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Nucleonic gamma-ray production in Pulsar Wind Nebulae

Abstract
Observations of the inner radian of the Galactic disk at very high energy (VHE) gamma-rays have revealed at least 16 new sources. Besides shell type supernova remnants, pulsar wind nebulae (PWN) appear to be a dominant source population in the catalogue of VHE gamma-ray sources. Except for the Crab nebula, the newly discovered PWN are resolved at VHE gamma-rays to be spatially extended (5-20 pc). Currently, at least 3 middle aged (\( t > 10 \) kyrs) PWN (Vela X, G18.0-0.7, and G313.3+0.6 in the “Kookaburra” region) and 1 young PWN MSH 15-5\( _2 \) (\( t = 1.55 \) kyrs) have been identified to be VHE emitting PWN (sometimes called “TeV Pleions”). Two more candidate “TeV Pleions” have been identified and have been reported at this conference [1].

In this contribution, the gamma-ray emission from Vela X is explained by a nucleonic component in the pulsar wind. The measured broad band spectral energy distribution is compared with the expected X-ray emission from primary and secondary electrons. The observed X-ray emission and TeV emission from the three middle aged PWN are compared with each other.

Keywords
X–rays · gamma-rays · Neutrinos

1 Introduction
The discovery of extended gamma-ray emission from pulsar wind nebulae (PWN) opens an exciting possibility to study the acceleration of particles in ultra-relativistic shocks. Acceleration at relativistic shocks is of relevance for the understanding of the mostly non-thermal emission seen from relativistic jets in active galactic nuclei (AGN) and gamma-ray bursts (GRBs). While the Lorentz factor assigned to the relativistic flow in AGN and GRBs is currently believed to be in the range of \( \Gamma \approx 10 \ldots 100 \) based upon arguments of opacity against pair production, the Lorentz factor of pulsar winds \( \gamma \) is largely undetermined. Using the potential drop of the last open field lines as a constraint: \( \gamma \leq e\Phi_{\text{open}}/(m_ec^2) = 2 \times 10^8(\dot{P}_{-13}/P_3)^{1/2} \) with \( P \) indicating the rotational period and \( dP/dt = \dot{P}_{-13} \times 10^{-13} \) s/s the rate of slowing down. The Lorentz factor has been determined in model dependent ways to be in the range of \( 10^6 \ldots 10^7 \) for the Crab nebula (see e.g. [2] and [3]). Even if this value is possibly smaller in other PWN, we are witnessing particle acceleration in ultrarelativistic shocks driven by the energetic pulsar wind. The total energy available by slowing down of the pulsar (assuming a moment of inertia \( I = I_{45}10^{45} \) g cm\(^2\)):

\[ \dot{E} = E_{34} I_{45} \dot{P}_{-13}/P^3 \text{ erg/s}. \]

Theoretical calculations of Fermi-type acceleration in relativistic shocks using widely different approaches (see e.g. [4], [5]) lead to the consistent conclusion, that (largely independent of the detailed parameters of the shock) particles in the downstream plasma are accelerated to follow a universal power-law for large Lorentz factors of \( s = 2.2 \ldots 2.3 \) which is compatible with e.g. the observed X-ray synchrotron spectrum of e.g. the Crab nebula. However, recent progress in the understanding of the downstream turbulence spectrum, a revision of this “universal acceleration” picture may be necessary (see e.g. [6], [7]). In the more recent calculations, the particle spectrum is found to be softer than in previous calculations (see above), to deviate from a universal power-law, and to show a stronger dependence on the Lorentz factor of the upstream medium and on the particular implementation of downstream turbulence. Similar conclusions have been found independently with particle-in-cell (PIC) simulations ([8], [9], [10]).

The presence of ions in the pulsar wind obviously complicate the structure of the shock and have been described
e.g. in [11], [12], [8]. Hoshino et al. (1992) [8] found that an admixture of ions in the wind can lead to acceleration of positrons in the downstream region by resonant absorption of magnetosonic waves emitted by the gyrating ions. In a recent PIC simulation [10] a larger ratio of ion mass \( m_i \) to electron mass \( m_e \) in the simulation has been used (previously, PIC simulations had been limited to values of \( m_i/m_e \approx 20 \)) and various energy fraction of ions have been considered. The overall efficiency of acceleration has been found to increase with the relative energy fraction carried by ions in the wind. The authors also show that the spectrum of non-thermal particles varies.

