The Highest Energy Neutrinos

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Abstract. Measurements of the arrival directions of cosmic rays have not revealed their sources. High energy neutrino telescopes attempt to resolve the problem by detecting neutrinos whose directions have not been scrambled by magnetic fields. The key issue is whether the neutrino flux produced in cosmic ray accelerators is detectable. It is believed that the answer is affirmative, both for the galactic and extragalactic sources, provided the detector has kilometer-scale dimensions. We revisit the case for kilometer-scale neutrino detectors in a model-independent way by focussing on the energetics of the sources. The real breakthrough though has not been on the theory but on the technology front: the considerable technical hurdles to build such detectors have been overcome.

1. Cosmic Rays and Neutrinos

An illustration of the neutrino sky is shown in Fig. 1 displaying a spectrum ranging from microwave neutrinos produced in the big bang to GZK neutrinos associated with the highest energy cosmic rays[1]. The GZK neutrinos are the decay products of pions produced in the interaction of cosmic rays with microwave photons. These are the same interactions that shape the Greissen-Zatsepin-Kuzmin absorption feature in the spectrum, hence their name. Prominently displayed in the figure is the flux of the highest energy atmospheric neutrinos observed up to $\sim 100 \text{ TeV}$ by the AMANDA experiment[2]. This beam, very successfully mined for particle physics by the Superkamiokande-generation of experiments, will be exploited at yet higher energies[3]. Because of its steep spectrum, events above several hundreds of TeV become very rare, leaving a clear neutrino sky to be explored for sources of cosmic neutrinos beyond the sun. Neutrino telescopes will open some ten orders of magnitude in neutrino wavelength, from their tens of GeV threshold to the EeV energy of GZK neutrinos. The existence of cosmic neutrinos with yet higher energy are a matter of speculation; they could be the decay products of cosmic remnants or topological defects associated with phase transitions in the early universe[4].

The neutrino fluxes anticipated[4] from non-thermal astronomical sources and, therefore, candidate cosmic ray accelerators such as active galaxies (AGN) and gamma ray bursts (GRB), dominate the atmospheric flux above $\sim 1 \text{ PeV}$; see Fig. 1. The energy fluxes are at the level of the flux, as far as we know unobservable, of big bang neutrinos. The high energy fluxes may nevertheless be observed by exploiting the relatively large neutrino interaction cross section in combination with detectors of gigaton size. Standard model physics is sufficient to establish that the cosmic fluxes shown are observable in a volume of 1 kilometer cubed instrumented with photomultipliers[4]. Neutrino telescopes detect the Cherenkov radiation from secondary particles produced in the interactions of high energy neutrinos in highly transparent and well shielded

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1 We use units GeV, TeV, PeV and EeV, increasing energy in steps of one thousand.
Figure 1. The neutrino sky from the lowest energy neutrinos produced in the big bang to the highest energies associated with the sources of the cosmic rays, here assumed to be gamma ray bursts or, alternatively, active galaxies. These will be the target of kilometer-scale neutrino detectors such as IceCube and KM3NeT. Neutrinos at intermediate energies, produced in the sun, supernovae and in collisions of cosmic rays in the atmosphere, have been studied by SuperK and similar detectors[8].

Deep water or ice. At the higher energies the neutrino cross section grows and secondary muons travel up to tens of kilometers to reach the detector from interactions outside the instrumented volume.

The construction of kilometer-scale instruments such as IceCube at the South Pole and the future KM3NeT detector in the Mediterranean, have been made possible by development efforts that resulted in the commissioning of prototypes that are two orders of magnitude smaller, AMANDA and ANTARES[5]. Their successful technologies have, in turn, relied on pioneering efforts by the DUMAND[6] and Baikal[7], as well as the Macro and SuperK collaborations[8]. While much larger than the latter, kilometer scale neutrino telescopes are insensitive to neutrinos in the MeV-GeV energy range and have a typical threshold of tens of GeV; this is the price one pays for reaching large detection volume. IceCube[9] is under construction and taking data with a partial array of 1320 ten inch photomultipliers positioned between 1500 and 2500 meter and deployed as beads on 22 strings below the geographic South Pole. Its effective telescope area already exceeds that of its predecessor AMANDA by roughly one order of magnitude. The detector will grow by another 14~18 strings in the 2007-08 Antarctic summer to be completed in 2011 with 80 strings[10].

