CHAPTER 7

NEUTRINO AND GAMMA-RAY SIGNATURES OF PeV COSMIC RAYS ACCELERATED BY PULSARS

7.1 INTRODUCTION

For studying fundamental physical issues in some extreme conditions like strong gravity, strong magnetic fields and high densities, rotation-powered pulsars and pulsar wind nebulae (PWNe) offer fascinating galactic sources next to supernovae remnants and excellent laboratories (Link & Burgio 2005, 2006). On the other hand, the probable candidates of extra-galactic origin for high-energy neutrino/gamma-ray radiation include gamma-ray bursts, active galactic nuclei etc. (Halzen & Hooper 2002). Pulsars are rotating neutron stars and it is known to us that they derive their power at the expense of their rotational energy. The major challenge in this field is however, for clear understanding of the energy conversion mechanisms of rotational power into observed electromagnetic radiation like gamma-rays and neutrinos. It is generally agreed that this occurs through acceleration of charged particles to extremely relativistic energies, using the rotating magnetic field as a unipolar inductor to create very high electric potential difference. Besides this feature, there is a divergence of thoughts regarding acceleration regions: whether the acceleration takes place in the intense field zone near the neutron star surface or in the outer magnetosphere near the speed of light cylinder, or even beyond the light cylinder in the wind zone. The particle acceleration may well be occurring in all of these regions, either in the same pulsar or in pulsars of different ages.

New detection methods and theoretical studies of rotation-powered and magnetically feeds compact objects are current subjects in TeV astrophysics. In recent years, many galactic pulsars and PWNe have been discovered to be gamma-ray emitters (da Oña 2011). These galactic sources can also potentially produce interesting event rates in neutrino telescopes. Since they are at shorter distances to the Earth ($\sim 1 \div 10$ kpc) compared to extra-galactic sources, the source luminosity required for a galactic source to produce the same event rate as an extra-galactic one, is few orders of magnitude smaller. In order to produce high energy neutrino fluxes, galactic sources must accelerate particles at sufficiently high energies. In this regard, Hillas derived the maximum energy E at which a particle of charge Z can be accelerated, from the simple argument that the Larmour radius of the particle should be smaller than the size of the acceleration region (Hillas 1984).

Recent results of Link and Burgio's (LB) (Link & Burgio 2005, 2006) calculations revealed that young ($t_{age} \lesssim 10^5$ yrs.) and rapidly rotating neutron stars having a stellar magnetic moment with a component anti-parallel to the spin axis, (as we expect in half of the neutron stars), could emit TeV muon neutrinos with fluxes observable by operating or planned large area neutrino telescopes such as *AMANDA-II,* and *Ice-Cube* (Halzen 1990) and *ANTARES*, *NEMO* and *NESTOR* (Carr 2003). As a conjecture to be verified by observations, Link and Burgio considered that protons or heavier ions are accelerated near the surface by the polar caps to PeV energies. When these accelerated ions interact with the thermal radiation field of pulsar, the Δ-resonance state (Δ^+ is an excited state of the proton, with a mass of 1232 MeV) may occur provided their energies exceed the threshold energy for the process. Though radiation losses limit the maximum energy that can be attained by the nuclei in the acceleration process, such an energy condition is expected to satisfy for several pulsars. Subsequently, the Δ^+ particles quickly decay to π^+, and finally muon neutrinos are produced.

The presence of a hadronic component in the flux of pulsar accelerated particles should result in the emission of high-energy neutrinos and gamma-rays simultaneously as both charged and neutral pions are produced in the interactions of energetic hadrons with the ambient photon fields surrounding the acceleration region. Here, we would show that for the model adopted by LB the estimated TeV gamma-ray fluxes from several nearby pulsars are higher than the observed upper limits of fluxes. In the quest for reasons of such inconsistency, we note that an implicit assumption in the Link and Burgio estimation of neutrino flux is that the polar cap area is equal to the neutron star surface area. Such an assumption seems unreasonable in view of the polar cap geometry (Beskin et al. 1993).

