Primary Cosmic Rays - Summary

by Dr. Helga Dénes (hdenes@yachaytech.edu.ec)

This summary is based on the book Chapters 6.1 - 6.3 from Klaus Grupen: Astroparticle Physics.

1 Charged Primary Cosmic Rays

Cosmic radiation produced in the sources is called **primordial cosmic rays.** This radiation is modified during its propagation in galactic and extragalactic space.

Cosmic rays arriving at the Earth's atmosphere are called **primary cosmic rays.** Primary cosmic rays are protons ($\sim$85%), He nuclei ($\sim$12%), heavy nuclei (up to iron, $\sim$ 3%). $\rightarrow$ an extraterrestrial sample of material. More even-even nuclei $\rightarrow$ more stable (Bethe-Weizsacker formula and pairing force, shell model $\rightarrow$ magic number nuclei are extremely stable)

Charged cosmic rays accelerated in sources can produce a number of **secondary particles** by interactions in the sources themselves. These are mostly unstable secondary particles: π and K, these can decay into γ, μ and ν. Secondary particles also emerge from the sources and may reach Earth.

The low-energy part of the primary spectrum is modified by the Sun's and the Earth's magnetic field. The active Sun reduces the cosmic-ray intensity because a stronger magnetic field.

If all energies are considered, there are equal numbers of protons and electrons so that there is no charge-up of our planet.

Measurmnet methods:
- direct detection: baloons, satellites, instruments on the space station
- atmospheric air Cherenkov technique
- measurement of extensive air showers via air fluorescence

1.1 Energy spectrum

The all-particle spectrum of charged primary cosmic rays is relatively steep, but it has some features:
- knee (10^{15}eV) $\rightarrow$ the spectrum steepens
- ankle (10^{19}eV) $\rightarrow$ the spectrum slightly flattens
- 6×10^{19}eV - strong cutoff

Origin:
- below 10^{15}eV - from the Galaxy. Cosmic rays originate predominantly from within our Galaxy.
- above 10^{15}eV - particles start to leak from the Galaxy, e.g. the Lorentz force of the Galactic magnetic field can not contain them. This can be true also for the extragalactic particles. The interaction with the magnetic field depends on the charge of the cosmic rays.

There are two mass groups of primary cosmic rays: groups of heavy and light primary masses according to the **observed electron-muon ratio in the air showers.**
- Iron-induced showers $\rightarrow$ have more muons, heavy nuclei produce electron-poor showers.
- Proton induced showers have less muons, they are electron-rich

The chemical composition of high-energy primary cosmic rays ($> 10^{15}$eV) is to large extent an unknown. However measurments indicate that the chemical composition of primary cosmic rays beyond the knee ($> 10^{15}$eV) changes towards to a higher fraction of heavy nuclei.

1.2 Greisen, Zatsepin, and Kuzmin (GZK) cutoff

cosmic rays above the energy of $\sim 6 \times 10^{19}$eV would interact with the cosmic blackbody radiation. Protons of higher energies would rapidly lose energy by this interaction process causing the spectrum to be cut off at energies around 6×10^{19}eV. Primary protons with these energies produce pions on blackbody photons via the

Δ resonance according to:

$$\gamma + p \rightarrow p + \pi^0$$

$$\gamma + p \rightarrow n + \pi^+$$

The GZK cutoff limits the mean free path of high-energy protons to $\sim$ 50Mpc. However, there are at least 3 AGN within this limit: M87 (in the Virgo galaxy cluster; Mrk 501 and Mrk 421, which are blazars)

Photons as candidates for primary particles have even shorter mean free paths ($\sim$50 kpc)

For iron primaries the GZK cutoff would be in that case at 3.4×10^{21} eV.

