100$ G strength (Eichler & Usov 1993; Tatischeff et al. 2004). It is worth noting that even if the HE radiation is leptonic in origin it is produced by much more energetic population than the one producing the synchrotron emission: $\gamma \sim 10^4$ rather than several tens.

Finally, search for the periodicity corresponding to the binary period $P = 78.53$ days was performed. None was found. Low statistics with the total number of the photons from the source $< 10^3$ probably precluded any observations of the periodical modulations.

The WR 11 system due to its proximity and relatively high galactic latitude remains the only detected system, only upper limits on their flux could be calculated for the rest of the CWBs in the list. It could be meaningless in the cases of WR 125, WR 137, and WR 147 with their spurious high TSs, so the limits were set only for WR 70 and WR 140 (see Tab. 4). WR 146 is a borderline case: with its TS $\sim 15$ and complicated neighbourhood the calculated ULs could also be difficult to interpret.

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**Table 3.** Adopted physical parameters of the WR11 system.

| Parameter               | unit     | WC8     | O7.5 |
|-------------------------|----------|---------|------|
| Mass-loss rate, $\dot{M}$ | $10^{-7} M_\odot$ yr$^{-1}$ | 80  | 1.8 (1) |
| Terminal wind velocity, $v_\infty$ | km s$^{-1}$ | 1450  | 2500 (1) |
| Luminosity, $L$         | $10^6 L_\odot$ | 1.7  | 2.8 |

**References:** If not otherwise specified, all values are taken from North et al. [2007]; (1) De Marco & Schmutz [1999].

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**Table 4.** Upper limits on the flux (95% CL) in the 0.1-100 GeV energy range.

| Name | $F_{100}$, $10^{-9}$ ph cm$^{-2}$ s$^{-1}$ |
|------|------------------------------------------|
| WR 70 | 2.6 |
| WR 140 | 1.1 |

**Figure 3.** The spectrum of the WR11 system. It could be seen that the ‘best-fit’ curve fits rather poorly due to the presence of an additional hard tail at the energies $E > 10$ GeV. This spectrum strongly resembles the spectrum of $\eta$ Car during its periastron passage (Reitberger et al. 2013). The upper limits indicated with arrows correspond to 95% CL.
4 SUMMARY

A search for HE emission from seven potential candidates was conducted. HE emission from the nearest system WR 11 (γ² Vel) was detected at 6.1σ confidence level ($T_S = 37.7$) with a simple power-law model (spectral index $\Gamma = 2.16 \pm 0.2$). The spectrum of the source is curved with a broad maximum around $\sim 1$ GeV and shows a hardening at energies above 10 GeV. The photon flux in 0.1-100 GeV range is $(1.8 \pm 0.6) \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$, the energy flux is $(2.7 \pm 0.5) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. At the adopted distance $d = 340$ pc that corresponds to luminosity $L = (3.7 \pm 0.7) \times 10^{31}$ erg s$^{-1}$, that is $\sim 6 \times 10^{-6}$ fraction of total wind kinetic power and $\sim 1.6 \times 10^{-4}$ fraction of power injected into the wind interaction region of this system. Upper limits were set on the HE luminosity of WR 70 and WR 140 systems. The detection of WR 11 by the Fermi LAT endorses colliding wind binaries as a new separate class of high energy sources.

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