High-energy Neutrinos from Cosmic Rays

Francis Halzen
Department of Physics, University of Wisconsin, Madison, WI 53706

Abstract. We introduce neutrino astronomy from the observational fact that Nature accelerates protons and photons to energies in excess of $10^{20}$ and $10^{13}$ eV, respectively. Although the discovery of cosmic rays dates back close to a century, we do not know how and where they are accelerated. We review the facts as well as the speculations about the sources. Among these gamma ray bursts and active galaxies represent well-motivated speculations because these are also the sources of the highest energy gamma rays, with emission observed up to 20 TeV, possibly higher.

We discuss why cosmic accelerators are also expected to be cosmic beam dumps producing high-energy neutrino beams associated with the highest energy cosmic rays. Cosmic ray sources may produce neutrinos from MeV to EeV energy by a variety of mechanisms. The important conclusion is that, independently of the specific blueprint of the source, it takes a kilometer-scale neutrino observatory to detect the neutrino beam associated with the highest energy cosmic rays and gamma rays. The technology for commissioning such instruments exists.

1 The Highest Energy Particles: Cosmic Rays, Photons and Neutrinos

1.1 The New Astronomy

While conventional astronomy spans 60 octaves in photon frequency, from $10^4$ cm radio-waves to $10^{-14}$ cm gamma rays of GeV energy, successful efforts are underway to probe the Universe at yet smaller wavelengths and larger photon energies; see Fig. 1. Gamma rays, gravitational waves, neutrinos and very high-energy protons are explored as astronomical messengers. As exemplified time and again, the development of novel ways of looking into space invariably results in the discovery of unanticipated phenomena. As is the case with new accelerators, observing only the predicted will be slightly disappointing.

Why pursue high-energy astronomy with neutrinos or protons despite the considerable instrumental challenges? A mundane reason is that the Universe is not transparent to photons of TeV energy and above (in ascending factors of $10^3$, units are: GeV/TeV/PeV/EeV/ZeV). For instance, a PeV energy photon cannot deliver information from a source at the edge of our own galaxy because it will annihilate into an electron pair in an encounter with a 2.7 Kelvin microwave photon before reaching our telescope. Only neutrinos can reach us without attenuation from the edge of the Universe at all energies.

At EeV energies, proton astronomy may be possible. Above 50 EeV the arrival directions of electrically charged cosmic rays are no longer scrambled by the...
ambient magnetic field of our own galaxy. They point back to their sources with an accuracy determined by their gyroradius in the intergalactic magnetic field $B$:

$$\frac{\theta}{0.1^\circ} \approx \left( \frac{d}{1\text{ Mpc}} \right) \left( \frac{B}{10^{-9} \text{ G}} \right) \left( \frac{E}{3 \times 10^{20} \text{ eV}} \right),$$

(1)

where $d$ is the distance to the source. Speculations on the strength of the intergalactic magnetic field range from $10^{-7}$ to $10^{-12}$ Gauss in the local cluster. For a distance of 100 Mpc, the resolution may therefore be anywhere from sub-degree to nonexistent. Proton astronomy should be possible at the very highest energies; it may also provide indirect information on intergalactic magnetic fields. Determining the strength of intergalactic magnetic fields by conventional astronomical means has been challenging.

1.2 The Highest Energy Cosmic Rays: Facts

In October 1991, the Fly’s Eye cosmic ray detector recorded an event of energy $3.0^{+0.35}_{-0.54} \times 10^{20} \text{ eV}$ [1]. This event, together with an event recorded by the Yakutsk air shower array in May 1989 [2], of estimated energy $\sim 2 \times 10^{20} \text{ eV}$, constituted at the time the two highest energy cosmic rays ever recorded. Their energy corresponds to a center of mass energy of the order of 700 TeV or $\sim 50$ Joules, almost 50 times the energy of the Large Hadron Collider (LHC). In fact, all
Fig. 2. The cosmic ray spectrum peaks in the vicinity of 1 GeV and has features near $10^{15}$ and $10^{19}$ eV referred to as the “knee” and “ankle” in the spectrum, respectively. Shown is the flux of the highest energy cosmic rays near and beyond the ankle measured by the AGASA experiment. Note that the flux is multiplied by $E^3$.

Active experiments \cite{3} have detected cosmic rays in the vicinity of 100 EeV since their initial discovery by the Haverah Park air shower array \cite{4}. The AGASA air shower array in Japan\cite{5} has now accumulated an impressive 10 events with energy in excess of $10^{20}$ eV \cite{6}.