1.3 Antiparticles

Antiparticles are extremely rare in primary cosmic rays. The measured primary antiprotons are presumably generated in interactions of primary charged cosmic rays with the interstellar gas. Antiprotons can be readily produced according to

$$p + p \rightarrow p + p + p + \bar{p}$$

The ratio of antiprotons to protons is $\sim 10^-4$ above 10GeV. The fraction of primary electrons in relation to primary protons is only 1%. Primary positrons constitute only 10% of the electrons at energies around 10 GeV. There is an increase over the expected positron flux at energies around 100GeV, as measured by the PAMELA (satellite) and AMS (international space station instrument) experiment. There is some indication of the existence of antihelium, but no heavier (Z > 2) antinuclei have been observed so far.

1.4 Sources

- active galactic nuclei e.g. quasars and blazars
- supernova explosions

However, there is no direct evidence. Charged particles, on the other hand, are subject to the influence of homogeneous or irregular magnetic fields. This causes the accelerated particles to travel along chaotic trajectories thereby losing all directional information before finally reaching Earth. Therefore, it is of very little surprise that the sky for charged particles with energies below 10^{14} eV appears completely isotropic. There are some hints that the origins of some of the events with energies $> 10^{19}$ eV could lie in the supergalactic plane, a cluster of relatively close-by galaxies including our Milky Way. It has also been discussed that the galactic centre of our Milky Way could be responsible for a certain anisotropy at 10^{18} eV. However this is based on very low statistics.

1.5 The highest energy cosmic rays

Particles with energies $> 10^{19}$eV the rate is only 1 particle per km^2 and year.

Several events were observed at $\sim 10^{20}$ **eV.** These are currently the highest energy known events. 10^{20} eV are also called Zevatrons.

There is some uncertainty associated with such high energy events due to the **Landau-Pomeranchuk-Migdal (LPM) effect**: The formulas for bremsstrahlung and pair creation in matter are inapplicable at high energy or high matter density. The effect of multiple Coulomb scattering by neighboring atoms reduces the cross sections for pair production and bremsstrahlung.

2 Neutrinos

Advantages of neutrino astronomy:

- not influenced by magnetic field
- they do not decay
- they can directly escape their source of production
- do not interact much while they propagate

Disadvantages of neutrino astronomy:

- neutrinos only interact trough the weak interaction → very low interaction cross section → very difficult to detect ($\sigma(\nu N) \approx 10^{-45}$ cm^2/nucleon)
- neutrinos ocsillate
- we do not know the exact mass of the neutrinos

Out of the 7×10^{10} neutrinos per cm^2 and s radiated by the Sun and arriving at Earth only one or two at most are 'seen' by our planet. As a consequence of this, neutrino telescopes must have an enormous target mass, and one has to envisage long exposure times.

For high energies the interaction cross section rises with neutrino energy. Neutrinos in the energy range of several 100 keV can be detected by radiochemical methods.

For energies exceeding 5 MeV large-volume water Cherenkov counters are used.

2.1 Atmospheric neutrinos

Primary cosmic rays interact in the atmosphere with the atomic nuclei of nitrogen and oxygen → nuclear fragments and predominantly charged and neutral pions are produced. The decay of charged pions (lifetime 26 ns) produces muon neutrinos:

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

Muons themselves are also unstable and decay with an average lifetime of 2.2 μs according to

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

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Because of this the expected ratio of N(ν_μ)/N(ν_e) = 2

2.1.1 Measuring the mass of neutrinos

The KATRIN (Karlsruhe Tritium neutrino) experiment measures the neutrino mass in a model-independant way via measurements of the kinematics of electrons from β decay. The fixed energy amount released in a beta decay (e.g. tritum ^{3}H) is shared by the electron, the neutrino and the nuclear recoil (e.g. ^{3}He). When we look for the maximum energies of the electrons and compare the measured values to the transition energy, we can check if it sums up together with the known nuclear recoil to the transition energy. If there is no difference the neutrino must be massless, if there is a difference this energy gap can be calculated into a neutrino mass.

