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RECENT DEVELOPMENTS IN ULTRA-HIGH ENERGY NEUTRINO ASTRONOMY

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Abstract. We outline the current situation in ultrahigh energy (UHE) cosmic ray physics, pointing out the remaining problems, in particular the puzzle concerning the origin of the primary radiation and the role of neutrino astronomy for locating the sources. Various methods for the detection of UHE neutrinos are briefly described and their merits compared. We give an account of the achievements of the existing optical Cherenkov neutrino telescopes, outline the possibility of using air fluorescence and the particle properties of air showers to identify neutrino induced events, and discuss various pioneering experiments employing radio and acoustic detection of extremely energetic neutrinos. The next generation of space, ground and sea based neutrino telescopes now under construction or in the planning phase are listed.

Keywords: neutrino astronomy, neutrino telescopes, neutrino detection.

1. Introduction

The principal aim of neutrino astronomy is to locate the sources of UHE component of the cosmic radiation (CR). CR is predominantly of hadronic nature. It is therefore expected that UHE hadronic interactions take place within the sources and in their immediate vicinity, copiously producing pions, kaons and other particles that are subject to decay, yielding a corresponding number of photons and neutrinos of different flavors. Consequently, an UHE hadron source is also expected to emit UHE neutrinos that are signatures of the hadronic processes. Their trajectories are not affected by magnetic fields; they point directly at the source and should be detectable.

In recent years cosmic ray physics has made great progress, in particular as concerns the primary all-particle spectrum. In the high energy regime ($E \geq 10^{14}$ eV), where air showers are the only source of information from which the properties of the primary radiation can be extracted in conjunction with simulations, the results of different experiments have deviated significantly until recently. After re-scaling the energy spectra of all major experiments of recent years, there is now good agreement with respect to the shape of the spectrum, i.e., the spectral index, and the intensity to within about 20 percent or better up to $\sim 5 \times 10^{19}$ eV.

Beyond this energy even the two most recent and largest experiments, the Telescope Array (TA) [48] in the northern hemisphere and the Pierre Auger Observatory (PAO) [5] in the southern hemisphere, show increasing differences between their respective spectra with increasing energy as they enter the region of the expected Greisen–Zatsepin–Kuzmin (GZK) cutoff [32, 59] (see Fig. 1a).

Unfortunately, the situation concerning the primary composition remains very unsatisfactory. The energy dependence of the $X_{\max}$ distributions and of other primary mass sensitive observables recorded by the TA and the PAO manifest different trends at UHE. In general, large differences exist between the compositions obtained by the different experiments in the air shower energy domain of the primary spectrum, which get worse with increasing energy.

Some progress can be reported concerning the correlation between the arrival direction of the most energetic events (air showers) and astrophysical objects. However, so far no object could definitely be identified as a source of UHE cosmic rays, and the results of the three most relevant experiments carrying out anisotropy studies (PAO, TA, and HiRes (now shut-down)) yield inconclusive results [5, 22, 48].

Neutrino astronomy is expected to solve the cosmic ray source puzzle, as mentioned before, provided an adequate flux of UHE neutrinos exists and can be detected. If no neutrino point source can be found but only a diffuse isotropic flux of UHE neutrinos, this would be additional evidence besides the drop of the all-particle spectrum beyond $\sim 5 \times 10^{19}$ eV and the increasing gamma ray fraction observed at UHE (Fig. 1b) for the existence of the GZK process,

$$p + \gamma_{2.7\,K} \rightarrow \Delta^+ \rightarrow n + \pi^+;\ \pi^+ \rightarrow \mu^+ + \nu_\mu,$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e, \text{ and}$$
$$n \rightarrow p + e^- + \bar{\nu}_e,$$

and similar reactions, which cause the cutoff.

