High Energy Neutrino Astrophysics

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This contribution presents an overview of the present status of high energy neutrino astrophysics. Included are descriptions of the possible sources, accelerated particles, methods of detection, and existing and planned experiments.

I. INTRODUCTION

Since early this century it has been known that a steady stream of charged nuclei, and to a lesser extent electrons and photons, reaches the Earth. The origin of the cosmic radiation, however, has not be explained satisfactorily. Finding an answer to this apparently simple question is complicated by the fact that extensive knowledge of several physical disciplines is required for an appropriate treatment of the problem. Astronomy, astrophysics, cosmology, nuclear physics and particle physics have all been united under the umbrella term of astroparticle physics for this purpose.

According to the phenomenology of Cosmic Radiation, three independent experimental methods are available for approaching the problem: (1) The measurement of the charged nuclei energy spectra allows the determination of the common emission of all sources of a certain particle type and energy [?], (2) the search for sources of gamma rays, which are necessarily produced in the same processes as the charged particles [?], and (3) the search for neutrino sources for the same reason as in (2) [?]. Whereas the first two methods have been explored intensively, neutrino astronomy is still in a phase of experimental development. Obviously this is a consequence of the different interaction probabilities of nuclei, photons and neutrinos. The large cross sections of nuclei and photons makes it comparably easy to detect these particles in balloon or satellite experiments - or at higher energies in Earth bound detectors- based on different techniques. However, the large cross sections of these particles are also responsible for their absorption either while still in the source, or in the intergalactic medium. Furthermore, due to deflection by magnetic fields, the charged particles rarely carry information about the location of their origin.

Neutrinos are produced as final decay products of various kinds of mesons in hadron interactions. Their interaction probability is small, so that they escape unaffected from the source region. If the source itself is dense, as in the case of supernovae, all other particles are absorbed already in the source and neutrinos may be the dominant energy carrier, transporting the most information out of the source. Also by the intergalactic photon and dust background they are not absorbed. Finally, neutrinos are neutral, so that the neutrino direction always points back towards the source.
Like other particles neutrinos can only be detected by their interaction products. The advantage gained by the directionality is balanced by the drawback that the interaction volume to be monitored experimentally has to be large and located deep under the Earth's surface to suppress the background of cosmic particles with higher interaction probabilities. Fortunately after several hundred meters of water-equivalent (1 hg/cm^2 = 1 mwe), all particles except muons and neutrinos, and above 13 kmwe also the muons, have died out so that it is possible to find appropriate detector locations.

II. PARTICLE FLUX UNDER GROUND

A. Atmospheric Particles

The overwhelming majority of cosmic radiation consists of charged nuclei at energies up to 10^{20}eV. The energy spectrum of the primary nuclei may be described in the energy region up to the "knee" at several PeV by a power law with a spectral index of about 2.7. This radiation is of special importance for neutrino astronomy because it produces the background to the neutrino induced muon signal: The primaries interact in the upper atmosphere with air nuclei. Light mesons (π and K) produced in these interactions have lifetimes long enough to allow them to interact with components of the atmosphere. Since the particles that penetrate deeply underground (muons and neutrinos) are produced nearly exclusively in the decay of these light mesons, the muon and neutrino spectra are steeper by one spectral index unit (3.7) at energies sufficiently high to neglect the meson masses. The more horizontal the zenith angle of the incident primary, the smaller the thickness of the atmosphere within the meson pathlength. Therefore the intensity of the decay products increases with the zenith angle at sufficiently high energies.

In these interactions, a small portion ($< 0.1\%$) of heavy (charmed) mesons are also produced. As they decay immediately, their spectrum reflects the primary spectrum and shows no angular dependence. Since the charm-production cross section in the forward direction can not be exactly calculated (due to lack of knowledge of the parton distribution functions at small Feynman x), one can only estimate the flux of muons and neutrinos far above 100 TeV to be dominated by this origin.

B. Extraterrestrial Neutrinos

Through the combined results of satellite experiments, Cherenkov telescopes, extended air shower arrays, and observations of radio telescopes, many of the properties of sources of high energy particle emittance have been determined. Since the information accessible in this manner stems from the source surface, up to now the actual particle acceleration mechanism could not be determined. Indeed it is possible to describe most of the phenomena either by purely leptonic models or by models which include hadron acceleration. So Neutrino Astronomy plays the role of an *experimentum crucis* between those two possibilities. But the intention in building neutrino telescopes is not restricted to this, since it is known already that the dominant part of the cosmic radiation *is* hadronic, and that the interaction of hadrons is accompanied by the production of electrons, photons and neutrinos. Unlike neutrinos, electrons and photons cascade down over long distances in such a way that the photon density rises roughly as E^2 with decreasing energy. The measurement of the isotropic photon background at low energies limits therefore the integral number of sources for highly energetic particles and the neutrino flux at the same time. This leads to the surprising effect that the lower the injection energy the higher the predicted neutrino flux. To allow several hundreds of (muon) neutrino events per year at an energy where the atmospheric background can be suppressed, a typical detector size of 1 km^3 of dense material is required.

