Correlation Studies of Cosmic Ray Flux and Atmospheric and Space Weather

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ABSTRACT

Since 1950’s there has been a growing interest of understanding the effects of cosmic ray radiation on the increase in average global temperature. Recent studies showed that galactic cosmic rays play a significant role in the formation of low cloud coverage and its consequent impact on the global temperature variation of the earth. A long-term measurement of the cosmic ray flux distribution at the surface of the earth has been established at Georgia State University. The current effort is focused on understanding the correlations between the
cosmic ray particle flux distribution and the atmospheric and space weather measurements.

In order to understand the observed atmospheric effects on cosmic ray flux, numerical simulations of cosmic muon and neutron flux variations at the surface of the earth have been carried out with varying air densities in the troposphere and stratosphere based on the Geant4 package. The simulation results show a remarkably good agreement with observations. The simulation results also show that the stratosphere air density variation dominates the effects on the muon flux changes while the density variation in the troposphere mainly influences the neutron count variation. This suggests that the long-term variation of muon flux could possibly direct us to a new path to understand the global climate warming trend.

INDEX WORDS: Cosmic rays, Global warming, Troposphere, Stratosphere, Geant4
CORRELATION STUDIES OF COSMIC RAY FLUX AND ATMOSPHERIC AND SPACE WEATHER

by

MATHES A.K. DAYANANDA

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Georgia State University

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CORRELATION STUDIES OF COSMIC RAY FLUX AND ATMOSPHERIC AND SPACE WEATHER

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DEDICATION

To my wife Prabha.
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LIST OF ABBREVIATIONS

• GSU - Georgia State University

• GCR - Galactic Cosmic Rays

• PMT - Photomultiplier Tube

• CAMAC - Computer Automated Measurement And Control

• NIM - Nuclear Instrument Module

• DAQ - Data Acquisition

• ADC - Analogue to Digital Converter

• PuBe - Plutonium-Beryllium

• CME - Coronal Mass Ejection

• IMF - Interplanetary Magnetic field

• GeV - gigaelectronvolt

• hPa - hectopascal

• mb - millibar
Climate is the pattern of variation in atmospheric temperature, pressure, humidity, wind and other meteorological parameters over a long period of time, ranging from months to thousands or millions of years. According to World Meteorological Organization, the classical period for averaging of these meteorological elements is 30 years. Studies have shown a rapid change of earth’s climate since the industrial revolution in the early 1900’s [1]. The average increase in earth’s temperature, referred to as global warming, is considered to be the primary forcing agent for climate variability. According to the NOAA (National Oceanic Atmospheric Administration) the average temperature of the earth has increased over the last 30 years despite no overall increase in the sun’s energy output. The temperature at the surface of the earth has increased by \( \sim 0.6 \, ^\circ C \) during the last century [2]. This rising temperature leads to changes in sea levels, rainfall patterns and can create catastrophic weather systems, crop failures, disease outbreak and impact on plants, wildlife and humans. In fact, recent studies showed a boost of daily crime rate in Dallas, Texas with temperature rises from low to moderate range (level off at temperature 80 \( \, ^\circ F \)), and a decreased rate when temperatures rise beyond 90 \( \, ^\circ F \) [3].

Currently there are two competing interpretations of the causes for the global warming: anthropogenic activities versus natural forcing. Since the industrial revolution, the amount of released greenhouse gas has been increased as the byproduct of various human activities. This drives a significant contribution to global warming. On the other hand, several natural factors such as large volcanic eruptions and changes in solar activity are believed to influence the climate of the earth [4]. Large volcanic eruptions such as eruption of mount Pinatubo in Philippine in 1991, can reduce the temperature of the earth’s surface [1].

It is well known that the sun plays an important role in the earth’s climate. Initially it
was believed that changes in solar irradiance drove the changes of earth’s climate. In 1801, William Herschel showed that the price of the wheat was directly connected to the sunspot numbers based on his observations [4]. In 1991, Friis-Christensen and Lassen showed the close correlation of solar cycle length with northern hemispheric temperature during the past 400 years [5, 6]. In 1993, Labitzke et al. found a correlation between 11-year variation of stratospheric pressures and solar activity [7]. According to the findings of Lean et al., there is a strong correlation between solar irradiance and surface temperature in the pre-industrial period from 1600 to 1800, implying that there is a predominant solar influence on climate change [8]. However, since 1970’s, they showed that the solar irradiance can account only for 0.1°C of surface temperature warming. This is too small to explain the current global warming.

Recent discoveries by Svensmark [9], suggested that climate variability is at least partially changed by the earth’s cloud cover which is influenced by galactic cosmic rays (GCR). GCR consists of very high energetic particles, primarily protons that flow into our solar system from far away in the galaxy. Some of them enter into the earth’s atmosphere and interact with atmospheric molecules and produce showers of secondary particles. GCR are the primary agent of producing ionization in the lower part of the atmosphere especially at 1 km to 35 km over the land and 0 to 35 km over the ocean [10]. This variation of ionization could potentially influence the formation of cloud cover in that region and consequently change the atmospheric temperature. Recent findings also show that cosmic ray flux is influenced by interplanetary magnetic fields and solar plasma wind [11, 12, 13], and earth’s atmospheric temperature and pressure [14, 15].

The Nuclear Physics Group at Georgia State University is working on long-term measurements of both cosmic ray muons and neutrons. The present effort is mainly focusing on understanding the correlations among cosmic ray flux, atmospheric and space weather observables. We hope that this study will eventually help to advance the predictive capabilities of state-of-science climate models.
1.1 Earth and space weather patterns

The American Meteorological Society, has shown considerable evidences for the current global warming [16]. Figure 1.1 shows the time profile of satellite based measurements of different atmospheric parameters. As shown in Fig. 1.1, not only the land surface temperature but also the temperature of sea surface, marine air temperature, troposphere temperature, ocean heat and humidity are all risen up. Observables that seen to be decreased are northern hemispheric snow cover, glaciers and arctic ice. Note that as shown in Fig. 1.1, the stratospheric cooling is subjected to an increase of greenhouse gases. These observations suggest the existence of global warming, since the industrial revolution in early 1900.

Sun is the major source of energy for the earth. Thus, variation of sun’s activity influence the earth climate. A well know historical example of a sudden climate change due to solar variability can be seen in the period between 1645 and 1715, which is known as the Maunder Minimum [17]. As shown in Fig. 1.2 during this time period there was an almost complete absence of sunspots implying that little solar activity. The Maunder Minimum coincided in time with an era of colder climate known as the little ice age, which is leading us to believe that there is a link between solar activity and earth temperature.