The presence of the so-called wisps in the Crab nebula has been used to argue for the presence of ions in the wind (see e.g. [13]): the compression caused by the ions leads to increased magnetic field and correspondingly more intense synchrotron radiation. Wisp-like features have been observed from PSR B1509-58 [14], however, the predicted time variation for the northern arc was not found in later observations [15]. The Vela PWN shows variable features along its jet which have been interpreted to be the result of a kink instability [16]. The ring like features in the Vela PWN have not been seen to vary with time even though the expected time scale should be similar to the one observed from the Crab nebula.

Besides the existence of wisp-like structures near the wind shock, ions are expected to leave other observable signatures. The downstream energy distribution of the ions follows a relativistic Maxwellian distribution with some modifications due to the energy loss of ion energy transferred to the non-thermal tail of accelerated pairs [8]. The temperature of the distribution is close to \( \gamma m_i c^2 \). At some distance to the shock, the ions will move diffusively outwards, loosing energy by adiabatic expansion. Gamma-rays and neutrinos will be produced predominantly in inelastic scattering of the nucleons on the ambient medium. Depending on the diffusion coefficient in the PWN, a large fraction of the particle energy can be converted into gamma-rays and neutrinos.

Here, we consider specifically the Vela X PWN, which has recently been detected to emit VHE gamma-rays [17]. In the final section, we will discuss similarities and differences to the other “TeV Plerions”. For a more general review of gamma-ray production in PWN see [18] in these proceedings.

### 2 Vela pulsar and Vela X

The Vela X region was initially discovered as an extended radio emitting region [19], south of the Vela Pulsar PSR B0833-45 located in the center of the Vela supernova remnant. The distance to the Vela pulsar is well known from parallax measurements to be 290 pc [20]. The Vela Pulsar spins with a period of 89.3 ms and slows down with \( \dot{P} = 1.247 \times 10^{-13} \) s/s which gives a current spin down luminosity of \( \dot{E} = 7 \times 10^{36} \) erg/s and an age of \( t \approx 11 \) kyrs [21].

X-ray emission from the Vela X region was discovered with the ROSAT X-ray telescope [22] and initially assumed to be a “jet” from the pulsar. The spectral range of the ROSAT PSPC instrument was not sufficient to clearly identify a non-thermal tail in the observed energy spectrum. Later high resolution measurements of the Vela pulsar with Chandra revealed a compact X-ray nebula with a double torus structure [23]. The morphology of the Vela compact nebula and its orientation suggest that the Vela X region is not a “jet” but rather the result of the interaction of the middle aged pulsar wind system with the reverse shock of the supernova shock wave. Hydrodynamic simulations of the interaction of an expanding PWN inside the shell remnant indicate that for middle aged PWN, the reverse shock will start to interact with the PWN leading ultimately to a compression of the PWN [24]. For the specific case of asymmetries in the density of the ambient medium into which the external shock of the supernova blastwave expands, the reverse shock will start to interact earlier with the expanding PWN along the direction where the ambient...
medium is more dense. The Vela X PWN shows indeed such asymmetry which could be the result of the interaction of the evolved PWN with an asymmetric reverse shock.

3 Non-thermal X-rays from Vela X: New results from ASCA

The X-ray observations of the Vela X region with ROSAT are not conclusive on the existence of a non-thermal power-law component in the energy spectrum. The ASCA satellite with its four X-ray telescopes \[25\] equipped with two Gas Imaging Spectrometers (GIS, \[26\]) and two Solid State Imaging Spectrographs (SIS, \[27\]) is ideally suited to image an extended region like Vela X at energies between 2–10 keV. Given the size of the Vela X region, we do not consider the SIS data with the smaller field of view. The GIS data were screened following the standard screening criteria. For the 4 early pointings (50021000, 50021010, 50021020, 50021030) no rise-time selection (Ohashi et al. 1996) was possible. These pointings cover mainly the region at the northern end of Vela X. See also Table 1 for an overview of the observation number, observation date, and exposure (combined GIS2 & GIS3). Since we are interested in the morphology of the Vela X region in non-thermal X-rays, we consider for the image only events with energies exceeding 2 keV. The data from the two GIS detectors have been added to increase the statistics. The particle background was estimated from Earth night sky observations and subtracted off the skymap and the resulting excess map with 0.5 arc min bins was divided by the exposure map. The analysis is similar to the one described in \[28\]. The resulting flux image is shown in Fig. 1 in grey scale. Note, the surface brightness is rather faint on the level of \(5 \times 10^{-6} \text{ counts/(s cm}^2 \text{ arc min}^2\)). The overlaid contours are from the excess map of the VHE gamma-ray source \[17\].