The AMANDA experiment has observed neutrinos with energies as high as $\sim 100$ TeV, at a rate consistent with the flux of atmospheric neutrinos extrapolated from lower energy measurements; see Fig. 1. The fluxes of cosmic neutrinos shown in the figure at higher energies are, in contrast, a matter of speculation. It is known that non-thermal sources such as supernova remnants, AGN and GRB accelerate electrons to energies close to 1 PeV. Their existence is inferred from the observation of TeV gamma rays whose spectrum extends to $\sim 100$ TeV in some sources[11]. All observations can be accommodated in models where the origin of the photons, from radio to TeV energy, is synchrotron radiation by the electrons and, at the highest energies, inverse Compton scattering of ambient light, primarily the synchrotron photons themselves. There is no reason why non-thermal sources would not accelerate protons or nuclei along with the electrons, turning them into sources of cosmic rays; unfortunately, at this time, no evidence for such cosmic ray accelerators exists. A conclusive signature for the presence of cosmic rays in the sources is the production of pions on ambient radiation and matter. Pion production is
revealed by observing the decay products, photons and neutrinos. While it has been a challenge to disentangle such pionic photons from those produced by purely electromagnetic processes[12], charged pions decaying into neutrinos yield incontrovertible evidence. The anticipated neutrino fluxes are shown in Fig. 1, assuming that AGN or, alternatively, GRB, happen to be the correct guess for the unknown sources of the cosmic rays. If not, the real sources may be revealed by neutrinos that, unlike charged primaries, point back to their site of origin. Neutrino astronomy must eventually succeed because, after all, cosmic rays exist. The critical question is whether our estimate of the level of the neutrino fluxes associated with the observed cosmic rays is robust; it sets the scale of the detector.

Table 1. Built as discovery instruments, neutrinos telescopes nevertheless target a range of particle and astrophysics problems.

| Favorite Sources                                           | Possible Science                                           |
|-------------------------------------------------------------|------------------------------------------------------------|
| Atmospheric \((\sim 100,000 \text{ per year, up to } 1000 \text{ TeV, charm?})\) | Oscillations                                               |
| GRB (successful and failed)                                 | New interactions                                           |
| AGN                                                        | Test of relativity and equivalence principle               |
| Starburst galaxies                                          | Sources of cosmic rays                                     |
| Supernova remnants                                          | Test of Lorentz invariance                                 |
| Also microquasars, magnetars, PWNe, binaries                | Planck scale physics, quantum decoherence                  |
| unidentified Egret sources, plane of the galaxy            | Sources of cosmic rays                                     |
| Cosmic rays interacting with microwave photons              | Sources of cosmic rays                                     |
| Dark matter                                                | Identify sources of cosmic rays                            |
| Cosmic rays interacting with the sun                       | Neutrino cross section at EeV energy                      |
| Supernovae explosion                                        | Annihilation in the sun, mostly spin-dependent             |
|                                                             | Backgrounds to WIMP search                                 |
|                                                             | Deleptonization, TeV emission, hierarchy, \(\sin \theta_{13}\) |