1.2 Understanding weather fluctuations

The climate change that we have experienced over the last 150 years is due to some combination of natural and human influences. Figure 1.3 shows the simulated results of temperature variations due to anthropogenic and natural factors [18]. According to these simulation models, the observed temperature pattern matches closely with the temperature changes due to the combined effects of human and natural causes.

Some possible sources of human induced climate variations are changes in greenhouse gas concentrations in the atmosphere, changes in aerosol particles from burning fossils fuels and changes in the earth’s surface reflectivity (albedo). Among these causes, the effect of greenhouse gases on rising temperature is dominant, especially the contribution from carbon
Figure (1.1) (color online) Some evidences for global warming. Note that the stratospheric cooling is subjected to an increases of greenhouse gases [16].
dioxide (CO$_2$) gas [1]. Figure 1.4 shows the changes of three greenhouse gases CO$_2$, methane (CH$_4$) and nitrous oxide (N$_2$O) which trap the outgoing long wave radiation and consequently increase the temperature of the earth [1]. As shown in Fig. 1.4 the amount of greenhouse gases released into the atmosphere has significantly increased since the industrial era.

In addition to purely anthropogenic drivers of climate change, there are natural processes such as volcanic eruptions and solar changes which can lead to a change in the climate system. In general large volcanic eruptions cool the earth by releasing aerosols into the stratosphere which consequently increase the absorption and reflection of incoming shortwave radiation. The cooling effect caused by volcanic activities can last for 2 to 3 years [4].

The link between earth climate and solar irradiation has been known for more than 200
Figure (1.4) (color online) Atmospheric concentrations of three greenhouse gases CO$_2$, NH$_3$ and N$_2$O over the last 2000 years [1].

years. Some findings show a strong correlation between solar irradiation and earth climate before the year of 1900 [8, 9]. However, since the industrial era, this correlation is not very significant, implying that changes of solar irradiation alone cannot explain the current global warming. Studies done by Svensmark [9] and others [19, 20], on the other hand, indicate that galactic cosmic rays may play a significant role in the temperature variation of the earth. It is shown that an 11-year average of northern hemispheric land and marine temperature is closely correlated with the measured variation in the cosmic ray flux [9]. Furthermore, there exists a causal relationship between GCR and low cloud coverage (< 3.2 km) which suggests that the formation of the low clouds is influenced by the atmospheric ionization produced by GCR [10]. Clouds play a significant role in the earth’s radiation budget by reflecting the incoming short waves (cooling) and trapping the outgoing long waves (heating). This causal relationship indicates that the variation in GCR may indirectly influence the earth’s temperature. Recent studies estimated that net cooling effect from global cloud cover is $\sim -27.7$ W/m$^2$ [10]. Furthermore, results of satellite cloud measurements and numerical cloud modeling show that net radiative force is changed by $\sim 0.5$ W/m$^2$ for a 1% change in the total cloud cover of the earth [9]. The recent findings also indicate that there is a correlation between cosmic rays and ozone depletion, especially in the polar ozone over Antarctica [21]. The low energy electrons produced by the cosmic radiation, react with
chlorofluorocarbons and produce Cl$^-$ ions. The ozone atoms in the atmosphere will then be destroyed as a result of photo-dissociation of the Cl$_2$ [21]. A long-term monitoring of cosmic ray flux variations allows us to independently verify the ozone-thinning effects due to cosmic ray radiations. Figure 1.5 shows causal relationships of cosmic rays with low cloud coverage [10] and total ozone [21].

Figure (1.5) (color online) Left plot shows the time profiles of percentage variation of low (> 680 hPa) cloud coverage (blue) with percentage variation of cosmic rays (red) [10]. Right plot shows the time profiles of percentage variation of total ozone (red) with percentage variation of cosmic ray intensity (magenta) [21].

Since there is a true impact of cosmic rays on climate changes, it is imperative to find out the factors that influence cosmic ray flux. Understanding these factors can lead us to quantify and predict the climate change due to cosmic rays. Observational evidences show that the low energy cosmic ray particles follow a 11-year variation with solar cycle.

The sun also has a long term, regular pattern of change, in addition to its sudden changes of activities. This pattern is called the sunspot cycle and the typical single cycle lasts for about 11-years as shown in Fig. 1.6. The shortest cycle can be 8 years while the longest lasts for 14 years. The number of sunspots during a cycle is a good indicator of solar activities. Solar minimum represents the period of time when sunspot numbers are relatively low while solar maximum represents the period of time when sunspot numbers are relatively high. The location of the sunspot depends on the solar activity in a cycle. Generally, they appear in the mid latitudes during the solar maximum and sunspots move closer to the equator as the sun reaches to solar minimum. At solar minimum there can be a
complete absence of sunspots. The number of sunspots is very important, because they are the visual evidence of intense magnetic activities in the sun. Recent studies done by NASA show that these magnetic fields are responsible for originating solar flares and coronal mass ejections [22]. The coronal mass ejection is a massive eruption of solar plasma wind and magnetic fields from the sun into the space, which can influence the earth and other objects in the solar system. The observation of 11-year solar cycle is due to the flipping of polarity of sun’s magnetic field. It is known that every 11-years the sun’s poles flip: south pole becomes north and north pole becomes south. Thus, every 22-years the poles return to the cycle’s starting position. The complex movement of magnetic fields inside the sun drives this flip. Figure 1.6 shows the anti correlation of long-term variation of cosmic ray neutrons and muons with sunspot number variation [9]. Figure 4.8 shows the short term modulation of cosmic ray muons measured at GSU, due to a coronal mass ejection.

![Figure 1.6](image_url) (color online) The variation of cosmic ray flux and sunspot numbers. Top curve is cosmic neutron flux variation measured in Climax, Colorado while middle curve is annual mean variation of cosmic muon flux. The bottom curve is the relative sunspot number [9].

While cosmic rays are modulated by space weather, there are influences of earth atmosphere on cosmic ray flux too. Temperature, pressure, and air density as well as diurnal
and seasonal variations determine the number of cosmic rays actually reaching the surface of the earth. Over the past decades, quite a few studies reported on the correlations between the earth weather and cosmic ray flux [9, 10, 17, 21, 23]. Cosmic ray neutron flux variation shows a strong anti-correlation with the atmospheric pressure. Figure 1.7 shows the neutron daily counts percentage variation (black) and pressure (red) measured at the Sodankyla Geophysical Observatory in Oulu, Finland in 2012 [24]. The solid lines are two-week moving averages.
by the IceCube Neutrino Observatory [25] and others [26].

