Cosmic Ray Air Shower Lateral Coincidences

Gordon McIntosh

University of Minnesota, Morris

Abstract

At the University of Minnesota, Morris, my students and I have begun to investigate the time and altitude dependence of air showers. Air showers are cosmic ray secondaries that spread out laterally around the primary cosmic ray direction. To investigate the air showers we have been measuring the lateral coincidences among three Geiger counters located at 0 cm, 15 cm, and 40 cm. The rate of lateral, triple coincidences in this configuration is 0.053 ±0.013 hr^{-1} at the surface. On 4 April 2015 the UMM Modern Physics class made a balloon launch that included a measurement of the lateral, triple coincidences versus altitude. Three triple coincidences were measured during the 1.75 hour flight. The rate of triple coincidences was 1.7±1.0 hr^{-1}. This rate is ~30 times the rate measured at the surface and indicates that showers of sufficient lateral extension to produce triple coincidences occur at a greater rate at higher altitudes.

Background

At UMM we have been developing balloon and surface based measurements to incorporate the study of cosmic rays into

- Modern Physics (a second semester sophomore level course)
- Projects in Science and Engineering (a first year seminar course) and
- Undergraduate research projects.

Cosmic rays provide an interesting intersection between balloon flights and the physics curriculum, and they provide one of the few opportunities for undergraduate students to study relativistic and subatomic particles.

High energy cosmic rays, mostly protons, are continuously impinging on the Earth's atmosphere from all directions. They interact with an atmospheric atom or molecule and generate neutral and charged pions, πs.

- π^os decay to photons in ~ 10^{-16} s. These photons pair produce electrons and positrons.
- $\pi^{\pm}$s engage in further collisions or decay into charged muons, μs, and neutrinos, νs.

If the $\pi^{\pm}$'s energy is high enough the relativistic time dilation permits further interactions before the particle decays. In the rest frame of the $\pi^{\pm}$s its lifetime is ~ 26 ns.

The cascade of particles generated by the primary cosmic ray is known as an extensive air shower or an air shower. The size and composition of the air shower changes as the shower proceeds more deeply into the atmosphere due to the creation, the decay, and the energy loss of particles.

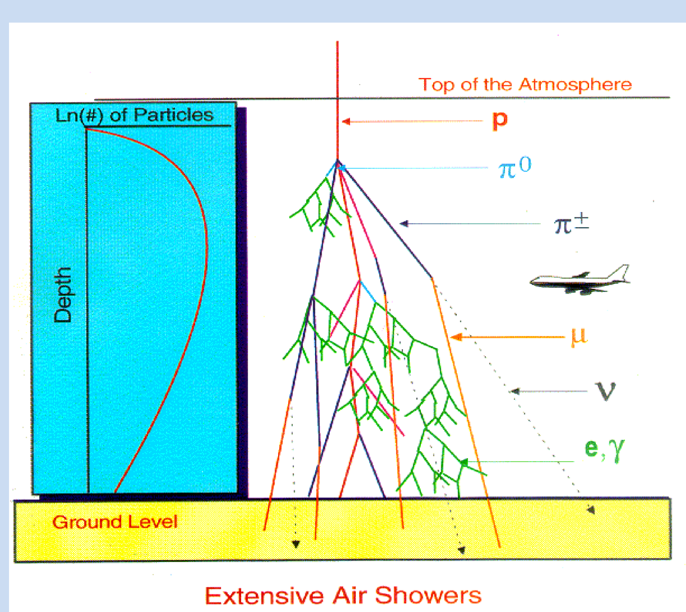

Figure 1. The changes in the constituents and lateral extension of an air shower as it propagates through the Earth's atmosphere. (http://www.physics.adelaide.edu.au/astrophysics/hires/uhecr.html)

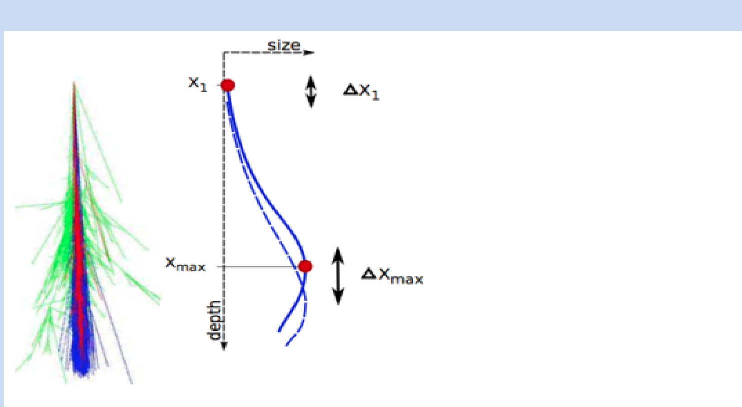

Figure 2. A simulation of air shower particle trajectories as the shower propagates through the atmosphere. The green trajectories represent μs, the blue trajectories photons, and the red trajectories πs or protons. (Cartiglia 2013)

