High Energy Neutrinos: Sources and Fluxes

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Abstract. We discuss briefly the potential sources of high energy astrophysical neutrinos and show estimates of the neutrino fluxes that they can produce. A special attention is paid to the connection between the highest energy cosmic rays and astrophysical neutrinos.

1. Introduction

High energy is defined here as that of neutrinos above atmospheric neutrino background, which is generated in cascades induced by cosmic rays in the atmosphere. The production mechanism is the decay chain of charged mesons and muons, i.e. $\pi^\pm \rightarrow \nu_\mu (\bar{\nu}_\mu) + \mu^\pm$, $\mu^\pm \rightarrow \bar{\nu}_\mu (\nu_\mu) + e^\pm + \nu_e (\bar{\nu}_e)$ and the respective chain of K decays.

Neutrinos from meson decay have energy spectrum steeper than that of the cosmic rays by one power of $E$. Neutrinos from muon decay are steeper by another power of $E$. Because of the steep atmospheric neutrino energy spectrum ($E^{3.7-4.7}_\nu$), we expect to start seeing astrophysical neutrinos at energies above 1 TeV. That threshold is somewhat uncertain because of the contribution of direct neutrinos from decays of charm and heavier flavors. Such neutrinos are expected to cross the meson decay neutrino spectrum at energies between 10 and 100 TeV.

There is an important question that we have to answer first: what is the intellectual value of the detection of astrophysical neutrinos compared to the detection of astrophysical TeV $\gamma$-rays, which is experimentally much easier. The reply to this question is even more important now after the extraordinary success of HESS and the incoming results of the Magic Cherenkov telescope [I].

The answer is that the Universe is not transparent to high energy $\gamma$-rays. Even in the absence of matter and local photon fields PeV $\gamma$-rays are absorbed in pair production interactions on the microwave background (MBR). TeV $\gamma$-rays are absorbed in the infrared/optical background (IRB). So one can have hidden sources of astrophysical neutrinos, either surrounded by large column densities of matter, or intense photon fields, or just being far away from us.

Classical high energy astrophysics is interpreting all processes as electromagnetic. Electromagnetic models have been very successful in describing the production of TeV $\gamma$-rays in different astrophysical objects. Only the detection of astrophysical neutrinos can point at the existence of hadronic processes at astrophysical objects.

There are two types of hadronic processes that lead to the production of mesons and the start of the meson and muon decay chains: inelastic hadronic interactions on matter (which we shall refer to as $pp$ interactions) and photoproduction interactions on photon fields ($p\gamma$ interactions). Apart from the interaction energy threshold, where the main process is the $\Delta^+$ production with
a cross section of 500 \( \mu b \), the photoproduction cross section is smaller than the \( pp \) inelastic cross section by two orders of magnitude. Since the microwave background density is higher than 400 cm\(^{-3} \), photoproduction interaction is four times more likely when the matter density is 1 cm\(^{-3} \). On the other hand the energy threshold for photoproduction is high because of the very low energy of the background photons. One way to express the minimum proton energy is \( E_{p}^{\text{min}} = (m_{\Delta}^2 - m_{p}^2)/2\varepsilon \), where \( \varepsilon \) is the energy of the background photon.

Traditionally we use to think of inelastic proton interactions in galactic astrophysical systems, such as supernova remnants, and of photoproduction interactions in powerful extragalactic objects [2]. These ideas are in the process of changing now, when the similarities of many galactic and extragalactic astrophysical systems start to emerge. We believe that in astrophysical environment all mesons and muons decay and the neutrino spectra are thus parallel to the meson (and cosmic ray) spectra. The only possible spectrum modification comes from energy loss of the mesons and, most likely, muons.

2. Galactic neutrino sources

There are several types of suspected galactic sources of astrophysical neutrinos. These include supernova remnants, powerful binary systems, microquasars, and the Galactic center.