This dissertation is organized as follows. **Chapter One** outlines the observations of the earth and space weather patterns and their corresponding physical mechanism. Details of primary and secondary cosmic ray distributions and cosmic ray particle detection methods are described in **Chapter Two**. An overview of cosmic ray particle detectors at Georgia State University and detailed discussion of the liquid scintillator detector are provided in **Chapter Three**. Data analysis and results are presented in **Chapter Four**. Modeling of the earth atmosphere and simulation results are provided in **Chapter Five**. Finally, conclusions are presented in **Chapter Six**.
CHAPTER 2

COSMIC RAYS

In 1936 Victor Hess was awarded the Nobel prize for the discovery of cosmic rays. About one hundred years ago in 1913, Hess measured atmospheric radiation levels at different altitudes and discovered that cosmic rays are the main source for variation of atmospheric radiation levels. Hess used several electroscopes for his radiation measurements made by flying in a balloon to an altitude about 6 km. Figure 2.1 (a) and (b) show the results of his study of cosmic radiation. As shown in Fig. 2.1, he found that the intensity of radiation levels increases with altitude. Some experiments done in later years confirmed that cosmic rays consist at least partly of charged particles since they are affected by the earth’s magnetic field [27, 28]. In 1936, Pfotzer showed that the intensity of cosmic radiation levels does not continuously increase as altitude increases. It reaches its maximum at an altitude of about 15 to 20 km and after that the intensity of the radiation decreases rapidly. The altitude of the maximum radiation intensity is called the Pfotzer maximum [29]. Figure 2.1 (c) shows the results of the Pfotzer’s measurement. Note that the altitude of Pfotzer maximum varies with geomagnetic latitude and the solar cycle.

Cosmic rays are high-energy particles consisting of 90% of protons, 9% of helium and rest with heavy nuclei [31]. Cosmic rays can have a wide range of energies, from around several GeV to $10^{20}$ eV. These particles impinge on the top of the atmosphere at a rate of about 1000 per square meter per second [32]. Upon entering the earth atmosphere, cosmic particles interact with atmospheric molecules and produce showers of secondary particles. This process leads to observe different radiation levels in the atmosphere as cosmic rays propagate through the air.
Figure (2.1) Figures (a) and (b) show the results of Vector Hess’s measurements in 1913 [30]. (c) shows the results of Pfitzer’s measurement in 1936 [29]. Curve B is the total cosmic ray flux variation as a function of altitude in arbitrary units. Curve A is the variation of cosmic ray counting rate as a function of average pressure after correcting for accidental coincidences.
According to their sources of origin, cosmic rays can be categorized into two groups; (1) galactic cosmic rays (GCR) - particles coming from outside the solar system and (2) solar cosmic rays - particles associated with solar flares and other energetic solar events. The majority of the cosmic particles come from outside the galaxy [33, 34], such as from active galactic nuclei, quasars or gamma ray bursts.

Very recently NASA’s Fermi Gamma-ray telescope, has revealed that a significant fraction of cosmic rays originate from supernova remnants [35]. This idea was first proposed by Enrico Fermi (1949). This does not mean that particles gain energy from the supernovae explosion itself. Cosmic ray particles are accelerated by the remnants of the supernova explosion such as expanding clouds of gas and magnetic fields that can last for thousands of years. The particles that are confined by a magnetic field move around randomly and they gain about 1% of their original energy with each round trip. Finally the particles escape the cloud with nearly the speed of light after a dozen to hundreds of random crossings.

The sun is also a sporadic source of cosmic rays. Solar cosmic rays are produced from solar flares and other disturbances in the photosphere of the sun [34]. In general the solar cosmic rays accompanied by solar flares have a wide energy range of MeV to BeV. The first solar cosmic ray event with BeV energy was observed by Forbush in 1942 [34]. There are two processes for the creation of solar energetic particles: from high energy solar flares originating during magnetic field re-connection or by shock waves associated with coronal mass ejections. Although solar flares occur very frequently in the sun, only few of them are energetic enough to produce solar cosmic rays. Currently it is possible to find minor increases in the cosmic ray particles outside the earth’s magnetosphere with satellite-borne instruments. Even though few solar cosmic rays are produced, understanding them is important, since they are hazardous to lives in outer space. Once the cosmic rays are generated from the solar flares, they are emitted into the space and some eventually reach the earth. During their flight, these cosmic rays experience disturbances from interplanetary magnetic fields. Therefore, the time profile of solar cosmic rays flux can be used to study the properties of interplanetary space.
The galactic cosmic ray flux is modulated by solar activity. It is observed that the average time duration between the minimum and the maximum solar activity periods is about 11-years. Thus an 11-year galactic cosmic ray variation pattern is observed as shown Fig 1.6. Furthermore galactic cosmic rays are modulated by sporadic solar activities such as coronal mass ejections. This type of a cosmic ray modulation is called a Forbush decrease event. Observational studies show that the stronger the interplanetary magnetic field and solar wind plasma speed, the lower the cosmic ray intensity records [12, 13]. Solar modulation effects decrease with increasing energy of the galactic cosmic particles, and it is not very significant for particles with energies above 15 GeV [2]. The solar modulation effects are further discussed in details in Chapter 4. As cosmic rays travel through magnetic fields in the heliosphere, their direction is changed, because they carry an electrical charge. By the time they reach the earth, their paths are completely obscure and provide very little information for us to trace their sources. Hence, scientists usually use indirect methods to find their origin.

2.1 Primary cosmic ray distribution

Cosmic rays bombard the earth’s atmosphere continuously and the maximum number of interactions occur between altitudes of 15 km and 20 km. Once cosmic rays interact with atmospheric nuclei, they undergo nuclear reactions, loose energy and generate showers of secondary particles that will also continue interactions with the atmosphere as they propagate towards the ground. The primary cosmic rays are nearly isotropic at most energies, because of their diffusive propagation in the galactic magnetic field [36]. A variety of methods have been used to measure the spectra of the primary cosmic rays, such as particle detectors in satellites, balloonborne detectors, measurements of secondary particles (muons and neutrons) detectors at the earth’s surface. Figure 2.2 shows the major components of primary cosmic rays for energies greater than 2 GeV/nucleon [36].