The X-ray morphology observed in the ASCA image is very similar to the ROSAT picture \[22\] and shows bright emission centered on the position of the pulsar with a narrow extension to the south and a re-brightening at the southern end of Vela X. A bright feature appears to the south east of the Vela X region which is marginally significant and unfortunately located at the edge of the field of view. More observations of this region at X-ray energies could be of interest as there appears to be an increase of the VHE signal towards that same unexplored region.

A more quantitative study of the X-ray morphology at different energies is beyond the scope of this paper. However it is noteworthy, that the size of the X-ray emitting region at energies of 2–10 keV appears to be smaller than the observed size in the soft energy band as e.g. the ROSAT PSPC data indicate.

In order to investigate possible spectral variations, we have sub-divided the extension of Vela X in three regions excluding the bright feature related to the compact nebula in the north by excising a 6 arc min radius region centered on the Vela Pulsar which includes the compact X-ray nebula \[29\]. The energy spectra of all three regions are compatible with a mixture of a thermal component and a power-law with a photon index of 2 and varying fluxes. The southern tip has also been observed with XMM-Newton. The ASCA energy spectrum of the southern tip has been cross-checked with the XMM-Newton spectra which show good agreement as both observations are well fit by a power-law component to be present up to 8 keV. This is consistent with the result of a combined ROSAT and ASCA SIS analysis \[30\] of the southern tip region.

In order to compare the observed X-ray emission and the VHE emission, an energy spectrum covering the entire length of the X-ray emitting region excluding a 6 arc min region centered on the Vela pulsar has been extracted. For the background estimate, the dim region to the east of the Vela X has been used. The resulting energy spectrum is well fit by a power-law with photon index \(\Gamma \approx 2\) and is shown in Fig. 3 together with the ROSAT flux and the BeppoSAX/XMM-Newton combined analysis of the compact nebula emission \[24\].

4 Nucleonic gamma-rays from Vela X

4.1 Observations

The first clear indication of a gamma-ray signal from the Vela X region was found with the H.E.S.S. telescopes with a luminosity in the observed energy range \(L_{0.6–65 \text{ TeV}} \approx 10^{33} \text{ erg/s} \ [17\] at the distance of 290 pc. The spatial extension of the TeV plerion is slightly larger than the size of the X-ray emitting region and extends for a full width at half maximum (FWHM) of 5.7 pc along the major axis and for a FWHM of 4.3 pc along the minor axis (again at a distance of 290 pc). The observed energy spectrum can be described by a power-law with a cut-off \(dN/dE = N_0(E/1 \text{ TeV})^{-\Gamma} \cdot \exp(-E/E_c)\) with the best fit parameters \(\Gamma = 1.45 \pm 0.09_{\text{stat}} \pm 0.2_{\text{sys}}\) and \(E_c = 13.8 \pm 2.3_{\text{stat}} \pm 4.1_{\text{sys}} \text{ TeV}\).
injection event and therefore, the particle distribution is assumed to follow a relativistic Maxwellian distribution with a temperature $k_B T = \gamma m_e c^2$.

When considering the relevant time-scales for the evolution of the particle distribution in comparison with the age of the Vela Pulsar, we assume Bohm-type diffusion and energy loss for the nucleons in inelastic scattering with the ambient medium with a density of $n = 0.6 \text{ cm}^{-3}$. This a lower limit to the overall density of this region derived from the emission measure of the plasma in X-rays. In principle, the total target density could be higher than this value in case of the presence of cold gas. The diffusion time $t_{\text{diff}} = 7300 \text{ yrs} Z^{-1} \eta (R_4)^2 B_{-5} E_{100}^{-1}$ is shorter than the age of the system and therefore, escape losses are negligible. The magnetic field of 10 $\mu$G is a reasonable value for the Vela X region (see also next section). More detailed calculation [31] indicate that the total energy in protons required to match the observed gamma-ray flux is $W_p \approx 10^{49} \text{ erg}$.

A fit of the energy spectrum of gamma-rays from proton-proton interaction assuming a relativistic Maxwellian distribution is shown in Fig. 2. The $\pi^0$ decay spectrum has been calculated using the parametrization given in [32]. The observed energy spectrum is well described for $E = 80 \text{ TeV}$ as the energy of the Maxwellian which translates into $\gamma \approx 8 \times 10^4$.