A young neutron star is generally encircled by PWN. In recent years, many Galactic PWNe have been discovered to be gamma-ray emitters (da Oña 2011). It was predicted that the gamma-ray luminosity of these nebulae is connected to the spin-down power i.e. the loss rate of rotational energy of the pulsar, and that pulsars with $\dot{E} > 10^{34-35}(\frac{d}{1kpc})^2$ erg-s^{-1} power nebulae that are detectable in gamma-rays (Aharonian et al. 1997). Positive ions, after gaining energy from pulsar gaps, will move away from the pulsar practically along the open field lines and will finally inject into the nebula. It was very likely that these energetic ions would be trapped by the magnetic field of the nebula for a long period, and consequently they should produce high-energy gamma-rays and neutrinos by interacting with the dense matter of the nebula's environment. We therefore estimate the expected flux of TeV gamma-rays from pulsar nebulae, and by comparing with the observation for a couple of well-known nebulae we checked the consistency of the polar cap model. We also calculate the flux of TeV neutrinos from a couple of PWNe.

Here, we first describe the production mechanism of the TeV gamma-rays and neutrinos in a pulsar environment, estimated the expected flux of gamma-rays from a pulsar for the *polar cap model* of hadrons acceleration as used by (LB). By comparing the *polar cap model* predicted gamma-ray fluxes from some potential young pulsars with the observations, the importance of the inclusion of polar cap area instead of neutron star surface area in the calculation has been emphasized. Incorporating such a feature in the model calculation of fluxes, the revised event rates in a neutrino telescope located at different observation sites on the Earth due to a few potential pulsars are obtained. Adopting the same featured model, fluxes of TeV gamma-rays and neutrinos from pulsar nebulae are found out.

7.2 TeV GAMMA-RAYS AND NEUTRINOS FROM PULSARS

In general, the acceleration of charged particles by astrophysical sources is described by two different kinds of models. The model which describes acceleration of electrons is the so-called *leptonic model* (Aharonian et al. 2008). On the other hand acceleration of heavier ions including protons is described by the so-called *hadronic model* (Halzen & Hooper 2002). Neutrinos are produced only in the *hadronic model* while gamma-ray production can be provided by both the models. Several detailed mechanisms have so far been suggested for acceleration of particles by pulsars that include the popular polar gap (Rudemann & Sutherland 1975, Arons & Scharlemann 1979, Daugherty & Harding 1996, Harding & Muslinov 1998) and the outer-gap models (Cheng et al. 1986).

