Simulating Scattering Processes in TGFs Using Monte Carlo Methods

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ABSTRACT

Terrestrial Gamma Ray Flashes (TGFs) are a high energy physics phenomenon that incorporates many different theories of particle interactions. Previous research focuses primarily on monte carlo simulations combining scattering events in the atmosphere[3]. We aim to verify the cross-sections of some of the dominant processes in Terrestrial Gamma Ray flashes (TGFs): Compton, Rayleigh, Elastic, and Moller scattering. For each process, we wrote up an individual monte carlo simulation in Python Jupyter Notebooks. In general, each monte carlo simulation probabilistically calculates the differential cross section of the respective scattering process then simulating the average total cross section over multiple trials. In the end our simulations on electron elastic scattering and compton scattering yielded the most accurate results and such are shown on this poster.

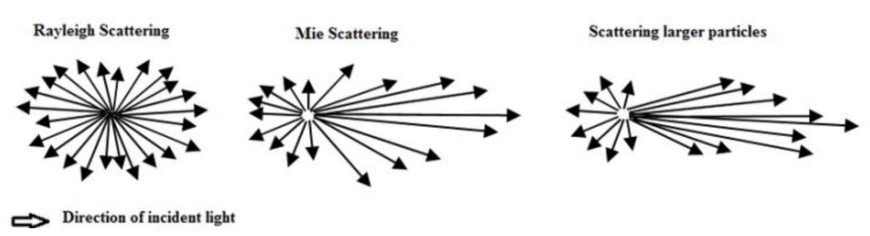
BRIEF INTRODUCTION TO TERRESTRIAL GAMMA RAY FLASHES

Terrestrial Gamma-Ray Flashes (TGFs) are concentrated pulses of high-energy Gamma Rays produced by the chaotic motion of electrons in Earth's atmosphere, typically during thunderstorms due to the strong electric fields created. Along with lower energy electromagnetic-radiation generated from the scattering mechanisms, beams of antimatter have been observed to be created by the most intense TGFs. There are two Key production mechanisms of antimatter: Wilson runaway electrons and Relativistic Runaway Electron Avalanches. Wilson runaway electrons are electrons accelerated in a high-energy electric field interacting. Relativistic Runaway Electron Avalanches (RREAs) are runaway electrons that undergo avalanche multiplication by colliding with other runaway electrons, creating secondary electrons and producing further collisions and secondary electrons.

The probability for each of these processes is found via the cross section of a scattering event of a specific process, which will take place when radiation-target interaction occurs. The radiant excitation and localized targets vary for each type of scattering but are dominated by electron elastic scattering (moller scattering), rayleigh scattering, and compton scattering. Moller scattering takes place between two electrons interacting via photon. Rayleigh scattering occurs with the interaction of polarized photons on particles much smaller than the wavelength of incoming light, primarily with atmospheric Nitrogen gas in our case. Compton scattering happens between a photon electron. These scattering processes are integral for studying the behavior of terrestrial gamma ray flashes because in these high energy, rapid bursts, an array of different types of particle interaction occurs.

