

# Cosmic Ray Air Shower Lateral Coincidences

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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 Aware RM60 Geiger counters located at 0 cm, 15 cm, and 40 cm. Most of these measurements have been carried out at the surface. The rate of lateral, triple coincidences of Geiger counter with this configuration is  $0.053 \pm 0.013 \text{ hr}^{-1}$  at the surface. On 4 April 2015 the UMM Modern Physics class made a balloon launch that included a measurement the lateral, triple coincidence versus altitude. Three triple coincidences were measured during the 1.75 hour flight. The rate of triple coincidences was  $1.7 \pm 1.0 \text{ hr}^{-1}$ . This rate is  $\sim 30$  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.

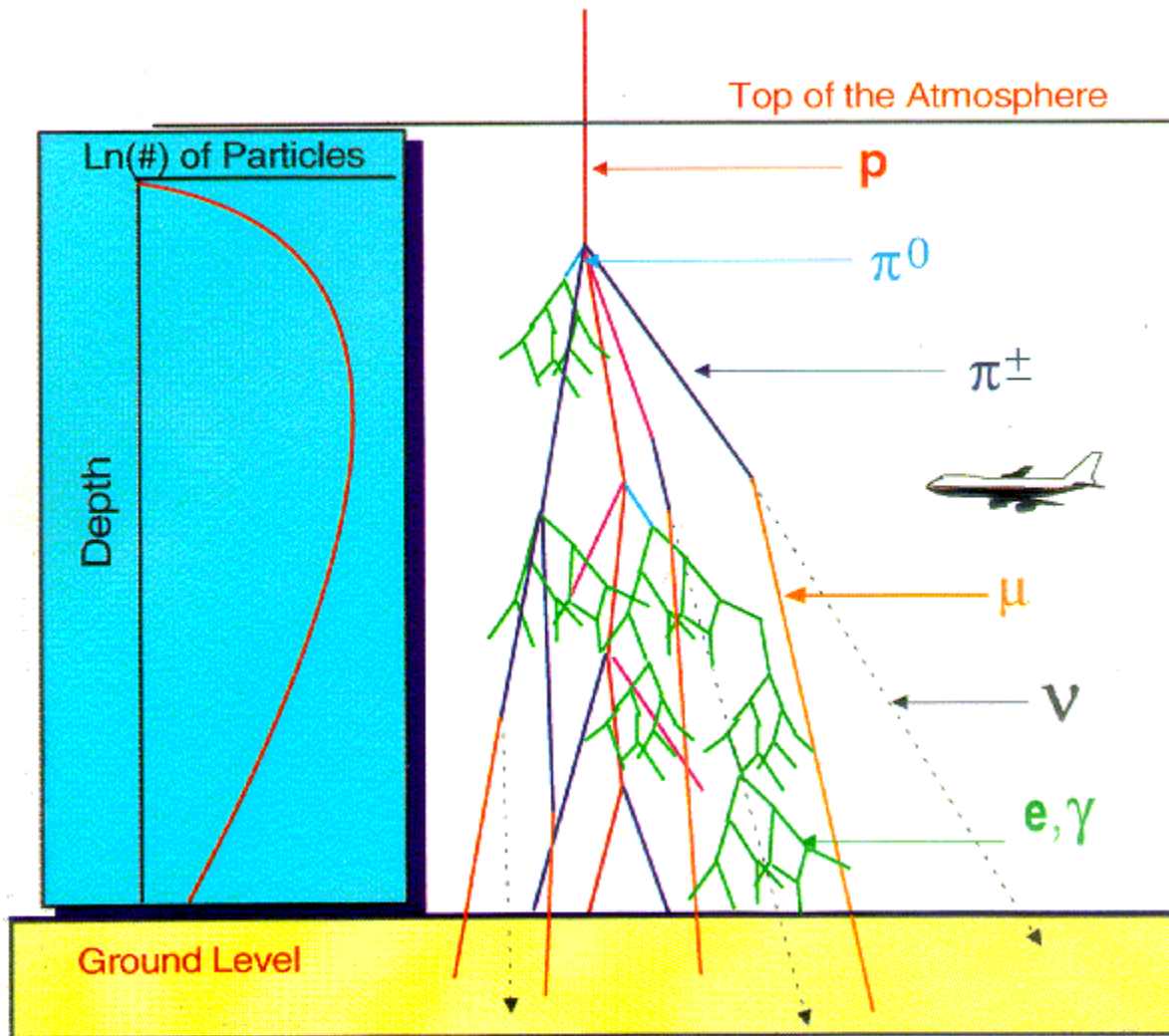
## I. Introduction

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 in 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 are continuously impinging on the Earth's atmosphere from all directions. These cosmic rays, the majority of which are protons, interact with an air atom or molecule. The interaction commonly generates neutral and charged pions,  $\pi$ s. The  $\pi^0$ s decay to photons in  $\sim 10^{-16}$  s. These photons pair produce electrons and positrons. The  $\pi^\pm$ s engage in further collisions or decay into charged muons,  $\mu$ s, and neutrinos,  $\nu$ s. If the  $\pi^\pm$ s energy is high enough the relativistic time dilation permits further interactions before the decay of the particle. In the rest frame of the  $\pi^\pm$ s the lifetime is  $\sim 26$  ns.