2. Neutrino reaction signatures and detection

A common feature of all high energy neutrino interactions, be it charged or neutral current reactions, initiated by any flavor (ν_e, ν_μ or ν_τ and their antiparticles), is a hadron cascade, emerging from the point

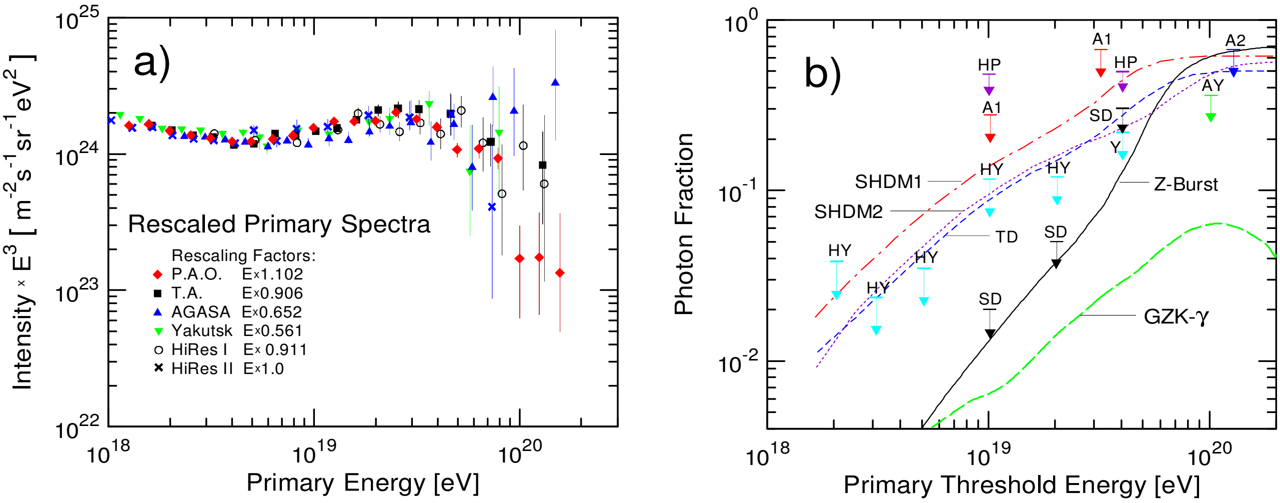

FIGURE 1. a) Re-scaled UHE primary all-particle spectra from the six major air shower experiments [52]. b) Photon fraction as deduced from different PAO measurements and predictions from various models. GZK-γ shows the contribution from GZK process (for details see [7]).

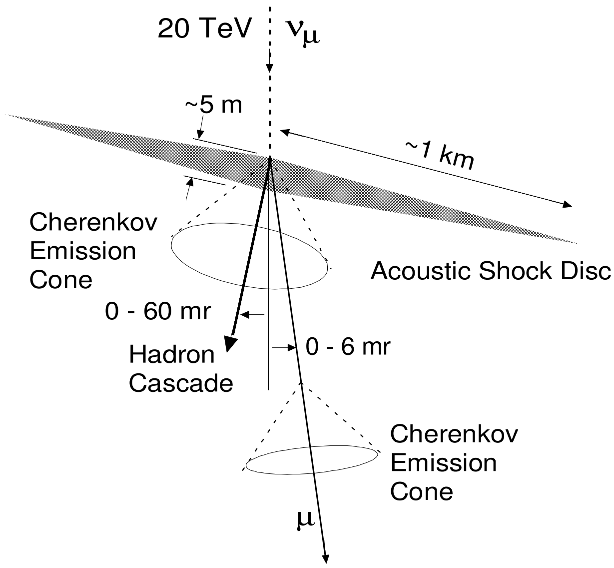

FIGURE 2. Characteristic effects caused by a high energy neutrino initiated interaction in a dense target medium. Analogous effects occur in ν_e and ν_τ triggered reactions. Note that in principle the Cherenkov process generates optical as well as radio emission.

of collision. The latter takes on average about 20 % of the incident energy at energies beyond $\sim 10^6$ GeV, whereas the bulk of the energy is taken by the forward going electron, muon or tau meson, emerging from the respective reaction, or by the scattered incident neutrino.

The common signature of all neutrino reactions in a dense target medium is illustrated, in principle, in Fig. 2 on the basis of a ν_μ interaction. The emerging muon must be replaced by an emerging electron or tau for ν_e or ν_τ initiated events, respectively.

Such events can be detected in principle by an array of optical, radio or acoustic sensors in a suitable medium (water, ice, rock, or a salt dome). Since neutrino events are rare, background rejection and shielding are of paramount importance. Depending on the physical properties of the target medium the propagation of parts of the Cherenkov emission (optical or radio) may be suppressed.