The accuracy of the energy resolution of these experiments is a critical issue. With a particle flux of order 1 event per km$^2$ per century, these events are studied by using the earth’s atmosphere as a particle detector. The experimental signature of an extremely high-energy cosmic particle is a shower initiated by the particle. The primary particle creates an electromagnetic and hadronic cascade. The electromagnetic shower grows to a shower maximum, and is subsequently absorbed by the atmosphere. The shower can be observed by: i) sampling the electromagnetic and hadronic components when they reach the ground with an array of particle detectors such as scintillators, ii) detecting the fluorescent light emitted by atmospheric nitrogen excited by the passage of the shower particles, iii) detecting the Cerenkov light emitted by the large number of particles at shower maximum, and iv) detecting muons and neutrinos underground.

The bottom line on energy measurement is that, at this time, several experiments using the first two techniques agree on the energy of EeV-showers within a typical resolution of 25%. Additionally, there is a systematic error of order 10% associated with the modeling of the showers. All techniques are indeed subject to the ambiguity of particle simulations that involve physics beyond the LHC. If the final outcome turns out to be an erroneous inference of the energy of the
shower because of new physics associated with particle interactions at the $\Lambda_{\text{QCD}}$ scale, we will be happy to contemplate this discovery instead.

The premier experiments, HiRes and AGASA, agree that cosmic rays with energy in excess of 10 EeV are not galactic in origin and that their spectrum extends beyond 100 EeV. They disagree on almost everything else. The AGASA experiment claims evidence that the highest energy cosmic rays come from point sources, and that they are mostly heavy nuclei. The HiRes data does not support this. Because of low statistics, interpreting the measured fluxes as a function of energy is like reading tea leaves; one cannot help however reading different messages in the spectra (see Fig. 2 and Fig. 3).

1.3 The Highest Energy Cosmic Rays: Fancy

**Acceleration to > 100 EeV?** It is sensible to assume that, in order to accelerate a proton to energy $E$ in a magnetic field $B$, the size $R$ of the accelerator must be larger than the gyroradius of the particle:

$$ R > R_{\text{gyro}} = \frac{E}{B}. $$

(2)

That is, the accelerating magnetic field must contain the particle orbit. This condition yields a maximum energy

$$ E \sim \gamma BR $$

(3)

by dimensional analysis and nothing more. The $\gamma$-factor has been included to allow for the possibility that we may not be at rest in the frame of the cosmic...
Table 1. Requirements to generate the highest energy cosmic rays in astrophysical sources.

| Conditions with $E \sim 10$ EeV |
|----------------------------------|
| Quasars $\gamma \simeq 1$ $B \simeq 10^4$ G $M \simeq 10^9 M_{\text{sun}}$ |
| Blazars $\gamma \gtrsim 10$ $B \simeq 10^3$ G $M \simeq 10^9 M_{\text{sun}}$ |
| Neutron Stars $\gamma \simeq 1$ $B \simeq 10^{12}$ G $M \simeq M_{\text{sun}}$ |
| Black Holes $\vdots$ |
| GRB $\gamma \gtrsim 10^2$ $B \simeq 10^{12}$ G $M \simeq M_{\text{sun}}$ |

The result would be the observation of boosted particle energies. Theorists’ imagination regarding the accelerators has been limited to dense regions where exceptional gravitational forces create relativistic particle flows: the dense cores of exploding stars, inflows on supermassive black holes at the centers of active galaxies, annihilating black holes or neutron stars. All speculations involve collapsed objects and we can therefore replace $R$ by the Schwartzschild radius

$$R \sim \frac{GM}{c^2}$$

(4)

to obtain

$$E \propto \gamma BM.$$  

(5)

Given the microgauss magnetic field of our galaxy, no structures are large or massive enough to reach the energies of the highest energy cosmic rays. Dimensional analysis therefore limits their sources to extragalactic objects; a few common speculations are listed in Table 1.

Nearby active galactic nuclei, distant by $\sim 100$ Mpc and powered by a billion solar mass black holes, are candidates. With kilogauss fields, we reach 100 EeV. The jets (blazars) emitted by the central black hole could reach similar energies in accelerating substructures (blobs) boosted in our direction by Lorentz factors of 10 or possibly higher. The neutron star or black hole remnant of a collapsing supermassive star could support magnetic fields of $10^{12}$ Gauss, possibly larger. Highly relativistic shocks with $\gamma > 10^2$ emanating from the collapsed black hole could be the origin of gamma ray bursts and, possibly, the source of the highest energy cosmic rays.