The flux of the cosmic rays at GeV energies is about 1 particle/$m^2/second$ as shown in Fig. 2.3. The flux is then decreased to 1 particle/$km^2/year$ as energy increases towards
to $10^{20}$ eV. As shown in the Fig. 2.3, energy spectrum of the primary cosmic rays can be described by the power law function $dN/dE \sim E^{-\alpha}$, where $dN/dE$ is the differential flux, $E$ is the energy per nucleon, and $\alpha$ is the differential spectral index of the cosmic ray flux. The $\alpha$ is approximately equal to 3.0, implying that above a given energy, the intensity of cosmic rays will be decreased by a factor of 100 for each decade in energy [37]. The following formula can be used to find the intensity of the primary nucleons in the energy range from
several GeV to 100 TeV [36].

\[
I_N(E) \approx 1.8 \times 10^4 \left[ \frac{E}{1 \text{ GeV}} \right]^{-\alpha} \frac{\text{nucleons}}{m^2 \text{ s sr GeV}},
\]  

(2.1)

where \( E \) is the energy per nucleon including the rest mass energy and here \( \alpha \) is 2.7.

The energy spectrum shown in Fig. 2.3 is a smooth curve below the energy \( \sim 10^{15} \text{ eV} \) and it is believed that cosmic rays with these energies originate from supernova explosions. The \( \alpha \) is equal to 2.7 in this energy range. The primary particles in this energy range are modulated by the magnetized plasma which are ejected from the sun. These solar wind particles usually decelerate and partially sweep out the lower energy GCR from the inner solar system. The intensity of GCR with the energy below 15 GeV, shows a significant anti-correlation with solar activities, such as, Forbush decrease events and 11-year solar cycle. Moreover, these GCR are typically influenced by the geomagnetic field. Therefore, rate of flux of GCR in the GeV energy range typically depends upon both location and time.

There are two noticeable kinks appearing just above \( 10^{15} \text{ eV} \) and \( 10^{18} \text{ eV} \) energy levels, where \( \alpha \) changes approximately from 2.7 to 3.1. These features of the spectrum are called the \textit{knee} and \textit{ankle}, respectively. Cosmic rays with energies above \( 10^{18} \text{ eV} \) are referred to as ultra high energy cosmic rays. The origin of these ultra high energy cosmic rays is still a mystery. The flux of the primaries in this energy range is extremely low, of the order of 1 \( \text{particle/km}^2/\text{century} \). Therefore the study of these cosmic rays needs detectors with very large acceptance. Pierre Auger Observatory is one of the experiments designed to study such a high energy particles [39].

2.2 Secondary cosmic rays

As primary cosmic rays undergo interactions with nuclei of the upper atmosphere, showers of new particles are produced that are generally called secondary cosmic rays that travel through the atmosphere to the earth’s surface. Some secondary particles, in turn, collide with other lower atmospheric nuclei and create even more secondary cosmic rays. All parti-
Figure (2.3) (color online) The primary energy spectrum of cosmic rays. The blue straight line and red curved line represent the theoretical power-law, and experimental measurement, respectively [38].

...cles are created within a fraction of a second. Eventually, only a small fraction of particles reach the ground, because they lose energy due to interactions with the atmosphere on their way. Figure 2.4 shows the typical components and branches of the secondary cosmic rays created in the atmosphere. Cascades of secondary cosmic rays can be divided into three groups as shown in the Fig. 2.4: (1) hadronic component (2) muonic component, and (3) electromagnetic component.

The hadronic component consists of protons, neutrons and meson particles of pions and kaons produced during the collision between primary cosmic rays and atmospheric nuclei. These hadrons can have a chance of further interaction with atmospheric nuclei. Mesons can decay into high energy muons which can penetrate to detectors deep underground. About 99% of charged pions decay into muons and their neutrinos while neutral pions decay into two gamma rays. According to Fig. 2.5, muons and their neutrinos are the most abundant
Figure (2.4) (color online) Typical components and branches of the secondary cosmic rays created in the atmosphere. The figure is from the reference [38].

particles at the ground level.

As a rule of thumb, the intensity of muons at the surface of earth is 1 particle $cm^{-2}min^{-1}$. The mean energy of muons at ground level is $\sim 4$ GeV. Typically, muons are produced at an altitude of $\sim 15$ km by meson decay and lose about 2 GeV mainly due to ionization before they reach the ground. In general, muons lose energy by ionization and three radiative processes: (1) bremsstrahlung, (2) production of $e^+e^-$ pairs and (3) photonuclear interactions [36].

The overall angular distribution of muon particles follow the $\cos^2 \theta$ distribution. Figure 2.6 shows the sea level muon energy spectrum for two angles, $\theta = 0^\circ$ and $\theta = 70^\circ$. As shown in Fig. 2.6, the flux of low energy muons is less at large angles ($\theta = 70^\circ$) than that of small angles ($\theta = 0^\circ$) while the flux of high energy muons is higher at large angles. These features can be understood since at large angles, low energy muons tend to decay before they reach the ground, resulting in a lower low energy muon count rate records at large angles. On the other hand, high energy pions tend to decay into muons before they interact with
Figure (2.5) (color online) Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq.2.1. The figure is from the reference [36]

air and consequently, the flux of higher energy muons at large angles increases.

As shown in Fig. 2.4, the electromagnetic component consists of electrons, positrons and photons. The cascade of particles of the electromagnetic component are mainly initiated by decays of charged and neutral mesons [36]. When a gamma ray which is a decay product of neutral pions, passes the vicinity of the nucleus of an atom, it produces an electron-positron pair. A gamma ray does not carry any charge. However, due to its electromagnetic nature, the gamma ray interacts with the electromagnetic field of the nucleus and forms an electron-positron pair. The minimum energy required for this pair production is about 1 MeV, which is equivalent to twice of the rest mass energy of an electron. The excess energy of the photon
is then converted into kinetic energy of the electron and the positron. As shown in Fig. 2.4, these fast moving electrons and positrons can emit gamma rays when they move close to another nucleus. The cycle of pair production and gamma ray generation will cease when the energy of the electron and positron is too small for the radiation process. These slow electrons will eventually come to rest once their energy is lost by the ionization process.

