# Gamma-rays and neutrinos from the pulsar wind nebulae

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## Abstract

We construct the time dependent radiation model for the pulsar wind nebulae (PWNe), assuming that leptons are accelerated in resonant scattering with heavy nuclei, which are injected into the nebula by the pulsar. We calculate the equilibrium spectra of these particles inside the nebula taking into account their radiation and adiabatic energy losses. The spectra of $\gamma$-rays are compared with the observations of the PWNe emitting TeV $\gamma$-rays and predictions are made for the expected $\gamma$-ray fluxes from other PWNe. Expected neutrino fluxes and neutrino event rates in a 1 km$^2$ neutrino detector from these nebulae are also calculated. It is found that only the Crab Nebula, and possibly the Vela nebula and MSH15-52, can produce detectable neutrino event rates.

## 1. Introduction

Young pulsars create relativistic winds which interact with the supernova envelopes creating the PWNe. These nebulae are filled with energetic particles which emit photons from radio up to TeV $\gamma$-rays (e.g. the nebulae around the Crab and Vela pulsars, PSR 1706-44, and PSR 1509-58). It is widely argued that this radiation is produced by leptons in the synchrotron and the inverse Compton (IC) processes. Here we investigate the radiation model for the PWNe in which not only leptons but also heavy nuclei can play important role.

## 2. The model

The energetic pulsar, formated during the supernova explosion, can have strong influence on the evolution of expanding supernova envelope due to the supply of energy in the form of electromagnetic waves and relativistic particles. We construct the simple model for the evolution of such pulsar-supernova envelope system in order to consider the processes which turn to the production of high energy radiation (see for details of the model in [3]). This model allows to determine the main parameters of the expanding nebula as a function of time (the outer radius of the nebula, the radius of the pulsar wind shock, the magnetic field inside the nebula, density of matter).

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pp. 2481–2484

Recently, Arons and collaborators (see e.g. [1]) have proposed that heavy nuclei, extracted from the neutron star, are accelerated in the pulsar wind zone (for the application to the Crab pulsar see [5]). These nuclei can reach energies as high as, $E_{\rm Fe} \approx 0.3\chi Ze\Phi_{\rm open}$, where $Ze$ is the charge of iron nuclei, $c$ is the velocity of light, $\Phi_{\rm open} = \sqrt{L_{\rm em}/c}$ is the total electric potential drop across the open magnetosphere. These nuclei can take a significant part, $\chi$, of the total energy lost by the pulsar. The iron nuclei generate the Alfven waves in the down-stream region of the wind shock, which energy is resonantly transfered to positrons present in the wind, as shown by particle-in-cell simulations [7]. As a result, the positrons obtain close to the power law spectrum with the spectral index $\delta_1$ between $E_1 = \gamma_{\rm Fe} m_{\rm e} c^2$ and $E_2 \approx \gamma_{\rm Fe} A m_{\rm i} c^2/Z$ [5], where $m_{\rm e}$ and $m_{\rm i}$ are the electron and ion masses, respectively. The spectrum is normalized to the conversion efficiency of energy from the iron nuclei to the positrons, $\xi$.

We calculate the equilibrium spectra of nuclei inside the expanding nebula taking into account: (1) their collisions with the matter of the nebula; (2) energy losses on adiabatic expansion; (3) their diffusion out of the nebula. The equilibrium spectra of positrons are mainly determined by their radiation energy loses on bremsstrahlung, synchrotron, and the IC processes and adiabatic expansion of the nebula. The knowledge on the equilibrium spectra of leptons and hadrons inside the nebula at an arbitrary time allow us to calculate the radiation produced in different processes. In further calculations we assume that the initial expansion velocity of of the bulk matter of the supernova is $V_{0,\rm Neb} = 2 \times 10^3$ km s$^{-1}$, and its mass $M_{0,\rm Neb} = 4M_\odot$ (as derived for the Crab Nebula [4]).

