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Neutrinos and cosmic rays

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ABSTRACT

In this paper we review the status of the search for high-energy neutrinos from outside the solar system and discuss the implications for the origin and propagation of cosmic rays. Connections between neutrinos and gamma-rays are also discussed.

1. Introduction

Observation of high-energy neutrinos of astrophysical origin would open a new window on origin of cosmic rays. Neutrinos are expected at some level in association with cosmic rays, both from interactions of accelerated protons and nuclei in or near their sources and from interactions of the cosmic rays during propagation in space. Sources are expected to accelerate some electrons as well as protons and nuclei. Because electrons radiate efficiently, it is difficult to discern from observation of photon spectra alone the extent to which protons are accelerated. Observation of neutrinos from gamma-ray sources would directly determine the level of acceleration of protons. Examples of possible sources are galactic supernova remnants and extragalactic objects such as gamma-ray bursts (GRB) and active galactic nuclei (AGN).

In addition, wherever gamma-rays are produced by interactions of cosmic rays during their propagation, neutrinos will also be produced. Examples of the latter are neutrinos related to the diffuse gamma-ray emission from the disk of the Milky Way [1] and *cosmogenic* neutrinos produced when cosmic rays of ultra-high energy (UHECR) interact with the cosmic background radiation (CMB) [2]. Both processes can be calculated in a straightforward way. For the Galaxy, the physics is pion production in interactions of cosmic rays with gas in the interstellar medium, and the neutrino flux follows directly from the observed diffuse gamma-radiation from the same source. The calculation of photo-pion production by protons in the cosmic microwave background (CMB) also follows from well-known physics, but in this case the level of neutrino production is highly uncertain because the ultra-high energy cosmic ray (UHECR) acceleration spectrum is unknown. Whether there are sufficient protons above the threshold of 3×10^{19} eV is one of the main unanswered questions of neutrino astronomy.

The discovery of neutrino oscillations [3] has important implications for neutrino astronomy. One expects only muon and electron neutrinos to be produced both in interactions with gas and in photo-pion production. However, the effect of oscillations on an astronomical baseline is that the initial flavor ratio evolves toward comparable numbers of all flavors for the observer. For example, for an initial flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ the ratio at Earth would be $1:1:1$ [4]. Since tau neutrinos are essentially absent above 100 GeV in the atmospheric neutrino background, identification of a ν_τ would be strong evidence for astrophysical origin. For this reason, the ability to distinguish neutrino flavors is important.

2. Status of searches for neutrino sources

The biggest signal is expected in the muon neutrino channel. Because of the long range of high energy muons, interactions of ν_μ outside the detector can produce muons that reach and pass through the detector. For an instrumented volume even as large as 10 km^3, the external ν_μ events are more numerous than interactions inside the instrumented volume. The most sensitive searches use the Earth as a filter against the downward background of atmospheric muons by requiring the muon track to be from below the horizon.

The most basic approach to neutrino astronomy is to look for an excess of events from a particular direction in the sky. AMANDA, Baikal, Antares and IceCube all make sky maps. The search can be binned or unbinned [5]. After accounting for the effective number of trials, no significant excess has been seen in any detector. A related approach is to look for an excess of events from a list of objects selected because they are likely neutrino sources. The source list for IceCube [6], for example, includes 13 galactic supernova

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remnants (SNR), and 30 extra-galactic objects, mostly AGN. With its instrumented km^3 volume, IceCube is by far the most sensitive detector at present. Published limits from IceCube during construction with 40 strings installed (IC-40) on specific point sources of neutrinos in the Northern sky are less than 10^{-11} cm^{-2} s^{-1} TeV^{-1}. With the full IceCube the sensitivity is now approaching 10^{-12} cm^{-2} s^{-1} TeV^{-1}, at which level TeV gamma-rays are seen from some blazars such as Mrk 401 [7].

A related approach is to look for neutrinos correlated in time, either with each other or with a gamma-ray event [8]. The strongest limit from IceCube in terms of constraining models that relate cosmic-ray origin with production of neutrinos is the absence of neutrinos in coincidence with GRB. Recently data sets from two years of IceCube while the detector was still under construction (IC-40 and IC-59) have been combined to obtain a significant limit [9] on models [10,11] in which GRBs are the main source of extragalactic cosmic rays. In total 215 GRBs reported by the GRB Coordinated Network between April 5, 2008 and May 31, 2010 in the Northern sky were included in the search. No neutrino was found during the intervals of observed gamma-ray emission.

To interpret the limits, the expected neutrino spectrum was calculated for each burst based on parameters derived [11] from features in the spectrum of the GRB. In particular, a break in the observed photon spectrum marks the onset of photo-pion production by accelerated protons interacting with intense radiation fields in the GRB jet. The neutrinos come from the decay of charged pions. Given a predicted neutrino spectrum, the expected number of events was calculated for each burst. The normalization of the calculation is provided from the intensity of photons in each burst together with an assumption for the ratio of energy in accelerated protons to energy in the electrons that produce the observed photons. With this normalization, 8 neutrinos are expected in 215 GRBs and none is observed. One possibility for relating the limit to the contribution of GRBs to ultra-high energy cosmic rays is to assume that the UHECR are injected as neutrons from the same photo-production processes in which the neutrinos are produced [12].

