A SEARCH FOR COSMIC SOURCES OF HIGH ENERGY NEUTRINOS WITH "SMALL" UNDERGROUND DETECTORS

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ABSTRACT

On the basis of our standard source calculations (Berezinsky et al., these proceedings) of high energy neutrino fluxes, we discuss some models of astrophysical object (single stars and binary systems), from which a detectable muon flux is expected in small underground detectors.

1. Introduction. In connection with the discussions on the DUMAND project[1], high energy neutrino sources were extensively studied (2-6). In particular, the feature of such a discussion was on sources which can be detected with very large underwater detectors, with area of order 1 km^2. In recent years, with the aim to search for proton decay, relatively small underground detectors have been built, which are used for several other purposes. As regards high energy neutrino astronomy, their small area in comparison to the DUMAND project limits the number of sources which are possibly detectable.

High energy neutrinos can be produced in cosmic sources as a result of pp-collisions between accelerated protons and the ambient gas through the chain of pions and kaons decays, as well as charmed mesons decay (prompt neutrinos). The main reaction for detection is $\nu_\mu + N \rightarrow \mu + X$, being, at large depth underground, the main background mainly due to atmospheric neutrinos. Since the path-length of high energy muons in the rock is large, while the dimensions of the underground detectors relatively small, muons are produced mainly outside the detector; moreover, since high energy muons retain the same direction of the parent neutrinos, the source is seen within the resolution angle of the detector.

The low energy limit of the experimental neutrino astronomy is defined by the angle $\vartheta_{\nu\mu}$ between the parent neutrino and the muon produced in the νN-collision. Since this angle $\vartheta_{\nu\mu} \approx 2.6\,(100\ \mathrm{GeV}/E_\nu)^{1/2}$ degrees increases with decreesing neutrino energy, the background within the resolution angle of the detector increases at low energies; at the same time, also the νN cross-section and the range of muons decrease. All these factors reduce the muon flux and, consequently, the signal to noise ratio in the direction of the source at low energy ($E_\nu \lesssim 10$ GeV).

Our calculations of a "standard source" of high energy neutrino astronomy (paper I, these proceedings) show that the horizon for small detectors (area $S \approx 100\ m^2$) is limited to our Galaxy. If the sources were transparent to gamma rays, then there will be a connection between neutrino and gamma fluxes; in this case, the limits on the gamma ray flux ($f_\gamma < 10^{-6}$ $cm^{-2}s^{-1}$ for the existing sources) show that in our Galaxy we cannot expect to observe stationary neutrino sources. Then we are left with the possibility to detect transient or hidden sources. The aim of this paper is to discuss such a sources of high energy neutrinos, and their detection with small underground detectors ;see (7) for a general discussion.

2. Detectable high energy neutrino sources.

2.1 It is well known that young supernova shells, filled with high energy particles, are a powerfull source of high energy neutrinos (8) during a period $\tau_\nu \approx 1.3\ 10^7$ s, (at time $t > \tau_\nu$ the high energy particles in the shell loose energy mainly due to the adiabatic expansion). Our standard source calculations are directly applicable to such a model, and, for a source located at the distance r = 10 kpc, with a cosmic ray luminosity $L_p = 10^{43}$ erg/s and an exponent $\gamma = 1.3$ of the integral spectrum (which is the commonly accepted value for the cosmic ray production), our results predict that of order 100 muons with energy $E_\mu \gg 1$ TeV cross an underground detector with an area $S = 100\ m^2$ during 1 year. This is undoubtely a detectable neutrino source.

For a steep spectrum ($\gamma = 2.1$), a cosmic ray luminosity $L_p = 10^{44}$ erg/s is needed to detect 5 muons with energy $E_\mu \gg 10$ GeV in the same detector during the same time. In this case, a rather high luminosity of the source is required, and nevertheless the signature remains poor.

2.2 A neutrino source made by an active pulsar imbedded in a supergiant (9), a model previously (10) considered in detail, can be easily interpreted on the framework of our standard source. Both for a flat spectrum ($\gamma = 1.3$) and for a steep one ($\gamma = 2.1$), the results on the flux of neutrino-produced muons in an underground detector with area $S = 100\ m^2$ are the same as for the previous case 2.1. This is, however, an example of a hidden source since, because of the large column density ($x \sim 10^5$ g/cm^2) along the supergiant radius, no gamma-rays are emitted from the surface of the system, and the source could be detected only through its neutrino emission.

