Feasibility of Muon Tomography to Determine the Electronic Structure of a Thundercloud

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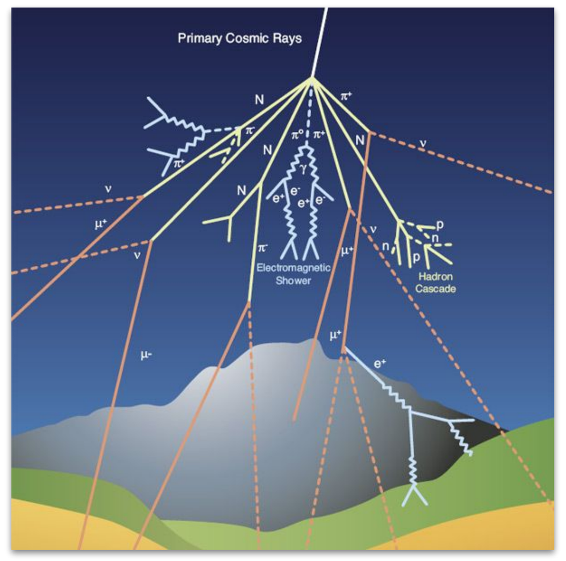
Background

Cosmic Ray Muons

Muons (μ) are subatomic particles that are a type of lepton and are classified as an elementary particle due to their lack of substructure. Muons have the same charge as electrons (-e) but weigh significantly more (~200 times more mass). When cosmic rays, high-energy particles from space primarily consisting of protons and alpha particles, impact the Earth's atmosphere, they generate high-energy collisions that produce cascades of lighter particles, which initially produce pions and kaons, and then decay to produce muons. With an average life of t - 2.2 μs, ground-bound muons travel close to light speed. Thanks to their speed and Einstein's relativity, muons can be detected at sea level; current research estimates a rate of 1 per square centimeter per minute. [5]



Thundercloud Formation

Thundercloud Formation can be broken down into two steps: cloud formation and charge separation. The cloud starts to form when warm, moist air rises. As the surrounding air gets colder with altitude, the water vapor in the rising air gets supercooled, becoming ice when attaching to small particles in the air. As this state is maintained, the ice particles will build up, becoming more and more massive until they fall due to their weight. The falling ice particles start a downdraft in the cloud that begins the charge separation process.

Many physical processes contribute to the overall charge separation between the top and bottom of the thundercloud. One theoretical process, which C.T.R. Wilson outlined, points to polarized water molecules as a main catalyst for this phenomenon. In fair weather there is a small electric field downwards in the air. As the water (or ice) falls through the air, the electric field creates an induced dipole moment in the water droplet. Because the surrounding air is conductive, there exist slow moving ions in the air. Since the water droplets are falling, the ions will only come into close contact with the underside of the water droplet, where the positive end of the dipole lives–thus positive ions are repealed from the water droplet, and negative ions come into the water droplet. The droplet obtains a net negative charge and falls, explaining how negative charge is carried into the lower part of the cloud, leaving an overall positive charge distribution in the high sections of the thundercloud.

The electric field in a thundercloud is not so simple as a parallel plate capacitor–the average charge density varies with altitude through the cloud, and at the base of the cloud there is a small concentration of positive charge, for reasons unknown to this day.

Motivation: Relation between Muon Charge Ratio and Thundercloud Structure

This project is directly inspired by Chilingarian et al. and their article *Muon Tomography of Charged Structures in the Atmospheric Electric Field*. The findings for this paper suggests that the muon charge ratio in a positive electric field will be less than the muon charge ratio when no electric field is present. On the other hand the muon charge ratio in a negative electric field will be less than the muon charge ratio under no electric field. It is important to note that the natural muon charge ratio is greater than one because there are more positive muons than negative muons (more matter than antimatter). With this finding, Chillingarian's group suggests that muon tomography can be a valid way to determine the structure of an electric field. This inspired our group to try to verify these findings by simulating muon interaction with electric fields in hopes of revealing a correlation between muon charge ratio and an electric field, which could be applied to obtain information about the electric field structure in a thundercloud.

CORISKA

What Is CORSIKA

- CORSIKA (COsmic Ray SImulations for KAscade) is an air shower simulation that uses C++ and Fortan77. It uses includes monte carlo simulations (which predict the possible outcomes and uncertain events and repeat them multiple times). Many different studies that look at cosmic rays, thunderclouds, and atmospheric electric fields used CORSIKA for modeling (such as A. Chilingarian, et al. [2]).
- Some important equations in studying muon charge ratio and thunderclouds are the:
  - The Mandelstam Variables are numerical quantities that encode the energy, momentum, and angles of particles in a scattering and is given by:

$$s = (p_1 + p_2)^2 c^2 = (p_3 + p_4)^2 c^2$$

  - The Muon-Electron Interaction Cross Section is the fraction of the total number of scattered particles that come out in the solid angle $d\Omega$, where omega traces the surface area of a sphere around the collision and is given by:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s\sin^4\theta/2}\left(1 + 4\cos^4\theta/\right.$$

  - The Kinetic Equation for Muon Intensity for Thundercloud is given by:

