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High energy neutrinos from binary systems of two massive stars

W. Bednarek

Department of Experimental Physics, University of Łódź, ul. Pomorska 149/153, 90-236 Łódź, Poland

Presenter: W. Bednarek (bednar@fizwe4.fic.uni.lodz.pl), pol-bednarek-W-abs3-og25-poster

Massive Wolf-Rayet stars in a compact binary system are characterized by very strong winds which collide creating a shock wave. If the wind nuclei accelerated at the shock can reach large enough energies, then they suffer disintegration in collisions with soft thermal radiation from the massive stars. Protons, dissociated from these nuclei, collide with the matter of the wind and a fraction of neutrons move in the direction of the massive stars and produce neutrinos in collisions with the matter of the stellar atmospheres. We calculate the γ-ray fluxes from cascades initiated by primary γ-rays and leptons produced by protons and the neutrino event rates for the example compact massive binary WR 20a. It is predicted that a few up to several muon neutrino events should be observed inside the 1 km^2 neutrino detector of the IceCube type in 1 yr, provided that the γ-ray flux at the GeV is on the level observed from the EGRET sources in the direction of WR 20a.

1. Introduction

Between 227 Wolf-Rayet (WR) stars [1], 39$\%$ form binary systems (including probable binaries), and about 15$\%$ of them form compact massive binaries with orbital periods < 10 days. One extreme example of a binary system, WR 20a, contains two WR stars with masses $\sim 70 M_\odot$, surface temperature $T = 10^5 T_5$ K $\approx 4\times 10^4$ K, and radii $\sim 20 R_\odot$ (where $R_\odot = 7\times 10^{10}$ cm is the radius of the Sun), on an orbit with the semimajor axis $a/2 \sim 26 R_\odot$ [2, 3]. Let's consider such a very massive binary composed of two massive WR type stars characterized by very strong winds, with mass loss rate $\dot{M} = 10^{-5}\dot{M}_{-5}$ M$_\odot$ yr$^{-1}\sim (0.8-8)\times 10^{-5} M_\odot$ yr^{-1}, wind velocities $v_{\rm w} = 3\times 10^3 v_3$ km s$^{-1}\sim (1-5)\times 10^3$ km s^{-1}, and surface magnetic fields up to $B = 10^3 B_3$ G $\sim 10^4$ Gs [4]. Such winds collide creating a double shock structure separated by the contact discontinuity which distance from the stars depends on their wind parameters. It is likely that the binary system WR 20a is responsible for one of the EGRET sources observed in this region, i.e. 2EG J1021-5835 and GeV J1025-5809 or 2EG J1049-5847 and GeV J1047-5840 [5, 7]. They have flat spectra with the index close to 2 [6] and fluxes at the level of $\sim 10^{-7}$ cm^{-2} s^{-1} above 1 GeV [7].

2. Acceleration of nuclei

Nuclei present in the stellar winds can be accelerated at such shock structure either due to the magnetic field reconnection (model I) or the diffusive shock acceleration mechanism (model II). The acceleration occurs in the fast reconnection mode provided that following condition is fulfilled, $\beta = 2m_{\rm e}/Am_{\rm p} \approx 10^{-3}/A < 8\pi\rho k_{\rm B}T_{\rm sh}/B_{\rm sh}^2 \approx 3.3\times 10^{-3}\dot{M}_{-5}/v_3 B_3^2 r^2$, assuming typical temperature of the plasma at the shock $T_{\rm sh} = 10^7$ K (e.g. [8]), density of the wind $\rho = \dot{M}/4\pi R^2 v_{\rm w} \approx 5.4\times 10^{10}\dot{M}_{-5}/v_3 r^2$ cm^{-3}, and distance from the star $R = rR_{\rm WR}$. Then, the reconnection occurs with the speed close to the Alfven velocity $v_{\rm A} = B_{\rm sh}/\sqrt{4\pi A m_{\rm p}\rho} \approx 7\times 10^8 B_3 v_3^{1/2}/r(\dot{M}_{-5}A)^{1/2}$ cm s^{-1}. Nuclei can reach maximum Lorentz factors of the order of $\gamma_{\rm max} \approx ZeB_{sh}L_{rec}v_A/Am_{\rm p}c \approx 2.6\times 10^6 B_3^2 L_{12} v_3^{1/2}/r^3\dot{M}_{-5}^{1/2}$, where $A/Z = 2$, $m_{\rm p}\approx m_{\rm n}$ is the nucleon mass, $L_{\rm rec} = 10^{12}L_{12}$ cm is the length of the reconnection region, c is the velocity of light, and e is the proton charge. In order to estimate the magnetic field strength after the shock, we apply the model for external magnetic field structure in the case of strong outflowing gas [9]. According to this model the magnetic field is a dipole type below the Alfven radius, $R_{\rm A}$, becomes radial above $R_{\rm A}$, and at the largest distances, determined by the rotation velocity of the star, i.e. at above $\sim 10R_{\rm WR}$, the toroidal component dominates. We are interested mainly in the region in which the dipole and radial components dominate. The Alfven radius for the example parameters considered in this paper, $v_3 = 1$, $B_3 = 1$, and $\dot{M}_{-5} = 3$, is at $R_{\rm A} \approx 1.3R_{\rm WR}$. Therefore, we estimate the magnetic field at the shock in the region of radial magnetic field from $B_{\rm sh} \approx B(R_{\rm WR}/R_{\rm A})^3(R_{\rm A}/R_{\rm sh})^2 \approx 750B_3/r^2$ Gs, where $R_{\rm sh}$ is the distance from the center of the star to the acceleration region at the shock, i.e. $R_{\rm sh} = rR_{\rm WR}$.