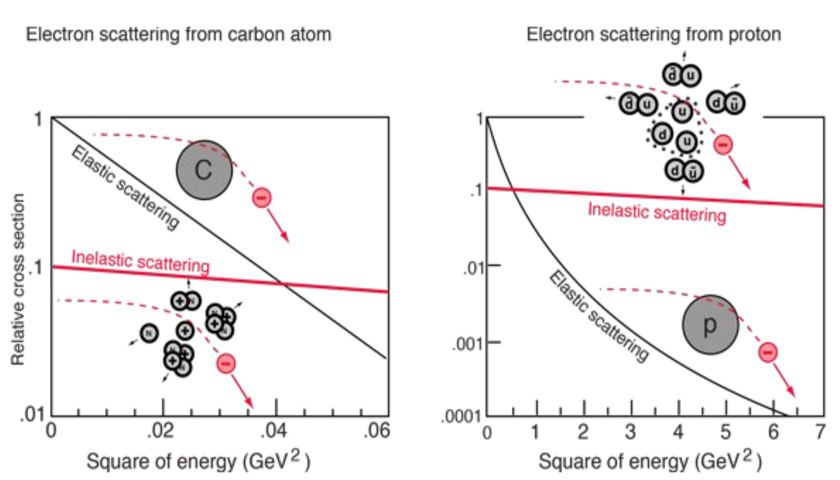
DIAGRAMS OF THEORY

Electron Elastic Scattering



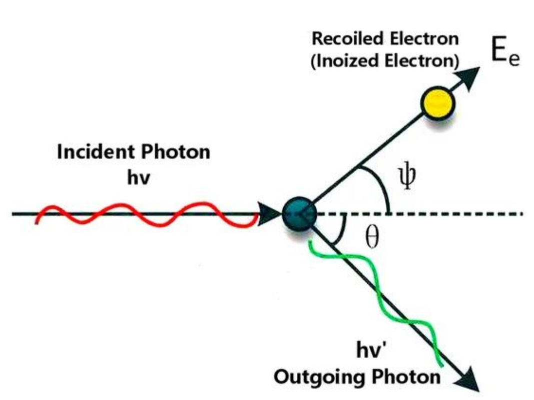
[Figure B]

Electron Elastic Scattering



[Figure A]

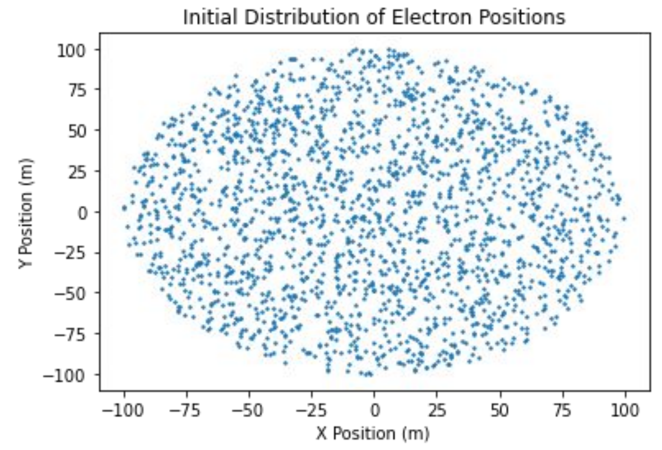
Compton Scattering

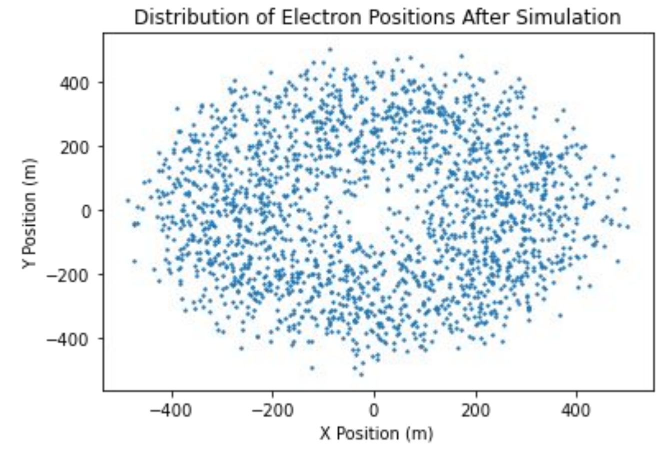


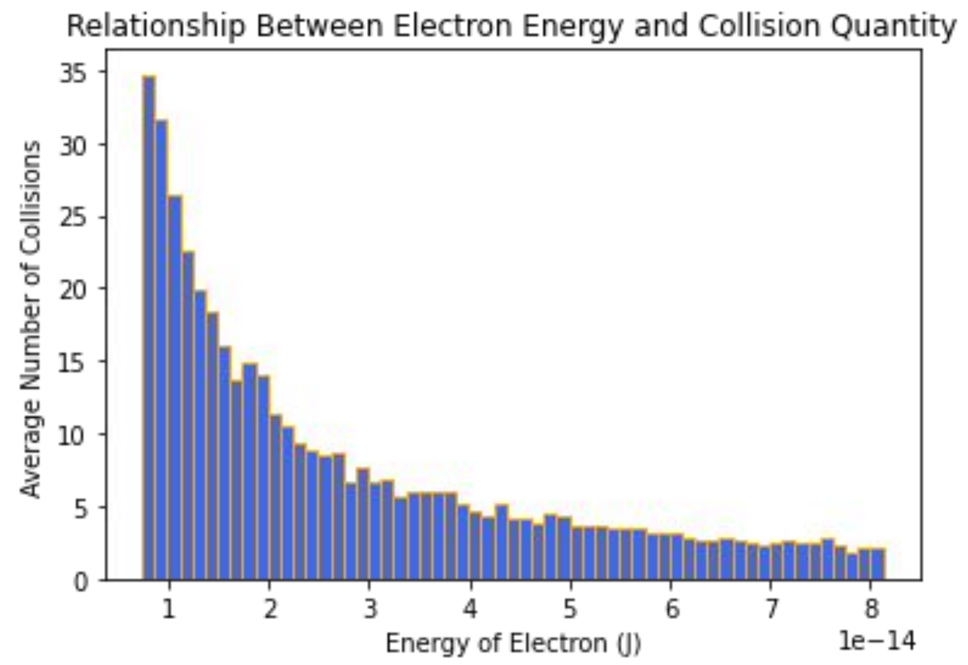
[Figure C]