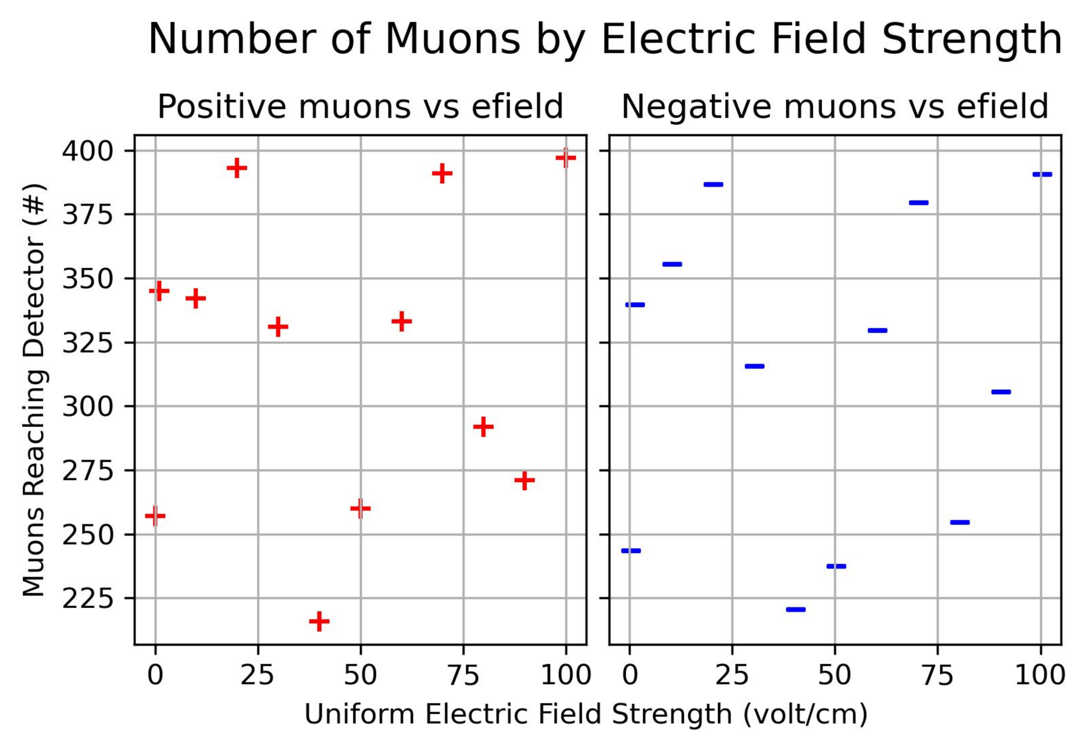
$$\frac{\partial J(z,\varepsilon)}{\partial z} - [\alpha - \beta(z)]\frac{\partial J(z,\varepsilon)}{\partial \varepsilon} + \frac{b}{z\left(\varepsilon^2 - (mc^2)^2\right)^{1/2}} J(z,\varepsilon) = U(z,\varepsilon),$$ [7]