### 2.3 Cosmic ray particle detection methods

All particle detectors work on the same basic principal. Once the particle comes into the detector, part or all of the energy of the particle is transferred to the detector material and the detector then converts that energy into readable signal. In other words, the particle detection is done through the energy loss of the particle when it traverses the detector material. The energy lost by the particle will produce ions, excited molecules, free radicals, scattered or
newly formed particles and change the energy of the molecules (vibrational, rotational) [40]. The main interactions of the charged particles with the matter are ionization and excitation and bremsstrahlung energy losses. In order to detect neutral particles, a charged particle must be produced during the interaction between neutral particles and the detector material. These charged particles are then detected through their characteristic interaction process [41]. As an example, in the case of detection of photons, electrons are produced in processes including the photoelectric effect, Compton scattering and pair production.

Currently there are several detection techniques available for cosmic ray studies. Based on the goal of the research, these studies can be divided into two main groups: direct experiments and indirect experiments. The direct experiments focus on studies related to the primary cosmic ray distribution while indirect experiments focus on studies related to the secondary cosmic ray distribution.

2.3.1 Direct experimental methods

As shown in Fig. 2.7, the direct experiments are typically carried out using satellite and balloon based instruments at higher altitudes. The main objectives of direct experiments are to investigate charge, direction, composition and energy spectra of the cosmic rays generally beyond the knee. The PROTON is an example for a satellite based experiment which observed cosmic ray spectra above energy of few TeV using ionization calorimeter and scintillators [42]. On the other hand experiments such as ATIC [43], JACEE [42], RUNJOB [42, 44], TRACER [45, 46] and others [47] are some experiments designed to carry out direct cosmic ray measurement using balloon-borne instruments. In fact, the ATIC experiment is designed to investigate the charge, composition and energy spectra of the cosmic rays over the energy range from several GeV to near 100 TeV. ATIC was initiated in December 2000 and has launched three successful long duration balloon flights from McMurdo, Antarctica. JACEE and RUNJOB experiments focus on the interactions and energy spectra of cosmic ray nuclei at the energies above 1 TeV [42, 44]. TRACER is developed to measure heavy cosmic ray nuclei \( 8 \leq Z \leq 26 \) in the energy range of \( 10^{13} \) to \( 10^{15} \) eV per nucleus around the pole.
regions [48].

![Diagram of cosmic ray detection methods](image)

Figure (2.7) (color online) Schematic diagram of cosmic ray detection methods.

2.3.2 Indirect experimental methods

As shown in Fig. 2.7, the indirect measurements are carried out generally on the ground or in the deep underground. These experiments mainly observe the secondary cosmic ray particles in order to study high energy primary cosmic rays, cosmic ray lateral and longitudinal distribution, cosmic ray neutrinos and correlation studies of cosmic ray flux with atmospheric and space weather etc. As shown in Fig. 2.7, one of the detection methods of secondary cosmic particles is the Cerenkov light detection. When a charged particle propagates with a velocity greater than the speed of light in the medium, the excited atoms in the vicinity of the particle emits light, called Cerenkov light, as they go back to the ground state. This Cerenkov light is in the forward direction of the particle motion and can be collected
onto photosensitive detectors. Another indirect technique is the detection of fluorescence light which is produced when cosmic ray charged particles interact with atmospheric nitrogen and cause it to emit ultraviolet light via the process of fluorescence. The fluorescence detectors are capable of detecting energy of air showers which help to find the energy of the primary cosmic ray. Pierre Auger observatory uses both of these observation methods to investigate origin and nature of cosmic of rays by observing their composition, arrival direction and energy spectra [39].

Detection of air showers with arrays of ground based detectors is another technique in indirect experiments. KASCADE [49], Tibet air shower array [50] and AGASA [51] are well known experiments in this category. These experiments typically consist of more than hundred of detectors(scintillators, calorimeters, proportional counters) placed over hundred of meters on the ground. The objectives of these studies are to understand the energy spectra and composition of primary particles around the knee region, study the configuration and variation of the solar and interplanetary magnetic fields, anistropy of galactic cosmic rays etc [49, 50, 51, 52].

Ground based experiments such as Oulu [24], ASEC [14], WILLI [53] focus on correlation studies of space and earth’s atmospheric weather patterns with the variation of cosmic ray neutron and muon flux. The Nuclear Physics group at Georgia State University is working on the long-term measurements of cosmic ray secondary flux distribution. This study includes the simultaneous measurements of cosmic ray muons and neutrons at the surface of earth. The objective of the project is to study the correlation between secondary cosmic ray flux variations and earth’s atmospheric and space weather patterns. Initially cosmic ray measurements are done only in the downtown Atlanta area, whereas at present the group has expanded its cosmic ray detector network and initiated data collection in China.
The Nuclear Physics Group at Georgia State University has built multiple generations of cosmic ray detectors. Four of the detectors are sensitive to cosmic muons and one liquid scintillator detector is sensitive to both cosmic muons and neutrons. Three of the detectors are currently running at downtown Atlanta and one is operating at the Hard Labor Creek Observatory, about 50 miles east of Atlanta. These detectors have been taking data since 2009. In 2011, a two paddle scintillator detector was installed at the Lanzhou University China in order to study dynamical cosmic ray flux and weather information on a global scale.

### 3.1 Liquid scintillator detector

In this study most of the analysis was done using the data collected by the liquid scintillator detector. Currently the liquid scintillator detector is running at GSU (33°44′56″N, 84°23′17″W). This liquid scintillator detector is named as Pot detector. The base of the Pot detector is a three-gallon of stainless steel stock pot filled with 10 liters of NE213 liquid scintillator. The diameter of the base of the Pot is 30.5 cm and the height of the detector is about 30 cm. The density of the liquid scintillator in the Pot is 0.0901 g/cm³, which has a hydrogen to carbon ratio of 1.287 [54]. Figure 3.1 shows the detector taking measurements in the 9th floor of the Petit building downtown Atlanta. Before it was moved to its present location in 2010, the Pot was used to take measurements in the fifth floor of the Natural Science Center (NSC) building. The Pot detector is sensitive to both cosmic ray muon and neutron particles. As shown in Fig. 3.1, two scintillator paddles (31 cm × 26 cm) are placed on the top and the bottom of the Pot as veto detectors. Since these paddles are only sensitive to cosmic muons, data from the paddles can be used to filter out the cosmic neutrons recorded in the Pot detector. However using the current setup it is not possible to
Figure (3.1) Pot detector is taking measurements in the 9th floor of the Petit building downtown Atlanta. Two scintillator paddles are installed top and bottom of the Pot to use as veto detectors.
Table (3.1) The list of CAMAC and NIM modules used in the DAQ system of the Pot detector