Nuclei can be also accelerated diffusively by the I order Fermi shock acceleration mechanism. In this case they obtain a power law spectrum with the index determined by the parameters of the plasma flow. Nuclei are accelerated to $\gamma_{\rm A}$ during the time estimated by $\tau_{\rm acc} \approx (R_{\rm L}/c)(c/v_{\rm w})^2$, where $R_{\rm L} = Am_{\rm p}\gamma_{\rm A}/(eZB_{\rm sh}) \approx 8\times 10^9\gamma_6 r^2/B_3$ cm is the Larmor radius required to complete acceleration to $\gamma_{\rm A} = 10^6\gamma_6$. The escape time of nuclei is estimated as $\tau_{\rm c} \approx 3R_{\rm sh}/v_{\rm w} = 10^4 rR_{12}/v_3$ s, where the radius of the WR star, $R_{\rm WR} = 10^{12}R_{12}$ cm. The maximum energies of nuclei are determined by the condition $\tau_{\rm c} = \tau_{\rm acc}$. Therefore, we expect the cut-off in the power law spectrum of nuclei at energies corresponding to $\gamma_{\rm max} = 3eZB_{\rm sh}R_{\rm sh}v_{\rm w}/cAm_{\rm p} \approx 4\times 10^6 R_{12}B_3v_3/r$. The heavy nuclei accelerated to Lorentz factors described by above formulae lose nucleons due to the photo-disintegration process in collisions with the thermal photons from the massive stars if the energies of photons in the reference frame of the nuclei, $E_\gamma = 3k_{\rm B}T\gamma_A(1+\cos\theta) = 25T_5\gamma_6(1+\cos\theta)$ MeV, are above ~ 2 MeV, where $k_{\rm B}$ is the Boltzmann constant, θ is the angle between photon and nucleus. The above condition gives the lower limit on the Lorentz factor of accelerated nuclei, $\gamma_{\rm min} \approx 8\times 10^4/T_5(1+\cos\theta)$. Let us estimate the efficiency of the photo-disintegration process of nuclei in the considered here scenario. The average density of thermal photons from both stars (with similar temperatures), at the location of the shock, can be approximated by $n_{\rm WR} \approx 4\sigma_{\rm SB}T^3/3ck_{\rm B}(R_{\rm WR}/R_{\rm sh})^2 \approx 2\times 10^{16}T_5^3/r^2$ ph. cm^{-3}. where $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant. Then, the mean free path for dissociation of a single nucleon from a nucleus is $\lambda_{A\gamma} = (n_{\rm WR}\sigma_{A\gamma})^{-1} \approx 3.5\times 10^{10}r^2/(AT_5^3)$ cm, where for the photo-disintegration cross section the peak in the giant resonance is applied, $\sigma_{\rm A\gamma} = 1.45\times 10^{-27}A$ cm^2 [10]. For the considered here binary system WR 20a, for which $R_{\rm sh} = a/2$ and so $r = 1.3$, the characteristic photo-disintegration time scale of nuclei with the mass number A, $\tau_{\rm A\gamma} = \lambda_{\rm A\gamma}/c \approx 30/A$ s, is much smaller than the acceleration time and the convection escape time of nuclei from the acceleration region at the shock (estimated above). Nuclei with the initial mass numbers between 4 (helium) and 16 (oxygen) should suffer complete fragmentation. Significant fraction of neutrons from disintegration of nuclei move toward the surface of the massive stars since the probability of dissociation of a single nucleon is the highest for the head on collisions of nuclei with thermal photons. These neutrons propagate along the straight lines and interact with the matter of stellar atmospheres. On the other hand, protons from disintegration of nuclei are convected outside the binary system along the surface of the shock structure in a relatively dense stellar winds.