UNIVERSITY OF MINNESOTA MORRIS

Theory

The energy of the second, or subsequent, generation air shower particle, E_G, is a fraction of the energy of the primary, or previous, generation particle. So

$$E_G = \frac{E_o}{f^G} \quad (1)$$

where E_o is the original particle energy, G is the number of generations of interactions, $1/f$ is the fraction of the energy supplied to the next generation particle. E_G represents the average energy of a particle in the Gth generation.

$$G_c = \frac{\log\left(\frac{E_o}{E_c}\right)}{\log(f)} \quad (2)$$

G_c is the number of generations that the primary cosmic ray will generate. Through these interactions the particles' energies decrease. If $E < E_c$ no further interactions will occur. The secondary particle's energy is no longer large enough to create new particles. For a larger primary particle energy, E_o, more generations, G_c, will be produced. The majority of the particles produced from the cosmic rays are πs. One third of the πs will be π^os and will produce no further particle interactions. So the number of $\pi^{\pm}$'s existing after generation G, $N_{\pi\pm}$, is

$$N_{\pi^{\pm}} = \left(\frac{2}{3}f\right)^G \quad (3)$$

In the last generation, G_c, the charged $\pi^{\pm}$s will decay to charged μs. The number of μs, N_μ, totals

$$N_\mu = \left(\frac{2}{3}\right)^{G_c}\frac{E_o}{E_c} \quad (4)$$

So

$$N_\mu \,\alpha\, E_o \quad (5)$$

The empirical relationship between the areal muon density, ρ_μ, and distance from the core of a shower, r, is

$$\rho_\mu = \frac{1.25\,N_\mu}{2\pi\Gamma(1.25)}\left(\frac{1}{320}\right)^{1.25} r^{-0.75}\left(1+\frac{r}{320}\right)^{-2.5} \quad (6)$$

at the surface of the Earth (Amsler et al. 2008). The practical edge of the shower, R, occurs when the ρ_μ times the detector area is 1.

Since the triple coincidence events are rare, we will assume they are observations that indicate ρ_μ is small at an r of 40 cm. As shown in Fig. 3, when ρ_μ is large it can be approximated by

$$\rho_\mu \,\alpha\, \frac{N_\mu}{r^{0.75}} \quad (7)$$

and when ρ_μ is small it can be accurately described by

$$\rho_\mu \,\alpha\, \frac{N_\mu}{r} \quad (8)$$

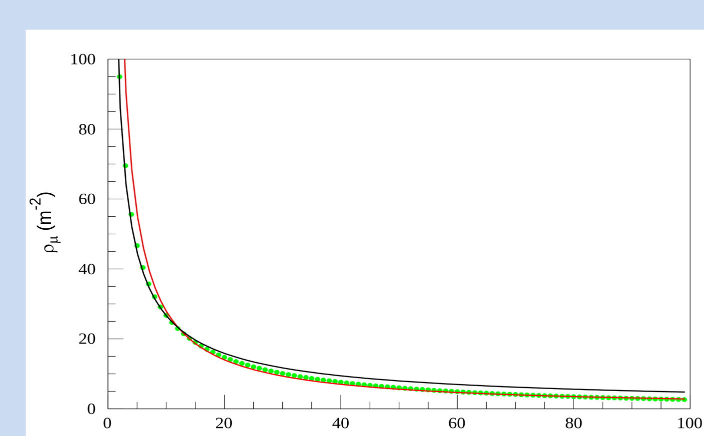

Figure 3. The ρ_μ as a function of distance from the core of the air shower. The green circles are an evaluation of equation 6. The red line is proportional to r^{-1}. The black line is proportional to $r^{-0.75}$. At large distances from the core $\rho_\mu \,\alpha\, r^{-1}$.

The relationship for small ρ_μ indicates that

$$R \,\alpha\, \frac{N_\mu}{\rho_\mu(R)} \quad (9)$$

So

$$R \,\alpha\, N_\mu \quad (10)$$

and therefore

$$R \,\alpha\, E_o \quad (11)$$

Relationship 11 indicates that measuring the lateral coincidences provides information about the energy of the primary cosmic ray. Unfortunately without the technology necessary to measure the energy of the particles detected, E_o cannot be calculated. But using balloon flights the rate of air showers generating triple coincidences can be measured and compared to the Earth surface measurements.