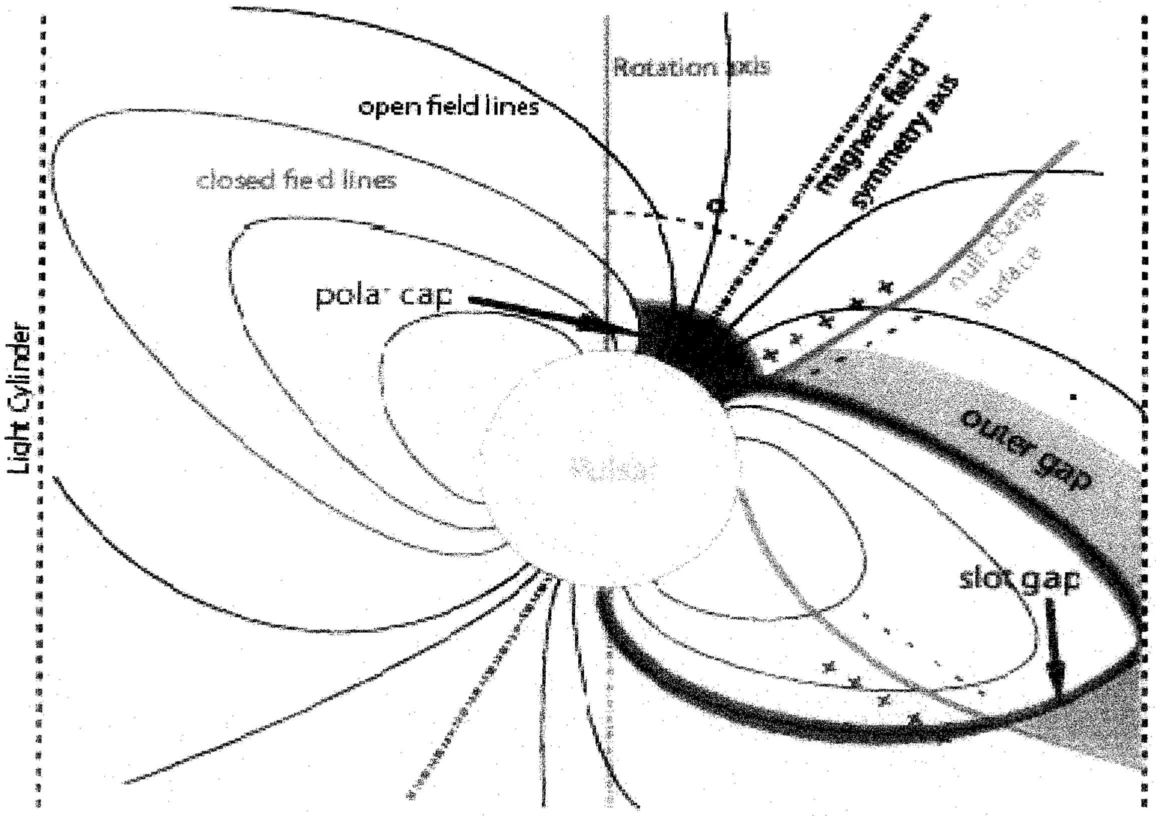

Fig.7.1: The polar cap region is possible candidate for locations within the pulsar's magnetosphere where the acceleration of particles and emission of γ-rays and neutrinos might take place.

In the polar gap model, acceleration of particles takes place in the open field line region above the magnetic pole of the neutron star. In contrast to that, in the case of outer-gap model acceleration occurs in the vacuum gaps between the neutral line and the last open line in the magnetosphere. Thus, the region of acceleration in the polar-gap model is close to the pulsar surface, while the same in the outer-gap model is close to the light cylinder as has been depicted clearly in **Fig.7.1**.

In the polar cap acceleration model, particles are extracted from the polar cap and accelerated by large rotation-induced electric fields, forming the primary beam. A region above the polar cap of a neutron star was proposed by several authors as location of particle acceleration (Rudermann & Sutherland 1975, Arons & Scharlemann 1979).

Electrons are released from the surface of the neutron star when the electron thermal emission temperatures are well below the neutron star surface temperature. Electrons are accelerated by the electric field induced by the rotating axial magnetic dipole. In the case of Crab, potential drops up to 10^{14} eV are induced in the polar cap region, accelerating electrons up to Γ-factors $\approx 10^8$. In this model the charge density at the surface of the pulsar even equals the Goldreich-Julian density (Goldreich & Julian 1969). The charge density $\rho(r)$ decreases as r^{-3}. Thus, magnitude of the parallel component of the electric field goes down to zero at the surface, but increases at much farther radii.

If the surface temperature is below the thermal emission temperature, a vacuum gap will be also formed. Thus, the parallel component of the electric field is not short out in the plasma. Accelerated charged particles will start an electromagnetic pair cascade as shown in **Fig.7.2**. Absorption mechanisms like magnetic pair creation and photon splitting (description was made in the domain of the QED and pronounced in magnetars) restrain gamma-rays with high energies to leave the polar cap area.

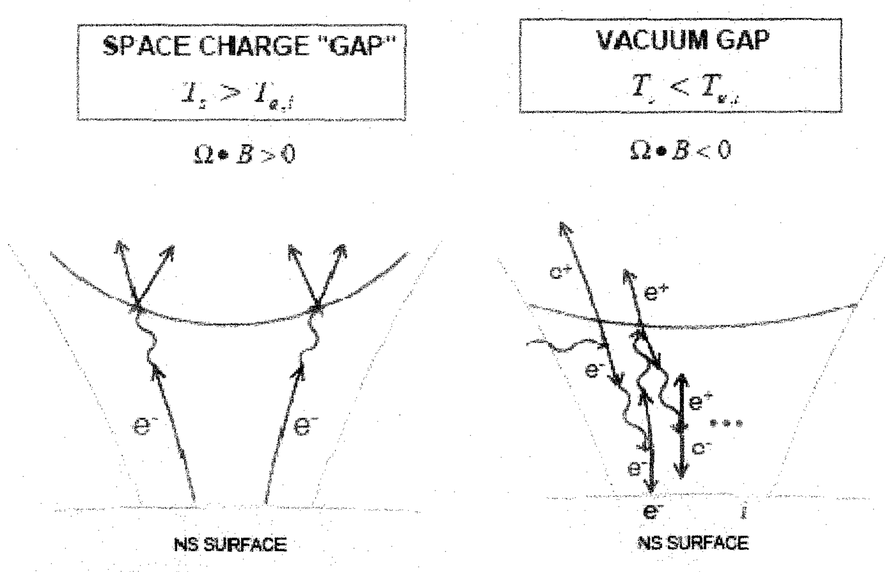

Fig.7.2: Space-charge limited flow and vacuum gap above a neutron star polar cap. T_S is the neutron star surface temperature while $T_{e,i}$ represents the electron or thermal temperature.

