The Antares neutrino telescope : performance studies and analysis of first data

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Chapter 1

High-energy neutrino astronomy

High-energy neutrino astronomy is largely motivated by the observation of very high-energy particles and photons from the cosmos. The charged particles are deflected by the galactic and extra-galactic magnetic fields. As a consequence, the measured directions of particles are no longer correlated with their origin. Interactions of high-energy photons and protons with background photons limit the distances they can travel through space and thus introduce an observational horizon. Neutrinos can be created through interactions of high-energy protons inside or in the vicinity of the astrophysical source. As neutrinos are neutral and interact only weakly with matter, they offer a possibility to study these sources.

In this chapter, a brief overview of the field of neutrino astronomy is given, along with an introduction of potential neutrino sources. For more detailed discussions, the reader is referred to [9] and [10].

1.1 Neutral particles

In contrast to charged particles, neutral particles are not deflected by galactic and extra-galactic magnetic fields. This makes neutral particles excellent probes for distant objects as they will point back to their source. In case of photons, this feature has been used for a long time in optical, and more recently, in X-Ray and γ ray astronomy.

The neutrino production process which is relevant in the context of cosmic accelerators is based on pion (π) production and decay. The main decay mode ($> 99.98\%$) of charged pions leads to muons (μ) and muon neutrinos (ν_μ).

$$\pi^+ \to \mu^+ + \nu_\mu \tag{1.1}$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu \tag{1.2}$$

where the $\bar{\nu}$ denotes the anti-neutrino. The muon decays to an electron (e), a muon- and an electron-neutrino with almost 100 % probability.

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \tag{1.3}$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \tag{1.4}$$

Pions can be created through inelastic collisions of high-energy protons (or nuclei) with ambient matter

$$p + p \rightarrow \pi^\pm + X \tag{1.5}$$

$$p + p \rightarrow \pi^0 + X \tag{1.6}$$

The neutral pion (π^0) decays with approximately 100 % probability to two photons

$$\pi^0 \rightarrow \gamma + \gamma \tag{1.7}$$

For astrophysical objects which are surrounded by a dense photon gas, pions can also be produced by

$$p + \gamma \rightarrow \pi^\pm + X \tag{1.8}$$

$$p + \gamma \rightarrow \pi^0 + X \tag{1.9}$$

In summary, neutrinos can be produced hadronically. Photons, however, can also be produced electro-magnetically. Electrons and positrons can produce photons either by synchrotron radiation or inverse Compton scattering.

1.2 Observations

1.2.1 Cosmic Rays

Almost a century ago, Victor Hess (1883-1964) performed experiments with electrometers suspended in balloons. His studies of ionising radiation at different altitudes led to the conclusion that these ’cosmic rays’ must have an extra-terrestrial origin. Since then, the phenomenon has been studied by a broad range of different instruments. The list of instruments includes satellite detectors and very large air shower arrays. Although the phenomenon has been known for almost 100 years, the origin of these particles remains unclear. A known feature of cosmic rays is the large observed range of energies. This is shown in figure 1.1. It can be seen from figure 1.1 that the flux of particles depends on the energy. Above 10 GeV, the cosmic ray flux as function of energy can be roughly described by a power law formula

$$dN/dE \propto E^{-\gamma} \tag{1.10}$$

were N is the number of observed events, E the energy of the primary particle and γ is the spectral index. The spectral index is about 2.7. Above 10^{15} eV, the spectral index steepens to about 3.1, introducing a feature called the ’knee’. At even higher energies, around 10^{19} eV, the spectrum shows a feature called the ’ankle’. At lower energies ($<$ 200 GeV) which are accessible to direct measurements by mass spectrometers, the composition is dominated by hydrogen and helium nuclei. It has been suggested that beyond the knee, the composition changes from protons to heavier elements [11]. The 'knee' and a composition change can be explained by a cut-off energy in the generation of cosmic rays which depends on charge or mass [12]. Protons with energies exceeding 10^{18} eV have a gyroradius larger than the thickness of the Galactic disc [13]. These particles are thus not confined to the Galactic disc. Above about 10^{19} eV, the range of protons and nuclei is limited by interactions with the cosmic microwave background [8]. This is known as the Greizen-Zatsepin-Kuzmin (GZK) cut-off. The interaction lengths of protons at these energies are shown in figure 1.2.