The cascade of particles generated by the primary cosmic ray is known as an extensive air shower or an air shower. As the air shower progresses into the atmosphere it spreads out laterally. Fig. 1 is a cartoon indicating the changes in size and composition of the air shower as the shower proceeds more deeply into the

atmosphere. The number and type of particles in the shower change with depth in the atmosphere because of the creation, the decay, and the energy loss of particles.



### Extensive Air Showers

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>)

Fig. 2 is a computer simulation of the progress of an air shower and shows the change in the lateral extension of the air shower as it progresses through the atmosphere.  $x_{\text{max}}$  indicate the maximum width of the air shower. More energetic primary cosmic rays generate a larger extension lower in the atmosphere.

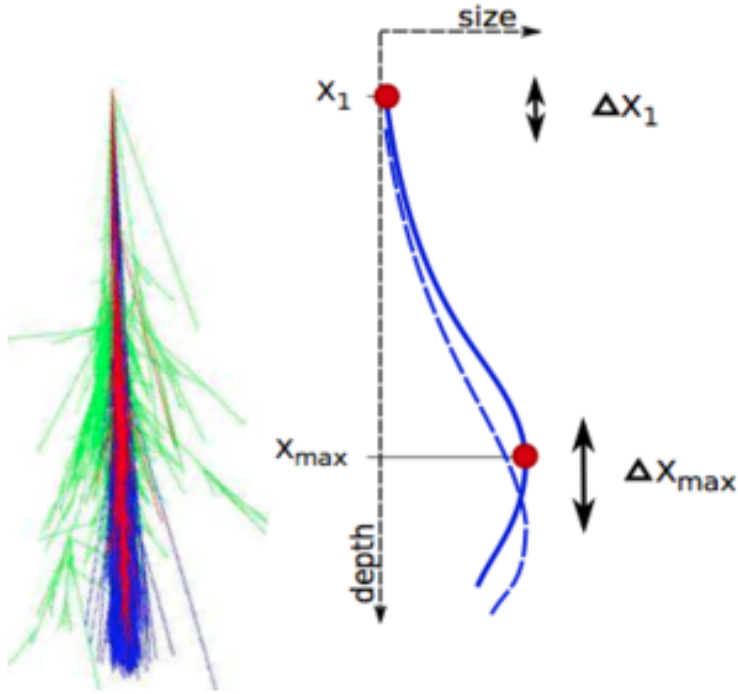


Figure 2. A simulation of air shower particle trajectories as the shower propagates through the atmosphere. The green trajectories represent  $\mu$ s, the blue trajectories photons, and the red trajectories  $\pi$ s or protons. (Cartiglia 2013)

## II. 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

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

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  $G$ th generation.

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

$G_c$  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  $\pi$ s. One third of the  $\pi$ s will be  $\pi^0$ s 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  $\mu$ s. The number of  $\mu$ s,  $N_\mu$ , totals

$$N_\mu = \left(\frac{2}{3}\right)^{G_c} \frac{E_0}{E_c} \quad (4)$$

So

$$N_\mu \propto E_0 \quad (5)$$

The empirical relationship between the areal muon density,  $\rho_\mu$ , 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  $\rho_\mu$  times the detector area is 1.