The maximum potential drop that may be induced across the magnetic field lines between the magnetic pole and the last field lines that opens to infinity is given by (Goldreich & Julian 1969)

$$\phi = \frac{B_S R^3 \Omega^2}{2c^2} \quad (7.1)$$

, where R is the stellar radius (neutron star) , B_s is the strength of magnetic field at neutron star surface, $\Omega = \frac{2\pi}{P}$ represents the rotational frequency and c is the speed of light. Accordingly, for young millisecond pulsar with high magnetic fields ($B_S \sim 10^{12}$ G), the magnitude of the potential could be as large as

$$\phi = 7 \times 10^{18} B_{12} P_{ms}^{-2}\ volts \quad (7.2)$$

,with $B_S \equiv B_{12} \times 10^{12}\ G$. But, in young pulsars the electric field along magnetic field lines is likely to be screened well below the vacuum potentials by the onset of electron – positron pair cascades in the strong magnetic field (Cheng & Rudermann 1977), and this would limit the potential to about 10^{12} eV. Though the flux of synchrotron radiation observed from the Crab and other PWN indicates such a possibility, questions like where in the magnetosphere are pairs created and how many are created, still not settled and one cannot rule out the possibility that ions can reach energies equal to a significant part of the total potentials drop through polar cap acceleration, particularly in view of the observed of gamma radiation of energies above tens and even hundreds of TeV from Crab and other PWN.

LB (Link & Burgio 2005, 2006) conjectured that protons or heavier nuclei are accelerated near the surface of a pulsar by the polar caps to PeV energies (corresponding to no/little screening) when the scalar product of the magnetic dipole moment and magnetic field vector i.e. $\mu . B < 0$ (such a condition is expected to hold for half of the total pulsars). When pulsar-accelerated ions interact with the ambient radiation field of pulsar, the Δ-resonance state may occur provided their energies exceed the threshold energy for the process. The important threshold condition for the creation of Δ-resonance state in proton-photon interaction is given by

$$\epsilon_p \epsilon_\gamma (1 - cos\theta_{p\gamma}) \geq 0.3\ GeV^2, \quad (7.3)$$

where ϵ_p and ϵ_γ stand for proton and photon energies, respectively, and $\theta_{p\gamma}$ is the incident angle between the proton and photon in the laboratory frame. In a young neutron star with surface temperature, $T_{\propto}$, the energy of a thermal photon near the surface of the neutron star is $2.8kT_{\propto}(1+z_g)$, $z_g(\sim 0.4)$ being the gravitational redshift. This implies that in a young pulsar atmosphere, the condition for the production of the Δ-resonance is $B_{12}P_{ms}^{-2}T_{0.1keV} \geq 3\times 10^{-4}$ (Link & Burgio 2005, 2006), where $T_{0.1keV} \equiv \left(\frac{kT_{\propto}}{0.1keV}\right), T_{\propto}\sim 0.1\ keV$ being the typical surface temperature of young pulsars. The surface of the young pulsar will emit brightly in soft X-rays, and the protons in accelerated nuclei will scatter with this radiation field. If the protons are sufficiently energetic, they will exceed the threshold for photo-meson production through the Δ-resonance (the Δ^+ is an excited state of the proton, with a mass of 1232 MeV). The Δ-resonance quickly decays into gamma-rays and neutrinos through the following channels

$$p+\gamma \rightarrow \Delta^+ \rightarrow p+\pi^0 \rightarrow p+2\gamma$$

$$p+\gamma \rightarrow \Delta^+ \rightarrow n+\pi^+ \rightarrow n+e^+ +\upsilon_e+\upsilon_\mu+\tilde{\upsilon}_\mu$$

This idea for υ_μ production was explored by (Zhang et al. 2003) in the context of magnetars. It can be shown that young pulsars could be strong sources of muon neutrinos with several tens of TeV energies and with fluxes observable by large-area neutrino observatories.

Since the charge-changing reaction takes place just one-third of the time, on the average four high-energy gamma-rays are produced for every three high-energy neutrinos (or for a muon neutrino antineutrino pair) when a large number of such reactions occur.