In the atmosphere, UHE neutrino initiated events cause air showers with particular characteristics that can be identified as such (late starting, downward going hadron poor showers; Earth skimming upward going showers, or, typical for ν_τ initiated events, showers that emerge from mountain sides or start in the air, whose axis projected backward points toward a mountain slope).

Since neutrinos have extremely small reaction cross sections and UHE astrophysical or cosmogenic neutrino fluxes are expected to be extremely low, as can be estimated from the CR spectrum and from various CR source and propagation models, huge detector systems (targets) are required to collect a statistically significant number of events. Consequently the *attenuation length* of the agent used to record, reconstruct and identify the events, i.e., optical or radio photons, or acoustic shock waves, is of prime importance (see Tab. 1). It determines the layout of the sensor matrix (fine or coarse meshed), the size and probably the price of a detector telescope.

3. Neutrino telescopes

3.1. Initial efforts and prototypes

The first attempt to search for cosmic neutrinos was made in Japan in the early 1960s, using an air shower array, looking for so-called hadron poor horizontal air showers as neutrino signature [47], however, without much success.

The decisive step which eventually led to the solution of the two major problems in the search for UHE cosmic neutrinos, their small reaction cross section and the expected low intensity, was made by

Technique	Target Medium	Frequency or Wavelength	Attenuation Length	Reference
Optical Cherenkov	water	400 nm	36 m	[43]
	water	470 nm	55 m	[43]
	ice	405 nm	$\sim 50 \div 100$ m	[35]
Air fluorescence	atmosphere	355 nm	$\simeq 14$ km	[25]
		355 nm	30^{+16}_{-10} km	[57]
Radio Cherenkov	ice	380 MHz	1450^{+300}_{-150} m	[19]
	ice	$250 \div 400$ MHz	$400 \div 700$ m	[23]
	ice	$100 \div 300$ MHz	495 ± 15 m	[34]
	lunar regolith	1 GHz	~ 20 m	[33]
	rock salt	94 MHz	330 m	[24]
	rock salt	1 GHz	> 250 m	[29]
Acoustic shock	sea water	10 kHz	~ 5 km	[11]
	sea water	20 kHz	~ 1 km	[11]
	ice	$10 \div 30$ kHz	312^{+68}_{-47} m	[2]

Table 1. Detection Technique and Corresponding Attenuation Length.

Markov [45]. He suggested using the ocean as a neutrino target and installing a giant three-dimensional matrix of optical sensors at great depth, to look for upward directed Cherenkov light trajectories of energetic muons emerging from UHE upward propagating muon neutrino initiated interactions.

This idea became the guideline for an international collaboration that was formed early in 1981 to develop the DUMAND (Deep Underwater Muon And Neutrino Detector) project, a giant detector matrix intended to be deployed in the Pacific, at great depth near Hawaii. The pioneering efforts of this collaboration eventually led to a very successful prototype system [17] that became the template for all subsequent deep water or deep ice optical Cherenkov neutrino telescopes. Unfortunately, the DUMAND project had to be abandoned in 1995 because of lack of funds. A Russian collaboration built a similar prototype in the early 1980s which was successfully operated in Lake Baikal and has been continuously expanded until now.

3.2. Deep-water/ice optical Cherenkov neutrino telescopes

Since the Cherenkov track of a muon emerging from a high energy ν_μ or $\bar{\nu}_\mu$ initiated interaction is the easiest clearly identifiable signature of all neutrino reactions, the initial searches for UHE astrophysical or cosmogenic neutrinos were focused on muon neutrinos, using huge optical sensor matrices at great depth for good shielding from downward going atmospheric muons, in large bodies of water or ice.

Today the list of large deep-water/ice optical detector matrices currently operating that serve as neutrino telescopes comprise besides NT-200 at Lake Baikal (since 1998) the ANTARES telescope in the Mediterranean (since 2007), and the giant 1 km^3 IceCube matrix in the deep ice at the South Pole (completed in December 2010), with the high resolution Deep Core detector embedded within it[1].

All these detectors are fine-meshed arrays with a typical sensor spacing of the order of about half of the attenuation length of the Cherenkov light in the respective media and yield a fair amount of reaction details. The pointing accuracy which increases with energy depends also on the detector type and configuration, and on the kind of neutrino reaction chosen to identify and reconstruct the event. As an example, the scattering angle between the reconstructed muon trajectory and the incident ν_μ in a charged current reaction is approximately 5 mr or less for an incident 20 TeV ν_μ (Fig. 2).