The above speculations are reinforced by the fact that the sources listed are also the sources of the highest energy gamma rays observed. At this point, however, a reality check is in order. The above dimensional analysis applies to the Fermilab accelerator: 10 kilogauss fields over several kilometers corresponds to 1 TeV. The argument holds because, with optimized design and perfect alignment of magnets, the accelerator reaches efficiencies matching the dimensional limit. It is highly questionable that nature can achieve this feat. Theorists can imagine acceleration in shocks with an efficiency of perhaps 10%.

The astrophysics of accelerating particles to Joule energies is so daunting that many believe that cosmic rays are not the beams of cosmic accelerators.
but the decay products of remnants from the early Universe, such as topological defects associated with a Grand Unified Theory (GUT) phase transition.

**Are Cosmic Rays Really Protons: the GZK Cutoff?** All experimental signatures agree on the particle nature of the cosmic rays—they look like protons or, possibly, nuclei. We mentioned at the beginning of this article that the Universe is opaque to photons with energy in excess of tens of TeV because they annihilate into electron pairs in interactions with the cosmic microwave background. Protons also interact with background light, predominantly by photoproduction of the $\Delta$-resonance, i.e. $p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + p$ above a threshold energy $E_p$ of about 50 EeV given by:

\[
2E_p\epsilon > (m_{\Delta}^2 - m_p^2).
\]

(6)

The major source of proton energy loss is photoproduction of pions on a target of cosmic microwave photons of energy $\epsilon$. The Universe is, therefore, also opaque to the highest energy cosmic rays, with an absorption length of

\[
\lambda_{\gamma p} = (n_{CMB} \sigma_{p+\gamma_{CMB}})^{-1}
\]

(7)

\[
\cong 10 \text{Mpc},
\]

(8)

when their energy exceeds 50 EeV. This so-called GZK cutoff establishes a universal upper limit on the energy of the cosmic rays. The cutoff is robust, depending only on two known numbers: $n_{CMB} = 400 \text{ cm}^{-3}$ and $\sigma_{p+\gamma_{CMB}} = 10^{-28} \text{ cm}^2$.[7,8,9,10]

Cosmic rays do reach us with energies exceeding 100 EeV. This presents us with three options: i) the protons are accelerated in nearby sources, ii) they do reach us from distant sources which accelerate them to even higher energies than we observe, thus exacerbating the acceleration problem, or iii) the highest energy cosmic rays are not protons.

The first possibility raises the challenge of finding an appropriate accelerator by confining these already unimaginable sources to our local galactic cluster. It is not impossible that all cosmic rays are produced by the active galaxy M87, or by a nearby gamma ray burst which exploded a few hundred years ago.

Stecker [11] has speculated that the highest energy cosmic rays are Fe nuclei with a delayed GZK cutoff. The details are complicated but the relevant quantity in the problem is $\gamma = E/AM$, where $A$ is the atomic number and $M$ the nucleon mass. For a fixed observed energy, the smallest boost towards GZK threshold is associated with the largest atomic mass, i.e. Fe.

**Could Cosmic Rays be Photons or Neutrinos?** Above question naturally emerges in the context of models where the highest energy cosmic rays are the decay products of remnants or topological structures created in the early universe with typical energy scale of order $10^{24} \text{ eV}$. In these scenarios the highest energy cosmic rays are predominantly photons. A topological defect will suffer a chain
Fig. 4. The composite atmospheric shower profile of a $3 \times 10^{20}$ eV gamma ray shower calculated with Landau-Pomeranchuk-Migdal (dashed) and Bethe-Heitler (solid) electromagnetic cross sections. The central line shows the average shower profile and the upper and lower lines show 1 $\sigma$ deviations — not visible for the BH case, where lines overlap. The experimental shower profile is shown with the data points. It does not fit the profile of a photon shower.

decay into Grand Unified Theory (GUT) particles X and Y, that subsequently decay to familiar weak bosons, leptons and quark or gluon jets. Cosmic rays are, therefore, predominately the fragmentation products of these jets. We know from accelerator studies that, among the fragmentation products of jets, neutral pions (decaying into photons) dominate, in number, protons by close to two orders of magnitude. Therefore, if the decay of topological defects is the source of the highest energy cosmic rays, they must be photons. This is a problem because there is compelling evidence that the highest energy cosmic rays are not photons:

