Nebulae of young pulsars: Emitters of TeV neutrinos and gamma-rays

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Introduction

High-energy neutrinos are expected to be produced in astrophysical objects by the decays of charged pions made in cosmic-ray interactions with surrounding photons and/or matter [1-3]. As these pions decay, they produce neutrinos with typical energies of 5% compared to those of the cosmic-ray nucleons [4]. These neutrinos can travel long distances undisturbed by either the absorption experienced by high-energy photons or the magnetic deflection experienced by charged particles, making them a unique tracer of cosmic-ray acceleration. Hence neutrinos are considered to be important probes for exploring the high energy Universe, and they may fill the missing link between the TeV gamma-rays and the PeV - EeV cosmic-rays. At the same time, neutrinos produced in cosmic-ray air showers provide information about hadronic physics in kinematic regions that are difficult to probe with terrestrial accelerators.

If the stars magnetic moment μ and angular velocity $\mathbf{\Omega}$ satisfy $\mu.\mathbf{\Omega} < \mathbf{0}$ (as one would expect for half of the neutron stars), protons/ions will be accelerated to infinity. If the neutron star is young, its surface will emit mainly soft X-rays or UV radiation, and the protons in accelerated nuclei will scatter with this radiation field. If the protons are sufficiently energetic, they will exceed the threshold for photomeson production through the Δ resonance (Δ^+ is an excited state of the proton, with a mass of 1232 MeV). The Δ^+quickly decays to a π^+, and muon neutrinos are produced through the following channels [5]:

$$p+\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p+\pi^o \rightarrow p+2\gamma \\ n\pi^+ \rightarrow n+e^+ +\nu_e+\nu_\mu+\bar{\nu_\mu} \end{cases}$$

We show that young neutron stars could be strong sources of muon neutrinos, with energies ~ 50 TeV, and with fluxes observable by large-area neutrino observatories.

A young neutron star is generally encircled by pulsar wind nebula. 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 high energy gamma rays and neutrinos by interacting with the matter of the nebula. 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 check the consistency of the model. We also calculate the flux of TeV neutrinos from couple of pulsar nebulae.

Magnetic trapping 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 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 (for instance magnetic field lines at wind shock). The Larmor radius of particles (even for proton) of energy about 1 PeV is expected

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to be smaller than the radius of nebula during most of the time of the evolution of nebula [6]. 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 traveled by the particles becomes comparable with the radius of nebula at the time of escaping. This time is somewhat uncertain due to uncertainty of the value of diffusion coefficient but is estimated as at least few thousand years.

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 nebula. These energetic ions will interact with the matter of the nebula. The rate of interactions (ξ) would be $n_0 c\sigma_{pA}$, where n_0 is the number density of protons in nebula and σ_{pA} is 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 roughly would be

$$\phi_\gamma \approx 2c\beta\eta f_d(1-f_d)n_o\left(\frac{R}{d}\right)^2 \xi m t \qquad (1)$$

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_o is taken as constant but actually at the early stages of pulsar n_o 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 $\sim 10^3/(6*m)$ TeV where for (laboratory) collision energy of 1 PeV m is about 32.

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. The model predictions are 0.6 and 0.4 in 10^{-12} $cm^{-2}s^{-2}$ corresponding to n_0 150 and 1 respectively. The observed integral gamma ray fluxes above 1 TeV from Crab nebula and Vela nebuae are 22.6 and 12.8 in 10^{-12} $cm^{-2}s^{-2}$.

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 $km^{-2}yr^{-1}$ and 0.1 $km^{-2}yr^{-1}$ respectively.

Conclusions

If protons are accelerated to UHE 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.

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