TeV gamma-rays from the Northern sky pulsar wind nebulae

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Abstract. We estimate the TeV $\gamma$-ray fluxes expected from the population of young pulsars in terms of the self-consistent time dependent hadronic-leptonic model for the high energy processes inside the pulsar wind nebulae (PWNe). This radiation model bases on the hypothesis of Arons and collaborators who postulate that leptons are accelerated inside the nebulae as a result of resonant scattering on heavy nuclei, which in turn are accelerated in the pulsar wind region or the pulsar inner magnetosphere. Our aim is to find out which PWNe on the northern hemisphere are the best candidates for detection at energies above 60 GeV and 200 GeV by the next generation of low threshold Cherenkov telescopes.

1. Introduction

Young pulsars lose their rotational energy in the form of relativistic winds in which particles can be accelerated to very high energies. These winds interact with the surrounding supernova, creating the pulsar wind nebulae observed from radio to X-ray energies. A few tens of such objects have been observed in TeV $\gamma$-rays (e.g. Srinivasan et al. 1997, Chadwick et al. 1999, Aharonian et al. 2001, Aharonian et al. 2002), but only four of them were detected in the past, i.e. the Crab Nebula (Weekes et al. 1989), the nebulae around the Vela pulsar (Yoshikoshi et al. 1997), PSR 1706-44 (Kifune et al. 1995, Chadwick et al. 1998), and PSR 1509-58 (Sako et al. 2000, Aharonian et al. 2005a). However, recent observation of the PSR 1706-44 by the HESS group (Aharonian et al. 2005b) does not confirm the detection of the TeV emission from this nebula. The estimated upper limit, on the level of a few percent of the Crab Nebula flux, is significantly below the flux reported previously. The observation of the $\sim$ 80 TeV $\gamma$-rays from the Crab Nebula (Horns et al. 2003, Aharonian et al. 2004) indicate the existence of particles with energies up to $\sim 10^{15}$ eV at least inside this PWNa. Therefore, PWNe seem to be one of the best candidates for the sites of cosmic ray acceleration (e.g. Bednarek & Protheroe 2002, Giller & Lipski 2002, Bednarek & Bartosik 2004). However,
details of the acceleration process inside the PWNe are mainly unknown. There is a hope that observation and modelling of the multiwavelength emission from such objects can provide an important information allowing to solve this problem. It is widely argued that the radiation in the PWNe is produced by leptons in the synchrotron and the inverse Compton processes (e.g. de Jager & Harding 1992, Atoyan & Aharonian 1996, Hillas et al. 1998, Aharonian et al. 2004). Possible contribution of hadrons at the highest energies has been also considered (e.g. Atoyan & Aharonian 1996, Bednarek & Protheroe 1997, Bednarek & Bartosik 2003).

In this paper we consider the time dependent hadronic-leptonic model for the production of radiation inside the PWNe basing on the acceleration model of hadrons and leptons inside the nebula, proposed by Arons and collaborators (see e.g. Galant & Arons 1994, Arons 1998). In this model we calculate self-consistently the multiwavelength spectrum produced by leptons and the high energy radiation generated by hadrons also responsible for the acceleration of leptons. The model is applied to the PWNe which have not been observed in the TeV $\gamma$-rays yet. We predict the expected fluxes from the population of relatively young PWNe on the northern hemisphere (with ages lower than $\sim 10^5$ yrs). The earlier modelling of the high energy processes in the PWNe, which base on pure leptonic models (e.g. Aharonian et al. 1997), give a list of pulsars on the whole sky which are the best candidates for TeV $\gamma$-ray observations due to their highest ratio of the spin down luminosity divided by the square of distance. Here we consider young pulsars which can be observed at the Northern hemisphere. Some of them are well known (and already considered by Aharonian et al. 1997) but others have been recently reported in the Parces Multibeam pulsar survey catalogs (Morris et al. 2002, Kramer et al. 2003) and original papers (e.g. Torii et al. 1997, Halpern et al. 2001, Camilo et al. 2002, Roberts et al. 2002, McLaughlin et al. 2002).