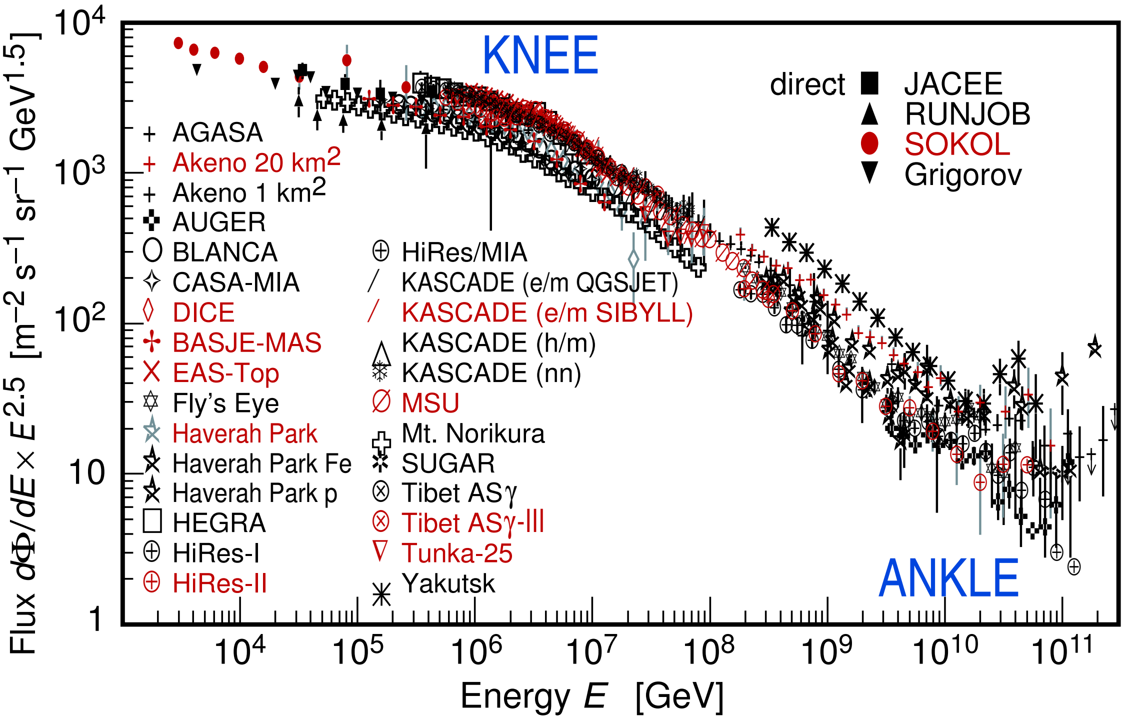

Figure 1.1: *The all-particle cosmic ray spectrum. Figure taken from [14].*

The existence of high-energy cosmic-rays suggests a possible source of high-energy neutrinos through pion-production. A likely acceleration mechanism for charged particles is the so-called *shock acceleration* (see for example [15]). Shock acceleration can occur at the boundary of two colliding plasmas. The shock acceleration predicts a spectrum with a power-law dependence and a typical exponent of about -2, in reasonable agreement with the observed energy spectrum of cosmic rays.

1.2.2 Gamma rays

The observations of high-energy gamma-rays started in the 1960's. At that time, it became possible to operate detectors outside the Earth's atmosphere aboard satellites. This allowed the detection of gamma-rays (MeV photons) which are not observable from the ground, as they are absorbed in the atmosphere. The EGRET instrument on board the Compton Gamma-Ray Observatory satellite was used to produce a sky map containing 271 sources of MeV gamma-rays (see figure 1.3). Higher-energy gamma-rays (~TeV) can be observed by ground based instruments which detect the cascades initiated by the energetic gamma-rays interacting with the atmosphere. However, high-energy gamma rays interact with the infra-red, microwave and radio background photons. As a consequence, the distance which high-energy gamma rays can travel through the Universe is limited. This effect is illustrated in figure 1.2.