7.3 GAMMA-RAY AND NEUTRINO FLUXES FROM PULSARS

Fluxes for gamma-rays and muon neutrinos from pulsars can be estimated in the polar cap model. The charge density of ions near the pulsar surface is $\rho_q \simeq eZn_0$, where $n_0(r) \equiv B_S R^3\Omega/(4\pi Zecr^3)$ is the Goldreich-Julian density (Goldreich & Julian 1969) of ions at a radial distance r. For acceleration to take place, there must be a charge-depleted gap (here the polar gap), and the density in the gap may be written as $f_d(1-f_d)n_0$, where $f_d<1$ is the depletion factor which is a model-dependent quantity ($f_d=0$ corresponds to zero depletion). The flux of protons accelerated by a polar cap is therefore

$$I_{pc} = cf_d(1-f_d)n_0 A_{pc}, \qquad (7.4)$$

where $A_{pc} = \eta\, 4\pi R^2$ is the area of the polar cap, η is the ratio of the polar cap area to the neutron star surface area, which is taken as unity by LB in their work. This means that A_{pc} was considered to be equal to the surface area of the whole neutron star in the original calculation by LB. The canonical polar cap radius is given by $r_{pc} = R(\frac{\Omega R}{c})^{1/2}$ (Beskin et al. 1993), and thus the parameter η can be rewritten as

$$\eta = \frac{\Omega R}{4c}. \tag{7.5}$$

The protons accelerated by a polar cap will interact with the thermal radiation field of the neutron star. The temperature of polar caps is expectedly higher than the neutron star's surface temperature, but the contribution of polar caps on the thermal radiation field of a neutron star should be negligible because of their small surface area in comparison with the surface area of the whole neutron star. For a young neutron star with surface temperature T_∞, the photon density close to the neutron star's surface is

$$n_\gamma(R) = \frac{a}{2.8k}[(1+z_g)T_\infty]^3, \tag{7.6}$$

a, being the Stefan-Boltzmann constant. Numerically, $n_\gamma(R) \simeq 9\times 10^{19} T_{0.1\,keV}^3\, cm^{-3}$. At a particular radial distance r, the photon density will be $n_\gamma(r) = n_\gamma(R)\left(\frac{R}{r}\right)^2$. The probability that a PeV energy proton starting from pulsar surface will produce Δ-resonance sate by interacting with thermal radiation field is given by (Link & Burgio 2005, 2006)

$$P_c = 1 - P(r) \tag{7.7}$$

with, $\frac{dP}{P(r)} = -n_\gamma(r)\sigma_{p\gamma}dr$. The threshold energy for the production of Δ-resonance state in $p\gamma$ interaction as given by equation **(7.3)** increases rapidly with distance from the surface of neutron star because of the $(1-cos\theta_{p\gamma})^{-1}$ factor (Link & Burgio 2005, 2006). Requiring conversion to take place in the range $R \le r \le 1.2R$ [at $r = 1.2R$, the value of $(1-cos\theta_{p\gamma})^{-1}$averaged over surface becomes double], P_c has been found as $\simeq 0.02T_{0.1keV}^3$ (Link & Burgio 2005, 2006). From a follow up calculation by LB, it is found that conversion probability is slightly lower than that mentioned above and can be parameterized as $P_c \simeq T_{0.1keV}^3$. Thus, the total flux of neutrino or gamma-ray generated in pulsar from the decay of Δ^+resonance is

$$I = 2c\xi A_{pc} f_d (1 - f_d) n_0 P_c \,, \tag{7.8}$$

where ξ is $4/3$ and $2/3$ for gamma-rays and muon neutrinos, respectively. Denoting the duty cycle of the gamma-ray/neutrino beam as f_b which has a typical value $f_b \sim 0.1 - 0.3$, the phase-averaged gamma-ray/neutrino flux at the Earth from a pulsar of distance d is given by

$$\phi \simeq 2c\xi\zeta\eta f_b f_d (1 - f_d) n_0 \left(\frac{R}{d}\right)^2 P_c \tag{7.9}$$

where ζ represents the effect due to neutrino oscillation. The decays of pions and their muon daughters result in initial flavour ratios $\phi_{v_e}:\phi_{v_\mu}:\phi_{v_\tau}$ of nearly $1:2:0$ but at large distance from the source the flavour ratio is expected to become $1:1:1$ due to maximal mixing of v_μ and v_τ. $\zeta = 1$ and ½ for gamma-rays and muon neutrinos, respectively.

