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Problem 43 Gamma-ray detection by IACTs

Gamma rays interacting with the Earth's atmosphere produce a pure electromagnetic cascade in the atmosphere, which can be quite well described by Heitler's model (see also Problem 30). All charged secondary particles in the cascade will produce Cherenkov light during their propagation through the atmosphere. As consequence, a Cherenkov circle with radius of about 1° will be projected on the ground. The Cherenkov light can be detected by an Imaging Atmospheric Cherenkov Telescope (IACT), if located within the Cherenkov cone.

a) By assuming that the Cherenkov light intensity is homogeneous within the Cherenkov cone (circle on the ground) and considering an air shower initiated by a photon, impinging vertically onto the atmosphere with an energy $E = 1$ TeV, compute the amount of photons collected by an IACT with a circular collecting area ($R_{dish} = 6$ m), located at 1800 m above sea level (a.s.l.) with an overall Cherenkov photon detection efficiency equal to 10%.

Hint: assume that the Cherenkov emission is generated around the shower maximum X_{max} and assume X_{max} being at 10 km a.s.l. Neglect any absorption of the Cherenkov light by the atmosphere. Use the formula

$$\frac{dN}{dx} = 380 Z^2 \sin^2\Theta \text{ photons cm}^{-1}$$

(see Problem 33) to calculate the number of Cherenkov photons emitted by each electron/positron, where Θ is the Cherenkov light emission angle and the air refractive index around X_{max} is $n_{air}^{X_{max}} = 1.0002$. Assume that all the electrons/positrons travel the same atmospheric depth X_0 equal to 36.66 g cm^{-2} (corresponding to $\sim$ 700 m at 10 km a.s.l.).

b) By assuming the same extensive air shower, estimate the number of secondary particles at X_{max} and see if any secondary particle can reach the ground level where the IACT is installed.

Hint: use Heitler's model to compute X_{max} and N_{max} and use the standard value of energy loss (2 MeV/(g cm^{-2})) by ionization to compute the remaining particle energy at the ground level (1800 m a.s.l., corresponding to $X = 840$ g cm^{-2}).

Problem 44 IACTs working in an array

IACTs are nowadays operated almost exclusively within an array of telescopes. At present, the H.E.S.S. experiment has 5 working IACTs in Namibia, VERITAS 4 IACTs in Arizona (USA), and MAGIC 2 IACTs at the Canary Islands (Spain). The Cherenkov Telescope Array (CTA) project is an international initiative, aimed to build the next generation ground-based very high-energy gamma-ray observatory. It will consist of over 100 telescopes of three different sizes, placed on two arrays, one in the Northern the other in the Southern Hemisphere, to cover the full sky (for more details see the website *www.cta-observatory.org*).

The big advantage of having IACTs working together in an array is that this enhances the overall IACT performances (energy threshold, energy resolution, direction resolution, etc.), without requiring to enhance the single telescope properties.

a) By considering the same air shower and the same IACT of Problem 43, and assuming that at least 100 Cherenkov photons must be detected to trigger an IACT, compute the energy threshold a stand-alone IACT.

b) If 2 IACTs are within the Cherenkov cone, we can assume the amount of Cherenkov photons required to trigger each IACT is reduced to 25. Compute the new energy threshold.

Problem 45 Energy production of the Sun

The energy in the Sun is produced through nuclear fusion. The fusion processes can be effectively described as $4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e$. During these processes 26.7 MeV energy are released, which are converted almost completely into radiation.

a) Calculate the total power of the Sun from the radiation received at Earth $L = 1.4\ \mathrm{kW/m^2}$. Use the units W and MeV/s. The distance Earth-Sun amounts to $r = 1.5 \cdot 10^8$ km.

b) How many fusion processes (as described above) happen per second? How much matter (in kg/s) is converted to energy?

c) Calculate the neutrino flux (ν_e) at Earth.
Hint: neutrinos are emitted isotropically from the Sun's nucleus and can freely escape from the interior of the Sun because of their extremely low cross-section.

Problem 46 Mean free path of solar neutrinos

The cross section for neutrinos with energy E_{cm} (center of mass system) for inelastic interactions with nucleons is given as

$$\sigma_{\nu-n} = 5 \cdot 10^{-44} \left(\frac{E_{cm}}{1\ \mathrm{MeV}} \right)^2\ \mathrm{cm}^2.$$

Calculate the mean free path $\lambda = 1/(\sigma_{\nu-n} n)$, with the number density n for neutrino capture of neutrinos with a lab energy of 1 MeV in the center of the Sun (typical density $\langle\rho\rangle \approx 100\ \mathrm{g/cm^3}$). Compare the result to the radius of the Sun.

Problem 47 SN 1987 A

Neutrinos from supernova SN 1987 A were observed with the Kamiokande detector. The following neutrinos were observed:

event no	t_{obs}	neutrino energy (MeV)
1	0	21.3
2	0.107	14.8
3	0.303	8.9
4	0.324	10.6
5	0.507	14.4
6	1.541	36.9
7	1.728	22.4
8	1.915	21.2

The observation times are given relative to the detection of the first neutrino.

a) Knowing the distance of the supernova is 52 kpc, calculate the travel time t_0 at the speed of light.

b) Show that a neutrino with mass m and energy E will take a total time of

$$t_{obs} - t_{em} = t_0 \left(1 + \frac{m^2}{2E^2}\right)$$

to reach the Earth.

c) According to astrophysical models the neutrinos were emitted within an interval of 2 s. Derive an upper limit for the neutrino mass from the data listed in the table. Assume all neutrinos have the same mass.

(This problem is based on W.D. Arnett and J.L. Rosner Phys. Rev. Lett. 18 (1987) 1906. This method provided at the time of publication one of the best upper limits for the neutrino mass.)

The solutions will be discussed during the werkcollege on 01.12.2016 in HG02.702.
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Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1617