Apart from environmental data these experiments have yielded a wealth of data on the cosmic ray muon flux, on muon physics and on atmospheric neutrino fluxes. Unfortunately no UHE cosmic neutrinos could so far be identified, only upper limits could be established, except for two PeV events in IceCube [37]. Nevertheless, the present data could already rule out some of the production models. The data on diffuse ν fluxes obtained from these experiments are presented in Fig. 3. The energy estimation of the events is a very difficult task and is not discussed here.

The major disadvantage of the optical Cherenkov technique is the relatively short attenuation length of light in water and ice, requiring densely instrumented detectors that make large volume telescopes extremely costly and impose ultimate limits. Generally speaking, deployment of optical detectors in the deep open ocean

[1] AMANDA, which began operation in 2000 at the location of IceCube had been shut-down some time ago.

(Pacific) has proven to be difficult and hazardous. Deployment in the calm Mediterranean is probably less problematic.

3.3. Air fluorescence detection of neutrinos & ν-initiated showers

Neutrino-induced air showers exhibit specific features that are easily detectable with Fly's Eye type air fluorescence detectors under certain conditions, as mentioned in Section 2 (late starting, highly inclined downward going showers; Earth skimming ν_τ initiated events, emerging from the ground or mountain slopes). Installations like the PAO are well suited and very promising for such tasks. They offer a huge atmospheric target volume because of the very long optical attenuation length of air, are relatively cost effective and have a high discovery potential for UHE cosmic tau neutrinos. The pointing accuracy of such telescopes is similar to that for hadronic showers. The upper limits of UHE ν_τ intensities from the PAO experiment are given in Fig. 3.

3.4. Radio detection of neutrinos

The negative results so far obtained with the existing optical detector systems in the search for astrophysical neutrinos have motivated several investigators to explore the so-called *Askar'yan radio emission effect* [15] which is caused by the negative charge excess in electromagnetic cascades in dense media. The charge excess is due to Compton scattering, positron annihilation and other minor contributing effects.

Since radio waves have a much longer attenuation length at some frequencies in a variety of dense media, such as ice, certain rocks and pure salt in so-called salt domes (see Tab. 1), a much larger ν-target volume can be equipped with a given number of radio detection elements (antennas) than in the case of an optical ν-target with the same number of optical sensors for recording the optical component of the Cherenkov emission in water or ice (RICE, Kravchenko et al. [40]).

Moreover, huge thick homogeneous surface layers or bodies of suitable target material, such as the Antarctic ice shelf or the giant Greenland ice cap, can be surveyed with balloon (ANITA, Gorham et al. [31]) or satellite bound antenna systems (FORTE, Lehtinen et al. [42]), that can record radio signals from neutrino induced cascades in the target from large distances because of the excellent propagation of radio waves in air and vacuum. An much larger target for UHE cosmic rays as well as neutrinos of all flavors is the vast layer of regolith on the lunar surface. This layer can be surveyed from a satellite based antenna system, orbiting the Moon, or for higher threshold energies with radio telescopes from Earth, recording lunar surface skimming UHE events. The latter approach had been explored by the GLUE [30], LUNASKA [38],NuMoon [54, 55] and LOFAR [56] projects. Radio detection experiments serve mainly to explore the energy spectrum and yield fewer details than the optical Cherenkov telescopes. The upper limits from these experiments are also plotted in Fig. 3.

3.5. Acoustic neutrino detection

The hadron recoil cascade resulting from UHE neutrino interactions in dense media causes a thermal shock, as outlined in Section 2 [14, 41]. Several attempts were made in water and ice, using the existing infrastructures of the optical Cherenkov telescopes, to implement microphones to explore the phenomenon, and to interpret the signal in terms of neutrino interactions (ANTARES/AMADEUS, Aguilar et al. [11]; SPATS, Abbasi et al. [4]). The method is still in its exploratory phase.

4. Next generation telescopes

The obvious lesson that we have learned so far in our exploration of the cosmos in search of the sources of UHE cosmic rays using neutrinos is that even larger detection systems are required, employing partly new concepts. Within the context of this paper we can only list the next generation experiments that appear likely to be operational within the current decade, without going into details.