A characteristic signature of the nucleonic production mechanism is the production of neutrinos. Using the corresponding parametrization for the production of muon and electron flavor neutrinos [32], we calculate the differential energy spectra for the two flavors also shown in Fig. 2.

Given the high energy cut-off and the reasonable angular extension of the Vela X region, we consider Vela X among the best candidates for a detection as a neutrino source with the future Neutrino telescope in the mediterranean sea.

4.3 X-ray emission from secondary electrons

Due to the interaction of nuclei with ambient medium, neutral and charged mesons are produced. While the neutral mesons (primarily $\pi^0$) decay to produce $\gamma$-rays, charged pions decay into electrons and positrons. These secondary electrons then in turn radiate mainly via synchrotron, inverse Compton, and Bremsstrahlung. The energy loss time of the electrons depends on the energy density of the background radiation field (magnetic field strength and soft photon density) and the particle number density. In the case of Vela X, synchrotron cooling dominates very likely with a cooling time expressed as a function of the characteristic energy of synchrotron radiation emitted: $t_{1/2} = 1.2 \text{ kyr} B_{-5}^{-3/2} E_{100}^{-1/2}$. The magnetic field strength in the Vela X region is difficult to estimate. The equipartition field derived from radio measurements of narrow structures can be estimated to be $20 - 50 \mu$G.
However, when taking the X-ray flux in the considered region, the equipartition field is $B_{eq} = 4 \mu G$. For such a small magnetic field however, electrons are not efficiently confined in the Vela X region and should have escaped already and would fill a larger volume which in turn should produce a considerably larger TeV plerion. Therefore, a magnetic field around 10 $\mu G$ is considered to be a realistic parameter to match the observed size of the TeV plerion.

The synchrotron emission from secondary electrons is calculated taking into account radiative cooling but neglecting escape losses (see above). The resulting synchrotron spectrum assuming a 10 $\mu G$ magnetic field after 11 000 yrs is shown in Fig. 3 together with the relevant measurements. Clearly, the secondary electrons’ contribution to the overall spectral energy distribution is negligible. In principle, the synchrotron component would dominate in the optical. However, the sensitivity for extended emission from the Vela X region in the optical is at least one order of magnitude above the expectation.

4.4 X-ray emission from primary electrons

In the framework of ion resonant acceleration, pairs are accelerated to follow a power-law which extends up to a maximum energy given by the energy of the upstream ions. With the observed gamma-ray spectrum, the upstream ion energy is constrained to be of the order of 100 TeV. Given the energy losses of the downstream ions, the upstream value $(\gamma m_i c^2)$ is higher than the temperature of the Maxwellian downstream distribution which is subsequently modified by adiabatic losses. We assume for simplicity that the pulsar is currently injecting a wind with a Lorentz factor of $\approx 10^5$ inferred from the fit of the observed gamma-ray spectrum neglecting time-dependent effects.

The primary electrons accelerated at the shock will therefore reach a maximum energy of $E_{\text{max}} \approx 100 A/Z$ TeV with $Z$ the charge and $A$ the mass number of the nuclei in the wind. Given the magnetic field in the downstream region (see below), this value limits the maximum energy of emitted synchrotron radiation. The magnetic field at the shock can be calculated in the standard MHD picture of PWN (e.g. [34]) by considering the distance of the shock to the pulsar, the total extent, and luminosity of the nebula. The most recent estimates range from $B(\theta_s = 33^\prime) = 72 \mu G$ assuming the position of the shock at an angular separation of 33 arc sec while using the value of 21 arc sec obtained by an elaborate fitting method of the torus [35].

The detection of unpulsed X-ray emission up to 200 keV with INTEGRAL from the Vela pulsar/PWN [38] indicates that possibly the nucleons would have to be only partially ionised to increase $(A/Z)$ and therefore the maximum energy of the pairs. Partially ionised nuclei have already been suggested in [8] in order to avoid exceeding the Goldreich-Julien current. It is quite interesting to note that most of the pulsars powering the TeV plerions have been also detected as INTEGRAL hard X-ray sources (see Hoffmann et al. these proceedings). More data on hard X-ray emission from TeV plerions is of great importance to understand the in situ acceleration at the pulsar wind shock and its maximum energy.

The Vela X region has not been detected to emit X-rays beyond $\approx 8$ keV. Taking all available data with INTEGRAL results in a conservative upper limit on the energy flux in the 20–60 keV band as shown in Fig. 4. Comparing the upper limit with the spectrum obtained with ASCA it is evident, that a cut-off in the X-ray spectrum with an energy $\approx 10$ keV is required not to violate the upper limit.