1. The highest energy event observed by Fly’s Eye is not likely to be a photon $^{12}$. A photon of 300 EeV will interact with the magnetic field of the earth far above the atmosphere and disintegrate into lower energy cascades — roughly ten at this particular energy. The detector subsequently collects light produced by the fluorescence of atmospheric nitrogen along the path of the high-energy showers traversing the atmosphere. The atmospheric shower profile of a 300 EeV photon after fragmentation in the earth’s magnetic field, is shown in Fig. 4. It disagrees with the data. The observed shower profile does fit that of a primary proton, or, possibly, that of a nucleus. The shower profile information is sufficient, however, to conclude that the event is unlikely to be of photon origin.
2. The same conclusion is reached for the Yakutsk event that is characterized by a huge number of secondary muons, inconsistent with a pure electromagnetic cascade initiated by a gamma ray.

3. The AGASA collaboration claims evidence for “point” sources above 10 EeV. The arrival directions are however smeared out in a way consistent with primaries deflected by the galactic magnetic field. Again, this indicates charged primaries and excludes photons.

4. Finally, a recent reanalysis of the Haverah Park disfavors photon origin of the primaries.

Neutrino primaries are definitely ruled out. Standard model neutrino physics is understood, even for EeV energy. The average $x$ of the parton mediating the neutrino interaction is of order $x \sim \sqrt{M_W^2/s} \sim 10^{-6}$ so that the perturbative result for the neutrino-nucleus cross section is calculable from measured HERA structure functions. Even at 100 EeV a reliable value of the cross section can be obtained based on QCD-inspired extrapolations of the structure function. The neutrino cross section is known to better than an order of magnitude. It falls 5 orders of magnitude short of the strong cross sections required to make a neutrino interact in the upper atmosphere to create an air shower.

Could EeV neutrinos be strongly interacting because of new physics? In theories with TeV-scale gravity, one can imagine that graviton exchange dominates all interactions and thus erases the difference between quarks and neutrinos at the energies under consideration. The actual models performing this feat require a fast turn-on of the cross section with energy that violates S-wave unitarity.

We have exhausted the possibilities. Neutrons, muons and other candidate primaries one may think of are unstable. EeV neutrons barely live long enough to reach us from sources at the edge of our galaxy.

2 A Three Prong Assault on the Cosmic Ray Puzzle

We conclude that, where the highest energy cosmic rays are concerned, both the accelerator mechanism and the particle physics are enigmatic. The mystery has inspired a worldwide effort to tackle the problem with novel experimentation including air shower arrays covering an area of several times $10^3$ square kilometers and arrays of multiple air Cerenkov telescopes. We here discuss kilometer-scale neutrino observatories. While these have additional missions such as the search for dark matter, their observations are likely to have an impact on cosmic ray physics.

Why we anticipate that secondary photons and neutrinos are associated with the highest energy cosmic rays is sketched in Fig. 5. The cartoon draws our attention to the fact that cosmic accelerators are also cosmic beam dumps that produce secondary photon and neutrino beams. Accelerating particles to TeV energy and above requires relativistic, massive bulk flows. These are likely to originate from the exceptional gravitational forces associated with black holes.
or neutron stars. Accelerated particles therefore pass through intense radiation fields or dense clouds of gas surrounding the black hole leading to the production of secondary pions. These subsequently decay into photons and neutrinos that accompany the primary cosmic ray beam. Example of beam dumps include the external photon clouds or the UV radiation field that surrounds the central black hole of active galaxies, or the matter falling into the collapsed core of a dying supermassive star producing a gamma ray burst. The target material, whether a gas of particles or of photons, is likely to be sufficiently tenuous for the primary proton beam and the secondary photon beam to be only partially attenuated. However, shrouded sources from which only neutrinos can emerge, as in terrestrial beam dumps at CERN and Fermilab, are also a possibility.

How many neutrinos are produced in association with the cosmic ray beam? The answer to this question, among many others\cite{25,26}, provides the rational for building kilometer-scale neutrino detectors.

Let’s first consider the question for the accelerator beam producing neutrino beams at an accelerator laboratory. Here the target absorbs all parent protons as well as the muons, electrons and gamma rays (from $\pi^0 \rightarrow \gamma + \gamma$) produced. A pure neutrino beam exits the dump. If nature constructed such a “hidden source” in the heavens, conventional astronomy has not revealed it. It cannot be the source of the cosmic rays, however, for which the dump must be partially transparent to protons.

