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Astroparticle Physics – 2015/16

Werkcollege 15 – 12.01.2016

Problem 53 Energy production of the Sun

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

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

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

Calculate the neutrino flux (ν_e) at Earth. Neutrinos are neutral particles which can escape from the interior of the Sun. They are radiated off isotropically.

Problem 54 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 $\langle\rho\rangle \approx 100$ g/cm^3). Compare the result to the radius of the Sun.

Problem 55 Cosmogenic neutrinos

Neutrinos produced through the interactions of ultra-high-energy cosmic rays with photons from the cosmic microwave background radiation 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 South Pole and consists og several light detectors deployed in 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 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 to provide additional background suppression by working as a *veto*. IceTop is also able to carry on studies of cosmic rays for energies up to 10^{18} eV.

a) Under the assumption that cosmogenic neutrinos are produced by pion decays following the GZK interaction (see Problem 41)

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

compute the typical energy of cosmogenic neutrinos.

Hint: assume $E_p = 6.4\ 10^{19}$, $E_{\pi+}$ 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 mass is 105.7 MeV/c^2

b) By assuming the cosmogenic neutrino flux is equal to $F_\nu = 3 \cdot 10^{-17}$ cm^{-2} sr^{-1} s^{-1} and the IceCube detector is isotropically sensitive, compute the rate of cosmogenic neutrinos detected per year by IceCube.

Hint: assume the ice density is equal to $\rho = 1$ g 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 .

Problem 56 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. The distance of the supernova is 52 kpc. Calculate the travel time t_0 at the speed of light. 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.

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 12.01.2016 in HG03.082.
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Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1516