2. Acceleration of particles inside the PWN

Pulsars with short periods and strong surface magnetic fields, created during the supernova explosions, are surrounded by the non-thermal compact nebulae (the so called pulsar wind nebulae - PWNe) observed from radio up to X-rays. These non-thermal nebulae are immersed in the expanding supernova remnants which shells are also observed in some cases from the radio up to X-rays. The PWNe contain relativistic leptons responsible for non-thermal emission from radio up to TeV $\gamma$-rays. The larger scale supernova remnants contain most of the mass of the expanding supernova. If hadrons are accelerated in the inner part of the PWNa, they can diffuse to the supernova remnant and interact with the mass of the supernova producing additional $\gamma$-rays.

Here we consider a scenario in which rotating magnetospheres of neutron stars can accelerate not only leptons but also heavy nuclei, extracted from positively charged polar cap regions. In fact, different aspects of the high energy phenomena around pulsars, such as the change in the drift direction of the radio subpulses (Gil et al. 2003), the existence of morphological features inside the Crab Nebula, and the appearance of extremely
energetic leptons inside it (Gallant & Arons 1994), can be naturally explained by the presence of heavy nuclei. Arons and collaborators (e.g. see Arons 1998) postulate that the Lorentz factors of iron nuclei, accelerated somewhere in the inner magnetosphere and/or the Crab pulsar wind zone should be,

$$\gamma_{Fe} \approx \eta Z e \Phi_{open}/m_{Fe}c^2 \approx 8 \times 10^9 \eta B_{12} P_{ms}^{-2},$$  

(1)

where \(m_{Fe}\) and \(Ze\) are the mass and charge of the iron nuclei, \(c\) is the velocity of light, and \(\Phi_{open} = \sqrt{L_{rot}/c}\) is the total electric potential drop across the open magnetosphere, \(L_{rot}(t) = B_s^2 R_s^4 \Omega^4 / 6 c^3 \approx 3 \times 10^{43} B_{12}^2 P_{ms}^{-4}\) erg s\(^{-1}\), is the pulsar energy loss rate for the emission of the magnetic dipole radiation, \(\Omega = 2\pi/P\), and the period of the pulsar, \(P = 10^{-3} P_{ms}\) s, changes with time according to \(P_{ms}(t) = P_{0 ms}^2 + 2 \times 10^{-9} B_{12}^2 t\), where \(P_{0 ms}\) is the initial period of the pulsar, \(B = 10^{12} B_{12}\) G is the surface magnetic field of the pulsar, and \(\eta\) is the acceleration factor which determines the Lorentz factor of nuclei in respect to the maximum allowed by the pulsar electrodynamics. Following Arons and collaborators, we assume that: (1) \(\eta\) is not very far from unity, adopting the value \(\eta = 0.5\); (2) iron nuclei take most of the spin down power of the pulsar, \(L_{Fe} = \chi L_{rot}\), where \(\chi = 0.95\). Unfortunately, this values are not predicted at present by any model for the acceleration of ions in the pulsar wind and can only be constrained by the high energy observations of the PWNe. The iron nuclei can be extracted from the neutron star surface and accelerated during the pulsar radio phase when the efficient leptonic cascades heat the polar cup region. For more details of the acceleration and propagation of nuclei inside the pulsar magnetosphere we refer to Bednarek & Bartosik (2003).

The iron nuclei generate Alfven waves in the down-stream region of the pulsar wind shock, which energy is resonantly transferred to leptons present in the wind (Hoshino et al. 1992). As a result, leptons obtain a spectrum close to a power law with the spectral index \(\delta_1 \approx 2\) between \(E_1 = \gamma_{Fe} m_e c^2\) and \(E_2 \approx \gamma_{Fe} A m_p c^2 / Z\) (see Gallant & Arons 1994), where \(m_e\) and \(m_p\) are the electron and proton mass, respectively. The spectrum is normalized to the conversion efficiency of energy from the iron nuclei to the positrons, \(\xi\). Note that the radiation from leptons depends on the product of the energy conversion from the pulsar wind to nuclei, \(\chi\), and the acceleration efficiency of positrons by these ions, \(\xi\). Therefore, decreasing the first coefficient and increasing the second one obtains the same level of radiation from positrons but a lower level of gamma-ray flux from hadronic interactions of ions with the matter inside the nebula. Since the dependence of \(\chi \cdot \xi\) on time is not predicted by any theoretical model we keep this value constant during the evolution of the nebula. Relativistic particles accelerated by the mechanism discussed above are captured inside the pulsar wind nebula losing energy on different processes.