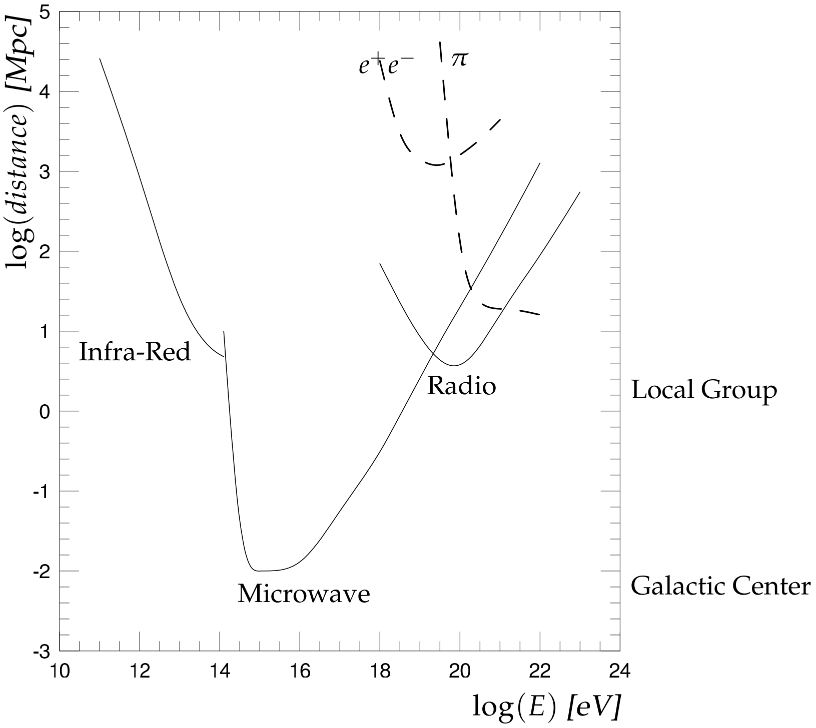

Figure 1.2: *Interaction lengths for high-energy photons (solid lines) and protons (dashed lines) with background photons as function of energy. Figure adapted from [16].*

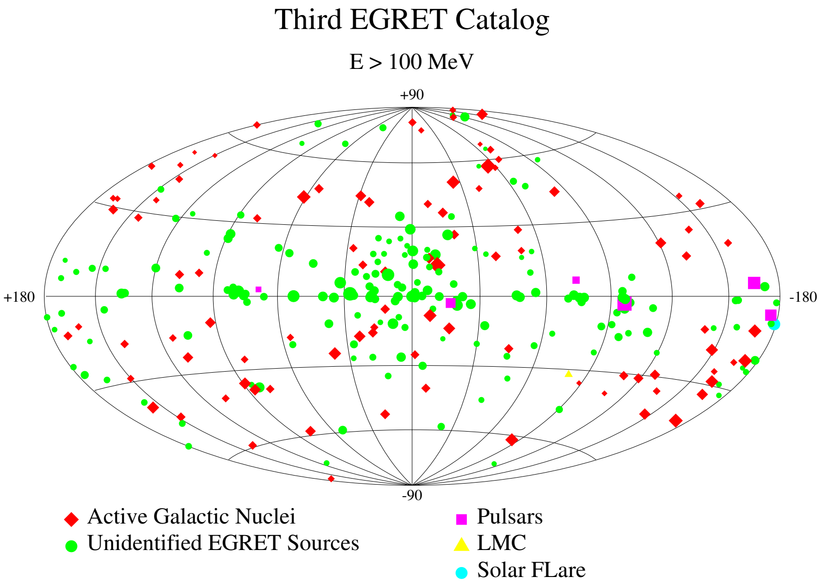

Figure 1.3: *The third EGRET catalog, showing sources of gamma rays with energies from 100 MeV to 30 GeV [17] in Galactic coordinates.*

1.3 Neutrino sources

In this section, some potential astrophysical sources of high energy neutrinos are discussed. The subject of neutrinos created by cosmic ray interactions in the atmosphere, will be covered in the following chapter.