## 3. Gamma-rays from the PWNe

At first, we confront the results of the calculations with the objects for which the high energy $\gamma$-ray emission has been observed, i.e. the Crab and Vela Nebulae and the nebula around PSR 1706-44. The high energy spectra from all these nebulae are fitted by the $\gamma$-rays produced by leptons in IC process and by hadrons in the interactions with matter (see Fig. 1a,b,c), assuming that the pulsars in these nebulae have been born with the initial periods of 15 ms. The surface magnetic fields of these pulsars are estimated from their observed periods and period derivatives. The efficiency of lepton acceleration by heavy nuclei is obtained from the comparison of the observed low energy spectrum with the calculated synchrotron spectrum. The other parameters of the model are chosen in order to get consistency with the present parameters of these nebulae and their pulsars available in the literature, e.g. expansion velocity, matter content, magnetic field inside the nebula (for details see [3]).

Based on the knowledge obtained from these fittings, we predict the $\gamma$-ray fluxes from other PWNe, which are promissing TeV $\gamma$-ray sources: MSH15-52 (PSR 1509-58), 3C58 (PSR J0205+6449), and CTB80) (PSR 1951+32). The

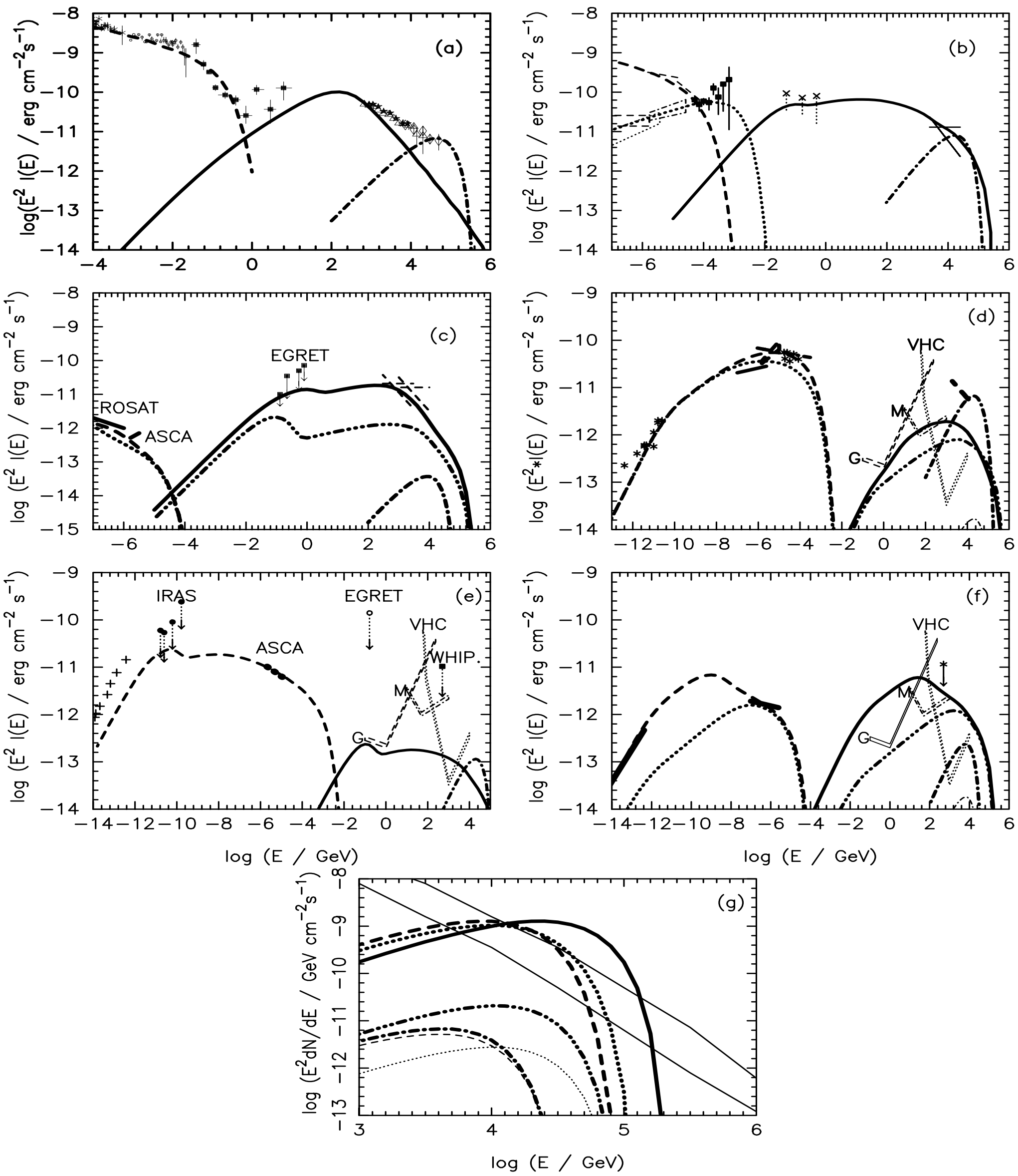

**Fig. 1.** The spectra of the Crab Nebula (a), the Vela Nebula (b), G343.1-2.3 (PSR 1706-44), (c), MSH15-552 (PSR 1509-58) (d), 3C58 (PSR J0205+6449) (e), and CTB 80 (PSR 1951+32) (f) are compared with the synchrotron spectra (dashed curves), and the $\gamma$-ray spectra from IC (full), and from decay of pions (dot-dashed). The synchrotron and IC spectra calculated for other soft targets inside the nebula are shown by the dotted and dot-dot-dot-dashed curves (see for details [3]). The sensitivities of new $\gamma$-ray telescopes are shown by the double curves: GLAST (G), MAGIC (M), Veritas, HESS, and CANGAROOO III (VHC). (g) Neutrino spectra from the Crab Nebula (full curve), the Vela Nebula (dashed), G343.1-2.3 (dot-dashed), 3C58 (dot-dot-dot-dashed), MSH15-52 (thin dotted), and CTB 80 (thin dashed) for the medium with density 0.3 cm$^{-3}$, and MSH15-52 for the medium with density 300 cm$^{-3}$ (dotted). The atmospheric neutrino background is marked by the thin full lines.

