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High Energy Neutrino Sources

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High energy neutrino sources

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High energy cosmic neutrinos can be produced by protons and nuclei accelerated in cosmic sources ('acceleration' neutrinos) as well as by relic Big Bang particles, cosmic strings, etc. (neutrinos of non-acceleration origin). The most promising 'acceleration' sources of neutrinos are supernovae in our Galaxy and active galactic nuclei (AGN). Detectable diffuse fluxes of 'acceleration' neutrinos can be produced by AGN and during the 'bright phase' of galaxy evolution. During the past few years it has been realized that the detectable flux of high energy neutrinos can be also produced by the relic Big Bang particles. The possible sources are annihilation of the neutralinos accumulated inside the Earth and the Sun, decay of neutralinos (due to the weak breaking of R-parity), and the decay of exotic long-lived particles from the Big Bang.

1. Introduction

The cosmic production of high energy neutrinos can be distinctly subdivided into acceleration and non-acceleration production.

Acceleration production implies the production of neutrinos due to collisions of accelerated particles (protons or nuclei) with atomic nuclei (pp-neutrinos) or with low-energy photons (pγ-neutrinos). In both cases neutrinos are born in the chain of pion or kaon decays.

High energy neutrinos can be also produced due to the decays or annihilation of massive particles (non-acceleration generation). The postulated examples include annihilation of neutralinos in the Earth and the Sun, decay of neutralinos due to weak R-parity breaking, decay of heavy and superheavy particles of cosmological origin, and the production and decay of superheavy particles from cosmic strings.

The typical source of acceleration neutrinos is an accelerator submerged in a cloud of gas or low-energy photons. The most promising sources of these neutrinos are young supernova (SN) shells, hidden sources, and active galactic nuclei (AGN).

Young SN shells can give a detectable neutrino flux during one year after the explosion in our Galaxy. Protons can be accelerated by a pulsar or pulsar wind (shock acceleration) or by the shock produced by SN explosion (the outer acceleration). Neutrinos are produced due to pp-interaction of accelerated particles with the gas of the expanding shell or with the ambient gas outside the shell.

In the case of a hidden source the accelerator is covered by large column density of gas or photons, so that all other high energy radiations are absorbed. Examples are given by the Thorne–Zytkow star and AGN.

The low-energy limit for neutrino astronomy ($E_\nu \gtrsim 0.1-1$ TeV) is connected with detection rather than production. These neutrinos are mostly efficiently detected due

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to muons produced in $\nu_\mu + N \to \mu + \text{all}$ scattering. Both the cross section and the muon path length underground increases linearly with energy up to $E_\nu \approx 1$ TeV. Thus for the flat neutrino spectra usually considered, $F_\nu \approx E^{-\gamma}$ with $\gamma = 2.1$–2.3, most of the events occur at energy about 1 TeV. Neutrinos produced in pγ-collisions can reach energies higher than 10^6–10^7 GeV.

Apart from the point-like sources of high energy neutrinos (SN, hidden sources, AGN, the Earth and the Sun, due to annihilation of neutralinos there), there can be a detectable diffuse flux of neutrinos produced by AGN, the bright phase in galaxy evolution and decay of the Big Bang particles. The large flux of atmospheric neutrinos prevents measurement of the diffuse flux at energies less 10^4–10^5 GeV.

The references for the models described above, can be found in the book by Berezinsky *et al.* (1990). In this paper we shall concentrate on recent progress in the study of high energy neutrinos from AGN.

2. High energy neutrinos from AGN

Active galactic nuclei with the pγ-mechanism of neutrino production have attracted the attention of researchers since the end of the 1970s (Berezinsky 1977; Silverberg & Shapiro 1979; Berezinsky & Ginzburg 1981). A new possibility for neutrino production in AGN was found by Stecker *et al.* (1991). This possibility was recently further developed by Szabo & Protheroe (1992), Mastichiadis and Kirk, Biermann (1992), Kazanas and Giovanioni, Mannheim, and Sikora, and Begelman (see Stenger *et al.* 1992).

The essence of these models can be described in the following way.

The accretion onto a massive black hole is considered as the energy source. It is tacitly assumed that the accretion is quasi-spherical, though the authors usually speak about radiation from the disc. One can consider a thick accretion disc with the width of the order of the radial distance to reconcile both ideas. The radial flow of accreting gas terminates by the shock at radial distance $r = r_{sh} = 20\, r_g$, where $r_g = GM/c^2 = 1.5 \times 10^{13} M_8$ cm, and $M = M_8 \times 10^8 M_\odot$ is the mass of the black hole. The protons are accelerated at the shock and produce neutrinos in pγ-collisions with the ambient photons. The flux of these photons and their spectrum is not calculated; it is taken from observations, and self-consistency of the models remains thus an open problem. According to the observations, the photons have a power-law spectrum with index $\alpha = -1.7$ and with a UV bump centred at $\epsilon \approx 30$ eV. A remarkable feature of these models is that only high energy neutrinos and soft X-rays can escape from the source. The protons accelerated at the shock front cannot diffuse upstream, rather they are dragged by the gas flow downstream until they are trapped by the black hole. The hard X-rays and gamma rays are absorbed due to $\gamma + \gamma \to e^+ + e^-$ collisions. In the model of Stecker *et al.* (1991) even high energy neutrons are absorbed in nγ-collisions. (As was noted in the papers by Berezinsky (1992) and Szabo & Protheroe (1992), the diffuse X-ray radiation in the model of Stecker *et al.* (1991) was overproduced by factor 30–50. A revised version of the calculations is given in the paper by Stecker *et al.* (1992).) Paradoxically, the neutrino radiation from individual galaxies is not observed, but the diffuse radiation, with the effects of galactic evolution taken into account, can be very large.