Generally we expect to see neutrinos from any object that generates \( \gamma \)-rays of hadronic origin (\( \pi^0 \rightarrow \gamma\gamma \)). The generic rule is that if an object produces \( \gamma \)-rays on a \( AE^{-\alpha}_{\gamma} \) spectrum from \( \pi^0 \) decay it will generate neutrinos from \( \pi^\pm \) decay on a spectrum \( A(1 - r_{\pi})^{\alpha - 1}E_{\nu}^{-\alpha} \), where \( r_{\pi} = (m_{\mu}/m_{\pi})^2 \). When one also accounts for the neutrinos from muon decay for flat injection spectra the neutrino flux is almost equal to the \( \gamma \)-ray flux.

Microquasars are mini versions of Active Galactic Nuclei that are respectively less powerful, but much closer to us. We shall discuss the neutrino production at AGN in the following section.

With its great power in any other wavelengths SGR A* could be also a neutrino source, especially after the detection of TeV \( \gamma \)-rays from that source [3]. The detected \( \gamma \)-ray emission extends up to 10 TeV on a flat \( E^{-2.2}_{\gamma} \) energy spectrum. See also the talk of D. Grasso at this meeting.

Before we briefly discuss the neutrino production at supernova remnants and binary systems, we want to introduce two guaranteed sources of neutrinos, neither of them of high astrophysical interest.

The first one is the Sun. The atmosphere of the Sun is more rarefied and thus the generated neutrinos reach much higher energy than atmospheric ones [4]. Thus at energies exceeding 1 TeV the Sun becomes a neutrino source that could be used for calibration of the neutrino telescopes.

Another guaranteed source is the central region of the Galaxy, where the EGRET group has measured diffuse GeV \( \gamma \)-ray emission with a spectral index of 2.3-2.4 [5]. The emission could indeed be diffuse, or it could be due to unresolved sources. Recently the HESS collaboration surveyed the central Galaxy and discovered 14 individual \( \gamma \)-ray sources extending upwards from 200 GeV [6]. If all these sources were hadronic, the generated neutrino emission would easily be detectable by km\(^3 \) neutrino telescopes.

2.1. Neutrino production at supernova remnants

There are two periods when a supernova can be a source of hadronic \( \gamma \)-rays and neutrinos. The production of signals at young supernova remnants is discussed in detail for \( \gamma \)-rays by Berezinsky&Prilutski [7]. The emission starts whenever protons can be accelerated and mesons start decaying rather then interacting and lasts while the target density in the expanding supernova shell is sufficiently high. Depending on the supernova parameter, the emission may last between one and three years. A modern discussion of the processes in young supernova like objects can be found in Ref. [8] who consider the emission from hypernova explosions in M82.
and NGC253. These collapsar neutrinos do not present a significant diffuse flux, but could be detectable by the coincidence with the hypernova event.

The other period of high energy signal activity is when the supernova envelope drags out enough interstellar matter to slow it down - during the Sedov phase, about 1000 years after the supernova. During that phase the lost kinetic energy of the remnant is converted into cosmic rays, and the matter density at the blast shock becomes higher [9]. It is even more likely that signals are produced when the expanding supernova remnant hits a dense molecular cloud [10]. The same conclusion was reached in an analysis [11] of the emission detected by the EGRET instrument from the vicinity of supernova remnants. Hadronic $\gamma$-ray production dominates over electromagnetic one when the matter density exceeds $100 \text{ cm}^{-3}$. This is the case of the remnant RXJ 1713.7-3946 that was observed by the HESS telescope [12]. HESS has a fine angular resolution and studied the strength of the $\gamma$-ray signal from different regions of the remnant. It is well known that RXJ 1713.7-3946 is hitting a molecular cloud of density higher than 100. It is thus possible that at least a fraction of the detected $\gamma$-ray flux of $1.7 \times 10^{-7} \text{ E}_{\text{TeV}}^{-2.2} \text{ cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ has $\pi^0$ origin and we can expect from the object a neutrino flux of the same order.