3. Production of gamma-rays

Nuclei and leptons are injected into the pulsar wind nebula which parameters are changing significantly during its evolution. To take into account this effect we have
constructed a simple model for the time evolution of the nebula under the influence of the pulsar following the previous works (e.g. Ostriker & Gunn 1971, Pacini & Salvati 1973). The basic parameters of the expanding nebula as a function of time such as: its outer radius and the radius of the pulsar wind shock, the velocity of expansion, the mass of the nebula, and the strength of the magnetic field inside the nebula, are determined by applying the step time numerical method. Numerical approach allows us to take into account the effects of energy conversion from nuclei to the expanding nebula due to their adiabatic energy losses. The model for the expansion of the nebula has to be relatively simple at this stage of calculations in order to take into account properly the time dependent radiation processes inside the nebula at different times after supernova explosion. Having in hand such a model, we can calculate the equilibrium spectra of leptons and nuclei at an arbitrary age of the nebula taking into account different energy loss processes. Leptons injected into the medium of the expanding supernova remnant suffer energy losses mainly on radiation processes, bremsstrahlung, synchrotron, and the inverse Compton, and due to the expansion of the nebula. The rate of their energy losses can be described by

$$-\frac{dE}{dt} = (\alpha_1 + \alpha_2)E + (\beta_1 + \beta_2)E^2 \text{ GeV s}^{-1},$$

where $\alpha_1 \approx 7.8 \times 10^{-16}N \text{ s}^{-1}$ describes the bremsstrahlung losses, where $N$ is the number density of the medium in cm$^{-3}$; $\alpha_2 = \frac{V_{\text{Neb}}(t)}{R_{\text{Neb}}(t)}$ describes the adiabatic losses due to the expansion of the nebula (Longair 1981) where $V_{\text{Neb}}(t)$ and $R_{\text{Neb}}(t)$ are the velocity of expansion and the radius of the nebula at the time $t$; $\beta_1 \approx 2.55 \times 10^{-6}B^2 \text{ GeV}^{-1} \text{ s}^{-1}$ the synchrotron energy losses, where $B$ is the magnetic field in G; and $\beta_2 \approx 1.05 \times 10^{-7}U_{\text{rad}} \text{ GeV}^{-1} \text{ s}^{-1}$, $U_{\text{rad}}$ is the energy density of different types of radiation inside the nebula in GeV cm$^{-3}$, the ICS losses in the Thomson regime in different types of soft radiation inside the nebula, i.e. the synchrotron radiation produced by leptons in the magnetic field of the nebula, the microwave background radiation (MBR), and the infrared photons emitted by dust inside the nebula. The energy losses of leptons on the ICS in the Klein-Nishina regime can be safely neglected in respect to the synchrotron energy losses. The density of synchrotron radiation depends on the spectrum of leptons which is in turn determined by their energy losses at the earlier phase of expansion of the nebula.

The coefficients, $\alpha_1, \alpha_2, \beta_1$, and $\beta_2$, depend on time in a complicated way due to the changing conditions in the expanding nebula (magnetic field, density of matter and radiation). Therefore, Eq. 2 can not be integrated analytically for the arbitrary time after supernova explosion. In order to determine the energies of leptons, $E$, inside the nebula at a specific time $t_{\text{obs}}$ which have been injected with energies $E_0$ at an earlier time $t$ we use the numerical approach. The step time method is applied in which the conditions in the nebula at the relatively short period, $t$ to $(t+\Delta t)$, are assumed constant. Applying the parameters of the nebula determined for the time $t$ the energies of leptons after the next time step $\Delta t$ are determined by solving equation Eq. 2 analytically. Next, the conditions inside the nebula are changed to values which are obtained from the
expansion model of the nebula at the time \( t + \Delta t \). The equilibrium spectrum of leptons at the time, \( t_{\text{obs}} \), is then obtained by summing over the spectra injected at specific time and over all time steps up to the present observed time \( t_{\text{obs}} \),