7.4 AVERAGE NEUTRINO AND GAMMA-RAY ENERGIES

The average fraction of energy transferred from the proton to the pion is ~ 0.2, or $200T_{0.1keV}^{-1}$, corresponding to a Lorentz factor of $\gamma_\pi = 1.4 \times 10^6 T_{0.1keV}^{-1}$. The pion decays in a time $\tau_d = \gamma_\pi \tau_\pi$, where $\tau_\pi = 2.6 \times 10^{-8} s$, and thus moves to $r \sim 10^3 R$ before decaying. The pion is in the densest part of the radiation field for only a short time, of order $R/c \simeq 3 \times 10^{-5} s$, and suffers negligible energy loss to inverse-Compton scattering. When the pion decays, it gives one-fourth of its energy to the muon neutrino, the rest going to the other three leptons. The resulting neutrino energy is then

$$E_{v_\mu} \simeq 50 T_{0.1keV}^{-1}\, TeV \tag{7.10}$$

As the parameter ξ is $4/3$ for gamma-ray compared to its $2/3$ value for muon neutrinos. Hence, it is expected that the average energy of the produced gamma-rays would be double to that for muon neutrinos, given by

$$E_\gamma \simeq 100 T_{0.1keV}^{-1}\, TeV \tag{7.11}$$

7.5 TeV GAMMA-RAYS FROM FEW POTENTIAL PULSARS

Though there are about more than 1800 pulsars known through radio detection, only a few have been detected in the gamma-rays. From observations made with gamma-ray telescopes on satellites so far, only *seven* high-confidence gamma-ray pulsars are known in the energy range up to a few GeV (Thompson 2003). Besides, three other pulsars namely $PSR\ B1046-58$, $B0656+14$ and $J0218+4232$ are considered to be gamma-ray emitters with a lower confidence level (Thompson 2003) in the same energy region. Some basic characteristic properties of the high-confidence *young* gamma-ray pulsars, namely distance (D), spin-down age (τ), period (P), the calculated magnetic field strength (B_S) at the neutron star surface, surface temperature (T_S) and pulsar duty cycle (f_b), are listed in **table 7.1.**

7.5.1 DETECTABILITY

None of the listed pulsars in **table 7.1** is, however, detected at TeV energies despite recent improvement in the knowledge of Galactic gamma-ray sky above 100 GeV, mostly by means of ground-based Imaging Atmospheric Cherenkov telescope systems such as the Collaboration of Australia and Nippon for a Gamma Ray Observatory in the Outback (CANGAROO), High Energy Gamma Ray Astronomy (HEGRA), High-Energy Stereoscopic System (HESS) or the Major Atmospheric Gamma-ray Imaging Cherenkov Observatory (MAGIC). Up to now, no evidence for pulsed emission from any other pulsar has been found from the observations (Chadwick et al. 2000 & Lessard et al. 2000), and only upper limits on the pulsed very high energy gamma-ray flux are derived under various assumptions on the characteristics of the pulsed emission. For the pulsars listed in **table** 7.1, the observed upper limits of integral fluxes are given in **table** 7.2. The upper limits are obtained from the differential spectra assuming a power-law differential spectrum with index -2.4. The upper limits of integral fluxes of gamma-rays from pulsars at around 100 TeV as obtained by the extensive air shower experiments such the Tibet (Amenomori et al. 2008[a] & Wang et al. 2008) are found less restrictive.

Assuming that pulsar-accelerated ions are protons, numerical values of the integral TeV gamma-ray fluxes are obtained for the pulsars listed in **table 7.2** from equation **(7.9)** and are also shown in the same table. It should be mentioned here that for the numerical estimation of flux, we take $Z=1$ and $f_d=1/2$ throughout the present work.

Source	d (kpc)	age (yr)	p (ms)	B_{12}	$T_{0.1keV}$	f_b
Crab	2	10^3	33	3.8	~1.7	0.14
Vela	0.29	$10^{4.2}$	89	3.4	0.6	0.04
B 1706-44	1.8	$10^{4.3}$	102	3.1	1	0.13
B 1509-58	4.4	$10^{3.2}$	151	0.26	1	0.26
J 0205+64	3.2	$10^{2.9}$	65	3.8	0.04	0.9

***Table** 7.1*: The characteristics of high-confidence young low-energy gamma-ray pulsars.

Source	Expected integral flux ($10^{-15} cm^{-2} s^{-1}$)		Observed upper limit of integral flux ($10^{-15} cm^{-2} s^{-1}$)
	$\eta = 1$	η as eqn. (7.5)	
Crab	1012	1.65	8(56)
Vela	208	0.123	10(20)
B 1509-58	67	0.0034	10(20)
B 1706-44	71	0.0025	10(20)

***Table** 7.2*: Comparison of predicted versus observed integral TeV gamma-ray fluxes from some nearby young gamma-ray pulsars. The numbers in parentheses are the energy thresholds in TeV for which upper limits are determined. The observed upper limits for Crab pulsar are due to (Aharonian et al. 2006[b]) whereas for the rest of the pulsars the observed upper limits are due to (Aharonian et al. 2007[b]).