Our Steering Card

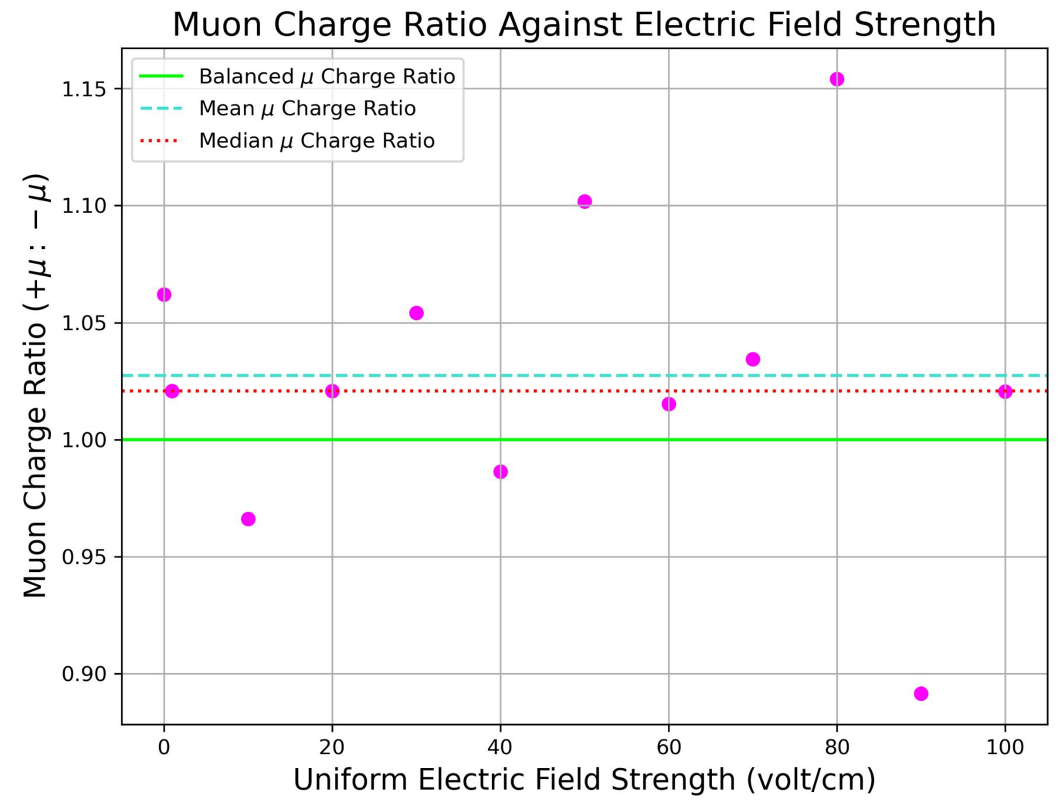
```
RUNNR   6                                run number
NSHOW   1                                number of showers to generate
PRMPAR  14                               prim. particle (1=gamma, 14=proton, ...)
ESLOPE  -2.7                             slope of primary energy spectrum
ERANGE  1.E5  1.E5                       energy range of primary particle (GeV)
THETAP  0.  0.                           range of zenith angle (degree)
PHIP    -180.  180.                      range of azimuth angle (degree)
SEED    1   0   0                        seed for 1. random number sequence
SEED    2   0   0                        seed for 2. random number sequence
*THIN    1.E-2  1.E2  0.                  thinning definition
*THINH   10.  10.                         relative threshold and weight for hadron thinning
OBSLEV  110.e2                              observation level (in cm)
MAGNET  23.025  42.008                      magnetic field centr. Berkeley
HADFLG  0  0  0  0  0  2                 flags hadr.interact.&fragmentation
ECUTS   1.  1.  0.001  0.001             energy cuts for particles
MUADDI  T                                additional info for muons
MUMULT  T                                muon multiple scattering angle
ELMFLG  F   T                            em. interaction flags (NKG,EGS)
STEPFC  1.0                              mult. scattering step length fact.

RADNKG  200.E2                           outer radius for NKG lat.dens.distr.
EPOPAR input ../epos/epos.param           !initialization input file for epos
EPOPAR fname inics ../epos/epos.inics    !initialization input file for epos
EPOPAR fname iniev ../epos/epos.iniev    !initialization input file for epos
EPOPAR fname initl ../epos/epos.initl    !initialization input file for epos
EPOPAR fname inirj ../epos/epos.inirj    !initialization input file for epos
EPOPAR fname inihy ../epos/epos.ini1b    !initialization input file for epos
EPOPAR fname check none                   !dummy output file for epos
EPOPAR fname histo none                   !dummy output file for epos
EPOPAR fname data  none                   !dummy output file for epos
EPOPAR fname copy  none                   !dummy output file for epos
LONGI   T  10.  F  F                     longit.distr. & step size & fit & outfile
ECTMAP  1.E11                             cut on gamma factor for printout
MAXPRT  1                                max. number of printed events
DIRECT  ./                               output directory
USER    you                              user
*PAROUT F F                               suppress DAT file
DEBUG   F  6  F  1000000                 debug flag and log.unit for out
EXIT                                     terminates input
```

- CORSIKA EPOS is the code we used and it is based on the neXus model. The neXus model is a combination of the VENUS AND QGSJET models with an addition of hard interactions and nuclear and high density effect. VENUS AND QGSJET are based on Gribov-Regge theory. The Regge theory is the study of particle scattering as a function of angular momentum, but angular momentum is allowed to be a complex number [3].

Data Input



The effects on the positive and negative muons by varying strengths of the electric field is show in this graph. While both subplots do not show a clear correlation, it is important to note that only one simulation has been conducted with each electric field strength, so each point currently contains high error.



This figure shows the muon charge ratio fluctuating against the electric field strength. While this plot seemingly has no correlation between the charge ratio and the field strength, it does support that the natural muon ratio is greater than one. However, as stated in the first figure, there are still uncertainties in the individual points themselves since they are first simulation data.

Results

The effects on the positive and negative muons by varying strengths of the electric field is shown in this graph. While both subplots do not show a clear correlation, it is important to note that only one simulation has been conducted with each electric field strength, so each point currently contains high error.

Conclusions and Next Steps

We used our data in a PCA (Principal component analysis). PCA is a analysis method of making large data sets with many variables into data with less variables (making it easier to study and understand) but still containing the crucial data. We have isolated key components that can vary muon charge ratio, rather than a code using linear algebra. We analyzed variables that previous papers had indicated as significant as well as using variables that we were interested in. The data that we gathered can be used in future PCA analysis of muon charge ratio and thundercloud reconstruction [6].

Further experiments that can be tested are including shapes of electric fields into the simulation itself. Our current experiment only uses the electric field that spans the entire atmosphere. Having a localized area (a cloud) in which an electric field is set up may produce different and more impactful results that allow us to further probe our research question. The difficulties will lie in diving deeper into the CORSIKA code and implementing the custom structure of the electric field. Once this challenge is figured out, we will be able to put in different shapes that represents the possible structures of the thundercloud and determine whether muon tomography is viable to reflect its electronic structure.

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Citations

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