The origin of the X-rays is very likely synchrotron emission from the primary electrons that are accelerated at the shock and show a radiative cooling break which moves from a few keV to below keV energies when extracting the energy spectra at increasing angular separation from the Vela pulsar [29]. This is consistent when considering the Vela X region, where it turns out to be below keV energies. Under the assumption of a constant injection rate with a power-law with index 2, the synchrotron spectrum for a 10 $\mu G$ field after 11 000 yrs is shown in Fig. 4. The total injected energy in electrons amounts to $W_e \approx 10^{45} B_5^{-2}$ erg between $E_{\text{min}} = 0.01$ TeV and $E_{\text{max}} = 200$ TeV with the minimum energy chosen close to $\gamma m_e c^2 = 0.5$ TeV.

5 Other TeV plerions

Besides the Vela X TeV plerion, at least two more middle aged PWN have been observed to be TeV plerions: G18.0-0.7 [39] and G313.3+0.6 [40] (the northern wing of the “Kookaburra”). It is interesting to point out similarities and distinct differences of these objects: All three objects have been also detected as INTEGRAL hard X-ray sources. The detection of unpulsed X-ray emission up to 200 keV with INTEGRAL from the Vela pulsar/PWN [38] indicates that possibly the nucleons would have to be only partially ionised to increase $(A/Z)$ and therefore the maximum energy of the pairs. Partially ionised nuclei have already been suggested in [8] in order to avoid exceeding the Goldreich-Julien current. It is quite interesting to note that most of the pulsars powering the TeV plerions have been also detected as INTEGRAL hard X-ray sources (see Hoffmann et al. these proceedings). More data on hard X-ray emission from TeV plerions is of great importance to understand the in situ acceleration at the pulsar wind shock and its maximum energy.

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Vela is closer to 50 kry which would be more consistent with the rather cold neutron star surface.

When comparing the spin down power of the pulsar with the radiative power (either in X-rays or gamma-rays), it is interesting to note that while in Vela, the radiative power accounts for less than 1 per cent of the spin down power, it accounts for a few per cent in the other objects. Finally, we consider the ratio of the published extension (12) for G18.0-0.7 and (23) for G313.3+0.6 aof the X-ray nebula $r_X$ to the radius of the TeV plerion $r_{TeV}$: for Vela X, this ratio is fairly close to 1 while it is only $r_X/r_{TeV} \approx 0.1$ for G18.0-0.7 and G313.3+0.6. It is beyond the scope of this paper to investigate the deeper reason for this large difference, but it is clear that the spatially resolved gamma-ray spectroscopy with H.E.S.S. combined with deep X-ray observations covering the same angular region will greatly improve the understanding of the underlying physical parameters.