\[
\frac{dN(t_{\text{obs}})}{dE} = \sum_{t'=0}^{t_{\text{obs}}} J(t') \frac{dN}{dE_0} dt,
\]

where \( dN/dE_0 dt \) is the injection spectrum of leptons at the time \( t, t' = t_{\text{obs}} - t \), and the jacobian \( J(t') = E_0/E(t') \) which describes the change of energy of lepton during the period \( \Delta t \) is calculated analytically by solving Eq. 2. The example spectra of leptons inside the nebula at the specific time after explosion of supernova and more details of these calculations are given in Bednarek & Bartosik (2003).

The knowledge on the equilibrium spectra of relativistic leptons as a function of time after supernova explosion allows us to calculate the photon spectra produced inside the nebula by these particles in different radiation processes. Leptons produce photons mainly in synchrotron, bremsstrahlung, and ICS processes. For the \( \gamma \)-ray energies, which are of interest in this paper (above 60 GeV and 200 GeV), the contribution of \( \gamma \)-rays from interaction of hadrons with the matter is negligible (see Bednarek & Bartosik 2003). Therefore hadronic \( \gamma \)-rays are not considered in this paper (they are calculated in Bednarek & Bartosik (2003) where the \( \gamma \)-ray spectra in the whole energy region are presented).

The conditions in the expanding nebula, i.e. the magnetic and radiation fields and the density of matter, change significantly with time in a different manner. Thus, the relative importance of specific radiation processes has to change as well. At the early stage of expansion of the nebula, the synchrotron energy losses of leptons dominate over the ICS and the bremsstrahlung energy losses. Therefore, most of the energy of leptons is radiated in the low energy range. When the nebula becomes older, the energy density of the synchrotron radiation inside the nebula decreases but the energy density of the MBR remains constant. Relative importance of the ICS losses increases with respect to the synchrotron energy losses. In fact, for the PWNe with the age \( \geq 10^4 \) yrs, the \( \gamma \)-rays are produced mainly by leptons scattering the MBR (not synchrotron photons). Therefore, the possible displacement of the pulsar from the place of its origin has no effect on the expected level of the \( \gamma \)-ray flux but only on the dimensions of the \( \gamma \)-ray source.

In order to determine precise contributions of these three radiation processes, we calculate the photon spectra produced by leptons with the equilibrium spectrum calculated for different times after supernova explosion. The multiwavelength spectra emitted by the pulsar wind nebulae with specific parameters at different times after supernova explosion are shown in Figs. 4 and 5 in Bednarek & Bartosik (2003).
4. Gamma-ray fluxes from specific PWNe

The model described above has been confronted with the known PWNe which have been reported as sources of high energy $\gamma$-rays. In order to calculate the multiwavelength spectra from specific PWNe, we have to fix some initial parameters of their pulsars and the expanding supernova envelopes. We apply the masses and the initial expansion velocities for most of the considered nebulae as observed in the case of the Crab Nebula, i.e. equal to $4.6 \pm 1.8$ M$_{\odot}$ (Fesen et al. 1997) and 2000 km s$^{-1}$ (Davidson & Fesen 1985). We are aware that the Crab Nebula is not typical in many ways but our aim is to give an order of estimate of the TeV fluxes for the future observations with the next generation Cherenkov telescopes. In the case of nebulae for which the ages can be estimated directly from their present expansion, we apply more reliable expansion velocities derived from their observed sizes. Based on the age of the nebula and the present period of the pulsar, we estimate the initial period of the pulsar. If the age of the nebula is unknown, we apply the value of 15 ms. Note, that the final result of our model is not very sensitive on the initial period of the pulsar in the case of older nebulae. Having fixed these important parameters we can calculate the synchrotron spectra produced by leptons inside specific nebulae as a function of their ages.

