High Energy CRs from Young Neutron Star and Their Interactions with the Ambient Matter

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Abstract

We have estimated the flux of gamma-rays and neutrinos that are produced from the decays of neutral and charged pions in the pulsar winds. The number density and energy spectrum of pions have been calculated assuming that the distribution of the protons in the downstream of the standing shock wave is a Maxwellian with very high temperature and high energy protons interact with each other. We compared the estimated flux of gamma-rays with the observed one for the Crab Nebula and discussed the possibility to detect the signals of high energy neutrino at km^3 detector such as IceCube.

1. Introduction

It has been long time since the possibility that a baryonic component is present and may be energetically dominant in pulsar winds was pointed out. Based on this scenario, many works on the emissivity of high energy gamma-rays and neutrinos have been reported. Beall and Bednarek (2002) pointed out the possibility that the baryons interact with the thermal radiation field in the supernova cavity. Amato et al. (2003) calculated the flux of high-energy gamma-rays and neutrinos produced from the interactions of the winds with the supernova remnant.

On the other hand, Hoshino et al. (1992) studied the properties of relativistic, transverse, magnetosonic collisionless shock waves in electron-positron-heavy ion plasma. They found that the proton spectra in downstream of the MHD shock which connects the pulsar wind with the supernova remnant is well fitted by a Maxwellian distribution function with temperature $k_B T_p / m_p c^2 \gamma \sim 0.34$.

Based on this study, we consider another possibility to produce high-energy gamma-rays and neutrinos in the downstream of MHD shock. The study presented by Hoshino et al. (1992) suggests the possibility that the distribution of the accelerated protons in the pulsar winds becomes the thermalized one and interact with each other. Thus we calculate the emissivity of high-energy gamma-rays

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and neutrinos that are produced in the downstream from the decays of neutral and charged pions. This picture is interesting and new one which should be investigated. As a model of the nebular flow, we adopt the formulation presented by Kennel and Coroniti (1984), although we assume in this study that protons are energetically dominant in the pulsar winds.

After calculating the flux of high-energy neutrinos from a pulsar with the amplitude of the magnetic field around the polar region $B \sim 10^{12}$G, we discuss the detectability of these signals at the Earth with km^3 high-energy neutrino detectors such as IceCube.

2. Method of Calculation

2.1. Nebular Flow

As stated in section 1, we adopt the model presented by Kennel and Coroniti (1984), assuming that protons are energetically dominant. In their model, the pulsar's spin down luminosity L just ahead of the shock is divided between particle and magnetic luminosity as follows:

$$L = 4\pi n\gamma r_s^2 m_p c^3(1+\sigma), \tag{1}$$

where n is the proper density of proton, u is the radial four speed of the flow, $\gamma^2 = 1+u^2$, r_s is the radial distance of the shock from the pulsar, m_p is the proton mass, c is the speed of light, $sigma$ is the ratio of the magnetic plus electric energy flux to the particle energy flux,

$$\sigma = \frac{B^2}{4\pi n u\gamma m_p c^2}, \tag{2}$$

and B is the observer frame magnetic field. The maximum energy of the protons just ahead of the shock is estimated by the potential difference between the equatorial plane and pole of the rotating neutron star (Goldreich and Julian 1969) as:

$$m_p c^2\gamma_{\max} = 3\times 10^{12} R_6 B_{12}/P^2 \quad \text{eV}, \tag{3}$$

where R_6 is the radius of the neutron star in 10^6 cm, B_{12} is the amplitude of the magnetic field at pole of the neutron star, and P is the period of rotation of the pulsar in second. We adopt $\gamma_{\max}$ for the bulk velocity of the pulsar wind in the upstream.

The upstream flow is connected to the downstream via the Rankine-Hugoniot relations for perpendicular shock. As for the downstream flow, the steady state equation of motion is adopted. Position of the termination shock is determined so as to achieve the pressure balance between the supernova remnant and downstream of the pulsar wind at the inner-edge of the supernova remnant. As for the distribution of the protons in the downstream, the Maxwellian with the temperature that gives the required pressure at each position is adopted.