ELECTRON ELASTIC SCATTERING SIMULATION

During a TGF event, the more common scattering processes involve Moller electron-electron scattering and collisions with atmospheric particles. In our simulation, we first derived and calculated the collision cross sections for the non-relativistic elastic cases of those phenomena, then simulated the propagation of electrons in the atmosphere using Monte Carlo techniques.



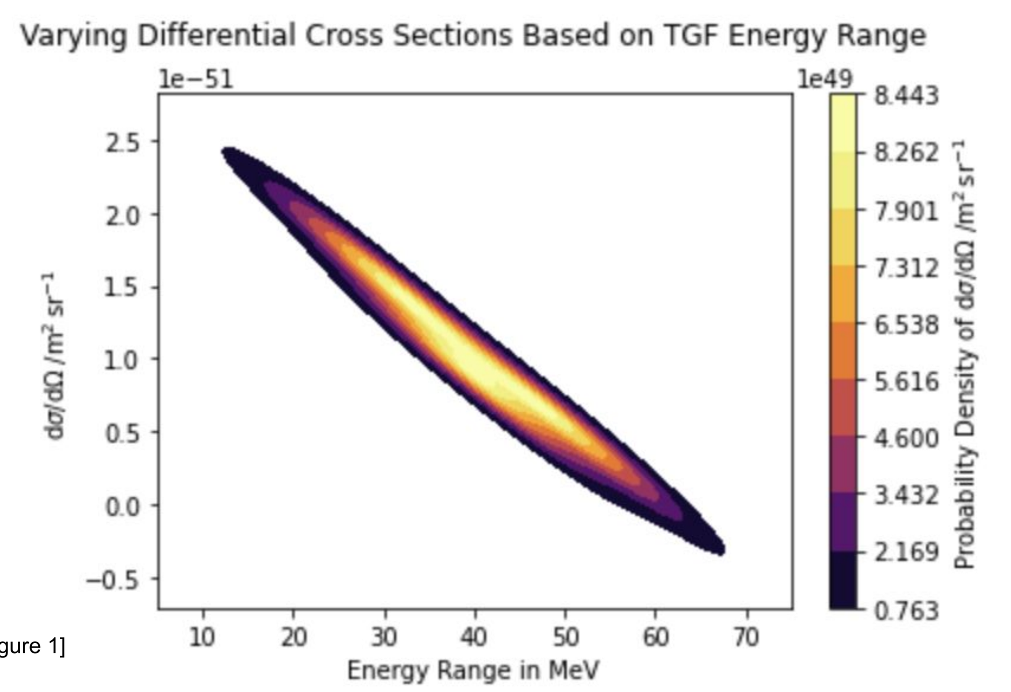




Shown on the left are the initial randomly generated spatial distribution of electrons and their final positions after simulating 1 μs of motion. Note that generally the movement of the electrons is to spread out to a greater radius while a few are scattered back closer to the origin. The rightmost plot shows the relationship between the randomly generated energy values of the electrons and the average number of collisions for electrons in each energy bin over the course of the simulation. This negative correlation is caused by a combination of the cross section for atmospheric and electron-electron scattering being larger for lower energies and that lower energy electrons would generally be concentrated into areas of a higher number density of electrons and thus collide more frequently.