From comparison of the calculated synchrotron spectra with the observed emission from the Crab Nebula, we estimate the acceleration efficiency of leptons by the nuclei and calculate the expected $\gamma$-ray spectra. It is found that the considered model can explain the main features of the $\gamma$-ray emission from this nebula (see Fig. 1). Better description of the Crab Nebula multiwavelength spectrum specifically at its lower synchrotron and IC part (in respect to the fitting presented in Fig. 6 in Bednarek & Bartosik 2003) is due to the more careful selection of the initial parameters of the pulsar (its initial period has been changed to 10 ms). The knowledge obtained from modelling of the known $\gamma$-ray nebulae allows us to predict the level of $\gamma$-ray emission from other nebulae observed in the radio and X-rays. These low energy observations permit us to constrain the efficiencies of lepton acceleration inside these nebulae.

In this paper we consider the population of young pulsars which can be observed by Cherenkov telescopes at zenith angles smaller than 50°. This cut-off (e.g. corresponding to the declination of the source greater than about $-22$° for the location of the MAGIC telescope) has been introduced in order to allow the observations of PWNe with low energy threshold. Our purpose is to predict which of them should be the most promising $\gamma$-ray sources for the future observations by the next generation of Cherenkov telescopes such as the MAGIC or VERITAS. Based on different pulsar catalogs (Taylor et al. 1993, Morris et al. 2002, Kramer et al. 2003) and the paper by McLaughlin et al. (2002, in the case of PSR J1740+1000) we have selected the classical radio pulsars with short periods (below $\sim 200$ ms), strong surface magnetic field ($> 10^{11}$ G), and characteristic ages not significantly larger than $10^5$ yrs. The parameters of some considered pulsars and their PWNe are shown in Table 1. Note, that in the case of some pulsars the surrounding nebulae have not been discovered yet. The older pulsars shown in Table 1...
has significantly moved from their birth place inside the supernova remnant. However this displacement does not have a big effect on the estimated here TeV γ-ray fluxes which are mainly produced in older PWNe by leptons scattering the MBR.

Based on the steady soft X-ray fluxes reported from the nebulae surrounding these pulsars ($L_{X,PWN}$) and our modelling of synchrotron emission, we estimate the efficiency of lepton acceleration by nuclei, $\xi$, in the case of every source and calculate the expected γ-ray fluxes at energies above 60 GeV and 200 GeV (see Table 2). The parameter $\chi = 0.95$ of energy conversion from the pulsar wind to the relativistic nuclei is kept constant for all PWNe. This procedure is not possible in the case of pulsars with unknown X-ray nebulae (B1913+10, J1837-0604, J1274+1000, B1809-19, J1800-21, and J1828-1101). Therefore, for these four pulsars (lack of references in Table 1), we apply the acceleration efficiencies of leptons, $\xi = 0.15$, derived for the pulsars with the closest parameters (i.e B1951+32 for B1913+10 and B1823-13 for five others).

The γ-ray fluxes from specific PWNe are calculated assuming their production only in the ICS process by leptons. We neglect possible contribution to the γ-ray spectrum from decay of pions produced in collisions of nuclei accelerated by the pulsar with the matter of the supernova envelope. This emission is mainly limited to energies above $\sim 10$ TeV and does not have a strong effect in the energy range just above $\sim 200$ GeV.
### Table 1. Pulsars and their PWNe