The relativistic nuclei accelerated at the shock take a fraction, ξ, of the kinetic power of the two stellar winds, $P_{\rm A} = \xi\dot{M}v_{\rm w}^2 \approx 6\times 10^{37}\xi\dot{M}_{-5}v_3^2$ erg s^{-1}. The parameter ξ is determined by the efficiency of acceleration of nuclei, which is usually assumed to be of the order of 10% of the available shock energy, and by the solid angle $\Delta\Omega$ subtended by the *active* part of the shock. The *active* part of the shock is determined by the power of the stellar wind which falls onto the shock region in which nuclei can be accelerated above $\gamma_{\rm min}$.

Provided that the complete disintegration of nuclei occurs, the flux of nucleons dissolved from nuclei in the case of monoenergetic acceleration in the reconnection regions (model I) is $N_{\rm n} = P_{\rm A}/m_{\rm p}\gamma_{\rm A} \approx 4\times 10^{34}\xi\dot{M}_{-5}v_3^2/\gamma_6$ N s^{-1}. In the case of nuclei with the power law spectrum (model II) the differential spectrum of nucleons is, $dN_{\rm n}/d\gamma_{\rm n}dt = K\gamma_{\rm n}^{-\delta}$, in the range $\gamma_2 = \gamma_{\rm max}$ and applying $\gamma_1 = 10^2$, δ is the spectral index, and the normalization constant is equal to $K = AP_{\rm A}/(Am_{\rm p}\ln(\gamma_2/\gamma_1))$ for $\delta = 2$ and $K = AP_{\rm A}(\delta-2)/(Am_{\rm p}(\gamma_1^{2-\delta)} - \gamma_2^{2-\delta}))$ for $\delta > 2$. The spectral index of particles accelerated in the shock depends on the Alfvenic Mach number of the plasma flowing through the shock. It is defined as $M = v_{\rm w}/v_{\rm A}$ (e.g. [11]), where $v_{\rm A}$ is the Alfven velocity defined above. For the parameters of WR 20a, we estimate the

Alfvenic Mach number as a function of distance from the star on $M \approx 2.3r$, where the density of the wind and the magnetic field strength at the shock location are calculated above. We conclude that the outer part of the shock, $r \gg 1$, fulfills the condition of the strong shock, $M \gg 1$, although in the inner part, the Alfven shock is probably created. Therefore, we consider the power law spectrum of accelerated nuclei with indexes between 2 (characteristic for a strong shock) and 2.3 (for a weaker shock).

3. Gamma-rays and neutrinos

Since the winds of the massive stars are very dense, protons from disintegration of nuclei have chance to interact with the matter of the winds. The characteristic time scale for collision of relativistic protons with the matter of the wind is $\tau_{\rm pp} \approx c\sigma_{\rm pp}\rho \approx 10^4 v_3 r^2/\dot{M}_{-5}$ s, where ρ is the density of the stellar wind estimated above. For the applied above parameters of the wind, $v_3 = 1$ and $\dot{M}_{-5} = 3$, $\tau_{\rm pp}$ is shorter than escape time scale of protons along the shock, $\tau_{\rm c}$, at distances less than $r \approx 3$, i.e. in the main part of the *active* shock.

We calculate the γ-ray spectra from decay of pions which are produced by protons in collisions with the matter of the wind by integrating the injection spectra of protons (monoenergetic or the power law) over the *active* part of the shock and applying the scale break model for hadronic interactions developed by Wdowczyk & Wolfendale [12] which is suitable for the considered energies of relativistic protons. Only single interaction of proton with the matter has been included. These high energy γ-rays originate relatively close to the surface of the massive stars, $r \sim 1.3 - 3$, and therefore they can suffer absorption in the thermal radiation coming from the stellar surfaces. In order to determine the final γ-ray spectra which escape from the binary system, we apply the Monte Carlo code developed by Bednarek [13] which follow the IC $e^{\pm}$ pair cascade in the anisotropic radiation field of the massive star. It is assumed that primary γ-rays are produced by protons isotropically at the part of the shock which is at the distance $r = 1.3 - 3$ from the massive stars. These spectra have been normalized to the γ-ray fluxes observed from the EGRET sources, 2EG J1021-5835 and GeV J1025-5809 and 2EG J1049-5847 and GeV J1047-5840 [5, 7], which are equal to $\sim 10^{-7}$ ph cm^{-2} s^{-1} above 1 GeV. Based on these normalizations we derive the required acceleration efficiencies of nuclei at the shock equal to $\xi \approx 5.5\%$ (for the monoenergetic injection) and $\xi \approx 6.5\%$ and 3% for the power law injection with the spectral indexes 2 and 2.3, respectively.

