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Type IIn supernovae as sources of high energy astrophysical neutrinos

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ABSTRACT

It is shown that high-energy astrophysical neutrinos observed in the IceCube experiment can be produced by protons accelerated in extragalactic Type IIn supernova remnants by shocks propagating in the dense circumstellar medium. The nonlinear diffusive shock acceleration model is used for description of particle acceleration. We calculate the neutrino spectrum produced by an individual Type IIn supernova and the spectrum of neutrino background produced by IIn supernovae in the expanding Universe. We also found that the arrival direction of one Icecube neutrino candidate (track event 47) is at 1.35° from Type IIn supernova 2005bx.

1. Introduction

The detection of very high energy astrophysical neutrinos in the IceCube experiment [1–3] opens up a new possibility for investigation of particle acceleration processes in the Universe. The neutrino production in cosmos is possible via the pp and $p\gamma$ interactions and the decay chains $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$, $\mu^{\pm} \to e^{\pm}\nu_e\nu_{\mu}$. The observed astrophysical flux emerges from under more steep air shower spectrum at about 50 TeV and has a cutoff at 2 PeV. Neutrinos typically carry a small part of the primary proton energy, $E_{\nu} \approx 0.05E_p$, so the protons with energies up to $E_{\max} \sim 10^{17}$ eV are required to explain the observations (this energy is $\sim 10^{17}$ eV/nucleon in the case of neutrino production by nuclei). Assuming an E^{-2} power-law spectrum, the measured differential flux of astrophysical neutrinos is $E^2F(E) = 2.9 \times 10^{-8}$GeV cm^{-2}s^{-1}sr^{-1} for the sum of the three evenly distributed neutrino flavors. The sources of observed neutrinos are not yet identified. The detected 54 events are scattered over the sky and do not show any evident correlation with any astronomical objects [3,4]. It seems that Galactic sources might account only for a minority of events. The detected astrophysical neutrinos could be produced in extragalactic sources of ultra high energy protons and nuclei. The discussion about potential sources of very high energy neutrinos in the light of the last experimental results can be found in [5–7] where other useful references are given.

Rare extragalactic Type IIn supernova remnants are considered in the present paper as sources of diffuse high energy neutrinos. It is well established that supernova remnants are efficient accelerators of protons, nuclei and electrons. They are the principle sources of Galactic cosmic rays. The diffusive shock acceleration mechanism suggested in [8–11] can provide the acceleration of protons and nuclei in the most frequent Type IIP, Ia, Ib/c supernova events up to about $10^{15}Z$ eV that allows to explain the spectrum and composition of Galactic cosmic rays with a proton-helium knee at 3 $\times$ 10^{15} eV and the maximum energy $\sim 10^{17}$ eV where iron nuclei dominate, see [12]. Two orders of magnitude higher $E_{\max} \sim 10^{17}$ eV/nucleon is needed to explain the IceCube neutrino observations. It can be achieved with the Type IIn supernovae that stand out because of extremely dense winds of their progenitor stars with a mass loss rate $10^{-3} - 10^{-1}$ $M_{\odot}$ yr $^{-1}$ [13]. As it will be shown below, the large kinetic energy of explosion and very high gas density in the acceleration region lead to the needed energy of accelerated particles and efficiency of neutrino production in pp interactions.

Diffusive shock acceleration by supernova shocks propagating in dense stellar winds was already considered in [14–16]. Simple analytical estimates showed that radiowaves, gamma-rays and neutrinos might be observable from the nearest Type IIn supernova remnants if the efficient diffusive shock acceleration takes place in these objects. In the present paper we develop this idea further and investigate whether the flux of neutrinos produced in extragalactic Type IIn supernova remnants can explain the IceCube data. For this purpose we perform a numerical modeling of the particle acceleration in a supernova remnant produced by Type IIn supernova explosion and calculate the neutrino production. Our model of nonlinear diffusive shock acceleration describes the remnant evolution and the production of energetic particles. The detailed description of the model was presented in [17] and the simplified version of the model was used in [12] for the explanation of the energy spectrum and composition of Galactic cosmic rays. Similar numerical models of diffusive shock acceleration in supernova remnants were developed and employed in [18–20].