| Pulsar | $P$ (ms) | $B$ ($10^{12}$ G) | Age (kyr) | $E$ ($10^{36}$ ergs/s) | Distance (kpc) | PWN/SNR | $L_{X,\text{PWN}}$ (range) | Ref. | \(\xi\) |
|--------|---------|-------------------|-----------|-------------------------|----------------|---------|----------------------|------|------|
| Crab   | 33.4    | 3.8               | 1.05      | 440                     | 2.0            | Crab Nebula | 3.7 (0.1-4.5 keV)  | 1    | 0.5  |
| J2021+3651 | 104.  | 3.2               | 17        | 3.4                     | 1.5            | G75.2+0.1   | 0.05 (0.3-10 keV)  | 2    | 0.25 |
| J2229+6114 | 51.6   | 2.0               | 10.5      | 22.0                    | 3.0            | G106.6+2.9  | 0.1 (0.5-10 keV)  | 3    | 0.15 |
| B1951+32 | 39.5    | 0.49              | 107       | 3.7                     | 2.5            | CTB 80      | 0.27 (0.2-10 keV)  | 4    | 0.15 |
| J0205+6449 | 65.   | 3.6               | 5.0       | 27.0                    | 3.2            | 3C58        | 1.0 (0.5-10 keV)  | 5    | 0.1  |
| B1823-13 | 101.5   | 2.8               | 21        | 2.9                     | 4.1            | G18.0-0.7   | 0.3 (0.5-10 keV)  | 6    | 0.15 |
| B1809-19 | 82.7    | 1.8               | 51        | 1.8                     | 3.7            | —           | —                   | —    | —    |
| B1913+10 | 35.9    | 0.35              | 170       | 2.9                     | 4.5            | —           | —                   | —    | —    |
| J1837-0604 | 96.3   | 2.1               | 34        | 6.0                     | 6.2            | —           | —                   | —    | —    |
| J1740+1000 | 154.  | 1.8               | 114       | 0.23                    | 1.4            | —           | —                   | —    | —    |
| J1800-21 | 133.6   | 4.3               | 16        | 2.2                     | 3.9            | —           | —                   | —    | —    |
| J1930+1852 | 136.  | 10.1              | 2.9       | 11.8                    | 5.0            | G54.1+0.3   | 2.1 (2-10 keV)    | 7    | 0.15 |
| J1811-1926 | 65.   | 2.0               | 2         | 6.4                     | 5.0            | G11.2-0.3   | 1.2 (1-10 keV)    | 8    | 0.15 |
| J1828-1101 | 72.1   | 1.05              | 77        | 1.6                     | 7.2            | —           | —                   | —    | —    |
| Vela    | 88.9    | 3.1               | 11.3      | 6.7                     | 0.3            | Vela SNR    | 0.1 (0.1-4 keV)  | 9    | 0.07 |
| B1706-44 | 102.0   | 3.1               | 17.4      | 3.4                     | 1.8            | G 343.1-2.3 | 0.03 (0.5-8 keV) | 10   | 0.03 |

1 Harnden & Seward (1984); 2 Hessel et al. (2004); 3 Halpern et al. (2001); 4 Li et al. (2005); 5 Torii et al. (2002); 6 Gaensler et al. (2003); 7 Camilo et al. (2002); 8 Roberts et al. (2003); 9 Becker et al. (1982); 10 Romani et al. (2005);
We consider two models for the soft radiation field inside the nebulae. In the first one, leptons scatter only synchrotron radiation (SYN) (produced by the same population of leptons inside the nebula) and the MBR. In the second model, we add additional infrared (IR) component created by the warm gas inside the nebula. Such infrared emission with the characteristic temperature of $\sim 100$ K is clearly observed in the spectrum of the Crab Nebula. The infrared target with temperature of $\sim 20$ K is required in the case of the nebula around PSR 1706-44 in order to explain the level of high energy $\gamma$-ray emission from this object reported by the early observations (Kifune et al. 1995, Chadwick et al. 1998). However, note that more recent observations of PSR 1706-44 by the HESS telescope (Khelifi et al. 2004) does not confirm the level of emission reported earlier, what may suggest that additional infrared target inside PSR 1706-44 is not needed. The nebulae much older than the nebula around PSR 1706-44 ($> 2 \times 10^4$ yrs) certainly do not require additional infrared target since their infrared emission by warm dust should be relatively weak.