2.2. Emissivity of High Energy Gamma-rays and Neutrinos

Next, we calculate the emissivity of high-energy gamma-rays and neutrinos using the formulation as follows (Mahadevan, Narayan and Krolik 1997):

$$F(E_\pi) = 2\pi c \int R^2 dR \int_1^{\gamma} d\gamma_1 \int_{\gamma}^{\infty} \gamma_2 \int_{-1}^{1} d\cos\theta \frac{d\sigma(\gamma_1, \gamma_2, \cos\theta)}{dE_\pi} n(R, \gamma_1) n(R, \gamma_2) \times \sqrt{(\vec{\beta_1} - \vec{\beta_2})^2 - (\vec{\beta_1} \times \vec{\beta_2})^2} \quad [\text{particles erg}^{-1}\ \text{s}^{-1}], \quad (4)$$

where γ_1, γ_2 are the respective Lorenz factors of the two protons, $\cos\theta = \vec{\beta_1} \cdot \vec{\beta_2} / \left|\vec{\beta_1}\right| \left|\vec{\beta_2}\right|$, R is the radius with respect to the neutron star, $n(R, \gamma)$ is the differential number density of protons at position R, and $d\sigma(\gamma_1, \gamma_2, \cos\theta)/dE_\pi$ is the differential cross section of proton-proton interaction.

The energy spectrum of gamma-rays produced through the decays of neutral pions in the fluid-rest frame is obtained as

$$F(E_\gamma) = 2 \int_{E_{\pi,\min}}^{\infty} dE_\pi \frac{F(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} \quad [\text{photons s}^{-1}\ \text{erg}^{-1}], \quad (5)$$

where $E_{\pi\,\min}$ is the minimum pion energy required to produce a gamma-ray with energy E_γ. In the observer's frame, the energy spectrum of photons are expressed as

$$\frac{F'(E'_\gamma)}{d\Omega'} = \sum_{\Delta V} \frac{F(E_\gamma)}{\Gamma^2 (1 - \beta \cos\theta')} \frac{1}{4\pi} \quad [\text{photons s}^{-1}\ \text{erg}^{-1}\ \text{sr}^{-1}], \quad (6)$$

where Γ is the bulk Lorenz factor of the fluid element at each position in the observer's frame, θ' is the angle between the line of sight and direction of the flow, and ΔV is the volume of the each fluid element. The dashes($'$) represent the quantum for the observer's frame. The flux of neutrinos can be also obtained similarly, although $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ is a 3-body process and slightly complicated.

3. Results

The estimated flux of gamma-rays is shown in figure 1. In this model, the bulk Lorenz factor is set to be $\gamma = 10^5$, which is likely to be the maximum value for Crab pulsar with $B_{12} = 5$, $P = 33$ms. The spectrum of the synchrotron radiation is also shown in this figure. We assumed that the initial bulk Lorenz factor and number density of electrons are same with the ones of protons. The estimated event rate as a function of muon threshold energy at km^3 detector of high-energy neutrinos such as IceCube is shown in the right panel of figure 1. The initial bulk Lorenz factors are set to be $\gamma = 10^5, 10^4, 10^3, 10^2, 10^1$, respectively. In the case of $\gamma = 10^5$, the signals may be detected in spite of the presence of the atmospheric neutrinos.

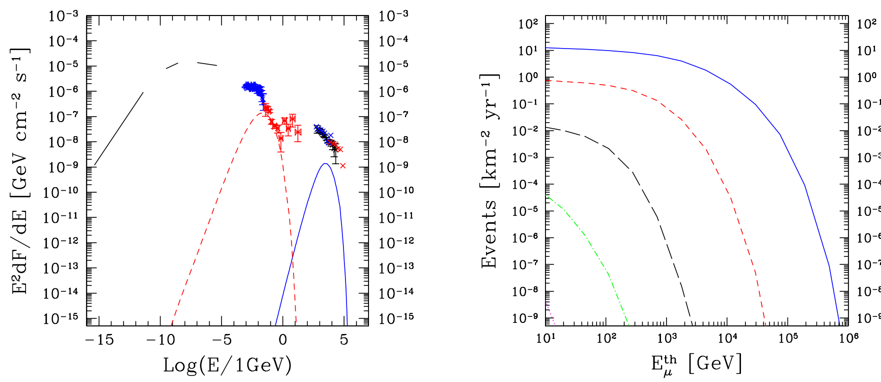

Fig. 1. Left Panel: Nonthermal radiation of the Crab Nebula and theoretical curves. Solid line corresponds to the gamma-rays produced through the decays of pions whereas dashed line corresponds to the synchrotron radiation. Initial bulk Lorenz factor is set to be $\gamma = 10^5$. Right panel: estimated detection rate of high energy neutrinos as a function of muon threshold energy. The theoretical curves correspond to $\gamma = 10^5, 10^4, 10^3, 10^2, 10^1$, respectively.

4. Conclusion

Based on the study Hoshino et al. (1992), we consider new possibility to produce high-energy gamma-rays and neutrinos in the downstream of MHD shock. By comparing the estimated flux of gamma-rays with the observed flux of Crab Nebula, the estimated flux of neutrinos with the atmospheric neutrino, we conclude that there may be possibility to detect signals from the decays of pions that are produced due to the effects considered in this study for the first time.

5. References

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