2.2 Solar neutrinos

There are 3 reactions in the pp-chain of Solar nuclear fusion that produce neutrinos:

$$p + p \to d + e^+ + \nu_e$$

$$^7Be + e^- \to ^7 Li + \nu_e$$

$$^8B \to ^8 Be + e^+ + \nu_e$$

- 86% of solar neutrinos are produced in this proton-proton reaction; continuous energy spectrum
- 14% are generated in the electron-capture reaction; discrete energy spectrum
- ^{8}B decay contributes only at the level of 0.02%; continuous energy spectrum

The Sun is a pure electron-neutrino source.

MSW (Mikheyev, Smirnov, and Wolfenstein) effect in the Sun plays a role for the oscillation of the solar electron neutrinos. Solar neutrinos can also be transformed by matter oscillations. The flux of electron neutrinos and its oscillation property can be modified by neutrino-electron scattering when the solar neutrino flux from the interior of the Sun encounters collisions with the solar electrons. This matter effect is particularly relevant for high-energy solar electron neutrinos. Flavour oscillations can even be magnified in a resonance-like fashion by matter effects. It relates to the fact that $\nu_e e^-$ scattering contributes a term to the mixing matrix that is not present in vacuum.

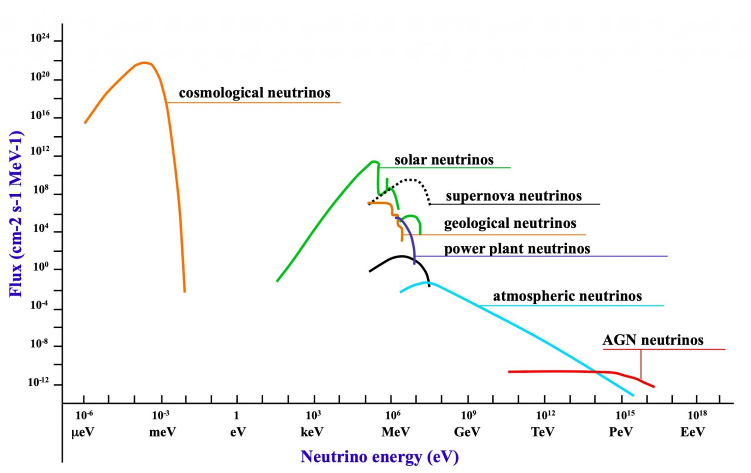

Figure 1: Neutrino flux as a function of neutrino energy. The labels showing the sources of the neutrinos. Figure source: https://neutrino-history.in2p3.fr/introduction-to-neutrino-sources/

2.3 Supernova neutrinos

When a neutron star is formed in a supernova (SM) explosion neutrinos get produced as well. When the electrons of the star are forced into the protons and a neutron star is born a neutrino burst of immense intensity is created:

$$e^- + p \rightarrow n + \nu_e$$

In addition to the electron capture process neutrinos are also created from thermal photons that create e^- - e^+ pairs which create Z, which decay into neutrinos. This process can create all three types of neutrinos:

$$e^- + e^+ \rightarrow Z \rightarrow \nu_x + \bar{\nu}_x$$

2.3.1 SN 1987A

From the closest modern supernova (SN1987A, Large Magellanic Cloud) 25 neutrinos were observed. The neutrinos are the first particles to arrive from the SN explosion. Since photons get emitted and absorbed during propagation, it takes them much longer to escape the explosion compared to the ν.

From these measurements the overall number end energy of the neutrinos can be estimated. Based on the arrival time interval of the neutrinos, which was approximately 10 s, we can calculate an upper limit for the neutrinos mass. We can also conclude that if the neutrinos were emitted at the same time, than they had different propagation times, which indicates slightly different mass for them and is in support of possible neutrino oscillation. Considering that the neutrinos may not be produced at the same time, the neutrino oscillation may not be necessary to explain the arrival times. However, there is plenty of other evidence for neutrino oscillation.

2.4 High-energy galactic and extragalactic neutrinos

Neutrinos have been produced in the early universe as well, however these are at low energies $\sim$ MeV, which are not detectable with current neutrino detectors.