It is worth noting that the supernova remnant SGR A East is in the error box of the HESS detection of SGR A* and it can not be proven that the detected TeV $\gamma$-ray emission does not come from this supernova remnant.

2.2. Neutrino production at binary systems
Powerful binary systems offer a large number of possibilities for particle acceleration and interactions. The emission from the compact object runs into the stellar wind of the companion star and shocks can be easily formed. The stellar wind provides enough nucleons for particle acceleration and the matter density of the star, the wind itself, and the accretion wake provide targets for interaction of the accelerated particles [13].

The observations of the central Galaxy by HESS [6] identified several binary systems as sources of TeV $\gamma$-rays. In the near future we will see if these binary systems are also sources of astrophysical neutrinos.

3. Extragalactic sources
The extragalactic sources that are usually considered are active galactic nuclei (AGN) and gamma ray bursts (GRB). Because of their high luminosity at other wavelengths, AGNs have been long suspected [14] as possible sources of astrophysical neutrinos. There are two possibilities for particle acceleration and interactions in AGN: the central region close to the black hole, and the AGN jet.

3.1. Generic AGN
The neutrino production in the central region of AGN has been first discussed in Refs. [15, 16]. Both papers calculate the accretion rate that is needed to support the black hole luminosity which gives them the nucleon density in the vicinity of the black hole. The photon density is estimated directly from the luminosity of the object. It turns out that the photon density exceeds the nucleon one by many orders of magnitude. The main energy loss of the accelerated protons will than be in photoproduction interactions that generate a neutrino flux of specific shape, that follows the proton spectrum above the interaction threshold and is flat below it.

The problem with these models is that they are very difficult to normalize since no other type of radiation can directly be observed - it is absorbed and downgraded in energy by the intense radiation field. One can only guess what fraction of the MeV/GeV isotropic background could be produced in such generic AGN.
3.2. AGN jets
The signals produced in the AGN jets are boosted by the Doppler factor of the jet which could be as high as 10. The detected TeV $\gamma$-ray emission from BL Lac objects is explained well with inverse Compton scattering of accelerated electrons. These models reproduce the double peaked distribution of the jet photon emission and can accommodate the fast variability of the sources.

Hadronic models of the jet emission were first developed by Mannheim[17]. These models can also reproduce the double peaked spectra, although the variability is more difficult to account for. It is quite possible that the $\gamma$-ray and neutrino emission in jets are not proportional to each other[18]. Under different astrophysical assumptions either strong $\gamma$-ray or strong neutrino signals are produced.

The basic principles of the proton acceleration and interactions are discussed in Ref. [19]. These are equally valid for AGN jets and gamma ray bursts, where the physics is similar to this in jets, but the conditions are more extreme.

3.3. Gamma ray bursts
The neutrino emission from GRB was discussed after these objects were suspected to be the sources of the highest energy cosmic rays [20]. The extremely high GRB luminosity and the average GRB Lorentz factor of 300 make the production of high energy neutrinos at these objects quite possible. The observed GRB photon spectrum has a break in the vicinity of 1 MeV, which in turn defines a neutrino spectrum with a break at about $10^{14}$ eV [21].

Once again, the photon emission and neutrino emission may not be proportional to each other[22]. Fast GRB jets with a Lorentz factor of up to 1,000 are very good photon emitters, while slow jets with a Lorentz factor around and below 100 may be very good neutrino emitters. The same conclusion is reached in a detailed calculation [23], where the neutrino production is discussed for GRB models with internal and external soft photon origin.

The best ones are stalled GRB [24], where the jet is not able to penetrate through the collapsing supermassive star. In such case, however, the main advantage of the GRB neutrino observation - time coincidences with the explosion - will be lost.