1. Galactic Sources

Neutrinos may be produced in the Galaxy either in the source of the charged cosmic radiation such as Supernovae, Supernova Remnants, or in strong X-ray and gamma ray sources such as X-ray binaries or neutron stars. Or, they may be produced indirectly by the interactions of the charged cosmic rays with the material of the galactic plane. The hard gamma-ray spectrum measured from the direction of the galactic plane and the high energies at which photons from the Supernova Remnant Crab were detected support especially the hadronic acceleration models.

2. Active Galactic Nuclei

Active Galactic Nuclei (AGN) are the most powerful energy sources in the sky. They consist of a supermassive black hole surrounded by an accretion disc which balances its energy by feeding relativistic jets of charged particles contained by magnetic fields. Jets pointing directly to the Earth (Blazars) produce a very hard gamma-ray spectrum. Therefore AGNs are good candidates to explain the events in the energy range of 10^{20} eV, provided protons are accelerated in the jets [?].

3. Transient Phenomena

The short (milliseconds to minutes) bursts of gamma-rays (GRB) at cosmological distances, leading to energy expulsions a hundred times that of a Supernova, are presently thought to be produced by a fireball product of two coalescing neutron stars. In this scenario, low energy neutrinos form directly in the fireball, and time-delayed neutrinos from possible beam dumps of the accelerated protons are predicted [?].

4. Cosmological Defects

Relics of the time of Grand Unification structure formation (magnetic monopoles, domain walls ...) may still be present in the Universe. They may decay hadronically, thus producing photons and neutrinos. If the highest energy events should turn out to be photonic then neutrinos from this source would also be required. Whereas for a long time it was thought that neutrinos from this source would be barely detectable, new detailed calculations show that fluxes comparable to that of GRBs or AGNs are possible [?].

Due to such sources as these one may expect in the order of 500 neutrino induced muons above 1 TeV per km^3 and year. This has to be compared to an isotropic background of muons due to atmospheric neutrinos of the order of 10000 events. The following characteristics then can be used to identify generic source types. The transient phenomena have through their predicted coincidence in space and time with gamma ray bursts the clearest signature making them to a primary target of the data analysis. AGNs would allow an identification by their location and by the isotropic energy spectrum. Classical astronomical objects (stars) can be identified by their location only. Cosmological defects as source have to be assumed if there are no spatial correlations and the measured energy spectrum fits to this prediction.

C. Particle Physics Aspects

Apart from the astrophysical questions which will be answered by neutrino telescopes, several questions from particle physics can be approached directly. These include the search for magnetic monopoles and for neutrino signals from the center of the Earth or the Sun [?], indicating the gravitational capture of WIMPS (the lightest supersymmetric particles), and for the typical pattern of interactions of the tau neutrinos. By an appropriate design of the detector a test of neutrino oscillations could be possible. Furthermore, in the case of a type II supernova in our galaxy, the time delay between the arriving neutrino flavors (if not destroyed by the mixing) may help to determine neutrino masses. Less prominent aspects are the determination of the charm production cross section or questions of the first nucleus-nucleus interaction in the high atmosphere, both with the help of the downward muon signal.

III. EXPERIMENTAL REQUIREMENTS

The necessary detector size of 1 km^3 can neither be achieved in a natural or artificial cavern, nor surveyed in other than transparent and homogenous material (i.e. water and ice). The most promising and straightforward technique is the detection of the Cherenkov light of charged products of neutrino interactions, which is already successfully used in water (Baikal) and ice (Amanda). In the future, the acoustic and radio signature of these interaction products may be used to extend the energy range and detector volume.

A. Muon Detection

For neutrino astronomy, atmospheric particles are a natural background for all additional extraterrestrial components. The atmospheric muon flux visible in underground detectors decreases by about a half order of magnitude per kmwe and at 13 kmwe falls below the flux of muons induced by neutrino interactions in the material (rock, water, ice) surrounding the detector. Since it is neither feasible to build a detector of the necessary size 13 km deep in ice or the ocean, nor 5 km deep below a rock surface, the underground detectors have to be able to reject this flux by the determination of the muon direction and thereby the distance between the detector and the surface in the muon direction. If this distance is larger than 13 km, the muon has to be regarded as neutrino-induced. Obviously this background reduction depends crucially on the detection and reconstruction efficiency and the angular resolution. For the underwater/ice detectors presently under construction the background has to be suppressed by 4 (Nestor), 5-6 (Antares, Amanda) orders of magnitude. The remaining background of muons from atmospheric neutrinos can be reduced either by the angular resolution (for the case of a search for point sources), or by a measurement of the integral neutrino-induced muon energy spectrum to determine the characteristic flattening due to extragalactic contributions. Though the latter technique requires an energy reconstruction in addition to a path reconstruction, the signal for this case is supposed to be 100 times stronger than in the former because the source positions are not known *a priori*. Regardless of the technique, the additional background reduction in this step has to cover two orders of magnitude.