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

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

and when  $\rho_\mu$  is small it can be accurately described by

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

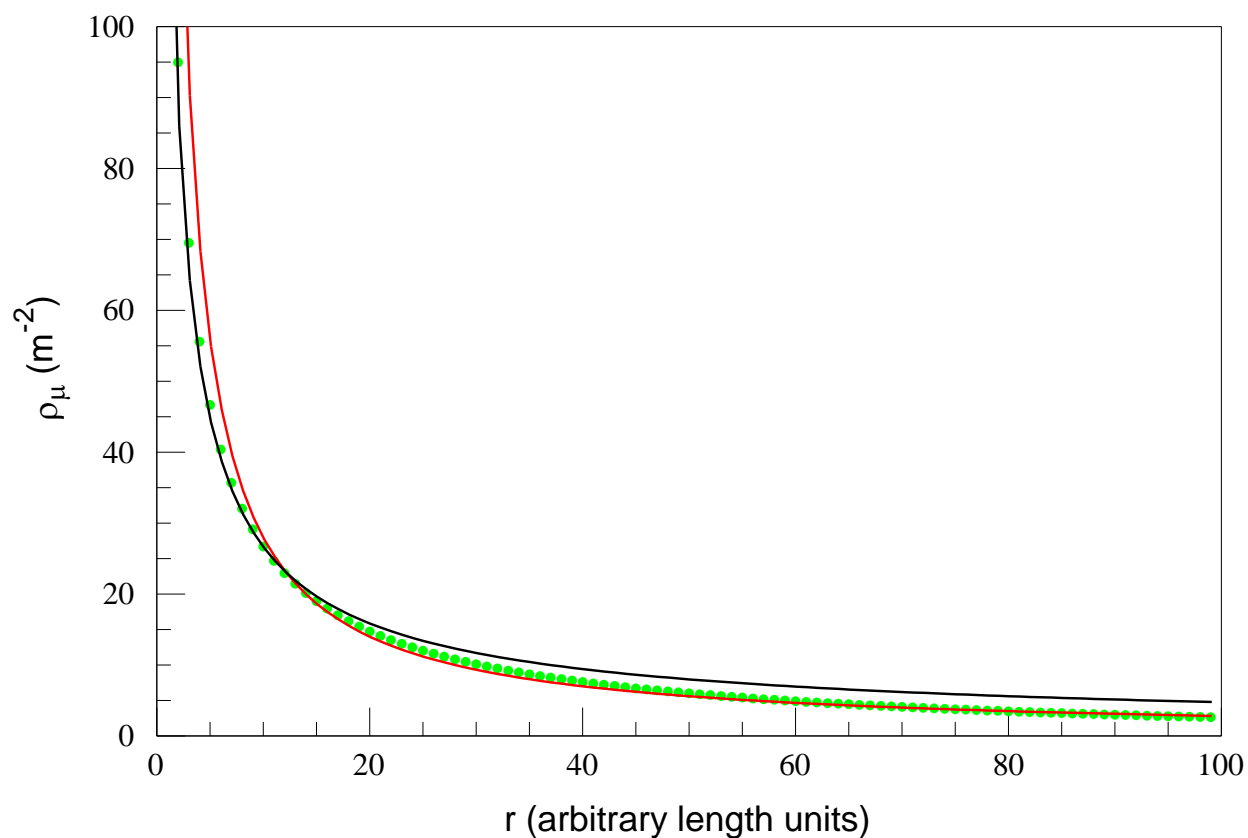


Figure 3. The  $\rho_\mu$  as a function of distance from the core of the air shower. The green circles are an evaluation of equation 6. The red line is proportional to  $r^{-1}$ . The black line is proportional to  $r^{-0.75}$ . At large distances from the core  $\rho_\mu \propto r^{-1}$ .

The relationship for small  $\rho_\mu$  indicates that

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

So

$$R \propto N_\mu \quad (10)$$

and therefore

$$R \propto E_o \quad (11)$$

since  $N_\mu \propto E_o$ .

Relationship 11 indicates that the number of triple coincidences measured is proportional to the number of showers with initial particle energy  $E_0$  or greater, i.e. 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,  $E_0$  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.

### III. Observations

The rate of triple coincidences was first measured in the laboratory with Geiger counters located at 0 cm, 15 cm, and 40 cm. The outputs from the Geiger counters were connected to a three input AND gate and the output signals were recorded. The measured rate was  $0.053 \pm 0.013$  counts  $\text{hr}^{-1}$ .

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 UMM balloon flight that carried the pod. The Pfozter 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  $1.7 \pm 1.0$  counts  $\text{hr}^{-1}$ . The rate of triple coincidences is at least 30 times greater above 15,000 m than it is at the surface. Not surprisingly air showers are more common at these altitudes. However the physics of air showers at these altitudes may be different than surface air showers. The different charged particle species existing at the altitudes achieved by the balloon, as well as  $E_0$ , will affect the production of triple coincidences.