In the other extreme, the accelerated proton interacts once, thus producing the observed high-energy gamma rays \cite{37}. It subsequently escapes the dump. We refer to this as a transparent source without absorption. Particle physics
Fig. 6. The neutrino flux from compact astrophysical accelerators. Shown is the range of possible neutrino fluxes associated with the highest energy cosmic rays. The lower line, labeled “transparent”, represents a source where each cosmic ray interacts only once before escaping the object. The upper line, labeled “obscured”, represents an ideal neutrino source where all cosmic rays escape in the form of neutrons. Also shown is the ability of AMANDA and IceCube to test these models.

directly relates the number of neutrinos to the number of observed cosmic rays and gamma rays \([27]\). Every observed cosmic ray interacts once, and only once, to produce a neutrino beam determined only by particle physics. The neutrino flux for such a transparent cosmic ray source is referred to as the Waxman-Bahcall flux \([28,29,30,31]\) and is shown as the horizontal lines labeled “W&B” in Fig. 6. The calculation is valid for \(E \simeq 100\) PeV. If the flux is evaluated at both lower and higher cosmic ray energies, however, larger values are found. This is shown as the non-flat line labeled “transparent” in Fig. 6. On the lower side, the neutrino flux is higher because it is normalized to a larger cosmic ray flux. On the higher side, there are more cosmic rays in the dump to produce neutrinos because the observed flux at Earth has been reduced by absorption on microwave photons, the GZK-effect. The increased values of the neutrino flux are also shown in Fig. 6. The gamma ray flux of \(\pi^0\) origin associated with a transparent source is qualitatively at the level of observed flux of non-thermal TeV gamma rays from individual sources \([27]\).

Nothing prevents us, however, from imagining heavenly beam dumps with target densities somewhere between those of hidden and transparent sources. When increasing the target photon density, the proton beam is absorbed in the dump and the number of neutrino-producing protons is enhanced relative to those escaping the source as cosmic rays. For the extreme source of this type, the observed cosmic rays are all decay products of neutrons with larger mean-free paths in the dump. The flux for such a source is shown as the upper horizontal line in Fig. 6.
The above limits are derived from the fact that theorized neutrino sources do not overproduce cosmic rays. Similarly, observed gamma ray fluxes constrain potential neutrino sources because for every parent charged pion ($\pi^{\pm} \rightarrow l^{\pm} + \nu$), a neutral pion and two gamma rays ($\pi^0 \rightarrow \gamma + \gamma$) are produced. The electromagnetic energy associated with the decay of neutral pions should not exceed observed astronomical fluxes. These calculations must take into account cascading of the electromagnetic flux in the background photon and magnetic fields. A simple argument relating high-energy photons and neutrinos produced by secondary pions can still be derived by relating their total energy and allowing for a steeper photon flux as a result of cascading. Identifying the photon fluxes with those of non-thermal TeV photons emitted by supernova remnants and blazers, we predict neutrino fluxes at the same level as the Waxman-Bahcall flux\textsuperscript{32}. It is important to realize however that there is no evidence that these are the decay products of $\pi^0$'s. The sources of the cosmic rays have not been revealed by photon or proton astronomy\textsuperscript{33,34,35,36}; see however reference\textsuperscript{37}.

For neutrino detectors to succeed they must be sensitive to the range of fluxes covered in Fig. 6. The AMANDA detector has already entered the region of sensitivity and is eliminating specific models which predict the largest neutrino fluxes within the range of values allowed by general arguments. The IceCube detector, now under construction, is sensitive to the full range of beam dump models, whether generic as or modeled as active galaxies or gamma ray bursts. IceCube will reveal the sources of the cosmic rays or derive an upper limit that will qualitatively raise the bar for solving the cosmic ray puzzle. The situation could be nothing but desperate with the escape to top-down models being cut off by the accumulating evidence that the highest energy cosmic rays are not photons. In top-down models, decay products eventually materialize as quarks and gluons that fragment into jets of neutrinos and photons and very few protons.

### 3 High Energy Neutrino Telescopes

Although neutrino telescopes have multiple interdisciplinary science missions, the search for the sources of the highest-energy cosmic rays stands out because it clearly identifies the size of the detector required to do the science\textsuperscript{38}.

