# Astroparticle Physics, NAASPH-12

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Exam, July 25, 2014; KVI
5 problems (total of 80 points).
Write the solution of every problem on a separate piece of paper with name and student number.

**Write clearly, it should be readable.**

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**Problem 1** (11 pnts in total)

Cosmic accelerators are conjectured to be the sources of the highest-energy particles detected at Earth. The details of the mechanism(s) for the acceleration of these particles is still unclear. Three species of very-high-energy particles, namely i) cosmic rays (atomic nuclei), ii) photons, and iii) neutrinos have been observed.

3 pnts a. Name for each of these three species an observatory or experiment for their detection.

4 pnts b. Describe the processes near the accelerator (the astronomical site) which can lead to the production of i) cosmic rays, ii) photons, and iii) neutrinos.

4 pnts c. Describe what may happen between the point of acceleration and detection at Earth for each of the three species; assume for simplicity that the sources are outside our own Galaxy.

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**Problem 2** (18 pnts in total)

Dark Matter has not yet been proven to exist. However, there are many indications that the energy density in the Universe today should be attributed for more than 20% to Dark Matter.

3 pnts a. Which other contributions can you list as part of the energy density of the Universe.

5 pnts b. Describe how these different contributions to the energy density have evolved from the past until today.

4 pnts c. Name at least four different observations that have led scientists to conclude that Dark Matter should exist. Explain briefly for each of the listed observations the reason to invoke Dark Matter as an explanation for that particular observation.

2 pnts d. There are direct and indirect methods to look for Dark Matter. What is the difference between these two detection techniques?

2 pnts e. Give two examples for experiments based on direct detection.

2 pnts f. Also at the LHC Dark Matter research takes place. What type of particles are being considered as candidates for Dark Matter?

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**Problem 3** (15 pnts in total)

Models for acceleration of charged particles in the cosmos can be based on so-called magnetic bottles.

5 pnts a. What are magnetic bottles?

5 pnts b. Describe the role of magnetic bottles in the acceleration process of charged particles.

5 pnts c. Describe the difference between the first and the second-order Fermi acceleration mechanism.

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**Problem 4** (27 pnts in total)

When high-energy cosmic rays enter the atmosphere of the Earth they create a cascade of secondary particles, called an extensive air shower. Such a shower generally has an hadronic (protons, neutrons, pions) and an electromagnetic component (photons, electrons, positrons). In addition, the shower contains an increasing number of neutrinos and muons.

6 pnts a. Give the argument why a neutral pion can decay electromagnetically into two photons and why the charged pion can i) not decay through strong interaction, ii) not through the electromagnetic, and iii) can decay via the weak interaction.

2 pnts b. Calculate the distance a pion can travel at 10 km height until a fraction $1/e$ survives, ignoring its decay. (assume for simplicity that the density is constant over large distances). Note that at the end of the exam some useful formulas are given.

2 pnts c. Calculate the energy a neutral pion should have such that a fraction $1/e$ survives after a distance of 3 km (assuming vacuum for simplicity).

2 pnts d. Indicate the main reaction process that creates the electromagnetic component in an extensive air shower induced by a cosmic-ray proton.

2 pnts e. Same question for the neutrino and muon content of the shower.

2 pnts f. Indicate in which part of the modeling of an air shower one needs to use the parton model. Also argue why one does not use experimentally measured data instead.

5 pnts g. Which component of the shower can be measured with the surface detectors (water tanks) at the Pierre Auger Observatory? Describe shortly the principle for detecting particles in these detectors.

3 pnts h. An extensive air shower will also emit radio waves. Describe the processes leading to coherent emission of electromagnetic waves.

3 pnts i. Why is coherence important for being able to detect the radiation?

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**Problem 5** (9 pnts in total)

An ultra-high energy photon (with energy $E_1$ and momentum in the $\hat{z}$-direction) knocks out a parton with mass fraction $x$ from a nucleon in the air. Assume that the nucleon (with mass $M \ll E_1$) is at rest. The parton that has been hit emits a low energy photon in a transverse $\hat{y}$-direction with energy $E_2$). In the scattering process a color-string is formed.

3 pnts a. Draw a schematic but clear diagram describing the process and indicate the four-momenta of the particles.

2 pnts b. Give the energy and momentum (in the $\hat{y}$- and $\hat{z}$-direction) of the emerging parton using energy and momentum conservation.

2 pnts c. Show that to a good approximation we may write $E_2 = xM(1 - xM/E_1)$ using $M \ll E_1$.

2 pnts d. Calculate the invariant mass of the color string in the approximation $x \ll 1$ in addition to $M \ll E_1$.

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**Some numbers**

Electron mass $m_e c^2 = 511\,\text{keV}$; Muon mass $m_\mu c^2 = 106\,\text{MeV}$; Pion mass $m_\pi c^2 = 140\,\text{MeV}$;
Proton mass: $m_p c^2 = 0.938\,\text{GeV}$
Conversion: $1\,\text{eV/c}^2 = 1.78 \times 10^{-36}\,\text{kg}$
Boltzmann's constant: $k = 8.62 \times 10^{-11}\,\text{MeV/K}$
Planck's constant: $h = 4.1 \times 10^{-15}\,\text{eV s}$
Avogadro's number: $N_A = 6 \times 10^{23}\,/\text{mol}$
Solar Mass: $\text{M}_\odot = 1.99 \times 10^{30}\,\text{kg}$
Parsec: $1\,\text{pc} = 3.1 \times 10^{16}\,\text{m}$
Velocity of Sun w.r.t. center Milkyway: $V_\odot = 270\,\text{km/s}$
Velocity of Earth in orbit around the Sun: $V_\oplus = 30\,\text{km/s}$
Typical galactic dark matter density: $\rho_{DM} = 9\ \text{k M}_\odot/\text{pc}^3$

**Air-shower physics**

At 10 km height the density of the atmosphere is $0.4 \times 10^{-3}\,\text{g cm}^{-3}$.
The penetration depth for pions in air is $\lambda_\pi = 120\,\text{g cm}^{-2}$, for protons $\lambda_p = 90\,\text{g cm}^{-2}$, and for iron is $\lambda_{Fe} = 5\,\text{g cm}^{-2}$.
The mean travel distance in vacuum of a pion with energy $E$ is $d_{\pi^0} = \gamma 25 \times 10^{-9}\,\text{m}$ and $d_{\pi^\pm} = \gamma 7.8\,\text{m}$ where the relativistic $\gamma$-factor is given by $\gamma = E/mc^2$ and $m_\pi c^2 = 140\,\text{MeV}$.

**Integrals**

For $c > 0$ we have:

$$\int_0^\infty c e^{-cx} dx = 1\,; \quad \int_0^\infty c\,x\,e^{-cx} dx = 1/c\,; \quad \int_0^\infty c\,x^2 e^{-cx} dx = 2/c^2$$