<table>
<thead>
<tr>
<th>Module</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>High voltage supplier (Tennelec TC 952)</td>
<td>Supply high voltage for PMTs</td>
</tr>
<tr>
<td>Discriminator (Ortec CF8000)</td>
<td>Discriminate signals</td>
</tr>
<tr>
<td>Coincidence unit (Lecroy 365AL)</td>
<td>Get coincident signal</td>
</tr>
<tr>
<td>ADC (Ortec AD811 ADC)</td>
<td>Measure ADC spectra of Pot PMTs</td>
</tr>
<tr>
<td>ADC (Lecroy 2249A ADC)</td>
<td>Measure ADC spectra of Paddle PMTs</td>
</tr>
<tr>
<td>Pre amplifier</td>
<td>Amplify dynode signals</td>
</tr>
<tr>
<td>Amplifier (Ortec 485)</td>
<td>Amplify dynode signals</td>
</tr>
<tr>
<td>Gate and delay generator (Ortec)</td>
<td>Generate gate signal for ADC measurements</td>
</tr>
<tr>
<td>GPIB interface (Lecroy 8901A)</td>
<td>For GPIB communication</td>
</tr>
</tbody>
</table>

filter out the cosmic neutrons since these paddles have less acceptance than the pot detector. Figure 3.2 shows the data acquisition (DAQ) system of the Pot detector.

As a cosmic particle propagates through the liquid scintillator in the Pot, molecules in the vicinity of the track will be excited. The excited molecules will emit visible light during the de-excitation process. These light signals will then be collected by the two photomultiplier tubes (PMT) installed on top of the Pot. The two PMTs convert the collected light signals into the detectable electric signals. Since PMTs generate output signals due to its noise, two PMTs are used in the current detector setup in order to extract a true signal by obtaining a coincidence signal. That is if both of the PMTs produce output signals within a very close time window (nano second level) then, the signal is considered as a true record of a cosmic ray particle that traversed in the material.

The data acquisition system of the Pot consists of CAMAC (Computer Automated Measurement And Control) and NIM (Nuclear Instrument Module) based electronic modules as shown in Fig. 3.2. Table 3.1 summarizes the list of modules currently used in the DAQ system. In addition, a PC is connected through GPIB card to communicate with the modules in the CAMAC crate.

Both anode and dynode signals from the PMT are used in the current experimental setup. The anode signal is used to trigger the system while dynode signal is used to measure the energy deposition by cosmic particles. Typical anode and dynode signals from the Pot
Figure (3.2) Data acquisition system of the Pot detector. DAQ is installed on the back side of the Pot detector cart which is capable of moving easily.
Figure (3.3) Typical anode (left figure) and dynode (right figure) signals from the Pot detector.

detector are shown in Fig. 3.3.

The supplied high voltages for two PMTs are $-1850$ V and $-2060$ V. Figure 3.4 illustrates the schematic diagram of the experimental setup. As the first step, the anode signal is fed into the discriminator module to filter out signals produced by the detector noise. Currently the threshold value set in the discriminator module is $-5$ mV. That is the discriminator module produces a logic output signal for any input signal greater than the $-5$ mV. The current threshold and high voltage values of PMTs were determined by after analyzing of high voltage and threshold scans, which are discussed in detail in section 3.1.1. As shown in Fig. 3.4 the coincidence unit will produce a logic signal for the two input logic signals from the discriminator. The logic coincidence signal (green) produced for two discriminator output signals is shown in Fig. 3.5.

This coincidence output signal is used to set the gate for dynode signal ADC measurements. However, as shown in Fig. 3.5 the width of the coincidence signal is 60 nS which is not sufficient to use as a gate signal for dynode signal ADC measurements. Therefore, a delay gate generator is used for making a gate signal for the ADC (Ortec AD 811) module, which measures the energy of the dynode signals from the PMT. Figure 3.6 shows the gate signal (green) produced by the delay gate generator for dynode signal ADC measurements.

The ADC measurement in the veto detectors is done at this time. The gate signal is supplied by the coincidence module for this measurement as shown in Fig. 3.4. This veto
Figure (3.4) (color online) The schematic diagram of the Pot detector setup.

Figure (3.5) (color online) The logic coincidence signal (green) produced for two discriminator output signals. The yellow and magenta color signals are output logic signals from the discriminator module.
Figure (3.6) (color online) The gate signal (green) produced by the delay gate generator for ADC measurements. Dynode signals of yellow and magenta color were from PMT1 and PMT2 respectively.

measurement is used to identify the output signals produced in the Pot due to cosmic ray muons. Note that each time two PMTs in the Pot detector produce a coincidence signal that event will be recorded in the data file with the time stamp and four ADC values.

Figure 3.7 shows the DAQ control window created using the LabVIEW software for the communication between the PC and modules in the CAMAC crates. The controllers on the left allow the user to select slots and channel numbers of the two ADC modules while the plots on the right side of the window display the four histograms for signal counts from the four PMTs.
Figure (3.7) (color online) DAQ control window of the Pot detector made by using the LabVIEW software. Four histograms display ADC measurements of the Pot and the veto detectors. The controllers on the left allow the user to select slots and channel numbers of the two ADC modules.
3.1.1 Detector construction

One should optimize the high voltage for the PMT and the threshold in the discriminator in order to do measurements from a detector. Without knowing the proper values for these two settings, the detector will not be able to take meaningful data. For instance, if the supplied voltage of the PMT is too high or discriminator threshold is too low, then too much of noise will be included in the measurement. On the other hand, if the high voltage is too low or threshold is too high, then the detector will not be able to work with maximum efficiency. Therefore it is necessary to optimize the high voltage and threshold values for both PMTs and the discriminator module used with the Pot detector. Once these values are set in the detector setup, the output (measured counts) will be independent of both supplied high voltages of the PMTs and the discriminator thresholds. Figure 3.8 shows a schematic diagram of the experimental setup used for scanning the suitable high voltage and the threshold values.

A Lecroy 2551 scaler module was used to count the cosmic ray particles traversing the
Pot. In fact, one minute average count was taken into account by varying the high voltage of PMT and threshold value of the discriminator. The high voltage was varied from $-1750$ V to $-2350$ V with the step size of $-50$ V while the threshold was changed from $-5$ mV to $-30$ mV with $-5$ mV step size. For each case data was collected for a 5 minute time interval. A LabVIEW program was used to communicate with the scaler module. Results are shown in Fig. 3.9 and Fig. 3.10.