Apart from planned extensions of existing installations, new projects, some of which are well under way, comprise the ARIANNA radio detection array to be installed on the Ross Ice Shelf in Antarctica [21] and the JEM-EUSO, a large air fluorescence detector to be installed on the International Space Station [27]. In addition there is the giant KM3NeT water Cherenkov array project in the Mediterranean [39], and the Lunar Orbiting Radio Detector, LORD [53], which are presently in the R&D phase.

5. Concluding Remarks

The lack of a positive result in our search for UHE astrophysical neutrinos with the present large deep water/ice optical Cherenkov telescopes and the promising exploratory work with the more economical radio detection systems strongly suggests that future efforts should be oriented in this direction. However, the sensitivity of the method needs to be improved. Even though the radio method does not seem to yield the details that the optical Cherenkov matrices can yield, establishing the energy scale and (approximate) arrival direction of UHE messengers should have priority over details. The acoustic technique, too, may be worth exploring further, but it seems to be less promising.

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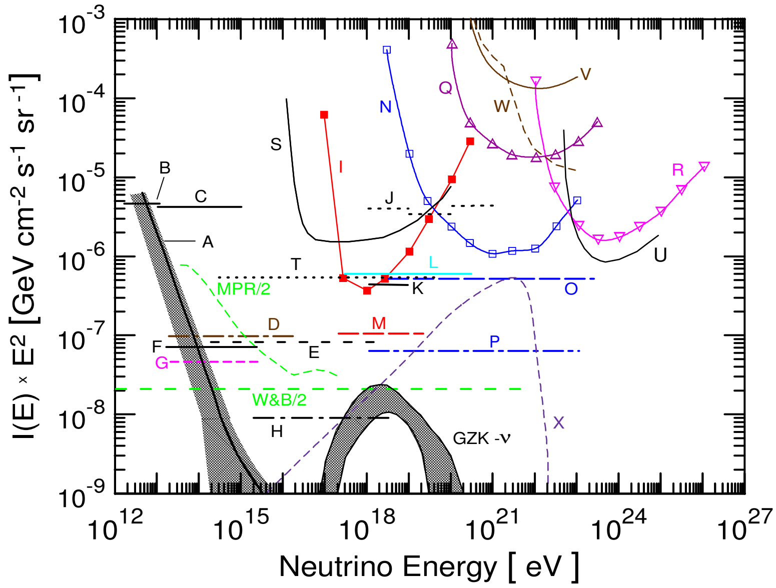

Figure 3. Compilation of the upper bounds of cosmic neutrino intensities as obtained by different experiments and from corresponding predictions: A, atmospheric neutrino intensity and uncertainty region [49]; B, Fréjus, $\nu_\mu + \bar{\nu}_\mu$ [51]; C, MACRO, $\nu_\mu + \bar{\nu}_\mu$ [12]; D, Baikal NT-200, $(\nu_e + \nu_\mu + \nu_\tau)/3$ [16]; E, AMANDA-II UHE 2000–02, limits for $(\nu_e + \nu_\mu + \nu_\tau)/3$ [9]; F, AMANDA-II, $\nu_\mu + \bar{\nu}_\mu$ limit [8]; G, ANTARES 2007–09, $\nu_\mu + \bar{\nu}_\mu$ [10]; H, full IceCube, 3 years, all flavors [36]; I, Auger diff., $\nu_\tau + \bar{\nu}_\tau$ [6]; J, HiRes, $\nu_e + \bar{\nu}_e$ [1]; K, HiRes, $\nu_\tau + \bar{\nu}_\tau$ [46]; L, RICE, all flavors [40]; M, Auger integral, $\nu_\tau + \bar{\nu}_\tau$ [6]; N, O, ANITA lite, all flavors [20]; P, ANITA-08, all flavors [31]; Q, GLUE-04, all flavors [30]; R, FORTE-04, all flavors [42]; S, T, IceCube IC22, all flavors [3]; U, WSRT/NewMoon, 20 hours, all flavors [55]; V, W, LUNASKA, all flavorsi [38]; X, Topological defects [50]; MPR/2, AGN based model [44], intensity/2; W&B/2 [18, 58] model intensities/2; GZK-ν, models [13, 28].

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