2.3 A pulsar in a binary system yields neutrinos in the direction of the Earth during the eclipse of the pulsar by the companion, because neutrinos are produced in the atmosphere of the latter, opposite to the line of sight to the observer. Our standard source calculations are applicable for the total duration of the eclipse ($t_\nu \approx 2\ 10^6$ s, if the companion is a 5 $M_\odot$ giant); for r = 10 kpc, $L_p = 10^{43}$ erg/s and $\gamma = 1.3$, the number of recorded muons per orbital period is ~ 20 at the energy threshold $E_\mu = 10$ GeV. In this case, it would also be possible to discover the periodicity of the neutrino emission from the system.

If the companion is a main sequence star with $M = 1\ M_\odot$, the nùmerical estimates are practically the same as for the previous model; however, in this case it is impossible to discover the periodicity of the neutrino pulsation.

2.4 As a result of accretion, a white dwarf in a binary system can undergo a supernova explosion with complete distruction. The energy emitted as cosmic rays, accelerated by the shock wave in the outer layers of the star, can reach an energy of 10^{51} erg, and neutrinos are produced when the accelerated protons hit the giant companion. Our standard source calculations predict that more than 200 muons with energy $E_\mu \geqslant 100$ GeV cross the $S = 100\ m^2$ underground detector during the short burst duration if the total energy emitted as cosmic rays is $3\ 10^{50}$ erg and the spectrum is flat ($\gamma = 1.3$).

3. High energy neutrinos from Cygnus X-3. We devoted(11) a special attention to Cyg X-3, which is currently interpreted in the framework of a binary system, proposed in 1979 (10) and further developed in 1982 (12), made by an active pulsar orbiting around a massive companion with orbital period of 4.8 hours. By connecting the neutrino and gamma-ray fluxes (assuming a target transparent to gamma rays) and by using the observed gamma radiation to fit the spectrum, one finds that the neutrino flux is:

$$j_\nu(>E) = \lambda\, 4.2\ 10^{-11}\ (\ E/1\ \mathrm{TeV})^{-1.1} \tag{1}$$

where λ is an enhancement factor that, for a gamma transparent target, is equal to the ratio of the durations of the neutrino and gamma pulses ($\lambda = \tau_\nu / \tau_\gamma$). By introducing this neutrino flux in our standard source calculations it is possible to estimate the number of muons crossing in 1 year an underground detector; for a 100 m^2 area detector, and for energy thresholds 10 GeV, 100 Gev, and 1 Tev one finds the values $6\ 10^{-3}\ \lambda$, $5\ 10^{-3}\ \lambda$, and $3\ 10^{-3}\ \lambda$ respectively. Therefore, to detect high energy neutrinos from Cyg X-3 in a small detector, a large enhancement factor $\lambda \gg 10^3$ is needed; however, this imposes serious constraints on the luminosity of the cosmic ray source in the binary system, that seem to be reasonable only for a young pulsar while any steady source should be ruled out.

The explanation of the excess of muons in the direction of Cyg X-3 observed in the Mont Blanc NUSEX experiment (13), as due to a flux of high energy neutrinos, requires the extreme choise of the parameters in the model; in particular it implies a very large cosmic ray luminosity of the source $L_p \approx 10^{42} - 10^{43}$ erg/s. With a neutrino flux compatible with the gamma ray observations, the interpretation of the muon excess as produced by neutrinos should be excluded. In addition the flux of muons produced by neutrinos is independent of the column density of rock above the detector, and this feature is in contraddiction with the NUSEX data. Thus we can conclude that the neutrino hypothesis to explain the excess of muons in the small detector seems to be unreasonable.

4. Conclusions. Neutrino astronomy with a small underground detector is characterized by the following considerations:

i) The low energy limit of neutrino astronomy is defined by the angle $\vartheta_{\nu\mu}$ between the parent neutrino and the muon produced in the inelastic νN collision; this limit is of order of $E_\mu \sim 10$ GeV.

ii) Only galactic sources can be detected with a small detector: at r = 10 kpc a cosmic ray luminosity $L_p = 10^{43}$ erg/s is needed. To detect extragalactic sources the scale of luminosity is $L_p = 10^{47}$ erg/s at r = 1 Mpc, and $L_p = 10^{49}$ erg/s at r = 10 Mpc.

iii) A detectable neutrino flux is expected for several models of sources: young supernova shells, supergiant fed by an active pulsar in its debris, and several models of binary systems (pulsar and giant, supernova explosion in the system).

iv) Under reasonable assumption, the detection of the neutrino flux from Cyg X-3 in a small underground detector seems to be excluded.

v) Our standard source calculations exclude the possibility to detect neutrinos from flares in the opposite side of the Sun or from the decay of solar neutrons.

References

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