Whereas the science is compelling, the real challenge has been to develop a reliable, expandable and affordable detector technology. Suggestions to use a large volume of deep ocean water for high-energy neutrino astronomy were made as early as the 1960s. In the case of the muon neutrino, for instance, the neutrino ($\nu_{\mu}$) interacts with a hydrogen or oxygen nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The blue Cerenkov light emitted along the muon’s ~kilometer-long trajectory is detected by strings of photomultiplier tubes deployed deep below the surface. With the first observation of neutrinos in the Lake Baikal and the (under-ice) South Pole neutrino telescopes, there is optimism that the technological challenges to build neutrino telescopes can hopefully be met.
The first generation of neutrino telescopes, launched by the bold decision of the DUMAND collaboration to construct such an instrument, are designed to reach a large telescope area and detection volume for a neutrino threshold of order 10 GeV. The optical requirements of the detector medium are severe. A large absorption length is required because it determines the spacings of the optical sensors and, to a significant extent, the cost of the detector. A long scattering length is needed to preserve the geometry of the Cerenkov pattern. Nature has been kind and offered ice and water as adequate natural Cerenkov media. Their optical properties are, in fact, complementary. Water and ice have similar attenuation length, with the role of scattering and absorption reversed. Optics seems, at present, to drive the evolution of ice and water detectors in predictable directions: towards very large telescope area in ice exploiting the long absorption length, and towards lower threshold and good muon track reconstruction in water exploiting the long scattering length.

DUMAND, the pioneering project located off the coast of Hawaii, demonstrated that muons could be detected by this technique\cite{39}, but the planned detector was never realized. A detector composed of 96 photomultiplier tubes located deep in Lake Baikal was the first to demonstrate the detection of neutrino-induced muons in natural water\cite{40,41}. In the following years, NT-200 will be operated as a neutrino telescope with an effective area between $10^3\sim5 \times 10^3 m^2$, depending on energy. Presumably too small to detect neutrinos from extraterrestrial sources, NT-200 will serve as the prototype for a larger telescope. For instance, with 2000 OMs, a threshold of $10\sim20 GeV$ and an effective area of $5 \times 10^4\sim10^5 m^2$, an expanded Baikal telescope would fill the gap between present detectors and planned high-threshold detectors of cubic kilometer size. Its key advantage would be low threshold.

The Baikal experiment represents a proof of concept for deep ocean projects. These do however have the advantage of larger depth and optically superior water. Their challenge is to find reliable and affordable solutions to a variety of technological challenges for deploying a deep underwater detector. The European collaborations ANTARES\cite{42,43,44} and NESTOR\cite{45,46,47} plan to deploy large-area detectors in the Mediterranean Sea within the next year. The NEMO Collaboration is conducting a site study for a future kilometer-scale detector in the Mediterranean\cite{48}.

The AMANDA collaboration, situated at the U.S. Amundsen-Scott South Pole Station, has demonstrated the merits of natural ice as a Cerenkov detector medium\cite{49}. In 1996, AMANDA was able to observe atmospheric neutrino candidates using only 80 eight-inch photomultiplier tubes\cite{49}. With 302 optical modules instrumenting approximately 6000 tons of ice, AMANDA extracted several hundred atmospheric neutrino events from its first 130 days of data. AMANDA was thus the first first-generation neutrino telescope with an effective area in excess of 10,000 square meters for TeV muons\cite{50}. In rate and all characteristics the events are consistent with atmospheric neutrino origin. Their energies are in the 0.1–1 TeV range. The shape of the zenith angle distribution is compared to a simulation of the atmospheric neutrino signal in
Fig. 7. The variation of the measured rate with zenith angle is reproduced by the simulation to within the statistical uncertainty. Note that the tall geometry of the detector strongly influences the dependence on zenith angle in favor of more vertical muons.

The arrival directions of the neutrinos are shown in Fig. 8. A statistical analysis indicates no evidence for point sources in this sample. An estimate of the energies of the up-going muons (based on simulations of the number of reporting optical modules) indicates that all events have energies consistent with an atmospheric neutrino origin. This enables AMANDA to reach a level of sensitivity to a diffuse flux of high energy extra-terrestrial neutrinos of order \( dN/dE_\nu = 10^{-6} E_\nu^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1} \), assuming an \( E^{-2} \) spectrum. At this level they exclude a variety of theoretical models which assume the hadronic origin of TeV photons from active galaxies and blazars. Searches for neutrinos from gamma-ray bursts, for magnetic monopoles, and for a cold dark matter signal from the center of the Earth are also in progress and, with only 138 days of data, yield limits comparable to or better than those from smaller underground neutrino detectors that have operated for a much longer period.

In January 2000, AMANDA-II was completed. It consists of 19 strings with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA forming the central core of the new detector. First data with the expanded detector indicate an atmospheric neutrino rate increased by a factor of three, to 4–5 events per day. AMANDA-II has met the key challenge of neutrino
astronomy: it has developed a reliable, expandable, and affordable technology for deploying a kilometer-scale neutrino detector named IceCube.