3. Neutrinos from the whole sky

It is important also to search for an excess of astrophysical neutrinos from the whole sky at high energy above the steeply falling background of atmospheric neutrinos. The Universe is transparent to neutrinos, so the flux of neutrinos from sources up to the Hubble radius may be large [29]. A toy model is helpful to illustrate this point. Assume a distribution of identical sources of neutrino luminosity L_ν (s^{-1} TeV^{-1}) with a typical separation of order $d = 10$ Mpc. The flux from a nearby source is $L_\nu/(4\pi d^2)$ (s^{-1} TeV^{-1} cm^{-2}). Integrating over the whole sky with a cutoff at the Hubble distance D_H the flux from the whole sky is

$$\phi \approx \int_0^{D_H} \frac{\rho L_\nu r^2}{4\pi r^2} \mathrm{d}\Omega \mathrm{d}r, \tag{1}$$

where $\rho \sim 1/d^3$ is the density of sources. In this case the ratio of the total flux of neutrinos from all directions to the flux from a nearby source is $\sim 4\pi D_H/d \sim 4000$ for $d = 10$ Mpc. Later we will cite examples of calculations for specific models of AGNs and GRBs, which take account properly of red shift for distant sources. In some cases the predicted diffuse fluxes are sufficiently high to constrain the models more than the point source searches. Before discussing the models, we first summarize the current status of the limits on diffuse fluxes of high energy neutrinos.

The limit from IC-40, shown as the solid (blue) line #7 in Fig. 1, is from an analysis of approximately 14,000 upward neutrino-induced muons in IC-40 [15]. This analysis proceeds by assuming a flux of neutrinos with three components: conventional atmospheric neutrinos from decay of kaons and pions; prompt neutrinos; and a hard spectrum of astrophysical neutrinos assumed to have an E^{-2} differential spectrum. Free parameters in fitting the data are the normalization of the prompt and astrophysical neutrinos. The normalization and slope of the atmospheric neutrinos are also allowed to vary within a limited range. The result is consistent with conventional atmospheric neutrinos, with no need for a contribution from prompt neutrinos and no evidence of a hard spectrum of astrophysical neutrinos. A limitation of the analysis is that the atmospheric neutrino background is represented by a simple power law extrapolation of the calculation of Ref. [19] beyond 10 TeV, and it averages over all angles below the horizon.

Also shown in Fig. 1 are several measurements of the flux of atmospheric neutrinos. The fit for atmospheric neutrinos from the IC-40 analysis that gives the diffuse limit is shown as a slightly curved band extending from 0.33 to 84 TeV. The reason that the diffuse limit applies at much higher energy (39 TeV to 7 PeV) is that it assumes a hard, E^{-2} differential energy spectrum for the neutrinos, in contrast to the steep ($\sim E^{-3.7}$) atmospheric spectrum. The experimental results on the high-energy flux of atmospheric $\nu_\mu + \bar{\nu}_\mu$ in Fig. 1 are from AMANDA [16,17] and IceCube-40 [18]. All the atmospheric neutrino spectra shown here are averaged over angle. The unfolding analysis of Ref. [18] extends to $E_\nu \approx 400$ TeV. The atmospheric fluxes shown are averaged over the upward hemisphere. At high energy atmospheric neutrinos from decay of charged pions and kaons have a significant angular dependence (the "secant theta" effect) with the intensity increasing toward the horizon. This angular dependence will be important in distinguishing atmospheric background from astrophysical signal in future analyses.

At the current level of sensitivity in the search for high-energy astrophysical neutrinos, the energy range where the atmospheric neutrino background becomes important is at 100 TeV and above, as illustrated by the crossover of the limits and the atmospheric fluxes in the Fig. 1. This energy is well beyond the range of detailed Monte Carlo calculations [19,20], which extend only to 10 TeV. In addition, this is the energy range where prompt neutrinos from decay of charm and heavier flavors may become important, but the expected level of this contribution is uncertain. The spectrum of prompt neutrinos is harder by one power than the spectrum of conventional atmospheric neutrinos in this energy range, and its angular distribution if isotropic. These features mimic a diffuse astrophysical flux to some extent. A possible strategy is to deter-

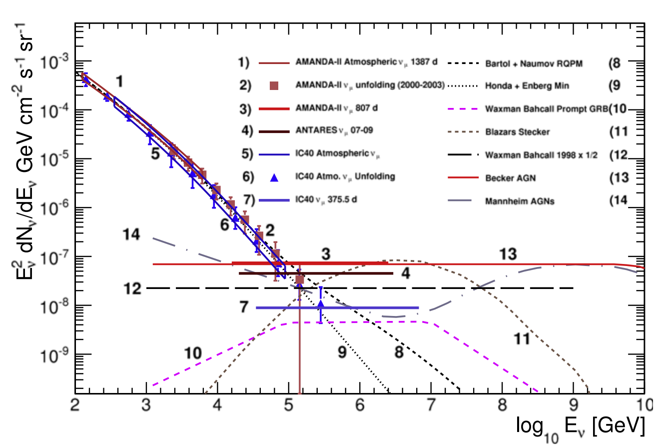

Fig. 1. Horizontal lines show limits on an E^{-2} spectrum of astrophysical muon neutrinos from AMANDA-II [13], Antares [14] and IceCube [15]. The plot is from Ref. [15] where full references are given. The limits are shown along with measurements of the flux of atmospheric muon neutrinos and anti-neutrinos.