Sources of high-energy galactic and extragalactic neutrinos can be:
- binary systems, where the compact object is a pulsar
- supernova remnants
- the Galactic Centre
- AGN

Pulsar binary systems: The pulsar can manage to accelerate protons to very high energies. These accelerated protons collide with the gas of the atmosphere of the companion star and produce predominantly secondary pions in the interactions. The pions then decay into ν and *gamma*. Because γ may get absorbed, the source would shine predominantly in ν_μ. These neutrinos can be recorded in a detector via the weak charged current:

$$\nu_\mu + n \rightarrow p + \mu^-$$

Muons created in these interactions follow essentially the direction of the incident neutrinos. For energies exceeding the TeV range, muon bremsstrahlung and direct electron pair production by muons dominate. The energy loss by these two processes is proportional to the muon energy and therefore allows a calorimetric determination of the muon energy.

Because of the low interaction probability of neutrinos and the small neutrino fluxes, neutrino detectors must be very large and massive. The only practicable candidates, which meet this condition, are huge water or ice Cherenkov counters.

The challenge is to distinguish the atmospheric neutrinos from the Galactic or extragalactic sources. This can be done by filtering the data: identifying the direction and the possible sources of origin and identifying other signals from the same source, like high energy photons or gravitational waves.

Identified sources:
- blazar TXS 0506+056 (AGN)
- Messier 77 (AGN)
- PKS 1424+240 (AGN)

2.5 Geoneutrinos

Nearly half of the Earth's heat comes from the decay of radioactive isotopes inside. Geoneutrinos provide a technique to probe directly the Earth's interior beyond the depth of 12 km. The three most common recations are:

$$^{238}U \rightarrow^{206} Pb + 8^4He + 6e^- + 6\bar{\nu}_e$$

$$^{232}Th \rightarrow^{208} Pb + 6^4He + 4e^- + 4\bar{\nu}_e$$

$$^{40}K \rightarrow^{40} Ca + e^- + \bar{\nu}_e$$

To measure the antineutrinos one uses the inverse-beta-decay reaction. For this reaction there is a threshold energy of 1.8 MeV corresponding to the difference between the rest- mass energies of the neutron plus positron and the proton. Due to this threshold antineutrinos from the potassium decay cannot be recorded in this reaction. However, these neutrinos can be measured by scattering on electrons. Antineutrinos from 238U and 232Th decay are detected by light signals from positron annihilation and photons from deuteron formation after $n + p \rightarrow d + \gamma$. These two signals are coincident in time and space and provide a powerful tool to reject, e.g., cosmic rays, which would only cause single signals.

2.6 Neutrino oscillation

A deficit in ν_e from the Sun and a deficit of ν_μ from atmospheric neutrinos indicates neutrino oscillation. In the lepton sector the eigenstates of weak interactions ν_e, ν_μ, and ν_τ are superpositions of mass eigenstates ν_1 , ν_2 , and ν_3. Neutrinos can be transformed during the propagation from the source to the observation. The states with different masses would propagate with different velocities and so the mass components get out of phase with each other. This could possibly result in a different neutrino flavour at the detector. The mixing angle θ determines the degree of mixing. This assumption requires that the neutrinos have non-zero mass. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix is the neutrino mixing matrix. Experiments can measure or set limits on the mixing angle and the mass differences between the neutrinos. At the moment we only have upper limits of these.

Evidence for neutrino oscillation
- deficit in ν_e from the Sun
- deficit of ν_μ from atmospheric neutrinos
- the ratio of upward- to downward-going muon neutrinos
- zenith-angle- (i.e., distance-) dependent deficit of muon neutrinos

Presently one favours that electron neutrinos oscillate into muon neutrinos and muon neutrinos convert into tau neutrinos.

The possible effect of Majorana-type neutrinos and hypothetical sterile neutrinos complicates the phenomenon of neutrino oscillations considerably. Sterile neutrinos (or inert neutrinos) are hypothetical particles that interact only via gravity and not via any of the other fundamental interactions of the Standard Model. This property can be characterised by the **weak isospin**, which deteremins if a particle can participate in weak interactions or not. Weak isospin is a quantum number relating to the electrically charged part of the weak interaction: Particles with half-integer weak isospin can interact with the $W^{\pm}$ bosons; particles with zero weak isospin do not.