The matter and photons in the interstellar space can be a target for the cosmic rays. Cosmic rays interacting with matter in the Galactic disc are a source of diffuse gamma-rays. These interactions can also produce neutrinos [18]. Very high-energy cosmic rays can also interact with background photons (microwave, infra-red, optical and ultra-violet). This can lead to a diffuse flux of so-called cosmogenic neutrinos [19].

Several potential neutrino sources are of interest. These include relativistic jets. Such a jet could provide an acceleration mechanism for protons through shock acceleration (either internal or external shocks). An observed high-energy gamma-ray flux could be an indication of hadronic interactions based on the assumption of neutral pion decay. Consequently, one expects neutrinos from the associated charged pion decays.

Supernova remnants A supernova is a luminous explosion due to the core collapse of a massive star. As a result an expanding shock wave consisting of ejected as well as swept up interstellar matter is created that envelopes the supernova remnant. At this shock wave, particle acceleration can occur. Supernova remnants within our Galaxy are believed to be responsible for the bulk of the cosmic rays below 1 PeV [20].

Recently, observations of TeV gamma-rays from a supernova remnant were found to favor π^0 decay as the main source of photon production [21],[22].

Active Galactic nuclei Active Galactic nuclei (AGN) are the brightest sources in the Universe. In the standard model of AGN, a very massive black hole ($10^6 - 10^{10}$ solar masses) accretes matter (several solar masses a year). Typically, two jets are observed, emerging at opposite sides of the accretion disc. In these jets, particles can be accelerated. These particle beams can interact with the ambient matter and photons. An AGN appears especially bright when one of the jets is oriented along our line of sight.

Very recently, the Pierre Auger Observatory found a correlation between the arrival directions of cosmic rays with energies above $6 \cdot 10^{19}$ eV and the positions of nearby AGN [7]. They found that out of 15 events with an energy above 60 EeV, 12 were located within 3.1° of AGN at distances less than 75 Mpc from Earth. The hypothesis of an isotropic distribution of these cosmic rays can be rejected with at least 99 % confidence level. This result suggests AGN are potential neutrino sources.

Gamma-ray bursts Gamma-ray bursts (GRBs) are very bright flashes of MeV gamma-rays, with durations varying from less than a second to a few hundred seconds. Various models are proposed. A subset of the GRBs, the 'long' bursts, are believed to be associated with the collapse of massive stars, or supernovae [23].

The observed signal is believed to be caused by a collimated relativistic jet with a high Lorentz factor containing photons, electrons, positrons and baryons. External and internal shocks provide a mechanism for acceleration of charged particles [24],[25].

Microquasars Microquasars are binary systems composed of an accreting massive object such as a black hole or neutron star and a companion star. They display relativistic radio-emitting jets, probably fed by the accretion of matter from the companion star. Microquasars resemble AGN, but at a much smaller scale. Recently, TeV gamma-rays were observed from two microquasars [26],[27] for which an hadronic interpretation of the observations has been published [28],[29].

Pulsar wind nebulae A pulsar wind nebula (PWN) is a nebula believed to be powered by a relativistic wind of particles and magnetic fields from a pulsar. They are often associated with very young supernova remnants. Gamma-rays with TeV energies have been measured from several PWN such as the Crab Nebula and Vela X. Gamma-ray fluxes are usually interpreted as being caused by leptonic acceleration, but hadronic interpretations also exist [30].

The association of a high-energy neutrino point source (or the exclusion of it), to the list of candidates, would be of great scientific benefit. It would allow a better understanding of the mechanism at work in these sources.

In contrast to the scenario of accelerated particles which interact causing neutrinos, there exist 'top-down' theories of neutrino production. In these scenarios, neutrinos are produced as a result of the decay or annihilation of massive particles. A large fraction of the matter content of the Universe is known to be non-luminous (see [14] for a review). A possible explanation is that this 'dark-matter' consists of so-called WIMPS (weakly interacting massive particles). Neutralinos, the lightest super-symmetric particles, are candidates for these WIMPS. Neutralinos can accumulate in massive objects such as the Sun and annihilate, with neutrinos as the only decay products that can escape. These neutrinos could be detected by the Antares detector also [31].