4. High energy neutrino fluxes and ultrahigh energy cosmic rays
Waxman&Bahcall did a simple calculation of the production of neutrinos at optically thin sources of UHECR [25], assuming that the total energy of the accelerated protons is converted to neutrinos. The calculation uses the emissivity that can maintain the flux of UHECR and gives an upper bound of the extragalactic neutrino flux, expressed as $E_\nu^2dN_\nu/dE_\nu = 5 \times 10^{-8}$ GeV cm$^{-2}$s$^{-1}$ in the case of $(1 + z)^3$ cosmological evolution of the cosmic ray sources. In terms of energy flux this is a straight line extending up to energies of $10^{20}$ eV.

This bound was discussed and somewhat relaxed in Ref. [26] where are a more sophisticated calculation was performed. The two bounds agree with each other only at $E_\nu$ of $10^{18}$ eV.

The upper bounds cannot be accepted as a upper limit on the astrophysical neutrino fluxes. It does not restrict, e.g. the fluxes from sources that are optically thick for nucleons and is exceeded by fluxes of cosmogenic neutrinos.

4.1. Cosmogenic neutrinos
These are neutrinos generated by photoproduction interactions of the extragalactic cosmic rays in the photon background. The most important universal target is the microwave background. The existence of such neutrinos was first proposed in Ref. [27] and developed in [28]. The relation of this flux to the cosmological evolution of the cosmic ray sources was discussed in [29]. The fluxes of cosmogenic neutrinos were more recently calculated in many other papers.

There are several important astrophysical inputs in such a calculation, the most important among which are 1) the emissivity of the cosmic ray sources, estimated from the the flux of the
UHECR, 2) the distribution of the UHECR sources, which is usually assumed to be isotropic and homogeneous, 3) the cosmological evolution of the cosmic rays sources, usually set parallel to this of star forming regions, and 4) the cosmic ray injection spectrum.

In the current Universe, at redshift $z = 0$, the proton threshold energy for photoproduction interactions on MBR is about $3 \times 10^{19}$ eV. The emissivity normalization is then set to an energy where one believes all cosmic rays are extragalactic. For cosmological evolution of the cosmic ray sources as $(1 + z)^3$ Waxman (1995) calculates the cosmic ray emissivity above $10^{19}$ eV to be $4.5 \times 10^{44}$ erg/Mpc$^3$/yr for a wide range of injection spectra.

The resulting diffuse flux $^{30}$ of $\mu^+ + \bar{\nu}_\mu$ peaks at about $5 \times 10^{17}$ eV and reaches $dN/d(lnE)$ of $3 \times 10^{-17}$ cm$^{-2}$s$^{-1}$ster$^{-1}$ at the peak for $E^{-2}$ injection spectrum of UHECR and $(1 + z)^3$ cosmological evolution of the cosmic ray sources. At higher energy the neutrino flux roughly follows the UHECR spectrum, while below $10^{16}$ eV the flux is flat.

Since only protons of energy above $3 \times 10^{19}$ eV interact on MBR the flux is lower for steeper injection spectra. If they were no cosmological evolution of the cosmic ray sources the peak moves to higher energy and the peak flux is lower by about a factor of 5. The relation between the cosmic ray injection power law index $\gamma$ and the cosmological evolution parameter $m$ from the $(1 + z)^m$ dependence can be expressed as $(1 + z)^{(m+\gamma-\frac{3}{2})}$ when the redshift integration is performed over $ln1 + z$ $^{33}$. For $(m + \gamma)$ greater than $\frac{3}{2}$ the production increases with redshift. Otherwise it decreases.

Most of the cosmogenic neutrino calculations are performed in the assumption that UHECR are protons. It was recently demonstrated $^{32}$ that there would be detectable flux of cosmogenic neutrinos even if UHECR were heavy nuclei. The neutrinos then peak at about $10^{14}$ eV ($\bar{\nu}_e$) from neutron decay, although there is also a secondary peak at higher energy, similar to the one shown in Fig. $^{11}$

4.2. Cosmogenic neutrinos from interactions on the infrared background

The infrared and optical background is another universal photon field that has been studied directly and through the absorption of the TeV $\gamma$-rays from distant systems. The IRB number density is smaller than that of MBR by factors from 250 to 400 in different models, but the important factor is that the proton threshold energy on interactions on IRB is about $10^{17}$ eV. The increased number of lower energy protons to a large extent compensates for the lower target density of IRB. The important region of IRB is the far and medium infrared regions where the number density is much higher than in the near infrared and optical range.