Source	Expected event rates ($km^{-2} yr^{-1}$)
Crab	0.009
Vela	0.0007
B 1509-58	0.00003
B 1706-44	0.00003

***Table** 7.3*: Expected event rates in a neutrino telescope due to some nearby young gamma-ray pulsars.

It is clear from **table 7.2** that the model with $\eta = 1$ is not consistent with the observed upper limits; the observed limits are substantially lower than the predicted fluxes. The observations made so far, however, do not rule out the model with η given by equation (**7.5**).

7.6 TeV NEUTRINOS FROM PULSARS

When η is given by equation (**7.5**), neutrino fluxes from nearby young gamma-ray pulsars would be much lower than estimated by LB (Link & Burgio 2005, 2006). A high-energy muon neutrino is usually detected indirectly through the observation of the secondary high-energy muon produced by the muon neutrino on interaction with the ice or rock in the vicinity of a neutrino telescope via charged current interactions. Large-area neutrino detectors use the Earth as medium for conversion of a muon neutrino to a muon, which then produces Cherenkov light in the detector. The track of the produced muon is usually reconstructed by detecting the produced Cherenkov light. The probability of the detection of muon neutrinos is the product of the interaction probability of neutrinos and the range of the muon and is $p_{v\to\mu} \simeq 1.3\times10^{-6}(\frac{\epsilon_{v\mu}}{1\,TeV})$ (Gaisser et al. 1995), where $\epsilon_{v\mu}$ is the energy of the incident neutrino. Combining (**7.9**) and $p_{v\to\mu}$ gives a muon event rate of

$$\frac{dN}{dAdt}=\phi_v p_{v\to\mu}=\int_{\epsilon_T}^{10\epsilon_T} d\epsilon_v\frac{d\phi_v}{d\epsilon_v}\,p_{v\to\mu}. \qquad (7.12)$$

The choice of the upper limit of integration is not very important, because the spectrum is steep. The expected event rates in a neutrino telescope due to potential young pulsars are given in **table 7.3**.

The event rates are clearly very low and thus possibility of observing pulsars by a kilometre-scale neutrino detector does not look bright.

7.7 GAMMA-RAYS AND NEUTRINOS FROM PULSAR WIND NEBULAE

A number of nebulae (plerions) have been discovered in radio, optical and X-ray bands such as Crab, the youngest one and most energetic source. Continuous injection of pulsar electrons into the nebula resulting from a statistical acceleration process is inevitable. The radio, optical and X-ray emission observed from plerions is believed to be due to synchrotron and ICs emissions (*leptonic origin*). It is likely that positive ions, after gaining energy from polar gaps, will move away from the pulsar practically along the open field lines and will finally inject into the nebula. It is very likely that these energetic ions would be trapped by the magnetic field of the nebula for a long period and consequently they should produce appreciable high-energy gamma-rays/neutrinos by interacting with the matter of the nebulae (*hadronic origin*).

7.7.1 MAGNETIC TRAPING OF PULSAR-ACCELERATED PeV IONS IN NEBULAE

Conservation of magnetic flux across the light cylinder entails that outside the light cylinder $B \sim r^{-1}$whereas far from the light cylinder the radial component of magnetic field varies as $B_r \sim r^{-2}$. Thus, far outside the light cylinder the azimuthal component of the magnetic field dominates over the radial field. Therefore, accelerated protons while moving away from the pulsar have to cross the field lines (e.g. magnetic field lines at wind shock). The Larmour radius of particles (even for proton) of energy about 1 PeV is expected to be smaller than the radius of nebula during most of the time of the evolution of nebula (Bednarek & Protheroe 2002, Bhadra 2006). Thus, it is very likely that energetic particles of PeV energies would be trapped by the magnetic field of the nebula. The energetic particles propagate diffusively in the envelope, and they escape from nebula when the mean radial distance travelled by the particles becomes comparable with the radius of nebula at the time escaping. This time is somewhat uncertain due to the uncertainty of the value of diffusion coefficient, but is estimated to be at least a few thousand years (Bednarek & Protheroe 2002, Bhadra 2006).

