V. S. Berezinskii. *The neutrino astronomy of high energies: sources and fluxes.* The idea of detecting high-energy cosmic neutrinos was first advanced by M. A. Markov in 1959.[1] Along with atmospheric neutrinos, he also discussed neutrino fluxes of extraterrestrial origin. During the last five years, these ideas have been developed[2-9] into an astronomy of high-energy neutrinos, the purpose of which is to search out cosmic objects by their neutrino emission. An important stimulus to this development was the series of workshops of the DUMAND project, which was originally conceived as a detector for atmospheric muons and neutrinos and was gradually transformed into a giant (10^9 m^3) underwater neutrino telescope project.

High-energy neutrino radiation is generated in cosmic objects as a result of collisions of accelerated particles (cosmic rays) with atomic nuclei (*pp* neutrinos) or with low-energy photons ($p\gamma$ neutrinos) in the decay chain of charged pions:

$$\begin{array}{ll} p+p\to\pi^{\pm}+\text{all others} & p+\gamma\to\pi^{\pm}+\text{all others}\\ \quad\hookrightarrow\mu\nu & \quad\longrightarrow\mu\nu\\ \qquad\hookrightarrow e\nu\bar{\nu} & \qquad\hookrightarrow e\nu\bar{\nu}\end{array}$$

The neutrino removes on the average 4–5% of the energy of the incident proton in each of these processes.

For a power-law spectrum of the accelerated protons ($\sim E^{-(\gamma+1)}$ for the differential spectrum), the number of neutrinos generated in the *pp* interaction increases with decreasing energy, but detection of the source is due largely to neutrinos with energies above 50 GeV. This is because the direction to the source is determined in the experiment from the path of a muon produced in the reaction $\nu_\mu+N\to\mu+\text{all}$. The angle of escape of the muon with respect to the direction of motion of the neutrino increases with decreasing energy, with the result that the background formed by atomospheric neutrinos within this angle also increases. For the usual source spectra ($\gamma<2$), moreover, most of the muons that penetrate the detector are produced with energies above 50 GeV, since the path length of muons in soil (or water) and the νN cross section increase linearly with the energy of the neutrinos. Thus, *pp* neutrinos with energies ~50–1000 GeV define the neutrino astronomy of ***high energies***.

Unlike that of the *pp* neutrinos, the production of $p\gamma$ neutrinos occurs in threshold fashion: in a "photon gas" with an average photon energy ω (in eV), most of the neutrinos are produced with energies in excess of $E_0\approx4\cdot10^{-2}\ \mu m_p/\omega\approx6\cdot10^6/\omega$ GeV, where μ and m_p are the masses of the pion and the proton. The thickness of the gas is small (less than 1 g/cm^2) for nearly all presently known sources, while the photon gas has such high densities for some sources (for example, galactic nuclei) that they are opaque to high-energy protons. This makes the $p\gamma$ mechanism of neutrino generation highly effective. It is interesting that for many sources, the $p\gamma$ mechanism gives a neutrino threshold energy of $\sim5\cdot10^6$ GeV, so that $E\gtrsim5\cdot10^6$ GeV defines the range of *superhigh-energy* neutrino astronomy. Intensity losses in the superhigh-energy-neutrino flux due to the dropoff ($\sim E^{-\gamma}$) of the proton spectrum are offset by the enhanced effectiveness of $p\gamma$ neutrino production, a significant increase in the interaction cross section of the neutrinos in the detector (due to the reaction $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons, which has a maximum in cross section at an energy of $5.5 \cdot 10^6$ GeV), and the possibility of using large volumes of water in acoustic neutrino detection. At superhigh energies there is not only the possibility of detecting discrete neutrino sources, but also the possibility of measuring the diffuse flux, since the atmospheric-neutrino background weakens considerably at these energies.

The neutrino astronomy of high and superhigh energies offers several unique opportunities as compared to gamma astronomy. In particular, it enables us to investigate dense objects and cosmologically remote times that are inaccessible to gamma-astronomical tools.