In Table 2 we report the PWNe which can be observed by the MAGIC and VERITAS telescopes with the highest $\gamma$-ray fluxes at energies above 60 and 200 GeV. These threshold values have been selected since they are the approximate lower limits of the past Cherenkov telescopes (e.g. Whipple) and the next generation of telescopes (e.g. MAGIC, VERITAS). The sources at the top have the highest chance of being detected according to our model. For comparison we also show the results of calculations for

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**Table 2. Predicted $\gamma$-ray fluxes above 60 (200) GeV from the PWNe**

| pulsar    | flux ($10^{-11} \text{phot. cm}^{-2} \text{s}^{-1}$) (SYN+MBR) | flux ($10^{-11} \text{phot. cm}^{-2} \text{s}^{-1}$) (SYN+MBR+IR) |
|-----------|----------------------------------------------------------|---------------------------------------------------------------|
| Crab      | --                                                       | 140. (25)                                                     |
| J2021+3651| 6 (2)                                                    | 30 (7)                                                        |
| J2229+6114| 4 (1)                                                    | 16 (4)                                                        |
| B1951+32 | 9 (1)                                                    | --                                                            |
| J0205+6449| 0.7 (0.2)                                               | 3 (0.8)                                                       |
| B1823-13 | 0.7 (0.2)                                               | 3 (0.6)                                                       |
| B1809-19 | 1 (0.2)                                                  | --                                                            |
| B1913+10 | 0.9 (0.1)                                               | --                                                            |
| J1837-0604| 0.5 (0.1)                                               | 2 (0.3)                                                       |
| J1740+1000| 0.7 (0.08)                                              | --                                                            |
| J1800-21 | 0.3 (0.07)                                              | 1 (0.2)                                                       |
| J1930+1852| 0.04 (0.01)                                             | 0.2 (0.04)                                                   |
| J1811-1926| 0.04 (0.02)                                             | 0.1 (0.04)                                                   |
| J1828-1101| 0.07 (0.01)                                             | --                                                            |
| Vela      | 37 (9)                                                   | 18 (4)                                                        |
| B1706-44 | 0.5 (0.1)                                               | --                                                            |
the two southern nebulae, around the Vela pulsar and PSR 1706-44, reported by early observations in TeV $\gamma$-rays. The presence of an additional infrared targets inside the young nebulae can change significantly, by a factor of $\sim (3 - 4)$, the predicted $\gamma$-ray flux at energies below a few TeV (compare the second and third columns in the Table 2). The $\gamma$-ray fluxes above 60 GeV are typically a factor of $\sim (4 - 5)$ higher than those above 200 GeV.

Only two PWNe on the northern hemisphere (accept Crab) can produce $\gamma$-ray fluxes on the level above $\sim 0.1$ of the Crab Nebula flux (assuming the presence of thermal infrared background as applied for the nebula around PSR 1706-44). The second brightest source on the list, the pulsar J2021+3651 inside the nebula G75.2+0.1, should shine on the level of $\sim (7-29)$% of the Crab Nebula above 200 GeV, i.e it should be inside the sensitivity limits of the HEGRA and the Whipple telescopes. However, note that in the case of this source we have applied the distance of 1.5 kpc, estimated from the dimensions of the nebula (Hessels et al. 2004), but not 12.4 kpc as obtained from the dispersion measure of the pulsar signal (Roberts et al. 2002).

There is a tendency, mentioned and discussed already by Aharonian et al. 1997, that pulsars with weaker surface magnetic fields, and hence lower magnetic fields inside their nebulae, are relatively stronger high energy $\gamma$-ray emitters. For example, compare the Crab pulsar with the PSR B1951+32. They have similar periods and distances, but differ by an order of magnitude in their surface magnetic field. The rotational energy loss of PSR B1951+32 is two orders of magnitude lower but the $\gamma$-ray flux is only $\sim 20$ times lower in spite of lower, by a factor of 3, efficiency of lepton acceleration. The same feature is clearly seen in the case of J1811-1926 and J0205+6449. For the same reason, the second youngest considered pulsar, J1930+1852, with the characteristic age of 2900 yrs, is also relatively inefficient $\gamma$-ray source. This is due to the fact that the high energy leptons injected in the past cool efficiently in a strong nebular magnetic field. They can not accumulate inside the nebula for a long time and that’s why can not produce strong high energy $\gamma$-ray fluxes at the present time.