IceCube is an instrument optimised to detect and characterize sub-TeV to multi-PeV neutrinos of all flavors (see Fig. 9) from extraterrestrial sources. It will consist of 80 strings, each with 60 10-inch photomultipliers spaced 17 m apart. The deepest module is 2.4 km below the surface. The strings are arranged at the apexes of equilateral triangles 125 m on a side. The effective detector volume is about a cubic kilometer, its precise value depending on the characteristics of the signal. IceCube will offer great advantages over AMANDA II beyond its larger size: it will have a much higher efficiency to reconstruct tracks, map showers from electron- and tau-neutrinos (events where both the production and decay of a $\tau$ produced by a $\nu_\tau$ can be identified) and, most importantly, measure neutrino energy. Simulations indicate that the direction of muons can be determined with sub-degree accuracy and their energy measured to better than 30% in the logarithm of the energy. Even the direction of showers can be reconstructed to better than $10^\circ$ in both $\theta$, $\phi$ above 10 TeV. Simulations predict a linear response in energy of better than 20%. This has to be contrasted with the logarithmic energy resolution of first-generation detectors. Energy resolution is critical because, once one establishes that the energy exceeds 100 TeV, there is no atmospheric neutrino background in a kilometer-square detector.

At this point in time, several of the new instruments, such as the partially deployed Auger array and HiRes to Magic to Milagro and AMANDA II, are less than one year from delivering results. With rapidly growing observational capabilities, one can express the realistic hope that the cosmic ray puzzle will be solved soon. The solution will almost certainly reveal unexpected astrophysics, if not particle physics.

For a recent review of neutrino astronomy and its relationship to cosmic rays, see Ref. [51].
**Fig. 9.** Although IceCube detects neutrinos of any flavor above a threshold of $\sim 0.1$ TeV, it can identify their flavor and measure their energy in the ranges shown.