Atmospheric particles are more than just background. They may serve as a test beam to calibrate the energy and angular resolution of the detector, and to monitor the detector efficiency and stability over time.

When the detector is well understood, one can consider additional physics questions, such as subtleties of the first hadron-hadron interaction or the search for the characteristic flattening of the atmospheric muon spectrum due to the contribution of charm decays.

B. Electron Detection

The electron-neutrino flux from extraterrestrial sources is connected by the production mechanism (meson decay) to the muon neutrino flux, and is supposed to have a similar energy spectrum and integral intensity.

Electromagnetic showers induced by electron neutrinos have a much shorter range than muons of the same energy, and can only be detected if the interaction is inside the detector. In large underground experiments the number of electron-neutrino interactions may reach the number of detectable neutrino induced muons. Electron-neutrino detection has two important advantages. First there is no background corresponding to the atmospheric muons (meaning that one can look upward), and second that the complete neutrino energy is released in a small spatial region, which makes the signature unique and the energy measurable. The underground detectors used currently for Neutrino Astronomy were designed as proton decay or atmospheric neutrino detectors. This holds for the prototype km^3-detectors as well. The mean track length within these detectors is small compared to the range of a typical neutrino induced muon. The sensitivity of the detectors is therefore substantially increased by interactions outside the detector. This effect gets smaller as one approaches the km^3-size.

IV. EXPERIMENTS

A. Progenitors and Boundary Conditions

The first generation of experiments sensitive to (atmospheric) neutrinos (IMB, Kamiokande, Fréjus, Soudan) were primarily built as proton decay detectors, sensitive in the energy range below 10 GeV. The investigation of the atmospheric neutrino flux with these detectors (typical exposure of several kty) has led to the discovery of the "atmospheric neutrino anomaly". The Super-Kamiokande collaboration, with a detector sensitivity of more than a factor of ten above this first generation, has claimed that the atmospheric neutrino anomaly is a consequence of neutrino oscillations. Super-Kamiokande is also the largest experiment which can, for mechanical reasons, be carried out in an artificial cavern.

Concurrently detectors operating as muon telescopes (Baksan and Macro) continue the search for point sources with effective areas of O(1000 m^2). Using the energy resolution as a tool for rejecting atmospheric neutrino induced background was first explored by the Fréjus analysis of neutrino induced muons [?](excluding several astrophysical and particle physical scenarios discussed at that time). The most stringent limit on the extraterrestrial neutrino flux, however, stems from the measurement of the isotropic photon flux measured by the EGRET satellite experiment. Since neutrinos and photons are both produced in the meson decay (independent from the meson source) but photons cascade down in energy on their path between their place of production and the Earth, the low energy (50 GeV) measurement of the isotropic photon flux limits also the neutrino flux. If one requires additionally, that the source of the highest energy cosmic rays is also the source of high energy neutrinos one may exclude via the hadron/neutrino ratio optically thin sources as strong neutrino sources. However, the source of high energy cosmic rays is not necessarily the source of high energy neutrinos nor are optically thin sources the most promising neutrino sources to study.

To be sensitive for models beyond the existing experimental limits, especially the EGRET limit, one needs (depending on the energy resolution of the detector) a detector with an effective area of 1 km^2.

B. Baikal

The first muon neutrinos using natural (lake) water as interaction and Cherenkov light propagation medium were detected by an experiment in the Lake Baikal in Siberia. The Baikal detector consisted at that time on 96 photomultipliers arranged on 4 strings submerged 1100 m below the surface (NT-96). Since then the detector has gradually been enlarged to its present size of 196 photomultipliers (NT-200). The Photomultiplier are arranged in pairs (up and down looking) in order to reduce the noise and allow a better rejection of down going muons. In order to suppress the background each muon has to have a minimal track length of 35 m within the detector. This results in an energy threshold of about 10 GeV. It is planned to enlarge this detector by one order of magnitude (NT-2000) while retaining the low energy threshold. Such an instrument would be an excellent tool for investigating the atmospheric neutrino flux and for searching for new phenomena (magnetic monopoles). The effective area, however, would stay one order of magnitude below the canonical requirement of 1km^2 needed to detect extraterrestrial neutrinos [?].

