V. S. Berezinskiĭ. *High energy neutrino astrophysics.* Cosmic neutrinos with $E_\nu \gtrsim 3$–100 GeV are produced in sources as a result of the interaction of accelerated protons and nuclei with a gas or with low energy photons: as result of this interaction charged π and K mesons are produced, in the decay chains of which neutrinos are formed. The idea of the existence of high energy cosmic neutrinos and of the possibility of recording them was proposed for the first time by M. A. Markov in 1959,[1] and the principal sources and the contemporary possibilities of high energy neutrino astrophysics were discussed for the first time in the review article of Ref. 2.

Neutrino astrophysics can be naturally subdivided into the fields of high and superhigh energies. The latter is characterized by neutrino energies of $E_\nu \gtrsim 10^7$ GeV. The generation of these neutrinos is dominated by the $p\gamma \to \pi^+ X$ processes, in the recording of these neutrinos the resonance production of a W^- boson ($\nu_e + e^- \to W^- \to$ hadrons) and the use of acoustic or radio methods of registration[3] enable one to hope for the future use of gigantic detecting volumes of a natural substance (water, ice). The present paper discusses high energy neutrino astrophysics ($E_\nu \gtrsim 30$–100 GeV). The production of neutrinos at these energies is dominated by the $pp \to \pi^\pm X$ processes, and the recording is dominated by $\nu_\mu N \to \mu^\pm X$ scattering. At an energy of $E_\mu \gtrsim 30$–100 GeV the muon preserves practically the direction of the neutrino giving rise to it, as a result of which an underground (underwater) muon detector is a neutrino telescope. Muons with an energy of $E_\mu \gtrsim 100$ GeV have a range in soil exceeding $0.5 \cdot 10^5$ g/cm^2, in the case of detectors of relatively small volume muons are produced primarily outside the detector and the determining parameter for the possibility of recording a neutrino flux turns out to be the detector area.

At present several underground detectors of high energy neutrinos are in operation with an area of $S \sim 100$ m^2. The most effective of these is the Baksan neutrino telescope of the Institute of Nuclear Research of the Academy of Sciences of

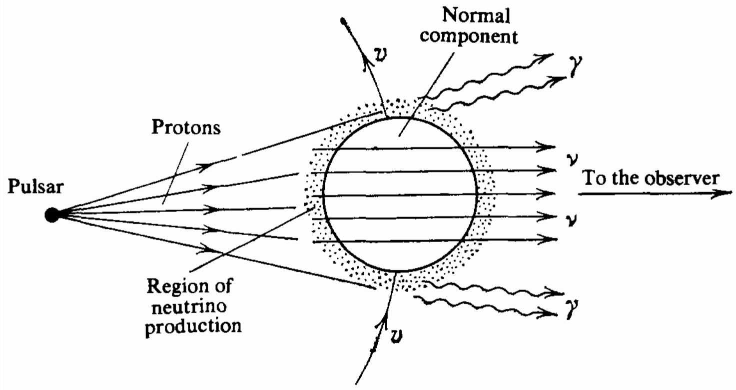

FIG. 1

the USSR [4], of dimensions $16\times16\times11$ m^3. The LSD detector (Institute of Nuclear Research of the Academy of Sciences of the USSR, the Institute of Cosmic Geophysics, Turin) under the Mont Blanc of dimensions $8\times7\times5$ m^3 has good possibilities for detecting high energy neutrinos. The recording of high energy cosmic neutrinos is also one of the tasks of proton decay detectors: IMB-USA (dimensions $22.8\times16.9\times17.8$ m^3); KEK-Japan (cylinder of diameter 15.6 m and height 16 m); "Frejus"-France, FRG ($18\times6.2\times6.2$ m^3); NUSEKS-Italy ($3.5\times3.5\times3.5$ m^3). Work is in progress on constructing a specialized deep underwater neutrino telescope in the Baikal of area $S\sim10^5$ m^2.[5] The project of the deep underwater installation DUMAND in the USA proposes an even greater detector area.

The horizon of the presently existing underground detectors of area $S\sim100$ m^2 is limited by the bounds of our Galaxy. In undertaking recording with a detector with $S\sim100$ m^2 even for galactic sources the luminosity in the form of accelerated particles must amount to 10^{41}–10^{43} erg/s with the index of the total production spectrum $\gamma=1.1$–1.3. Sources with such high luminosity must be short lived (for example, $\tau\sim10$ years for a pulsar with $L\sim10^{43}$ erg/s). An example of such a neutrino source is the dense outer shells of supernovae during the period from 2 weeks to 5 months after a flareup.[6] Protons can be accelerated both by the Fermi mechanism directly in the outer shell, and in the magnetosphere of a young pulsar. Flareups of supernovae in the Galaxy are expected to occur with the frequency of 10^{-1} to 10^{-2} a^{-1}. Another model is a close binary system with a young pulsar as the compact companion.[7]

An interesting class of objects are the so-called "hidden" neutrino sources. They are characterized by a relatively low flux of radiation (from $pp\to\pi^0X$, $\pi^0\to2\gamma$ reactions). An example of such a source is the binary system of an active pulsar and the core of a giant star, both situated within a common outer shell,[8] the gamma radiation is absorbed in the outer shell and according to all the observational parameters the star does not differ in any respect from a usual giant star with the exception of the fact that it emits a flux of high energy neutrinos.