Fig. $^{11}$ shows in its left panel the yields from interactions on the MBR and on IRB for propagation on distance of 1 Mpc. The photoproduction interactions are modeled with the SOPHIA code $^{33}$. Although the IRB yield for proton energy of $10^{20}$ eV is much lower than that on MBR, there are also yields from $10^{19}$ and $10^{18}$ eV protons.

The right-hand panel of Fig. $^{11}$ shows the cosmogenic neutrinos generated on MBR and on the IRB from the model of Ref. $^{34}$. The calculation uses the cosmological evolution of IRB as calculated in this model up to redshift of 5. Waxman’s cosmic ray emissivity is used together with injection spectrum $\gamma=1$ and cosmological evolution $(1 + z)^3$ of the cosmic ray sources.

The total flux of cosmogenic neutrinos consists of roughly equal parts of MBR and IRB interaction neutrinos. The IRB flux covers wider energy range and is slightly shifted to lower energy. The decrease of the number of high energy neutrinos in IRB interactions can be explained with the fact that UHECR protons interact mainly on the MBR.

The picture changes for steeper cosmic ray injection spectra. The number of lower energy protons grows faster, and so does the contribution of the IRB interactions. For $\gamma=1.5$, for example, the IRB peak is higher than the MBR one by more than a factor of 3 and the total neutrino energy distribution is shifted to lower energy.
The IRB contribution thus decreases the dependence of the cosmogenic neutrino flux on the cosmic ray injection spectrum. While the MBR neutrino flux decreases for steeper injection spectrum, the IRB flux rapidly increases. Accounting for the total photon field makes the cosmogenic neutrino flux roughly independent of the proton injection spectrum.

5. High energy neutrino fluxes

Left-hand panel of figure 2 shows $\nu_\mu + \bar{\nu}_\mu$ fluxes predicted for five potential neutrino sources. The atmospheric neutrino fluxes within $1^\circ$ from the source are indicated with a shaded region. Upper end is for horizontal neutrinos and lower one - for vertical neutrinos.

The curve labeled 1) shows the neutrinos that we expect from the direction of the Sun \[1\]. Curve 2) shows the neutrino fluxes expected from the supernova remnant IC443 if the $\gamma$-rays detected by EGRET are all of hadronic origin \[11\]. Curve 3) shows the expected neutrino fluxes if the TeV $\gamma$-ray outburst of Mrk 501 is of hadronic origin. Curve 4) shows the minimum and maximum fluxes expected from the core region of 3C273 \[16\]. Curve 5) shows the neutrino flux predicted for the jet of 3C279 \[17\].
The right-hand panel of figure 2 shows several different diffuse astrophysical neutrino fluxes. The shaded area indicates the vertical and horizontal fluxes of atmospheric neutrinos. Waxman&Bahcall bound is indicated with W&B.

The curve labeled 1) shows the neutrinos expected from the central Galaxy in the assumption that all diffuse γ-rays detected by EGRET are created by cosmic ray interactions with matter. Curves 2) are diffuse fluxes from cores of AGN. Flux 3) is the isotropic AGN neutrino flux from AGN jets, where pp interactions are added to the high energy photoproduction interactions. Flux 4) is the prediction of diffuse neutrinos from GRB in the assumption that GRBs are sources of the ultrahigh energy cosmic rays. Flux 5) is a nominal cosmogenic neutrino flux as calculated in Ref. using the luminosity and cosmological evolution model from the W&B limit. Finally, for comparisons with diffuse astrophysical neutrinos we show the neutrino flux that is needed by the Z-burst model to become the production mechanism for UHECR.

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[1] See HESS and Magic presentations at this meeting