Thus the faith of neutrino astronomy is intertwined with cosmic ray physics beyond the traditional subject of GZK neutrinos. While kilometer-scale neutrino detectors are discovery experiments with missions as diverse as particle physics and the search for dark matter — see Table 1 — their size as astronomical telescopes is very much anchored to the observed fluxes of galactic and extragalactic cosmic rays. Cosmic accelerators produce particles with energies in excess of \(10^{8}\) TeV; we still do not know where or how. The flux of cosmic rays observed at Earth follows a broken power law; see Fig. 2. The two power laws are separated by a feature dubbed the “knee”. Circumstantial evidence exists that cosmic rays, up to perhaps EeV energy, originate in galactic supernova remnants. Any association with our Galaxy disappears in the vicinity of a second feature in the spectrum referred to as the “ankle”. Above the ankle, the gyroradius of a proton in the galactic magnetic field exceeds the size of the Galaxy and we are witnessing the onset of an extragalactic component in the spectrum that extends to energies beyond 100 EeV. Observation of the GZK feature in the HiRes and Auger spectra near the energy threshold for pion production on microwave photons, confirms the existence of an extragalactic component.
At the energies of interest here, the cosmic ray spectrum consists of a sequence of 3 power laws. The first two are separated by the “knee” (left panel), the second and third by the “ankle”. There is evidence that the cosmic rays beyond the ankle are a new population of particles produced in extragalactic sources; see right panel.

2. Neutrinos Associated with the Sources of the Cosmic Rays

2.1. Extragalactic Cosmic Rays

It is routinely emphasized how small cosmic ray particle fluxes are; this may be besides the point. The energetics of the accelerator is likely to be more revealing. A hint in this direction comes from conventional astronomy. While the diffuse universal flux of photons falls by eighteen orders of magnitude between microwave and GeV-energy, the energy carried by the particle flux drops by less than five. Sources are known that emit most of their energy in TeV photons. The energy is the key. The argument has been well advertised for galactic cosmic rays where energetics points at their supernova origin. By integrating the observed flux in Fig. 2 we can obtain the energy density $\rho_E$ of cosmic rays in the galaxy from the relation that flux = velocity \times density, or

$$4\pi \int dE \left\{ E \frac{dN}{dE} \right\} = c\rho_E. \tag{1}$$

The answer is that $\rho_E \sim 10^{-12} \text{erg cm}^{-3}$. This is also the value of the corresponding energy density $B^2/8\pi$ of the microgauss magnetic field in the galaxy. The accelerating power needed to maintain this energy density is $10^{-26}\text{erg/cm}^3$’s given that the average containment time of the cosmic rays in our galaxy is $3 \times 10^7$ years. For a nominal volume of the galactic disk of $10^{67}\text{cm}^3$ this requires an accelerator delivering $10^{41}\text{erg/s}$. This happens to be 10% of the power produced by supernovae releasing $10^{51}\text{erg}$, or the one percent of a solar mass that is not released in neutrinos, every 30 years. This coincidence is the basis for the idea that shocks produced by supernovae expanding into the interstellar medium are the origin of the galactic cosmic rays[13].

Let’s follow the same logic for the extragalactic component in Fig. 2. The flux above the ankle is often summarized as “one $10^{19}\text{eV}$ particle per kilometer square per year per steradian”. This can be translated into an energy flux

$$E \left\{ E \frac{dN}{dE} \right\} = \frac{10^{19}\text{eV}}{(10^{10}\text{cm}^2)(3 \times 10^7\text{sec})\text{sr}} = 3 \times 10^{-11}\text{TeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}. \tag{2}$$

Following the procedure applied above to the galactic component we obtain an energy density of

$$\rho_E = \frac{4\pi}{c} \int_{E_{\text{min}}}^{E_{\text{max}}} 3 \times 10^{-8} \frac{dE}{E}\frac{\text{GeV cm}^3}{\text{cm}^3} \approx 10^{-10}\text{TeV cm}^{-3}, \tag{3}$$

taking the extreme energies of the accelerator(s) to be $E_{\text{max}}/E_{\text{min}} \approx 10^3$. 

Figure 2. At the energies of interest here, the cosmic ray spectrum consists of a sequence of 3 power laws. The first two are separated by the “knee” (left panel), the second and third by the “ankle”. There is evidence that the cosmic rays beyond the ankle are a new population of particles produced in extragalactic sources; see right panel.
The energy content derived “professionally” by integrating the spectrum in Fig. 2 assuming an $E^{-2}$ energy spectrum, typical of shock acceleration, with a GZK cutoff, is $\sim 3 \times 10^{-19}$ erg cm$^{-3}$. This is within a factor of our back-of-the-envelope estimate recalling that 1 TeV = 1.6 erg. The energy density represents the universe’s filling factor in cosmic rays, equivalent to 410 microwave-energy photons per cubic centimeter.