2.7 Detectors

2.7.1 Radiochemical detectors

- Davis experiment (USA)
- GALLEX gallium experiment (Italy)

First historic experiments:

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-$$

The produced argon atoms are counted with electron capture where ^{37}Cl is produced, since the electron gets captured from the innermost shell the electrons of the ^{37}Cl atom are rearranged under emission of either characteristic X rays or by the emission of **Auger electrons**.

The Auger effect or **Auger-Meitner effect** is a physical phenomenon in which the filling of an inner-shell vacancy of an atom is accompanied by the emission of an electron from the same atom.

Gallium experiments work similar:

$$\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$$

2.7.2 Water Cherenkov detectors

- Super-Kamiokande (Japan)
- The Sudbury Neutrino Observatory (SNO) (Canada)
- Hyper-Kamiokande (Japan)
- Baikal Deep Underwater Neutrino Telescope (Russia)
- NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research Project (Greece)
- ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) (France)
- KM3NeT (Cubic Kilometre Neutrino Telescope) (Mediterranean Sea)

Detection method:

$$\nu_e + e^- \rightarrow \nu_e + e^+$$
$$\nu_e + N \rightarrow \nu_e + N'$$
$$\nu_\mu + N \rightarrow \mu^- + N'$$

and similar for anti neutrinos. The charged leptons can be detected via the Cherenkov effect in water.

In the GeV range electrons initiate characteristic electromagnetic cascades of short range while muons produce long straight tracks. This presents a basis for distinguishing electron from muon neutrinos. On top of that, muons can be identified by their decay in the detector thereby giving additional evidence concerning the identity of the initiating neutrino species.

Muons have a well-defined range and produce a clear Cherenkov pattern with sharp edges while electrons initiate electromagnetic cascades thereby creating a fuzzy ring pattern.

Since the emission of the charged leptons follows essentially the direction of the incident neutrinos, the direction of the neutrino source can be determined.

SNO experiment can tell the difference between charged and neutral currents:

$$\nu_e + d \rightarrow p + p + e^-$$

is the charged current, which is only relevant for electron neutrinos.

$$\nu_x + d \to p + n + \nu_x'$$

is the neutral current where x can stand for any neutrino. The neutrons produced in this reaction are captured by deuterons giving rise to the emission of 6.25-MeV photons. The total neutrino flux measured by the NC reaction is in agreement with the expectation of solar models. $\to$ evidence for neutrino oscillation.

In a water Cherenkov counter in the ocean bio-luminescence and potassium-40 activity presents an additional background, which is not present in ice. In practical applications it became obvious that the installation of photomultiplier strings in the antarctic ice is much less problematic compared to the deployment in the ocean.

2.7.3 Ice Cherenkov detectors

- AMANDA (Antarctic Muon And Neutrino Detector Array) (Antarctica)
- ICECUBE (Antarctica)

Because of the extremely high transparency of ice at large depths in Antarctica and the relatively simple instrumentation of the ice, ice Cherenkov counters are presently the most favourable choice for a realistic neutrino telescope. To protect the detector against the relatively high flux of atmospheric particles, it has become common practice to use the Earth as an absorber and concentrate on neutrinos, which enter the detector 'from below' or the other side of the planet.

The neutrino detector itself consists of a large array of photomultipliers that record the Cherenkov light of muons produced in ice (or in water). In such neutrino detectors the photomultipliers have to be mounted in a suitable distance on strings and many of such strings will be deployed in ice (or water).

IceCube detects 275 atmospheric neutrinos daily and about 100,000 per year. The interaction cross section is smaller for high-energy neutrinos. ICECUBE detects ~ 250 high energy (> 100 TeV) neutrinos per year.

2.7.4 Liquid scintillator detectors

- KamLAND (Japan)
- Borexino (Italy)