High-energy neutrino astronomy can employ only optical means of detection (G. T. Zatsepin's paper is devoted to this subject), in which the maximum volume of the detector will evidently be limited to 10^9 m^3. At this volume it will be possible to detect galactic sources and only isolated events from extragalactic sources. In other words, the neutrino astronomy of high energies (50–1000 GeV) is essentially a galactic astronomy. The most interesting galactic sources are young (less than 1 year old) supernova shells and "hidden sources"—pulsars or black holes surrounded by a large thickness of matter.

Young supernova shells may contain cosmic rays as a result of various accelerating processes: pulsar acceleration in the rarefied space between the pulsar and the shell, magnetic-dipole acceleration in the shell, or plasma acceleration mechanisms in the shell (reclosing of magnetic force lines, plasma turbulence, etc.). For a shell with a mass $M \sim 1\ M$ and an expansion rate of $\sim 1 \cdot 10^9$ cm/sec, nuclear cosmic-ray energy losses dominate for ~5 months, so that the shell is an active neutrino emitter during this time. The Baksan neutrino telescope can register a neutrino flux with energies $E \sim 100$ GeV from a supernova outburst 10 kpc distant if the cosmic-ray luminosity of the source is $\sim 10^{41}$ erg/sec; for an installation with an area of 1 km^2, the necessary luminosity is $2 \cdot 10^{37}$ erg/sec.

As an example of a "hidden source," let us consider a supergiant with a mass of 10 $M_\odot$, a shell radius $R \approx 7 \cdot 10^{13}$ cm, and an average shell density $\bar{\rho} \approx 3 \cdot 10^{-9}$ g/cm^3 with a binary system at its center: a pulsar and a massive-star core similar to a white dwarf. If the luminosity of the pulsar is $3 \cdot 10^{38}$ erg/sec, i.e., above the Eddington limit for a neutron star (pulsar), radiation pressure will create a vacuum space around the pulsar and, at the same time, the luminosity will remain below the Eddington limit for the entire system ($1.3 \cdot 10^{39}$ erg/sec). Cosmic rays accelerated in the cavity will produce pp neutrinos in the shell—the only type of radiation that escapes to the outside—since the x-ray and γ radiations are fully thermalized in the shell (which has a thickness of $\sim 2 \cdot 10^5$ g/cm^2). As observed in all types of electromagnetic radiation, the system would look like an ordinary giant with a luminosity of $\sim 2 \cdot 10^{38}$ erg/sec and a temperature of ~2500 K, and only detection of its neutrino emission would bring out its complex structure.

Two more interesting extragalactic neutrino sources should be mentioned: active galactic nuclei and young galaxies in the bright phase of their development.

High-energy neutrino fluxes from galactic nuclei are expected both in the magnetoid model and in the black-hole model. This stems from the possibility of acceleration of the particles to high and superhigh energies in these models and from the presence of gas and electromagnetic radiation in the nucleus of the galaxy. These models can be differentiated on the basis of the relation between the neutrino and gamma-ray fluxes.[8]

One of the most intriguing possibilities presented by neutrino astronomy is the hope of peering into the remote past of the Universe, all the way to red shifts $z \approx 10$-30, in a search for the "bright phase" of galactic development, i.e., the period of formation of first-generation stars and other violent processes that accompany the formation of galaxies.[3,9] Of all the high-energy particles produced during that period, only neutrinos could have survived to the present day. The neutrino spectrum generated in collisions of accelerated protons with relic photons has a maximum at an energy that is directly related to the red shift z of the bright-phase epoch:

$$E_m = 6.1 \cdot 10^6 \left(\frac{20}{1+z}\right)^2 \text{GV} .$$

Thus, if the flux is large enough to permit measurement of the neutrino spectrum, the bright phase could be dated by determining the position of the maximum of the spectrum.

We estimate that problems of extragalactic astronomy will require a detector volume of $\sim 3 \cdot 10^{11}$ m^3, which is attainable only in the acoustic detection technique. Measurement of diffuse neutrino fluxes at $E \sim 5 \cdot 10^6$ GeV (i.e., near the maximum of the $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons resonance) will be aided by the smallness of the atmospheric-neutrino flux at these energies. The expected numbers of events with energies above $5 \cdot 10^6$ GeV are 100–1000 yr^{-1} from the bright phase, 100 yr^{-1} from Seyfert galaxies, and 20 yr^{-1} from "direct" atmospheric neutrinos.

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