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The paper is organized as follows. In the next Sections 2 and 3 we describe the modeling of particle acceleration and calculate the spectrum of neutrinos produced in Type IIn supernova remnants. These results are used in Section 4 for the calculation of the diffuse neutrino background in the expanding Universe. The discussion of results and conclusions are given in Sections 5 and 6.

2. Nonlinear diffusive shock acceleration model

Details of our model of nonlinear diffusive shock acceleration can be found in [17]. The model contains coupled spherically symmetric hydrodynamic equations and the transport equations for energetic protons, ions and electrons. The forward and reverse shocks are included in the consideration.

The hydrodynamical equations for the gas density $\rho(r, t)$, gas velocity $u(r, t)$, gas pressure $P_g(r, t)$, and the equation for isotropic part of the cosmic ray proton momentum distribution $N(r, t, p)$ in the spherically symmetrical case are given by

$$\frac{\partial\rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}r^2 u\rho \tag{1}$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - \frac{1}{\rho}\left(\frac{\partial P_g}{\partial r} + \frac{\partial P_c}{\partial r} + \frac{\partial P_m}{\partial r}\right) \tag{2}$$

$$\frac{\partial P_g}{\partial t} + u\frac{\partial P_g}{\partial r} + \frac{\gamma_g P_g}{r^2}\frac{\partial r^2 u}{\partial r} = -(\gamma_g - 1)\left(\Lambda(T)n^2 + (w-u)\frac{\partial P_c}{\partial r}\right) \tag{3}$$

$$\frac{\partial N}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}r^2 D(p,r,t)\frac{\partial N}{\partial r} - w\frac{\partial N}{\partial r} + \frac{\partial N}{\partial p}\frac{p}{3r^2}\frac{\partial r^2 w}{\partial r}$$
$$+ \frac{1}{p^2}\frac{\partial}{\partial p}p^2 b(p)N + \frac{\eta_f\delta(p-p_f)}{4\pi p_f^2 m}$$
$$\times\rho(R_f+0,t)(\dot{R}_f - u(R_f+0,t))\delta(r-R_f(t))$$
$$+ \frac{\eta_b\delta(p-p_b)}{4\pi p_b^2 m}\rho(R_b-0,t)(u(R_b-0,t)-\dot{R}_b)\delta(r-R_b(t)) \tag{4}$$

Here $P_c = 4\pi\int dpp^3 vN/3$ is the cosmic ray pressure, P_m is the magnetic pressure, $w(r,t)$ is the advection velocity of cosmic rays, T, γ_g and n are the gas temperature, adiabatic index and number density respectively, $D(r, t, p)$ is the cosmic ray diffusion coefficient. The radiative cooling of gas is described by the cooling function $\Lambda(T)$. The function $b(p)$ describes the energy losses of particles. In particular the energy losses due to pp interactions and the radiative cooling are important at early evolutionary stages of IIn supernovae.

Cosmic ray diffusion is determined by particle scattering on magnetic inhomogeneities. The cosmic ray streaming instability increases the level of magnetohydrodynamic (MHD) turbulence in the shock vicinity [9] and even significantly amplifies the absolute value of magnetic field in young supernova remnants [21,22]. It decreases the diffusion coefficient and increases the maximum energy of accelerated particles. The results of continuing theoretical study of this effect can be found in review papers [23,24]. In our calculations below, we use the Bohm value of the diffusion coefficient $D_B = pvc/3qB$, where q is the electric charge of particles, B is the magnetic field strength.

