Astroparticle Physics

Instructor: A.M. van den Berg

You don't have to use separate sheets for every question.
Write your name and S number on every sheet
There are **5 questions** with a total number of marks: 47

WRITE CLEARLY

(1) (Total 12 marks)
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.

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

(b) (3 marks)
Describe or sketch how these different contributions to the energy density have evolved from the past until today.

(c) (4 marks)
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.

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

(2) (Total 12 marks)
The flux of cosmic rays changes over many orders of magnitude when the energy of a cosmic ray changes.

(a) (2 marks)
Give an approximate relation between flux and energy (or sketch the flux spectrum).

(b) (2 marks)
Describe the generic processes which are used to model the acceleration mechanism of cosmic rays; explain their difference.

(c) (2 marks)
What is the GZK process? Describe which particles interact in this process and which reaction productions can emerge from this process.

(d) (2 marks)
What is the effect of the GZK process on the flux spectrum?

(e) (2 marks)
In Figure 1 you see the event horizons of photons and high-energy protons as a function of their energy and of the traveled distance through the cosmos, i.e. from the source to Earth. The extra-galactic galaxy M87 has been suggested to act as a possible site for acceleration because of the apparent jet which is visible in optical and radio wavelengths. The distance to this galaxy is about 16.4 Mpc. Would you consider these

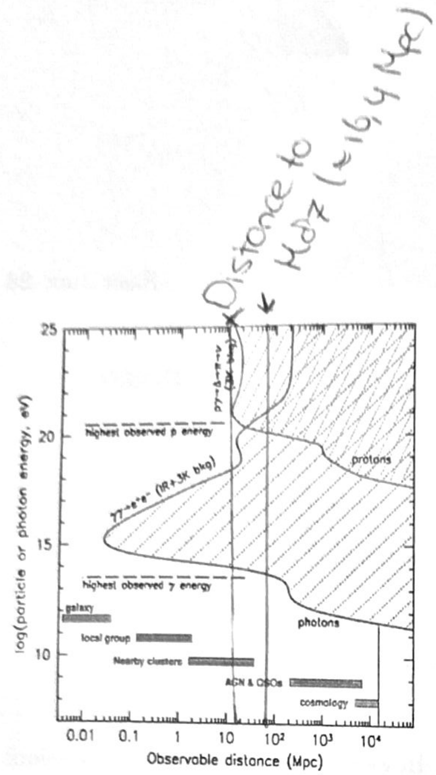

FIGURE 1. The event horizons for protons (red solid line) and photons (blue solid line) as function of their energy and the distance between the source and Earth.

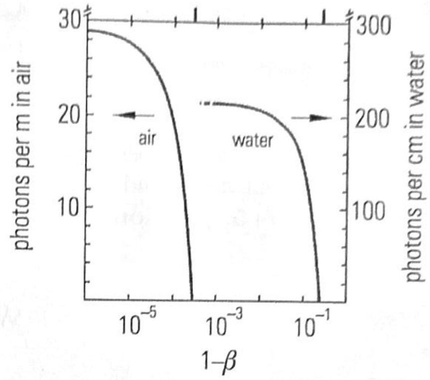

FIGURE 2. Variation of the Cherenkov photon yield of singly charged particles in water and air.

two event horizons to be relevant for the observation of very high energy protons and gamma rays if they are created in M87?

(f) (2 marks)
Explain your answers.

(3) (Total 7 marks)

(a) (2 marks)
What are magnetic bottles? Provide a schematic picture of a magnetic bottle.

(b) (2 marks)
Describe the role of magnetic bottles in the acceleration process of charged particles.

(c) (3 marks)
Explain that the force acting on a charged particle in a magnetic bottle is proportional to $-\frac{\partial B_z}{\partial z}$, where z is the symmetry axis of the bottle.
Hint: assume that the magnetic field strength in a magnetic bottle has cylindrical symmetry with only components in the z and r direction and use that the divergence operator in cylindrical coordinates (r, ϕ, z) can be written as:

$$\vec{\nabla} \cdot \vec{B} = \frac{1}{r}\frac{\partial(rB_r)}{\partial r} + \frac{1}{r}\frac{\partial B_\phi}{\partial \phi} + \frac{\partial B_z}{\partial z}$$

(4) (Total 8 marks)
A high-energy photon with an energy of 10^{10} eV enters into the atmosphere and creates an electromagnetic shower.

(a) (2 marks)
Estimate the position of the shower maximum in radiation lengths and in penetration depth.

(b) (4 marks)
The refractive index, n, of air at sea-level is given by $n-1 = 2.7\times10^{-4}$, a quantity which is proportional to pressure. An ultra-relativistic (take $\beta = 1$) charged particle traveling vertically downwards at a penetration depth of 100 g cm^{-2} in the atmosphere emits Cherenkov radiation. Assume an exponential atmosphere with density ρ and height h related by $\rho = \rho_o \exp(-h/H)$, where $H = 6.5$ km. The total atmospheric depth is 1030 g cm^{-2}. Calculate at which height above sea level (in m or km) the emission is created and calculate the Cherenkov angle at that height.

(c) (2 marks)
Use Figure 2 to estimate the number of Cherenkov photons created by one of the secondary electromagnetic particles at this depth of 100 g cm^{-2} over a path length of one radiation length.

(5) (Total 8 marks)
In the early stages of the Universe the lighter nuclei were created.

(a) (2 marks)
Discuss the physics of primordial nucleosynthesis.

(b) (2 marks)
What are the relevant reactions?

(c) (2 marks)
Explain why the primordial nuclei are limited to isotopes of hydrogen, helium, and lithium.

(d) (2 marks)
Given that at the freeze-out time of neutrons, the ratio of neutrons to protons is equal to 0.20, that the neutron lifetime is 890 s, and that after 300 s after this freeze-out time almost all free neutrons have ended up in ^{4}He, explain how this leads to a helium mass fraction of 0.24 for the early Universe.