C. AMANDA

The AMANDA detector is located exactly at the geographical South Pole. The first stage, consisting of 302 photomultipliers, nearly all down facing, at a depth of 1500 m to 2000 m in the ice, was finished in the austral summer 96-97. Compared to water, ice has the advantage that there is no noise due to radioactive K^{40} or bioluminescence. There are also no problems due to sediment collecting on the optical modules or movement of the strings. Furthermore the absorption length of Cherenkov light in ice is even longer than in water. However, the South Pole ice contains air bubbles below 1200 m and horizontal dust structures affecting the scattering length of light [?]. Since the detector calibration must be started after the deployment, only after that can the ice properties and the detector geometry be studied. The knowledge of the ice properties then has to be added to the Monte Carlo detector simulation and to the reconstruction programs. The so-obtained agreement between data and Monte Carlo allowed the reconstruction of the angular dependence of the down going muon flux up to 80° with the first four strings alone. With the same four string detector events in coincidence with the SPASE-South Pole array [?] have been investigated showing that the angular resolution is about 5° in agreement with the Monte Carlo expectation. The first analysis of the complete 10 string detector show, that due to the larger number of photomultipliers the angular resolution is a factor of two better for this configuration. A search for neutrino induced muons in 113 days of the 1997 data shows good agreement between the expected number of events and the number of recorded events. In the future the accuracy and efficiency of the reconstruction will be further improved, and the energy reconstruction will be investigated. Here the smaller scattering length compared to water should improve the energy resolution of the detector. By next year the outer ring of strings around the detector will be completed. AMANDA II then will be a 21 string detector with 800 photomultipliers and an effective area of $3 \cdot 10^4$ m^2. It is planned to construct within the following years ICECUBE, a km^3 array. [?,?]

D. ANTARES

ANTARES is one of two experiments, which intend to use the open Mediterranean sea as a detector medium. Since string deployment, retrieval and maintenance in the open sea are technical challenges, the ANTARES collaboration concentrated their effort first on a systematic and detailed study of these questions for a 2400 m deep site close to Toulon (France). The ANTARES collaboration has deployed one test string to this depth, operated it for one year, and has finally successful recovered it. With this string the sedimentation of biomaterial on upward facing photomultipliers and the effect of water currents have been studied. Due to the background from K^{40} radio activity and bioluminescence the photomultipliers have to be operated in pairs. The experience gained can now be used to deploy strings for particle detection. [?]

E. NESTOR

The second Mediterranean experiment NESTOR is planned to be located close to the Greek island of Pylos. This site was chosen to take advantage of a sharp fall off (to 4500) m near the shoreline yielding the possibility to deploy strings at a depth of up to 4000 m. If realized, an experiment at this location would have an atmospheric background of 50 to 100 times smaller than at the other sites. Furthermore, investigations have shown an excellent water quality. Problems due to sedimentation or biofouling are also expected to be slight. The NESTOR detector is planned as a 200 m tall "tower" consisting of twelve mechanical stable hexagonal "floors" with a diameter of 30 m. At the corners of the hexagon, pairs of up- and down looking Photomultipliers will be mounted. Due to the high photomultiplier density the energy threshold of a single NESTOR tower will be about 10 GeV. Higher thresholds and correspondingly effective areas may be reached by the eventual deployment of seven towers. [?]

F. Alternatives

The neutrino detection via the Cherenkov light of the secondaries in water or ice has a lower energy threshold that allows an overlap with the upper thresholds of existing experiments. The atmospheric particles can be used for the detector calibration. This technique seems, however, not to be extendable to much larger detector volumes than one cubic-kilometer. To explore higher energies and correspondingly smaller fluxes two experimental approaches shall be mentioned. Using the radio emission of the secondaries instead of the Cherenkov light as signal the RICE collaboration intends to improve the sensitive volume in the South Pole ice to 10 km^3, leading to an energy sensitivity

above several PeV. [?]
The giant AUGER air shower array will be able to detect the fluorescence light from horizontal air showers over an area of 3000 km^3. Since only neutrinos can penetrate horizontally so deep in the atmosphere this detector becomes sensitive for neutrinos with energies above 10^4 PeV. [?]

To cover the complete sky at least two telescopes, one at the northern and one at the southern hemisphere are desired. For the South Pole location the galactic plane will be buried under an huge background of down going muons, making measurements or galaxy extremely difficult. Because of the size limitation of the Baikal experiment candidates are ANTARES or NESTOR at the northern hemisphere and AMANDA in the south.

V. CONCLUSION

Neutrino Astronomy is a well motivated new physical discipline. The results of this research are expected to contribute answering many questions from the fields of astronomy, particle physics and cosmology. The technical properties of appropriate detectors have been defined and the existing prototype detectors show that these specifications are reachable and financially feasible. Scientific curiosity opens here one of the few remaining new windows to the universe and it does not take much imagination to see that the *terra incognita* behind this window may still hide several surprising discoveries.

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