Radboud Universiteit Nijmegen
Afdeling Sterrenkunde
Jörg R. Hörandel
Antonio Bonardi

Astroparticle Physics – 2015/16
Werkcollege 10 – 01.12.2015

Problem 38 Simulation of the propagation of extra-galactic cosmic rays

Cosmic rays with energies above 10^{18} eV are believed to have an extra-galactic origin. Several simulation codes have been developed in the last decades in order to study their propagation through the extra-galactic medium and to calculate their properties when they arrive at Earth.

a) Given a point-like source located at 25 Mpc from the Earth, estimate with the CRPropa simulation software the dispersion of the arrival direction of protons with energies of 5, 20, 50, and 100 EeV, respectively (1 EeV = 10^{18} eV). Draw a histogram of the particle arrival energy for the 4 different cases.

Hint: Use the VISPA web interface (HTTPS://VISPA.PHYSIK.RWTH-AACHEN.DE/) to run the CRPropa software. You must create an account (it takes few minutes) at first, then go to "examples", and open the CRPropa example. Upload to the server and open the Python script which has been provided to you (APP_TUTORIAL.PY) and run it by typing "python %file" in the Commandline field on the upper right corner. A text file will be generated, copy it on your computer and write a code for the analysis. Note: in the text file, the arrival energy is the 4^{th} entry, while the arrival direction angle α is given by the combination of Px, Py, and Pz (entries 8, 9, and 10)

$$\alpha = \arccos\left(\frac{Px}{\sqrt{Px^2 + Py^2 + Pz^2}}\right).$$

Use the R_{80} parameter (it is defined as half of the opening angle of a cone, centered on the source direction and containing 80% of the total amount of particles arriving at Earth) to evaluate the dispersion of the arrival direction.
Note: simulation execution time depends almost linearly on the number of events you generate. If you generate 10^6 events, the simulation code will take between 5 and 15 minutes.

b) Draw the extra-galactic propagation track of a proton, a Helium nucleus, and an Oxygen nucleus with an energy E = 100 EeV. Describe the main differences between the 3 different cases.

Hint: use the script TRAJECTORIES.PY, which is the CRPropa example provided on the VISPA web interface.

see reverse side!

Problem 39 Electron-to-muon ratio in air showers

Extensive air showers are initiated by interactions of high-energy cosmic rays with atomic nuclei in the atmosphere. In Problem 31 it has been shown how two showers with the same energy and initiated by different particles have a different development due to the different interaction cross-sections of the impinging particles.

a) Discuss qualitatively the difference between air showers induced by protons and by iron nuclei with the same total energy. Which particle (proton or iron nucleus) interacts (on average) higher up in the atmosphere? Which particle yields on average secondary particles with a larger mean energy? How does this influence the decay of (unstable) secondary particles? Which primary particle (proton or iron nucleus) yields more muons in the atmosphere?

By assuming the total energy of an air shower is the sum of the energy in the electromagnetic and the muonic component, and given the fact that different primary particles will provide different muon amounts, it is evident that showers can be characterized by the ratio of the number of electrons to the number of muons in the shower, the N_e/N_μ ratio. In ground-based air shower experiments, muons are usually disentangled from electrons, by placing two kinds of particle detectors: one almost bare on the ground (a shelter is present only to protect the detector from the elements), and a second one, covered by a certain thickness of an absorber material (e.g. lead or iron). In that way, all the electrons/positrons will be stopped and only muons will be able to reach the second detector (usually called "muon detector").

b) Assume an extensive air shower close to its shower maximum (i.e. $X = X_{max}$), evaluate the minimum required absorber thickness (in g cm^{-2}) for the muon detector. By assuming a density of $\rho_{Fe} = 7.9$ g cm^{-3}, evaluate also the geometrical thickness.

Problem 40 Muon charge ratio

In extensive air showers muons are produced by the decay of short-living particles (mainly pions and a few kaons), which are produced in the hadronic first interactions of the particle cascade. The muon charge ratio, i.e. N_{μ^+}/N_{μ^-}, has been measured by several experiments in different energy ranges to be constant and equal to ~ 1.3 with a small increase at the uppermost energies ($E_\mu > 10^{12}$ eV).

Perform a research about the experiments which measured the muon charge ratio and explain why N_{μ^+}/N_{μ^-} is not equal to 1.

The solutions will be discussed during the werkcollege on 01.12.2015 in HG03.082.

Student assistant: Antonio Bonardi a.bonardi@astro.ru.nl

Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1516