The power required for a population of sources to generate this energy density over the Hubble time of $10^{10}$ years is $\sim 3 \times 10^{37}$ erg s$^{-1}$ per (Mpc)$^3$ or, as often quoted in the literature, $\sim 5 \times 10^{44}$ TeV per (Mpc)$^3$ per year. This works out to[14]

- $\sim 2 \times 10^{44}$ erg s$^{-1}$ per active galaxy, or
- $\sim 2 \times 10^{51}$ erg per cosmological gamma ray burst.

The coincidence of these numbers with the observed energy radiated by these sources in photons, explains why AGN and GRB have emerged as leading candidates for the cosmic accelerators. In either case, it suffices that the shocks associated with acceleration near the black hole dump roughly equal energy in electrons and protons to accommodate the observed coincidence, with the electron energy observed as radiation by synchrotron and inverse Compton scattering.

For GRB the argument is a carbon copy of the one favoring galactic supernova as cosmic ray accelerators. Observations show that, within one gigaparsec cubed, 300 GRB dump about $10^{51}$ erg of energy into the universe in a single year. They therefore supply roughly $10^{44}$ erg yr$^{-1}$/Mpc$^3$ in radiation and, assuming equal energy in protons, we conclude that they represent an environment that can accommodate the observed energetics of the extragalactic cosmic rays. A problem is that the same argument can be made to validate AGN as the sources of the highest energy cosmic rays; see above. In the end, the answer may lay elsewhere.

Where do neutrinos fit into this? The assumption that the energy in neutrinos coincides with the matching energies observed in electromagnetic radiation and cosmic rays yields the level of neutrino fluxes associated with the cosmic rays shown in Fig. 1. In the end the neutrino flux is therefore the flux of Eq. 2. It is often referred to as the Waxman-Bahcall "bound"[15].

The assumption of a matching neutrino flux is rather generic. Cosmic rays are accelerated in regions of high magnetic fields associated with shocked particle flows driven by the gravity of a black hole. They interact with the radiation fields surrounding the black hole. The most important processes are $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$ and $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$. While the secondary protons may remain trapped in the acceleration region, roughly equal numbers of neutrons and decay products of neutral and charged pions escape. The energy escaping the source is therefore distributed among cosmic rays, gamma rays and neutrinos produced by the decay of neutrons, neutral pions and charged pions, respectively. This generic scenario accommodates the observation of equal energy in cosmic rays and electromagnetic radiation, and extends it to neutrinos. Clearly both GRB and AGN environments can accommodate this scenario although with very dissimilar black holes and radiation targets for pion production. If we take this picture seriously, our previous estimate must be corrected for the fact that the pion takes only 25% of the energy of the secondary neutron thus changing the energy balance between cosmic rays and neutrinos and reducing their flux. In the end we estimate that the muon-neutrino flux associated with the sources of the highest energy cosmic rays is loosely confined to the range

$$E_\nu^2 dN/dE_\nu = 1 \sim 5 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

(4)

depending on the cosmological evolution of the cosmic ray sources. Model calculations assuming that active galaxies or gamma-ray bursts are the actual sources of cosmic rays yield event rates similar to the generic energetics estimate presented; see Fig. 3.

The anticipated neutrino flux thus obtained has to be compared with the limit of $7.4 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ reached after the first 4 years of operation of the completed AMANDA detector in 2000–2003 [16]. On the other hand, for conservative assumptions for the charm
Figure 3. Our estimate of the flux of neutrinos associated with the sources of the highest energy cosmic rays (the shaded range labeled WB) is compared to the limits established by the AMANDA experiment reached with 800 days of data[16]. AMANDA’s sensitivity is within a factor of 2 of the most optimistic predictions. Also shown are fluxes predicted by specific models of cosmic ray accelerators: active galaxies labeled StSa[17] and MPR[18], GRB[19] and the diffuse flux produced by cosmic ray producing active galaxies on microwave photons[20] labelled RB. Data for the background atmospheric neutrino flux are from the AMANDA experiment. The IceCube experiment will be sensitive to all predictions after a few years of operation of the full detector. It has sensitivity to the larger fluxes by operating the partially completed detector that already now exceeds AMANDA in instrumented volume.