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### References

1. D.J. Bird *et al.*: Phys. Rev. Lett. **71**, 3401 (1993)
2. N.N. Efimov *et al.*: *ICRR Symposium on Astrophysical Aspects of the Most Energetic Cosmic Rays*, ed. M. Nagano and F. Takahara (World Scientific, 1991)
3. [http://www.hep.net/experiments/all sites.html](http://www.hep.net/experiments/all sites.html) provides information on experiments discussed in this review. For a few exceptions, we will give separate references to articles or websites.
4. M. Ave *et al.*: Phys. Rev. Lett. **85**, 2244 (2000)
5. [http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/](http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/)
6. *Proceedings of the International Cosmic Ray Conference*, Hamburg, Germany, August 2001
7. K. Greisen: Ann. Rev. Nucl. Science **10**, 63 (1960)
8. F. Reines: Ann. Rev. Nucl. Science **10**, 1 (1960)
9. M.A. Markov, I.M. Zheleznykh: Nucl. Phys. **27**, 385 (1961)
10. M.A. Markov in *Proceedings of the 1960 Annual International Conference on High-energy Physics at Rochester*, ed. by E.C.G. Sudarshan, J.H. Tinlot, A.C. Melissinos (1960)
11. F.W. Stecker, M.H. Salamon: Astrophys. J. **512**, 521 (1999), [astro-ph/9808110](http://arxiv.org/abs/astro-ph/9808110)
12. R.A. Vazquez *et al.*: Astroparticle Physics **3**, 151 (1995)
13. J. Alvarez-Muniz, F. Halzen, T. Han, D. Hooper: Phys. Rev. Lett. **88**, 021301 (2002), [hep-ph/0107057](http://arxiv.org/abs/hep-ph/0107057)
14. R. Emparan, M. Masip, R. Rattazzi: Phys. Rev. D **65**, 064023 (2002), [hep-ph/0109287](http://arxiv.org/abs/hep-ph/0109287)
15. P. Jain, D.W. McKay, S. Panda, J.P. Ralston: Phys. Lett. B **484**, 267 (2000), [hep-ph/0001053](http://arxiv.org/abs/hep-ph/0001053)
16. A. Jain, P. Jain, D.W. McKay, J.P. Ralston: [hep-ph/0011310](http://arxiv.org/abs/hep-ph/0011310)
17. C. Tyler, A.V. Olinto, G. Sigl: Phys. Rev. D **63**, 055001 (2001), [hep-ph/0002251](http://arxiv.org/abs/hep-ph/0002251)
18. S. Nussinov, R. Shrock; Phys. Rev. D 59, 105002 (1999), hep-ph/9811322.
19. S. Nussinov, R. Shrock: Phys. Rev. D 64, 047702 (2001), hep-ph/0103041.
20. G. Domokos, S. Kovesi-Domokos: Phys. Rev. Lett. 82, 1306 (1999), hep-ph/9812266.
21. G. Domokos, S. Kovesi-Domokos, P.T. Mikulski: hep-ph/0006328.
22. A. Watson: these proceedings
23. H.J. Volk: these proceedings
24. C. Tao: these proceedings
25. F. Halzen: 'The case for a kilometer-scale neutrino detector', in Nuclear and Particle Astrophysics and Cosmology, Proceedings of Snowmass 94, ed. by R. Kolb, R. Peccei
26. F. Halzen: 'The Case for a Kilometer-Scale Neutrino Detector: 1996', in Proc. of the Sixth International Symposium on Neutrino Telescopes, ed. by M. Baldocci, (Venice, 1996)
27. F. Halzen, E. Zas: Astrophys. J. 488, 669 (1997), astro-ph/9702194.
28. J.N. Bahcall, E. Waxman: Phys. Rev. D 64 (2001), hep-ph/9902388.
29. E. Waxman, J.N. Bahcall: Phys. Rev. D 59 (1999), hep-ph/9807285.
30. K. Mannheim, R.J. Protheroe, J.P. Rachen: Phys. Rev. D 63, 023003 (2001), hep-ph/9812398.
31. J.P. Rachen, R.J. Protheroe, K. Mannheim: presented at The 19th Texas Symposium on Relativistic Astrophysics: Texas in Paris, Paris, France, 14–18 Dec 1998, astro-ph/9908031.
32. J. Alvarez-Muniz, F. Halzen: UW-Madison report MADPH-00-1167 (2002)
33. T.K. Gaisser, R.J. Protheroe, T. Stanev: Ap.J. 492, 219 (1998)
34. L. O’C. Drury, F.A. Aharonian, H.J. Völk: A & A 287, (1994) 959.
35. J.A. Esposito, S.D. Hunter, G. Kanbach, P. Sreekumar: Ap.J. 461, (1996) 820.
36. W. Bednarek, R. J. Protheroe: Phys. Rev. Lett. 79, 2616 (1997)
37. The Cangoroo collaboration: Nature 416, 797 (2002)
38. T.K. Gaisser, F. Halzen, T. Stanev: Phys. Rept. 258, 173 (1995) [Erratum ibid. 271, 355 (1995)], hep-ph/9410384.
39. J.G. Learned, K. Mannheim: Ann. Rev. Nucl. Part. Science 50, 679 (2000)
40. ‘Cosmic Rays in the Deep Ocean’, the DUMAND Collaboration (J. Babson et al.), ICR-205-89-22, Dec 1989, 24pp, Published in Phys. Rev. D 42, 3613 (1990)
41. I.A. Belolaptikov et al.: Astroparticle Physics 7, 263 (1997)
42. V.A. Balkanov et al.: Astro. Part. Phys. 14, 61 (2000)
43. E. Aslanides et al.: astro-ph/9907432 (1999).
44. F. Feinstein [ANTARES Collaboration]: Nucl. Phys. Proc. Suppl. 70, 445 (1999)
45. T. Montaruli [ANTARES Collaboration]: Proceedings of TAUP 2001: Topics in Astroparticle and Underground Physics, Assergi, Italy, 8–12 Sep 2001, hep-ex/0201009.
46. L. Trascatti, in Procs. of the 5th International Workshop on Topics in Astroparticle and Underground Physics (TAUP 97), Gran Sasso, Italy, 1997, ed. by A. Bottino, A. di Credico, P. Monacelli: Nucl. Phys. B70 (Proc. Suppl.), 442 (1998)
47. P.K. Grieder [NESTOR Collaboration]: Nuovo Cim. 24C, 771 (2001)
48. L. Trascatti [NESTOR Collaboration]: Nucl. Phys. Proc. Suppl. 70, 442 (1999)
49. Talk given at the International Workshop on Next Generation Nucleon Decay and Neutrino Detector (NNN 99), Stony Brook, 1999, Proceedings to be published by AIP.
50. The AMANDA collaboration: Astroparticle Physics 13, 1 (2000)
51. E. Andres et al.: Nature 410, 441 (2001)
52. F. Halzen, D. Hooper: Repts. Prog. Phys., in press, astro-ph/0204527.