At the present time the greatest interest is evoked by the model of a hidden source which represents an unusual "neutrino pulsar"[8] (cf., Fig. 1): a beam of protons accelerated in the magnetosphere of a young pulsar gives rise to neutrinos (by means of the $pp\to\pi^\pm X$, $\pi^\pm\to\mu\nu$, $\mu\to e\nu\bar\nu$ reaction) in the atmosphere of the massive component on the "opposite" (with respect to the observer) side of the star. The observed γ radiation is generated when the atmosphere crosses the line of sight with a thickness of $x\sim10$–100 g/cm^2: at lesser thicknesses the production of pions by the beam is not effective, and at greater thicknesses the γ radiation is absorbed. As a result, the γ flux is reduced compared with the neutrino flux by a factor τ_γ/τ_ν, where τ_γ and τ_ν are the duration of the gamma and the neutrino pulses $\tau_\nu\sim2R/v$ and $\tau_\gamma\sim H/v$, where R is the radius of the normal component, v is the velocity of orbital motion, H is the height of the homogeneous atmosphere of the star).

The model described above was used in Ref. 9 to explain the high energy radiation from Cygnus X-3.[10]

We present the results of our calculations of the flux of neutrinos of energy higher than E from Cygnus X-3 on the assumption that the pulsar emits accelerated protons in the form of a beam of solid angle Ω and with the energy spectrum $AE^{-(\gamma+1)}$

$$j_{\nu_\mu+\bar\nu_\mu}(>E)=\frac{1}{4\pi r^2}\,\frac{\gamma-1}{\gamma}\,\frac{1}{1-\alpha^\gamma}(\varphi_{\nu_\mu}+\varphi_{\bar\nu_\mu})\cdot\frac{4\pi}{\Omega}\,\frac{R}{\pi A}\,L_pE^{-\gamma};\qquad(1)$$

here $j_{\nu_\mu+\bar\nu_\mu}$ is the flux of muon neutrinos and antineutrinos averaged over the observed period of the source $T=4.8$ h, $r=10$ kpc is the distance to Cygnus X-3, γ is the index of the total proton spectrum, $\alpha\approx0.5$ is the fraction of the energy retained by a proton in a pp collision, φ_{ν_μ} and $\varphi_{\bar\nu_\mu}$ are the dimensionless neutrino yields[11], R is the radius of the star, A is the distance between the star and the pulsar, L_p is the luminosity of the pulsar in accelerated particles expressed in GeV/s and E is the neutrino energy in GeV; the coefficient $R/\pi A$ in (1) is related to the duration of the neutrino pulse $\tau_\nu=(R/\pi A)\,T$. The flux of gamma radiation of energy above E is expressed by a similar formula

$$j_\gamma(>E)=\frac{1}{4\pi r^2}\,\frac{\gamma-1}{\gamma}\,\frac{1}{1-\alpha^\gamma}\,\varphi_\gamma\,\frac{\varphi\pi}{\Omega}\,\frac{\tau_\nu}{T}\,L_pE^{-\gamma},\qquad(2)$$

where $\varphi_\gamma=0.95\,(\varphi_{\nu_\mu}+\varphi_{\bar\nu_\mu})$.

For $E\gtrsim10^3$ GeV the observed gamma flux amounts to $j_\gamma(>1$ TeV$\approx3\cdot10^{-11}$ cm^{-2} s^{-1} and $\gamma\approx1.0$ for energies up to $E_\gamma\approx10^3$ TeV. The number of muons with energy above 1 TeV, crossing per year an underground detector with $S\approx100$ m^2 is equal to

$$n_\mu(>1\,\text{TeV}) \approx 6{,}7\cdot 10^2 \frac{4\pi}{\Omega}\,\frac{R}{\pi A}\,\frac{L_p}{10^{43}\,\text{erg/s}}.$$

Agreement with the gamma flux given by (2) in this case requires a small value of τ_γ/T.

Recently preliminary data have been obtained on recording the muon flux in the direction of Cygnus X-3 by the detectors NUSEKS and IMB. It is not clear whether they can be interpreted with the aid of a neutrino flux from this source.

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