A compilation of the recent calculations for $\nu_\mu + \bar{\nu}_\mu$ neutrino fluxes is given in figure 1. The reference flux is that of atmospheric neutrinos (atm): only fluxes above

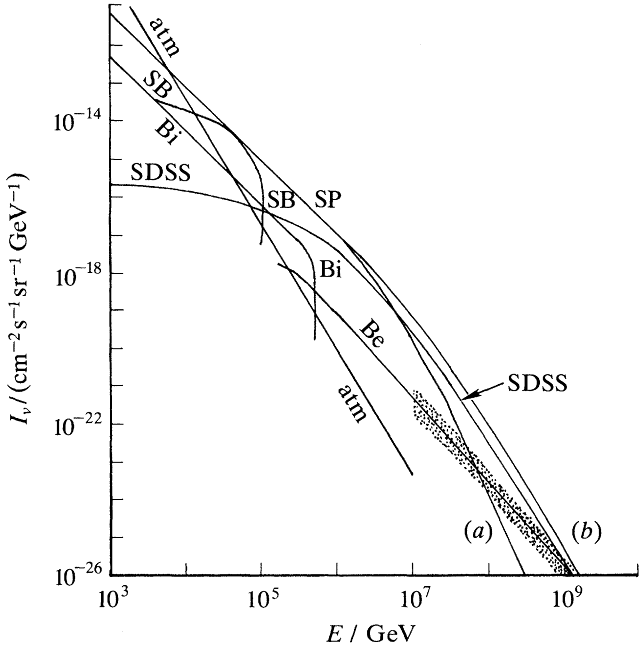

Figure 1. Diffuse fluxes of $\nu_\mu+\bar{\nu}_\mu$-neutrinos from AGN. The following notation is used: atm, atmospheric neutrino flux; SDSS, Stecker *et al.* (1992); SP, (*a*) and (*b*), Szabo & Protheroe (1992); SB, Sikora & Begelman (1992); Bi, Biermann (1992); Be, Berezinsky (1977). The shaded area refers to the flux from the bright phase in galaxy evolution (Berezinsky & Ozernoy 1981).

it are detectable. The flux as calculated by Stecker *et al.* (1992) is given by curve SDSS. Only pγ-neutrino production is considered in this work. Much more detailed calculations were performed by Szabo & Protheroe (1992) for the model basically similar to the Stecker model. At low energies the neutrino flux as calculated by Szabo & Protheroe, is higher than in the Stecker model due to pp-production of neutrinos having been taken into account (see the SB curve in figure 1). The curves (*a*) and (*b*) correspond to the different assumptions about radial velocity of the gas flow. Biermann (1992) used a somewhat different model (see the curve Bi in figure 1). He assumed acceleration by the shock in the jet emitted from the inner part of the accretion disc. Neutrinos are produced in pp-collisions. Non-transparency for hard X-rays and soft γ-radiation is not explicitly shown in this paper. If we assume that half of the energy of the accelerated protons is transferred to the photons, we obtain equipartition between magnetic field and photon field. In this case, according to the formula given by the author, the maximum neutrino energy is about 5×10^5 GeV, as shown in figure 1.

The calculations by Sikora & Begelman (1992) are performed in a more self-consistent fashion. Their results for a red shift $z=5$ are shown by the curve SB.

The curve Be gives the flux for a different AGN model (Berezinsky 1977). The dotted area is for the flux from the bright phase in the galaxy evolution (Berezinsky & Ozernoy 1981).

As one can see from figure 1 the crucial problem for the detectability of diffuse neutrino flux is the maximum energy for the accelerated protons and thus for neutrinos.

We shall consider here this problem in some detail.

There are two points where the calculations below are different from the calculations of other authors. Stecker *et al.* (1991, 1992) and Szabo & Protheroe (1992) claim that the maximum proton energy is proportional to the luminosity. In both works $L \propto M$ is used, while actually

$$L \propto GM\dot{M}/r_{sh} \propto \dot{M}c^2,$$

and E_p^{max} should be considered as a function of two independent parameters: L and M, or M and $\dot{M}$.

The second point is the gravitational energy release between $r_{sh} = 20r_g$ and $r_{hor} = 2r_g$, which is neglected in most calculations. Allowance for it increases the density of the target photons and thus decreases the proton maximum energy.

Let us assume that 10% of the gravitational energy release at $r = r_{sh}$ is transferred to the protons, and half of it to neutrinos,

$$L_\nu = 0.05\ GM\dot{M}/r_{sh}, \tag{1}$$

where G is the gravitational constant, M is the mass of the black hole, and $\dot{M}$ is the rate of accretion.