5. Discussion and Conclusion

We predicted top 10 pulsar wind nebulae which should be observable in TeV $\gamma$-rays at the Northern hemisphere with the highest fluxes at energies above 60 GeV and 200 GeV (Table 2). None of the considered PWNe turns out to be comparable in brightness to the Crab Nebula. If the effective collection area of the constructed telescopes (MAGIC, VERITAS) is $\sim 10^5$ m$^2$ down to 60 GeV then the 10 top PWNe should produce $\gamma$-ray rates above $\sim 25\gamma$/hr at energies above 60 GeV. However, the actual detection capabilities will differ for specific experiments since they depend on the efficiency of $\gamma$-ray selection criteria from the hadronic background.

Present observations do not constrain the predictions of our model for the pulsars observable from the Northern hemisphere (listed in Table 1). The upper limits available in the literature (although at higher energies) are above fluxes predicted in this paper,
see e.g. PSR 1951+32 (Srinivasan et al. 1997), PSR J0205+6449 (Hall et al. 2001), PSR B1823-13 (Hall et al. 2003, Fegan et al. 2005, Aharonian et al. 2005c), or PSR 2229+6144, PSR J2021+3651, PSR B1823-13 (Fegan et al. 2005). However, note that some of these upper limits are quite close to the fluxes predicted in the model with additional infrared background inside the nebula (e.g. for J2229+6144 and J2021+3651, Fegan et al. 2005 and PSR B1823-13, Aharonian et al. 2005). Recently the HESS group reports the upper limits for the nebulae around the two southern pulsars, Vela and PSR 1706-44 (Khelifi et al 2005, Aharonian et al. 2005) on the level of only a few percent of the Crab Nebula flux, i.e. significantly lower than the earlier positive reports (Yoshikoshi et al. 1997, Kifune et al. 1995, Chadwick et al. 1998). If confirmed, the model with an additional infrared target inside the nebula around PSR 1706-44 would predict the TeV γ-ray fluxes too high (see Bednarek & Bartosik 2003). In the case of the Vela pulsar the confrontation of our model, predicting the TeV flux on the level of ∼30% of the Crab Nebula, with the new observations is more complicated due to the proximity of the Vela pulsar to the Sun. Our modeling shows that the magnetic field in the main volume of the Vela nebula is comparable to the magnetic field inside the interstellar medium (except for only a very small region around the pulsar). We estimate the dimension of the TeV source in the case of the Vela nebula by calculating the diffusion distance of leptons with energies 100 TeV during the age of the nebula (∼10⁴ yrs) in the magnetic field of ∼3×10⁻⁶ G. The Bohm diffusion coefficient has been applied. It is found that leptons can diffuse as far as ∼5 pc from the pulsar. However the synchrotron and IC energy loss time scales for 100 TeV leptons in this magnetic field and the MBR are comparable to the age of the Vela nebula. Therefore, leptons with energies 100 TeV can diffuse from the pulsar up to ∼5 pc without drastic energy losses. For the distance of the pulsar from the Sun equal to ∼300 pc, the TeV γ-ray source with dimension ∼5 pc should have the angular extend on the sky as large as ∼1°. Therefore, we conclude that the TeV source around the Vela pulsar should be quite extended on the sky and that’s why difficult to observe by the Cherenkov telescopes.

When estimating the TeV γ-ray fluxes from the population of the PWNe, we applied the basic parameters of their supernova remnants, e.g. the expansion velocity and the mass of exploding supernova, as derived for the Crab Nebula. In fact, these parameters are mainly unknown for these nebulae. The increase of the initial mass of the expanding supernova has an effect on the γ-ray flux produced by relativistic nuclei in collisions with the matter at energies above a few TeV but gives negligible effect on the fluxes at ∼200 GeV. The increase of the initial expansion velocity effects the dimension of the nebula at a specific time after explosion. Larger nebula means weaker magnetic field and, as we discussed above, larger fluxes of TeV γ-rays due to the less efficient synchrotron cooling of relativistic leptons.
Tyk gamma-rays from the Northern sky pulsar wind nebulae

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