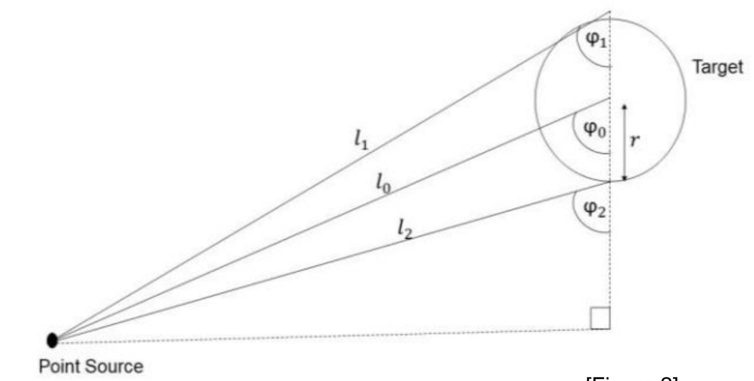
COMPTON SCATTERING SIMULATION

Compton scattering is crucial in determining the spectral and temporal attributes as well as the duration of a TGF. Modeling this process can help us understand the behavior of bremsstrahlung photons when they inelastically collide with electrons during the event. In short, the simulation we built was dependent on the non-relativistic angle of incidence at the center of the localized phenomenon (the target). In this case, we assumed the target to be spherical in nature. After probabilistically determining a range of angles to consider and randomly selecting from that range, we used the Klein-Nishina formula in order to calculate the differential cross section between photons and electrons in a high energy, inelastic Compton scattering event. From there, we built multiple trials to calculate the total cross section using varying scattering angles and integrating with bounds close to historically documented TGF energy ranges.

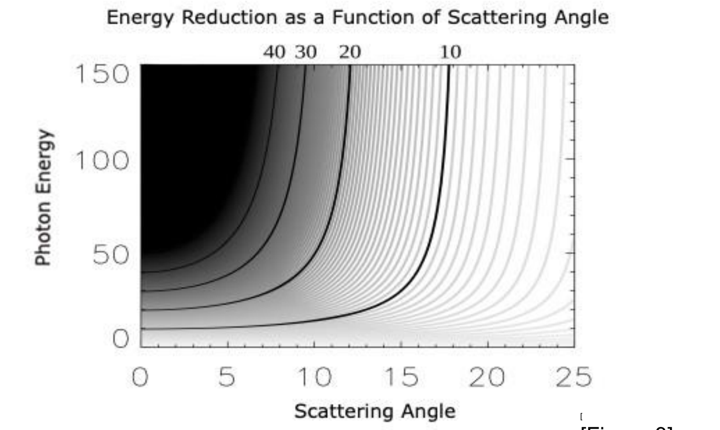


[Figure 1]

The end results showed that for an experimental setup with an initial incident angle of 30 degrees and photon energy bound conditions from 0-150 MeV, the average total cross section was approximately 1.19 barns. Figure 1 demonstrates the kernel density estimate for differential cross sections as a function of energy. The energy range chosen mimics the highly energetic conditions that induce a terrestrial gamma ray flash. Figure 2 shows the schematic of the physical environment the simulation was based on. The Monte Carlo simulation stochastically determined the scattering angle the point source struck on the target shown in Figure 2. The graph in Figure 3 is a visual demonstration of how Compton scattering effects TGFs - particularly the degree of energy reduction based on increasing scattering angles. The depicted contour curves are the photon energies in a TGF event after Compton scattering.



[Figure 2]



[Figure 3]

FURTHER RESEARCH

Moving forward from these results, we would determine the cross-sections for rayleigh scattering, positron-electron annihilation, and pair-production. Rayleigh scattering was one other event that was attempted to be simulated, however due to time and complexity could not be finished; moving forward Rayleigh scattering would be the next differential cross section for us to simulate for most of the work is done. Moving beyond these scatterers we would also look at pair production and annihilation, from our readings, these three processes also appeared to be relevant but given the time constraints we chose only to simulate four different types of scattering[4].

In the initial stages of our research phase, we attempted to use the Geant4 simulation toolkit; however, given the technical difficulties encountered and the time constraints, we subsequently changed the goal of our project. With more time, we would like to return to utilizing the Geant4 to verify our theory as well as incorporate multiple collision types into one simulation. A visual representation of each scattering event would also prove advantageous.

CONCLUSION

We calculated the cross-sections for Compton, Rayleigh, Elastic and Moller Scattering, to determine the relative probabilities of each of these collisions in a Terrestrial Gamma Ray flash. The relative probabilities we found were an order of magnitude from the accepted values of the the cross-sections for the scattering processes simulated. In our electron elastic scattering simulation we outlined the behavior of how a concentrated cluster of electrons would move and interact with both the air they are traveling through and other electrons, as well as finding a correlation between individual electron energy and the frequency of collision events. The results from the Compton Scattering simulation detail the total cross section within the probable energy range of a terrestrial gamma ray flash. This, in turn, can tell us approximately how many photons are scattered in a given circular region of the TGF environment. The possible error margins may revolve around the oversimplified environmental setup applied to extreme high energy events.

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