spectra of these nebulae are constrained by the X-ray observations which allows us to fix the acceleration efficiency of leptons by heavy nuclei. The fittings to the broad band spectra of these nebulae, from radio up to X-rays and the predicted fluxes of $\gamma$-rays are shown in Fig. 1d,e,f. The TeV emission from MSH15-52 (reported in [8]) can be explained in this model if the high density medium is present close to this PWNa. The $\gamma$-ray flux from 3C58, $\sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, is below the sensitivity limits of the new generation $\gamma$-ray telescopes (GLAST - 1 yr sensitivity, MAGIC, VERITAS - $5\sigma$, 50 hours, $> 10$ events). On the other hand, the $\gamma$-ray flux predicted from CTB 80, a few $10^{-12}$ erg cm$^{-2}$ s$^{-1}$, should be observed by all these telescopes.

## 4. Neutrinos from the PWNe

Since a significant part of $\gamma$-rays from some of these PWNe is produced in hadronic processes, the detectable neutrino fluxes are also expected. Fig. 1g show the spectra of neutrinos from these PWNe calculated for the set of parameters used above (see for details [3]). Only in the case of the Crab Nebula this neutrino spectrum is clearly above the atmospheric neutrino background (ANB) within 1$^{\mathrm{o}}$ of the source. The expected neutrino event rate in a 1 km$^2$ neutrino detector is estimated on $\sim 1.3$ per yr (applying the muon neutrino detection probabilities calculated in [6]). The neutrino spectra from the Vela nebula and MSH15-52, provided that it is close to the high density medium with density 300 cm$^{-3}$, are comparable to the ANB. The expected neutrino event rate from these sources in a 1 km$^2$ detector is also close to 1 per yr. However, since these neutrinos have lower energies, their possible detection is less optimistic than in the case of the Crab Nebula. We do not predict detectable neutrino event rates from other considered PWNe.

## 5. References

1. Arons J. 1998, Mem.Soc.Ast.Ital. 69, 989
2. Bednarek W. 2003, A&A submitted
3. Bednarek W., Bartosik M. 2003, A&A in press (astro-ph/0304049)
4. Davidson K., Fesen R.A. 1985, ARAA 23, 119
5. Gallant Y.A., Arons J. 1994, ApJ 435, 230
6. Gaisser T.K., Grillo A.F. 1987, Phys.Rev. D 39, 1481
7. Hoshino M. et al. 1992, ApJ 390, 454
8. Sako T. et al. 2000, ApJ 537, 422