It is clearly seen in both Fig. 3.9 and Fig. 3.10 that the number of hits per minute increases with increasing high voltage while it decreases with increasing threshold values. In order to find the proper high voltage and threshold values, one should carefully identify the plateau region of both figures. That is the region where the response of the detector to cosmic rays is independent of both the supplied high voltage and discriminator threshold. As show in Fig. 3.9, this plateau region of PMT1 lies in the voltage between $-1750$ V and $-1950$ V while for PMT2, it lies in the voltage region of $-1700$ V to $-1850$ V. Hence, $-1850$ V is selected as the proper high voltage for both PMTs. Note that the number of hits per minute is lower in the PMT2 compared to that of the PMT1. Based on the results shown in Fig. 3.10, it is hard to find a plateau region for threshold values. From $-10$ mV to $-15$ mV region can be approximately considered as a plateau region. However, it was decided to set the threshold value at $-5$ mV (lowest threshold setting) for measurements, since there is no significant count difference between $-5$ mV and the region of $-10$ mV to $-15$ mV.
Figure (3.9) (color online) High voltage scan of the PMT1 (top figure) and the PMT2 (bottom figure) of the Pot detector.
Figure (3.10) (color online) Threshold scan of the PMT1 (left two figures) and the PMT2 (right two figures) of the Pot detector. Two figures in the bottom row show the threshold scan for the high voltages from $-1700$ V to $-2000$ V.
The Pot detector setup is capable of measuring the ADC spectra. ADC stands for the analogue to digital converter and it indicates the amount of energy deposited by the particle in the detector material. The energy deposited by the particle is proportional to the area of the corresponding PMT signal (Fig. 3.6). Generally the dynode signal of a PMT is used to get the ADC spectrum, since the dynode signal is more precise than the anode signal. It is imperative to have this ADC information to distinguish between charged and neutron particles measured in the Pot detector. Currently the ADC spectra of both the Pot and the two paddles are recorded. As mentioned earlier, scintillator paddles are only sensitive to charged particles. Therefore, by analyzing both the paddle and the Pot ADC spectra, it is possible to identify some charged particle signals in the Pot. Note that the electronics of Pot are triggered by the two PMT signals in the Pot, and that is two fold coincidence. This means that when the coincidence signal is present, the computer records the ADC values of the paddle PMTs together with that of the PMTs of the Pot. The PMT installed in the Pot gives out both dynode and anode signals while only an anode signal can be taken from the paddle PMT. Figure 3.11 shows the typical ADC spectra of the two PMTs in the Pot.

Four different ADC spectra in Fig. 3.11 show the energy deposition by different particles. The top black curve represents the ADC spectrum of all particles which came into the Pot. The diagram in Fig. 3.12 helps to understand the realistic situation of particles passing through the Pot detector setup. The magenta curve in Fig. 3.11 represents a charged particle passing through all three detectors. This situation is displayed in Fig. 3.12 (a).

To identify the signal from a charged particle, ADC spectra of paddles (Fig. 3.13) can be used. Any peaks below an ADC value of 10 shown in Fig. 3.13, represent noise of the ADC module. This ADC value of 10 is called the pedestal value. Hence, any ADC value higher than the pedestal, indicates the presence of a charged particle.

The green curve in Fig. 3.11 indicates the energy spectrum of charged particles passing through one of the paddles and the Pot. Figure 3.12 (b) displays the situation. The blue ADC spectrum in Fig. 3.11 represents neutrons and charged particles passing only through the Pot but not through either of the paddles as displayed in Fig. 3.12 (c). Note that the
Figure (3.11) (color online) ADC spectra of PMT1 (top) and PMT2 (bottom) of the Pot. Color code of ADC spectra are as follows. Black: all particles without applying any cuts, magenta: charged particles pass through all 3 detectors, green: charged particles pass only through one of the paddles and the Pot, blue: neutrons and charged particles pass only through the Pot.

Peak appearing around the ADC value of 2000 in Fig. 3.11 is due to overflow of the ADC module. This AD811 ADC module is an 11 bit module and consequently, the maximum value that can be measured is 2047.
3.1.2 Detector sensitivity to neutrons

As mentioned previously, the Pot detector is sensitive to both cosmic ray muons and neutrons. To test the detector sensitivity for neutrons, the detector calibration was done at Georgia Institute of Technology with a 1 Curie Plutonium-Beryllium (PuBe) source. The energy spectrum of the PuBe source has three different neutron peaks, with energies of $\sim 3$ MeV, $\sim 5$ MeV and $\sim 8$ MeV as shown in Fig. 3.14 [55].

Three different experimental setups were used during the detector calibration; (1) with the PuBe source, (2) with the PuBe source and plastic sheets and (3) without the source for a background test. Each data set consists of $\sim 16$ hours of data. Figure 3.15 shows cosmic count variation during the background test. Each bin in Fig. 3.15 shows the average count per 10 minutes. The count variation during the background test has no significant peaks or dips except for the very first bin. Hence this data set can be used to remove the background counts in other two data sets.

Figure 3.16 (a) shows the detector setup used for the measurement done with the PuBe
source. The source was placed 50 inches away from the Pot and collected data for 16 hours. ADC energy spectra of both PMTs were analyzed. The neutron spectrum is shown in Fig. 3.17 in green after subtracting the background and a clear neutron peak around the ADC value of 22 can be seen in the ADC spectra of both PMTs of the Pot. Note that the two data sets (background data set and data set taken with PuBe source) have the same duration. This confirms that the Pot is sensitive to low energy neutrons and it can be seen in the ADC spectra of both PMTs. It is interesting to see how the detector responds if a plastic sheet is placed in between the source and the Pot. The purpose of using the plastic sheet is to slow down the neutrons coming from the source. Figure 3.16 (b) illustrates the detector setup with plastic sheets. Plastics are hydrogen rich material. Since the size of the hydrogen atom and the neutron are similar, there is a higher chance of colliding neutrons with hydrogen atoms. Therefore plastic is a good material to slow down neutrons. Figure 3.18 shows the effects of plastic sheets on the neutron spectra measured in the Pot. The ADC spectra of both PMTs are shown in the right two plots in Fig. 3.18. The time duration of ADC measurement
with the plastic sheets is similar to other two measurements, the background test and the measurement with only using PuBe source. No additional normalization method is necessary here when subtracting two ADC spectra (spectra with PuBe source and spectra with source and sheets). The resulting spectrum (green) is plotted on the right side of Fig. 3.18. This green spectrum represents the energy spectrum of neutrons slowed by the plastic sheets and their mean ADC values are close to previous measurements taken with only PuBe source. Furthermore, as shown in Fig. 3.18, there is a positive neutron peak indicating that the Pot is sensitive to low energy (slow) neutrons. Currently the sensitivity of the Pot detector for the full energy range of neutrons cannot be determined precisely with the current setup.
Figure (3.15) (color online) The average count variation in ten minute time intervals. Data were collected without the PuBe source during the background test done at Georgia Institute of Technology.