Observations

The rate of triple coincidences was measured in the laboratory with Aware RM60 Geiger counters located at 0 cm, 15 cm, and 40 cm. The counters were connected to a three input AND gate. The measured rate was 0.053 ± 0.013 counts hr^{-1}.

A balloon pod was instrumented with Geiger counters set at the same separations and connected through a three input AND gate to a Stratostar module. A single Geiger counter was also included in the pod to measure the omnidirectional cosmic ray rate. Fig. 4 shows the results from the 4 April 2015 flight. The Pfotzer maximum, the altitude of maximum omnidirectional rate, occurs at about 20,000 m as has been noted by previous AHAC papers (Adams et al. 2011; McIntosh 2012).

The altitudes of the measured triple coincidences are also shown in Fig. 4. All the triple coincidences were detected above 15,000 m. Three coincidences in the 1.75 hour flight produce a rate of 1.7 ± 1.0 counts hr^{-1}. The rate of triple coincidences is at least 30 times greater above 15,000 m than it is at the surface. The physics of air showers at these altitudes is different than surface air showers. The different charged particle species existing at these altitudes, as well as E_o, will affect the production of triple coincidences.

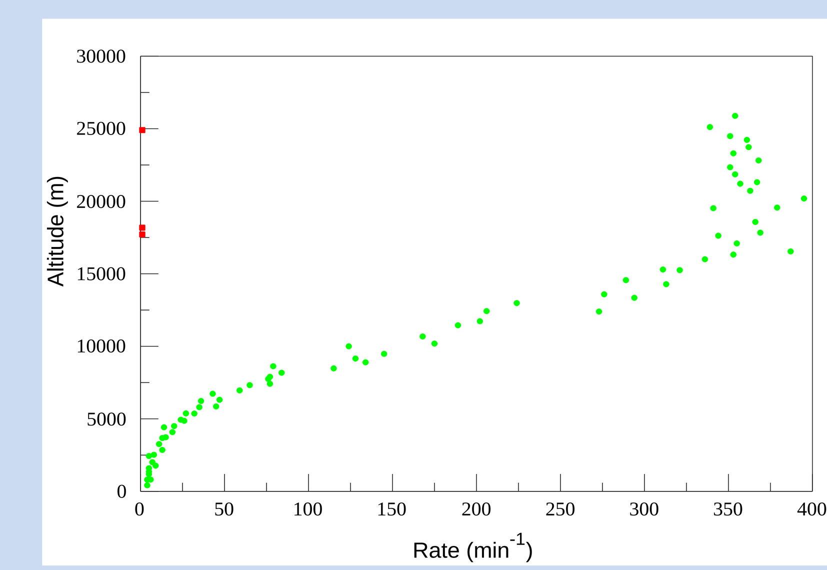

Figure 4. Geiger counter rates for omnidirectional detections (green circles) and lateral, triple coincidences (red squares) versus altitude.

Future Work

- More Geiger counters and larger separations to produce more instructive results.
- Larger area detectors and longer times at high altitude for improved statistics.
- Attempts to determine the energy or species of the detected particles .
- Flights to detect the presence of highly energetic solar wind particles in the atmosphere.

Conclusions

- It is now possible for undergraduate students to study air shower physics through relatively inexpensive electronics and balloon flights.
- Air showers represent an overlap of high energy physics and available technologies that should stimulate the interests of students.
- Air shower observations and analyses provide challenging, scientifically rich, relatively unexplored projects for undergraduates.

References

Adams, A., Brauer, E, & Stroman, J. 2011, "A Small Geiger Counter Array," Proceedings of the Academic High Altitude Conference, University of Iowa, Ames, IA, 1

Amsler, C. et al., 2008, Physics letters, B667, Chapter 24. Cosmic Rays

Cartiglia, N. 2013, "Measurement of the proton-proton total, elastic, inelastic and diffractive cross sections at 2, 7, 8 and 57 TeV," arXiv:1305.6131

Eggert, N. 2008, "A Measurement of the Cosmic Muon Decoherence Curve with Silicon Photomultipliers." Methods of Experimental Physics, University of Minnesota

Grieder, P. 2010, Extensive Air Showers, Springer, New York, New York

McIntosh, G. 2012, "Cosmic Ray Measurements," Proceedings of the Academic High Altitude Conference, Trevecca Nazarene University, Nashville, TN, 133

Acknowledgements

Thanks to the UMM Spring 2015 Modern Physics class and to the UMM Physics discipline.