The γ-ray fluxes produced by protons at the shock region in collisions with the matter of the winds via decay of pions are also accompanied by the high energy neutrinos. We calculate the spectra of muon neutrinos. They are above the atmospheric neutrino background (ANB) and above the sensitivity limit of the 1 km^2 neutrino detector of the IceCube type. In the case of monoenergetic injection of nuclei they are also above the present sensitivity of the AMANDA II neutrino detector. However due to the localization of the source on the Southern hemisphere this model cannot be at present excluded. The number of events produced by the muon neutrinos in the 1 km^2 neutrino detector of the IceCube type can be estimated from $N_\mu = \frac{S}{4\pi D^2}\int P_{\nu\rightarrow\mu}(E_\nu) dN_\nu/dE_\nu dt dE_\nu$, where $S = 1$ km^2 is the surface of the detector, $P_{\nu\rightarrow\mu}(E_\nu)$ is the energy dependent detection probability of muon neutrino [14].

Applying estimated above values for ξ, the distance to WR 20a equal to 5 kpc [15], and typical wind parameters of the WR stars, $\dot{M}_{-5} = 3$, $v_3 = 1$, we predict in the case of the model I $N_\mu \sim 56$ (48) muon neutrino events inside 1 km^2 detector in 1 yr for the case of neutrinos arriving from the directions close to the horizon (no absorption inside the earth) and from the nadir (partial absorption inside the Earth). The neutrino event rate predicted in the case of model II is $N_\mu \sim 22$ (20) and ~ 5.5 (5) muon neutrino events in 1 km^2 in 1 yr provided that nuclei are accelerated with the power law spectrum and spectral indexes equal to 2 and 2.3, respectively. The high event rates predicted for the monoenergetic spectrum of protons (model I) should be easily tested by the future 0.1 km^2 Antares telescope.

A fraction of neutrons, η, dissolved from nuclei can fall onto the surfaces of the massive stars. η can be calculated from the formula $\eta(\gamma_{\rm n}) = 2F(\cos\theta_{\rm D}, 1)/F(\cos\theta_{\rm D}, 1) + F(\cos\theta_{\rm D}, -\cos\theta_{\rm D})$ where $F(x,y) = \int_{\rm x}^{\rm y} \sigma_{\rm A\gamma} n_{\rm WR}(\varepsilon, \cos\theta)(1+\cos\theta) d\varepsilon d\cos\theta$, $\theta_{\rm D}$ is the angle intercepted by the massive star observed from the distance r. We have found that η weekly depends on the Lorentz factor of nuclei, except for the Lorentz factors for which efficient fragmentation start to occur ($\eta \sim 0.52, 0.33, 0.22$ for $R_{\rm sh} = 1.3R_{\rm WR}$, $2R_{\rm WR}$, and $3R_{\rm WR}$, respectively). Neutrons which fall onto the surface of the massive stars produce charged pions in collisions with the matter of the stellar atmospheres. Pions from the first interaction are produced at the characteristic densities $\rho \sim 3 \times 10^{14}$ cm^{-3} (estimated from the p-p cross section and applying the characteristic dimension of the stellar atmosphere $\sim 0.1R_{\rm WR}$). In such conditions pions with the Lorentz factors $\gamma_{\rm n} = 10^6$ decay before interacting with the matter since they pass only ~ 0.3 g cm^{-2}.

We have calculated the spectra of neutrinos produced by neutrons in the atmospheres of the massive stars applying the scale break model for hadronic interactions, taking into account the fraction of neutrons falling onto the stars η, and the multiple interactions of neutrons with the matter of the stellar atmospheres. The neutrino event rates, for the acceleration models considered above, are estimated on $N_\mu \sim 40$ (36) events for the monoenergetic spectrum of neutrons, and 14 (13) and 3.5 (3.2) events for the power law spectra of neutrons with the index 2 and 2.3, respectively. These event rates are lower than that produced by protons since only a fraction of neutrons interact. From another site this effect is partially compensated by the multiple interactions of neutrons with the matter of the stellar atmospheres. Note moreover that neutrinos produced by neutrons are emitted within the limited range of angles, α, around the plane of the binary system defined by, $\tan\alpha \sim \sqrt{R_{\rm max}^2 - R_{\rm o}^2}/(R_{\rm o} - R_{\rm WR})$ (see values defined above), i.e within $\alpha \sim 79^{\rm o}$ for $R_{\rm max} = 2R_{\rm WR}$. This angle is much larger than the eclipsing angle of the WR 20a binary system $\sim 40^{\rm o}$. Therefore neutrinos produced by neutrons can be also potentially observed from non-eclipsing binaries. However, in the case of WR 20a, which inclination angle is $\sim 74.5^{\rm o}$ [3], the observer is located inside the eclipsing cone.

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