The neutrino event rate is obtained by folding the flux predicted with the probability that the neutrino is actually detected in a high energy neutrino telescope; only one in a million neutrinos of TeV energy interacts and produces a muon that reaches the detector. This probability is given by the ratio of the muon and neutrino interaction lengths in the detector medium, $\lambda_{\mu}/\lambda_{\nu}$[4] and therefore grows with energy. For the flux range estimated above we anticipate 100–500 detected muon neutrinos per km$^2$ per year, with the higher range close to what is already ruled out by AMANDA. In any case, the lower value represents the more realistic estimate as previously argued and the 100 events predicted will be further reduced by the realities of rejecting detector backgrounds, especially for spectra steeper than the $E^{-2}$ assumed throughout. On the other hand, IceCube’s effective area for muon neutrinos exceeds 1 km$^2$ and equal fluxes of electron and tau neutrinos are expected[9]. If IceCube construction remains on schedule, the instrument will accumulate 1 km$^2$ year of data within the next two years; the confrontation of these arguments with data is imminent, certainly on the 40 year timescale it took to develop the technology for the detectors.
2.2. Cosmic Neutrinos Associated with Galactic Supernova Remnants

Can kilometer-scale neutrino detectors observe neutrinos pointing back at the accelerators of the galactic cosmic rays? It is believed that galactic accelerators are powered by the conversion of $10^{50}$ erg of energy into particle acceleration by diffusive shocks associated with young (1000–10,000 year old) supernova remnants expanding into the interstellar medium. The cosmic rays will interact with hydrogen atoms in the interstellar medium to produce pions that decay into photons and neutrinos. These provide us with indirect evidence for cosmic ray acceleration. The new twist here is that the eventual observation of pionic gamma rays allows for a straightforward determination of the neutrino flux.

The HESS telescope has opened a new era in astronomy by producing the first resolved images of sources in TeV gamma rays, particularly, in this context, of the supernova remnant RX J1713.7-3946 [22]. While the resolved image of the source reveals TeV gamma ray emission from the whole supernova remnant, it shows a clear increase of the flux in the directions of known molecular clouds. This is suggestive of protons, shock-accelerated in the supernova remnant, interacting with the dense clouds to produce neutral pions that are the origin of the observed increase of the TeV photon signal. The magnitude of the photon flux is consistent with a site where protons are accelerated to energies typical of the main component of the galactic cosmic rays. A similar extended source of TeV gamma rays tracing the density of molecular clouds has been identified near the galactic center. Protons, apparently accelerated by the remnant HESS J1745-290, diffuse through nearby molecular clouds to produce a signal of TeV gamma rays that traces the density of the clouds [23]. Fitting the observed spectrum by purely electromagnetic processes is challenging because the relative height of the inverse Compton and synchrotron peaks requires very low values of the $B$-field, inconsistent with those required to accelerate the electron beam to energies that can accommodate the observation of 100 TeV photons. Nevertheless, an exclusively electromagnetic explanation of the non-thermal spectrum is not impossible, even favored by some [24]. One can, for instance, partition the remnant in regions of high and low magnetic fields that are the respective sites of acceleration and inverse Compton scattering.

Supernovae associated with molecular clouds are a common feature of associations of OB stars that exist throughout the galactic plane. Although not visible to HESS, possible evidence has been accumulating for the production of cosmic rays in the Cygnus region of the galactic plane from a variety of experiments [25, 26, 27]. Most intriguing is a Milagro report of an excess of events from the Cygnus region with a steady flux of several times that of the Crab.