Cosmic ray particles are scattered by moving waves and it is why the cosmic ray advection velocity w may differ from the gas velocity u by the value of the radial component of the Alfvén velocity $V_{Ar} = V_A/\sqrt{3}$ calculated in the isotropic random magnetic field: $w = u + \xi_A V_{Ar}$. The factor ξ_A describes the possible deviation of the cosmic ray drift velocity from the gas velocity. We use values $\xi_A = 1$ and $\xi_A = -1$ upstream of the forward and reverse shocks respectively, where Alfvén waves are generated by the cosmic ray streaming instability and propagate in the corresponding directions. The damping of these waves heats the gas upstream of the shocks [25] that is described by the last term in Eq. (3). The heating limits the total compression ratio of cosmic ray modified shocks. In the downstream region of the forward and reverse shock at $R_b < r < R_f$ we put $\xi_A = 0$ and therefore $w = u$.

We use a simple approach to describe the magnetic amplification. It is assumed that a small fraction $0.5M_A^{-2} \sim 0.001$–0.01 of the shock ram pressure goes into the energy of the amplified magnetic field. The parameter M_A is similar to the Alfvén Mach number of the shock and determines the value of the amplified magnetic field strength far upstream of the shock. The field compression at the shock increases this value by a factor of 10, so the magnetic energy downstream equals several percent of the shock ram pressure. This is in agreement with the magnetic energy estimates obtained using the thickness of X-ray filaments in young SNRs [26].

Bell's non-resonant streaming instability [21] is a good possibility for the magnetic amplification. The acoustic instability can also effectively amplify magnetic fields at cosmic ray modified oblique SNR shocks propagating in stellar winds [27]. MHD turbulence created during the interaction of the pre-existing density inhomogeneities and the shock precursor could result in the magnetic field generation either [28]. An additional generation of turbulence that provides cosmic ray scattering near the shock may be also due to the development of a filamentary instability [29,30].

The amplified magnetic field might play a dynamical role downstream of the shock. We take the magnetic pressure and magnetic energy flux into account downstream of the shock (see also [31]). This is a new element in comparison with our work [17] where the magnetic field spatial distribution was prescribed. The magnetic energy density is transported in the downstream region as the gas with the adiabatic index γ_m. Its impact on the shock dynamics is taken into account via the Hugoniot conditions. Upstream of the forward shock where dynamical effects of magnetic fields are small, the coordinate dependence of the magnetic field B can be described as:

$$B(r) = \sqrt{4\pi\rho_0}\frac{V_f}{M_A}\left(\frac{\rho(r)}{\rho_0}\right)^{\gamma_m/2}, \tag{5}$$

Here ρ_0 and $\rho(r)$ are the undisturbed gas density at the shock position and the density of the medium where the shock propagates respectively, V_f is the speed of the forward shock. In the shock transition region the magnetic field strength is increased by a factor of $\sigma^{\gamma_m/2}$, where σ is the shock compression ratio. The expression similar to Eq. (5) is also used in the upstream region of the reverse shock.

Below we use the adiabatic index of isotropic random magnetic field $\gamma_m = 4/3$. For this value of the adiabatic index, the magnetic pressure $P_m = B^2/24\pi$ is three times smaller than the magnetic energy density $(= B^2/8\pi)$.

Two last terms in Eq. (4) correspond to the injection of thermal protons with momenta $p = p_f$, $p = p_b$ and mass m at the forward and reverse shocks located at $r = R_f(t)$ and $r = R_b(t)$ respectively[1]. The dimensionless parameters η_f and η_b determine the efficiency of injection.

We neglect the pressure of energetic electrons and treat them as test particles. The evolution of the electron distribution is described by equation analogous to Eq. (4) with function $b(p)$ describing synchrotron and inverse Compton (IC) losses and additional terms describing the production of secondary leptons by energetic protons and nuclei. The secondary electrons and

[1] We use indexes f and b for quantities corresponding to the forward and reverse (backward) shock respectively.