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Particles and the Cosmos – 2017/18

Werkcollege 12 – Gamma-rays and neutrinos

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Problem 24 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 21). 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 with energy $E = 1$ TeV and with vertical arrival direction, compute the amount of photons collected by an IACT with a circular collecting area ($R_{dish} = 6$ m), with an overall Cherenkov photon detection efficiency equal to 10%, and located at 1800 m above sea level (a.s.l.).
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

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

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 ~ 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 $\cdot$ 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 25 Energy spectra of TeV gamma rays

Assume hadronic particles (protons and nuclei) are accelerated in a Supernova Remnant. The remnant is visible in TeV gamma rays through gammas from neutral pion decay.

The energy spectrum of the observed gamma rays has the shape

$$\frac{dN}{dE_\gamma} \propto E_\gamma^\beta \text{ with } \beta = -2.1.$$

a) What is the shape of the energy spectrum of the corresponding hadronic (mother) particles?
Hint: assume in hadronic interactions 1/3 of the energy is transferred to neutral pions. The latter decay into two photons $\pi^0 \to \gamma\gamma$.

b) Gamma rays up to energies of 100 TeV have been observed. Estimate the maximum energy of hadrons accelerated in this source.

Problem 26 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

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

a) 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 $\langle\rho\rangle \approx 100 \text{ g/cm}^3$).
Hint: discuss the difference for the given case between center of mass and laboratory reference frame.

b) Compare the result obtained to the radius of the Sun $R_{Sun} = 7 \cdot 10^5$ km.

Problem 27 Neutrino mass estimation from 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

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

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.)

Problem 28 Cosmogenic neutrinos

Neutrinos produced through the interactions of ultra-high-energy cosmic rays (UHECRs) with photons from the cosmic microwave background radiation (CMB) are called "Cosmogenic neutrinos". Due to their low flux and very small interaction cross-section, their detection requires huge detectors with very efficient background suppression.

IceCube is a 1 km^3 neutrino detector located at the geographic Southern Pole and consists on several light detectors buried into the polar ice. The 3.5-km-thick ice layer works both as target material and as background suppressor. When a neutrino interacts in the sensitive region, a cascade of secondary particles is generated and Cherenkov light is then produced. By collecting the Cherenkov photons the properties of the interacting neutrino (energy, flavor, direction) are inferred. On the ice surface, an array of frozen water Cherenkov detectors (called IceTop) have been installed for providing additional background suppression by working as a *veto* for extensive air showers . Moreover, IceTop is also able to carry on study of cosmic rays for energies up to 10^{18} eV.

a) Under the assumption Cosmogenic neutrinos are produced by pion decays following the GZK interaction (see Problem 23)

$$p + \gamma_{3K} \to n + \pi^+$$

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

compute the typical energy of Cosmogenic neutrinos.
Hint: assume the proton energy $E_p = 6.4\ 10^{19}$, the pion energy E_{π^+} equal to 15% of E_p, and that the neutrino is emitted in the same direction of the pion. Remember that the pion mass is equal to 139.6 MeV/c^2 and the muon one is 105.7 MeV/c^2 .

b) By assuming the cosmogenic neutrino flux equal to $F_\nu = 3 \cdot 10^{-17}$ cm^{-2} sr^{-1} s^{-1} and the IceCube detector isotropically sensitive, compute the rate of Cosmogenic neutrinos detected per year by IceCube.
Hint: assume the ice density equal to $\rho = 1$ g $\cdot$ cm^{-3} and use the following nucleon-neutrino cross-section

$$\sigma_{\nu-n} = 7.84 \cdot 10^{-36} \left(\frac{E_\nu}{GeV}\right)^{0.363}$$

which is valid for $E_\nu > 10^{16}$ eV .

The solutions will be discussed during the werkcollege on 08.12.2017 in HG00.058.
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Lecture web site: http://particle.astro.ru.nl/goto.html?partcos1718