If the TeV gamma ray signals are indeed of pionic origin, only particle physics establishes the rate of the accompanying neutrinos. Proton-proton collisions yield two charged pions for every neutral pion, with every charged pion decaying into a muon neutrino and antineutrino (one from the pion decay, the other from the decay of the secondary muon) and a neutral pion into two photons. So, the muon neutrino flux would be equal to the photon flux were it not for a factor two reduction from oscillations. The prediction is simple; to first order there is one muon neutrino for every photon produced in the source. Because the protons transfer on average 20% of their energy to secondary pions, and the four leptons in the charged pion decay chain $\pi \rightarrow \mu(\rightarrow e + \nu_e + \nu_\mu) + \nu_\mu$ take roughly equal energy, neutrinos with 0.05 of the cosmic ray energy are produced. Similarly, photons with 10% of the proton energy originate from the decay of neutral pions. Accelerators producing cosmic rays reaching the “knee” must produce photons with energies up to 100 TeV and neutrinos up to half that energy. This requirement is consistent with observations of RX J1713.7-3946 and MGRO J2019+37 discussed above. They are the targets for neutrino observation of neutrino telescopes located in the Southern and Northern hemispheres, respectively.

Whereas the relation between neutrino and gamma ray fluxes is direct, the information on their spectrum is often limited. This is especially the case for the hotspot MGRO J2019+37 where we have to model the spectrum on the basis of a measurement at a single energy; the
spectral slope has not been measured. Uncertainties in the calculation are associated with the propagation of the cosmic rays, with the value of the magnetic fields, and the age of the remnant. After investigating the wide parameter space of models for MGRO J2019+37, it has been shown[28] that the neutrino flux can nevertheless be predicted within a factor of 2 once the model flux is normalized at 12.5 TeV to the Milagro data and a limit at GeV energy is imposed reflecting the fact that EGRET did not observe a GeV counterpart [29]. The neutrino rate from this single source is within the range \(2 \leq \frac{dN}{dt} \leq 3.8\) events per year with the IceCube threshold at 50 GeV. The range is bound by the fact that the Milagro observation strongly constrains the flux in the energy range 1–20 TeV, where the neutrino detection probability is highest, resulting in similar predictions for dissimilar SNR characteristics.

The irreducible atmospheric background, due to neutrinos produced in the Northern atmosphere in cosmic ray showers, is calculated using the results of Ref. [30]. In 15 years of operation we predict \(4.5 \sigma \leq \frac{N}{\sqrt{N_{\text{atmo}}} \leq 7.7 \sigma}\) and if the higher end of the predicted event rate range is realized, 5 \(\sigma\) is possible in 4.3 years; see Fig. 4.

We note that the Milagro collaboration [31] has recently detected multiple additional sources besides MGRO J2019+37, most with fluxes close to 0.5 Crab. The sources with possible counterparts in the GeV range indicate a spectral index of \(\sim -2.3\). If we compute the flux of neutrinos from the Milagro sources (not including the Crab Nebula) detected with post-trial significance of greater than 5 \(\sigma\) assuming a power-law index of \(-2.3\), we get a total event rate in IceCube of 6.9 neutrinos/year. If we also include the more tentative sources, the event rate increases to 11.5 neutrinos/year. In the long run, a correlation analysis of the IceCube and Milagro skymaps should make the detection of these sources likely.

3. Looking Forward
While neutrino “telescopes” are discovery instruments with a variety of missions, the hope is that they may contribute to the resolution of the century old puzzle of the origin of cosmic rays, either by the detection of GZK neutrinos or by directly observing neutrinos from the accelerators. Between now and the next TAUP meeting we can look forward to

- Results from IceCube that, by operating the detector as it grows, will reach a km\(^2\)year aperture.
- Enhanced sensitivity of the Auger experiment to neutrinos that initiate horizontal air showers.
• The initial design of a kilometer-scale neutrino detector in the northern hemisphere.
• A new flight of the ANITA experiment as well as a wealth of other ideas and initiatives on detecting the acoustic and radio signatures produced by GZK neutrinos in ice, water, salt, permafrost . . .

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