References

1. Carrigan, S.: Pulsar ensemble studies with H.E.S.S. In: These proceedings. Aharonian et al. (in preparation)
2. Arons, J.: Pulsars as gamma ray sources. AAS 120, 49–60 (1996)
3. Bogovalov, S.V. & Aharonian, F.A.: Very-high-energy gamma radiation associated with the unshocked wind of the Crab pulsar. MNRAS 313, 504–514 (2000)
4. Bednarz, J. & Ostrowski, M.: Energy Spectra of Cosmic Rays Accelerated at Ultrarelativistic Shock Waves. PRL 80, 3911–3914 (1998)
5. Achterberg, A. et al.: Particle acceleration by ultrarelativistic shocks: theory and simulations. MNRAS 328, 393–408 (2001)
6. Lemoine, M., Pelletier, G. & Revenu, B.: On the Efficiency of Fermi Acceleration at Relativistic Shocks. ApJ 645, L129-L132 (2006)
7. Niemiec, J. & Ostrowski, M.: Cosmic Ray Acceleration at Ultrarelativistic Shock Waves: Effects of a “Realistic” Magnetic Field Structure. ApJ 641, 984–992 (2006)
8. Hoshino, M. et al.: Relativistic magnetosonic shock waves in synchrotron sources - Shock structure and nonthermal acceleration of positrons. ApJ 390, 454–479 (1992)
9. Spitkovsky, A.: Simulations of relativistic collisionless shocks: shock structure and particle acceleration. In: T. Buli, B. Rudak, G. Madejski (eds.) Astrophysical Sources of High Energy Particles and Radiation, Torun, Poland, 20–24 June 2005, 345–350, AIP Conference Proc. 801, 2005
10. Amato, E.& Arons, J.: Heating and Non-thermal Particle Acceleration in Relativistic, Transverse Magnetosonic Shock Waves in Proton-Electron-Positron Plasmas. astro-ph/0609034 accepted for publication in ApJ
11. Hoshino, M. & Arons, J.: Preferential positron heating and acceleration by synchrotron maser instabilities in relativistic: positron-electron-proton plasmas. Phys. of Fluids 3B, 818–833 (1991)
12. Gallant, Y. et al.: Relativistic, perpendicular shocks in electron-positron plasmas. ApJ 391, 73–101 (1992)
13. Gallant, Y. & Arons, J.: Structure of relativistic shocks in pulsar winds: A model of the wisps in the Crab Nebula ApJ 435, 230–260 (1994)
14. Gaensler, B.M. et al.: Chandra Imaging of the X-Ray Nebula Powered by Pulsar B1500-58. ApJ 560, 878–893 (2002)
15. DeLaney, T. et al.: Time Variability in the X-Ray Nebula Powered by Pulsar B1509-58. ApJ 640, 929–940 (2006)
16. Pavlov, G.G. et al.: The Variable Jet of the Vela Pulsar. ApJ 591, 1157–1171 (2003)
17. Aharonian, F.A. et al.: First detection of a VHE gamma-ray spectral maximum from a cosmic source: HESS discovery of the Vela X nebula. A&A 448, L43-L47 (2006)
18. Bednarek, W.: High Energy Emission from Pulsar Wind Nebulae. In: These proceedings.
19. Rishbeth, H.: Radio Emission from the Vela-Puppis Region. Aust. J. Phys. 11, 550 (1958)
20. Caraveo, P.A. et al.: The Distance to the Vela Pulsar Gauged with Hubble Space Telescope Parallax Observations. ApJ 561 930–937 (2001)
21. Taylor, J.H. Manchester, R.N., & Lyne A.G.: Catalog of 558 Pulsars. ApJS 88, 529–568 (1993)
22. Markwardt, C.B. & Ögelmann, H.: An X-ray Jet from the VELA Pulsar Nature 375 40 (1995)
23. Helfand, D.J., Gotthelf, E.V., & Halpern, J.P.: Vela Pulsar and Its Synchrotron Nebula. ApJ 556 380–381 (2001)
24. Blondin, J., Chevalier, R.A., & Frierson, D.M.: Pulsar Wind Nebulae in Evolved Supernova Remnants. ApJ 563 806–815 (2003)
25. Serlemitsos, P.J. et al.: The X-ray telescope on board ASCA PASJ 47 105–114 (1995)
26. Ohashi, T. et al.: The Gas Imaging Spectrometer on Board ASCA PASJ 48 157–170 (1996)
27. Burke, Et al., IEEE Trans. Nucl. Sci. 41, 375 (1994)
28. Roberts, M. et al.: The ASCA Catalog of Potential X-Ray Counterparts of GEV Sources. ApJS 133 451–465 (2001)
29. Mangano, V. et al.: The extended hard X-ray emission from the Vela Plerion. A&A 436 917–923 (2005)
30. Markwardt, C. B. & Ögelmann H.B.: The ASCA Spectrum of the VELA Pulsar Jet. ApJ 480 L13-L16 (1997)
31. Horns, D. et al.: Nucleonic gamma-ray production in Vela X. A&A 451 L51-L54 (2006)
32. Khren, S.R., Aharonian, F.A., & Bugayov, V.V.: Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime. PRD 74 034018 (2006)
33. Mignani, R.P., De Luca, A. Kargaltsev, O. et al.: Search for the Optical Counterpart of the Vela Pulsar X-ray Nebula. ApJ 594 419–427 (2003)
34. Kennel, C.F. & Coroniti, F.V.: Confinement of the Crab pulsar’s wind by its supernova remnant. ApJ 283 694–700 (1984)
35. Sefako, R. R. & de Jager, O.C.: Constraints on Pulsar Magnetospheric and Wind Parameters for the Compact Nebulae of VELA and PSR B1706-44. ApJ 593 1013–1023 (2003)
36. Ng, C.-Y. & Romani, R.W.: Fitting Pulsar Wind Tori. ApJ 601 479–484 (2004)
37. Bogovalov, S.V. et al.: Interaction of pulsar winds with interstellar medium: numerical simulation. MNRAS 358 705–715 (2005)
38. I. Hermsen, priv. communication