### IV. Future Work

In future laboratory measurements and balloon flights the physics behind these results and other ideas will be examined. For example:

1. A pod incorporating more Geiger counters and larger Geiger counter separations should produce more coincidences and improved results.
2. Larger area detectors and more flights or longer times at high altitude should produce more detections and improved statistics. Better statistics will allow for more accurate comparisons and analyses.
3. Above the Pfozter maximum, air showers will have a different particle composition and energy than air showers near the surface. Can the energy or species

of the detected particles be determined? Do these changes change the efficiency of the Geiger counters?

4. The highest rate of triple coincidences, representing lateral spread of the air shower, may not occur at the same altitude as the Pfitzer maximum of omnidirectional counts. Can the altitude difference be measured and interpreted?

5. Can flights during times of solar activity detect the presence of highly energetic solar wind particles in the atmosphere?

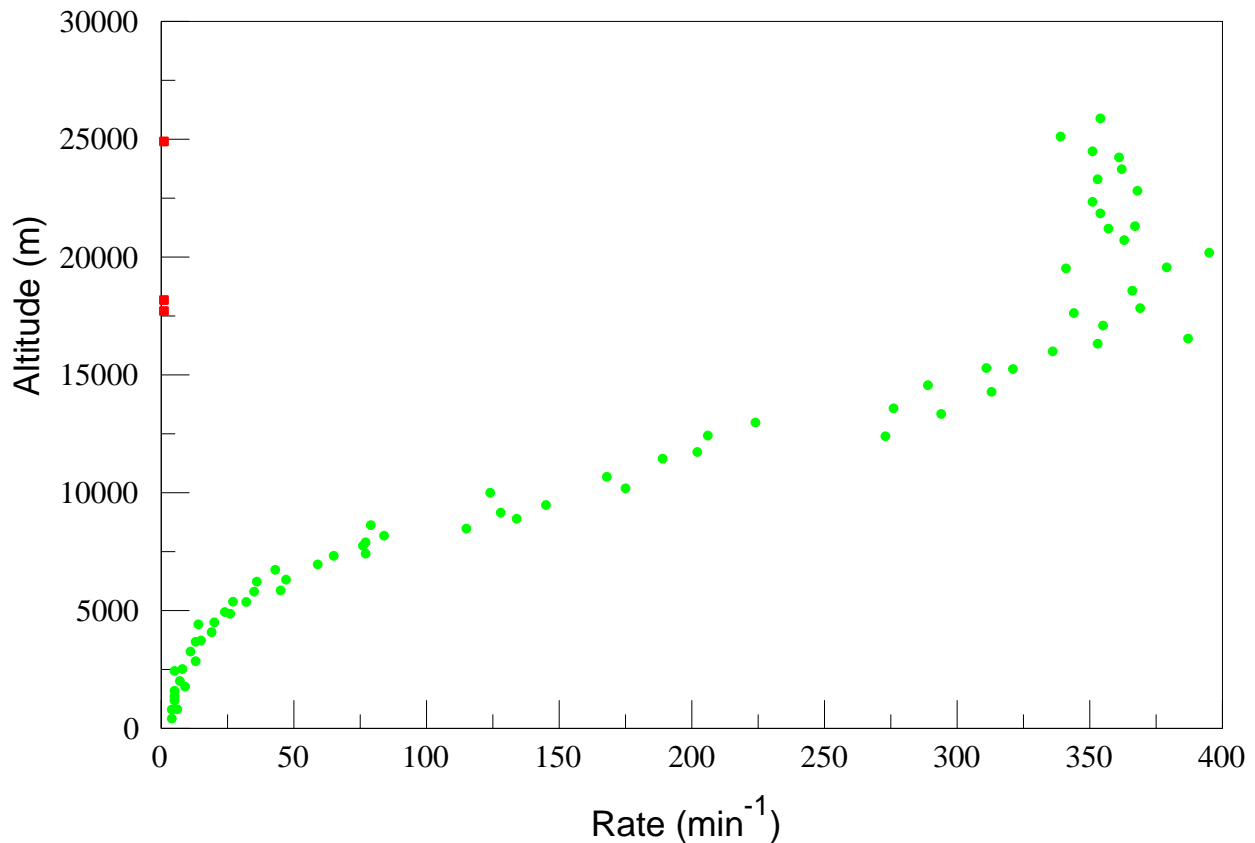


Figure 4. Geiger counter rates for omnidirectional detections (green circles) and lateral, triple coincidences (red squares) versus altitude.

## V. Conclusion

The study of air shower physics is now available to undergraduate students 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 in both of these areas. Air shower observations and analyses provide challenging, scientifically rich, relatively unexplored projects for undergraduates.

## VI. References

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