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# Astroparticle Physics – 2016/17

## Werkcollege 11 – 17.11.2016

**Problem 39** GZK Cutoff

High-energy cosmic rays (protons) can interact with the photons of the 3 K microwave background. If the protons exceed a minimum energy $E_{GZK}$, high-energy pions are produced via the interactions

$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

or

$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow n + \pi^+.$$

This effect has been predicted on 1965 by the physicists Greisen, Zatsepin, and Kuz'min. Hence, the name GZK effect. These interactions take place only if the energy of the 3 K photons exceeds $m_\Delta c^2 = 1232$ MeV in the rest frame system of the protons.

*a)* Calculate the threshold energy $E_{GZK}$ for a proton.
Hint: the energy of the photons is given as $\epsilon_\gamma \approx 2.5$ meV.

*b)* By using the superposition model, calculate the energy threshold for an iron nucleus too. Discuss if the GZK cutoff plays a significant role in the attenuation of ultra high-energy heavy nuclei during their propagation.

*c)* Knowing that the density of the 3 K photons is $n_\gamma = 411$ photons/cm$^3$ and the cross section for the above mentioned interactions is $\sigma_{p\gamma} = 300$ $\mu$b (1 b=$10^{-24}$cm$^2$), calculate the mean free path of the protons in units of [Mpc].

**Problem 40** Sources of extragalactic cosmic rays

Estimate the number of sources (AGN) which are required to sustain the observed flux of extragalactic cosmic rays.

The energy density of extragalactic cosmic rays amounts to about $\rho_E = 3.7 \cdot 10^{-7}$ eV/cm$^3$. Calculate the total cosmic-ray power in a sphere with a radius of $r = 75$ Mpc. This is the volume visible by the Pierre Auger Observatory at the highest energies (GZK radius). The typical power in the jets of AGN is of the order of $10^{44}$ to $10^{46}$ erg/s. Assume about 10% of this power is converted into cosmic rays. Use the Hubble time ($10^{10}$ years) as upper limit for the residence time of the cosmic rays in the volume.

Use these quantities to estimate the number of AGNs required to produce the observed cosmic-ray power.

**Problem 41** High-energy gamma rays

List the most common production mechanisms for high-energy gamma rays (photons with energies exceeding 100 MeV).

What means Synchrotron Self Compton (SSC)? Sketch a typical spectrum of a high-energy gamma-ray source in which SSC plays an important role.

**Problem 42** Inverse Compton effect

X rays with a mean energy $E_\gamma = 5$ keV are observed from a region of interstellar matter. The x rays are produced through inverse Compton effect between electrons and photons of the 3 K microwave background.

**a)** What is the most probable energy of the 3 K background radiation in keV?
Hint: use Wien's displacement law to estimate the most probable energy and note the discrepancy with the value ($2.5 \cdot 10^{-3}$ eV) given in Problem 39.

**b)** Calculate the corresponding energy of the electrons. Use the relation $E'_{ph} = \gamma_e^2 \cdot E_{ph}$. $\gamma_e$ is the Lorentz factor of the electrons and $E'_{ph}$ and $E_{ph}$ the energies of the photons.

The solutions will be discussed during the werkcollege on 17.11.2016 in HG02.702.
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Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1617