Assuming that 10% of the gravitational energy at $r > 2r_g$ is transferred to X-ray radiation,

$$L_x = 0.1\ GM\dot{M}/2r_g, \tag{2}$$

we obtain

$$L_x/L_\nu \approx r_{sh}/r_g = 20. \tag{3}$$

Let us assume further that this X-ray radiation is reprocessed by the cascade process to the power-law spectrum,

$$n_x(\epsilon) \propto \epsilon^{-1.7}, \tag{4}$$

with a cut off at $\epsilon_m \approx 1$ MeV. Then we obtain for the number density of the photons which are able to photodissociate a proton with energy E_p to a nucleon and pion:

$$n_X(>\epsilon) = \frac{60}{7\pi}\frac{L_\nu}{cr_{sh}^2\,\epsilon_m}\left(\frac{\mu m_p}{E_p\,\epsilon_m}\right)^{-0.7} \tag{5}$$

where μ and m_p are the masses of pion and proton, respectively.

The maximum proton energy E_p^{max} can be found equalizing the acceleration time

$$t_{acc} = \frac{3}{u_1 - u_2}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right) \tag{6}$$

and the characteristic time of energy losses due to photopion production

$$t_{loss} = (0.5\,\sigma_{p\gamma}\,n_X(>\epsilon)\,c)^{-1}. \tag{7}$$

In (6) and (7) u_1 and u_2 are the fluid velocities upstream and downstream, respectively ($u_1/u_2 = 4$ for strong shock), D_1 and D_2 are the diffusion coefficients upstream and downstream, respectively, $\sigma_{p\gamma}$ is the cross section of pion production, and $n_X(>\epsilon)$ is given by (5). Using for the diffusion coefficients $D \approx r_B\,c$, where $r_B = E/eB$ is gyroradius and B the magnetic field, we obtain

$$\frac{E_p^{max}}{\sqrt{(\mu m_p)}} = \left(\frac{7\pi}{600}\frac{eBcr_{sh}^2}{L_\nu\,\sigma_{p\gamma}}\frac{u_1^2}{c^2}\right)^{0.588}\left(\frac{\epsilon_m}{\sqrt{(\mu m_p)}}\right)^{0.176}. \tag{8}$$

Putting in (8) numerical values $B = 1\times10^3$ G, $\epsilon_m \approx 1$ MeV, $\sigma_{p\gamma} = 1\times10^{-28}$ cm^2 and $u_1 = \xi u_{ff}$, where $u_{ff} = c(2r_g/r_{sh})^{\frac{1}{2}}$ is the free-fall velocity at the position of the shock $r_{sh} = 20r_g$, and ξ is a numerical coefficient with a value between $\frac{1}{3}$ and $\frac{1}{10}$, we obtain (for $\xi = \frac{1}{3}$)

$$E_p^{max} = 3.7\times10^6\ L_{45}^{-0.588}\ M_8^{1.18}\ \text{GeV}, \tag{9}$$

where L_{45} is the neutrino luminosity in units of 10^{45} erg s^{-1}. The related cut-off energy in the diffuse neutrino spectrum is

$$E_\nu^{max} = 6.2\times10^4\ L_{45}^{-0.588}\ M_8^{1.18}\ (3/(1+z_{eff})). \tag{10}$$

If an ultraviolet bump is also formed at $r \approx 2r_g$ (e.g. due to the radiation of cold dense clouds (M. Rees, personal communication), then it is enough to have $L_{UV} \approx 0.01\ GM\dot{M}/(2r_g)$ for the effective energy losses of protons. The maximum energy of the proton is determined in this case by the kinematical condition of pion production on photons with energy $E_{UV} \approx 30$ eV:

$$E_p^{max} \sim \mu m_p/\epsilon_{UV} \sim 4\times10^6\ \text{GeV}, \tag{11}$$

which is practically the same as given by (9).

As one can see, these calculations are in good agreement with that by Sikora & Begelman (1992).

A short comment is in order.

The assumption of Stecker *et al.* (1991, 1992) and Szabo & Protheroe (1992) $L \propto M$ holds for the models with $\dot{M} \propto M$ (which is generally not true). Equation (9) gives in this case $E_p^{max} \propto L_{45}^{0.6}$. Since $M_8 \lesssim 10$ one can gain only a factor 4 for the maximum proton (neutrino) energy.

3. Conclusions

In this paper attention is given mostly to a review and discussion of the diffuse high-energy neutrinos flux from AGN. The crucial parameter for the detectability of the flux is the maximum energy of accelerated protons. On the basis of gravitational energy release at distances smaller than the shock radius, r_{sh}, we claim that the maximum proton energy is about 4×10^6 GeV for AGN with neutrino luminosity $L_\nu = 1\times10^{45}$ erg/s and for the mass of black hole $M = 1\times10^8\ M_\odot$. Therefore, the diffuse flux from AGN can produce a bump over the atmospheric neutrino flux with energy centred about 6×10^4 GeV.

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