7.7.2 GAMMA-RAYS AND NEUTRINOS FROM NEBULAE OF YOUNG PULSARS

As pointed out in the preceding section, the pulsar-injected ions of PeV energies should be trapped by the magnetic field of the nebula for a long period, and consequently there would be an accumulation of energetic ions in the nebula. These energetic ions will interact with the matter of the nebula. The rate of interactions (ξ) would be $nc\sigma_{pA}$, where n is the number density of protons in nebula and σ_{pA} is the interaction cross-section. In each such interaction, charged and neutral pions will be produced copiously. Subsequently, the decays of neutral pions will produce gamma-rays whereas charged pions and their muon daughters will give rise to neutrinos.

If m is the mean multiplicity of charged particles in proton-ion interaction, then the flux of gamma-rays at a distance d from the source would roughly be

$$\phi_\gamma \approx 2c\beta\eta f_d(1-f_d)n_0(\frac{R}{d})^2\xi mt, \tag{7.13}$$

where β represents the fraction of pulsar-accelerated protons trapped in the nebula and t is the age of the pulsar. Note that there should not be any reduction of flux due to pulsar duty cycle in the case of emission to nebula. Though n_0 is taken as constant, but actually at the early stages of pulsar, n_0 should be larger owing to the smaller pulsar period. So, the above expression gives only a lower limit of flux. Typical energy of these resultant gamma-rays would be $\sim 10^3/(6m)$ TeV where for (laboratory) collision energy of 1 PeV, m is about 32 (Alner et al. 1987).

Numerical values of the integral TeV gamma-ray fluxes from two nearby nebulae, Crab nebula and Vela nebula, have been estimated for perfect trapping of pulsar-accelerated protons in nebulae and are shown in **table 7.4**. The observed integral gamma-ray fluxes above 1 TeV from Crab nebula (Aharonian et al. 2006[b]) and Vela nebula (Aharonian et al. 2006[c]) are also given in **table 7.4** for comparison.

PWNe	n (cm^{-3})	Expected flux ($\times 10^{-12} cm^{-2} s^{-1}$)	Observed flux ($\times 10^{-12} cm^{-2} s^{-1}$)
Crab nebula	150	0.6	22.6
Vela nebula	1	0.4	12.8

Table 7.4: Comparison of predicted versus observed integral gamma-ray fluxes from two nearby PWN.

The neutrino fluxes from the nebulae would be of nearly the same to those of gamma-rays. Incorporating the neutrino oscillation effect, the expected event rates in a neutrino telescope due to TeV muon neutrinos from Nebulae of Crab and Vela are 0.2 and 0.1 $km^{-2}yr^{-1}$, respectively. Note that the event rates obtained here are rough numerical values. The flux will be higher if the accelerated ion is heavier than proton.

7.8 DISCUSSION AND CONCLUSIONS

The neutrino telescopes currently taking data have not detected any excess from discrete sources yet, although some models could already be constrained by the limits they are providing. Results from neutrino telescopes such as Antartic Muon and Neutrino Detector Array (AMANDA-II) and ANTARES with long exposure time are available. Crab pulsar was not detected as neutrino source. The Crab pulsar would be a strong source, but only if $\boldsymbol{\mu}.\boldsymbol{B} < 0$. If the Crab is a neutrino pulsar, and the temperature is close to the observational upper limit, lack of detection by AMANDA-II requires, $f_d \lesssim 0.01$, which seems surprisingly low in the face of current models of charge-depleted gaps.

Our present work suggests that pulsars (within 10 kpc of Earth and younger than 10^5 yrs.) are unlikely to be strong sources of TeV neutrinos. The non-detection of any statistically significant excess from the direction of any pulsar by the AMANDA-II is thus as per expectations.

If protons are accelerated to PeV energies by the pulsar, then pulsar nebulae are more probable sites of energetic neutrinos provided energetic particles of PeV energies are efficiently trapped by the magnetic field of the nebulae. But, even for pulsar nebulae the expected event rates are small and the detection of pulsar nebulae by the ongoing neutrino telescopes, such as the Ice Cube (Halzen 2006), is very low. We expect that experiments with the proposed High Altitude Water Cherenkov (HAWC) detector will be constantly used to survey large regions of the sky in particular the galactic plane, at gamma-ray energies up to 100 TeV with 10 to 15 times the sensitivity of Milagro (Li 2013).