Figure (3.16) Experimental setup used during the Pot calibration. (a) The PuBe source was placed 50 inches away from the Pot. (b) One inch thick plastic sheet was placed in between the Pot and PuBe source.
Figure (3.17) ADC spectra of PMT1 (top raw) and PMT2 (bottom raw) of the Pot. The right two plots show ADC spectra of neutrons (green), obtained by subtracting the black spectrum (no source) from the red spectrum (with PuBe).
Figure (3.18) ADC spectra of PMT1 (top raw) and PMT2 (bottom raw) of the Pot. The right two plots show ADC spectra of neutrons (green), obtained by subtracting the black spectrum (with PuBe) from the red spectrum (with PuBe and sheets).
3.1.3 Detector sensitivity to gamma rays

A Cobalt-60 ($^{60}$Co) source was used to test the sensitivity of the Pot detector to low energy gamma rays. $^{60}$Co decays to nickle-60 ($^{60}$Ni) by beta decay and emits two gamma rays with energies of 1.17 MeV and 1.33 MeV [56], according to the following equation,

$$^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^- + \bar{\nu}_e + \text{gamma rays}$$

As shown in Fig. 3.19, the $^{60}$Co source was placed under the detector and the number of counts was measured using a scaler module with different threshold values of the discriminator.

The average count for ten minutes (with an increment of one minute counts) was used for this analysis. The high voltages of both PMTs were set to $-1850$ V. The results are shown in Fig. 3.20.
Figure (3.20) (color online) Variation of scaler counts as a function of threshold values. The top and bottom plots represent PMT1 and PMT2 count variations. The red and blue curves show counts measured with the $^{60}$Co and without the source.
Two conclusions can be drawn from the results shown in Fig. 3.20: (1) a significant increment of counts (mainly in the low threshold values) shows in the PMT1, when the $^{60}$Co source is present. However, this trend is not seen in the PMT2. Therefore, further analysis was needed to properly understand the sensitivity of the Pot detector for low energy gamma rays; (2) for all threshold values, the counts recorded by the PMT2 are significantly lower than the counts recorded by the PMT1. Hence, the PMT2 needs to operate at higher voltage. Currently it is $-1850$ V for both PMTs.

To match the number of counts recorded by both PMTs, a test was done by measuring the counts in two PMTs for different threshold values while increasing the high voltage of the PMT2. The optimum high voltage for the PMT2 was determined to be $-2060$ V. This value is at the plateau region of the high voltage scan shown in Fig. 3.9. The following Fig. 3.21 shows the comparison of number of counts for both PMT1 and PMT2. The optimum high voltages for PMT1 and PMT2 are $-1850$ V and $-2060$ V respectively.

To understand the sensitivity of the Pot detector to low energy gamma rays, a test was done by placing the $^{60}$Co source directly below the PMT2 while covering the PMT1 with lead bricks. Figure 3.22 shows the experimental setup.

Measured scaler counts in both PMTs from the new experimental setup are shown...
Figure (3.22) Experimental setup for analyzing the sensitivity of the Pot detector for low energy gamma rays. The $^{60}$Co source was placed directly below the PMT2 while PMT1 was covered with lead bricks.
in the top of Fig. 3.23. The bottom panel of Fig. 3.23 shows the scaler counts from the second measurement performed with the new experimental setup without using the $^{60}$Co source. As shown in the top Fig. 3.23, the scaler counts of the PMT2 are clearly higher (mainly in the low thresholds values) than that of in the PMT1. The explanation for the observed result is that the $^{60}$Co source emits two gamma rays with energy $\sim 1$ MeV which requires a high Z (atomic number) material for detection of these two gamma rays. However the liquid scintillator material in the Pot detector is made of low Z material which is not suitable for the low energy gamma ray detection. The increment of scaler counts in the PMT2 with the source present is observed because gamma rays penetrate through the liquid scintillator material and strike the photo cathode of the PMT. This leads to more counts in the PMT2 and fewer in the PMT1, which was shielded with lead bricks, thick enough to stop penetrating $\sim 1$ MeV gamma rays. Therefore, the Pot detector is not sensitive to $\sim 1$ MeV gamma rays. This conclusion can be further confirmed by comparing the coincidence counts of both PMTs. Figure 3.24 illustrates the variation of coincidence counts as function of threshold values. As shown in Fig. 3.24, the coincidence counts show no significant change due to the presence of $^{60}$Co source. Therefore, one can remove the signals of low energy gamma rays in the Pot detector by using the coincidence configuration.
Figure (3.23) (color online) Scaler count variation in the PMT1 (green) and the PMT2 (magenta) as a function of threshold values. Measurements were done by shielding the PMT1 with lead bricks.
Figure (3.24) (color online) Variation of coincidence count of the Pot as function of threshold values. The blue curve shows the count variation with the $^{60}$Co source while red curve represents the variation of counts without the source.
3.2 Other detectors

3.2.1 Two paddle telescope

A two scintillator paddle telescope was used to detect cosmic ray muon particles at the earth’s surface. Each of two scintillator paddles have a dimension of 33 cm × 7 cm × 1 cm with a detecting area of 230 cm². The detector acceptance can be changed by changing the separation of the paddles. The detector is currently running with the paddles at approximately 16 cm apart. The detector took data from 1/27/2010 to 7/31/2010 on the 5th floor of the Natural Science Center building at GSU before being moved to the 9th floor of the Petit Building, where the detector is currently taking data. Figure 3.25 (a) shows the two scintillator paddle telescope setup on the 9th floor of the Petit Building.

3.2.2 Four paddle telescope

The four paddle telescope consists of four scintillator paddles each of which has a dimen-
sion of 31 cm × 25.5 cm × 1 cm. The separation of each paddle is about ~ 50cm (distances of each paddle from the bottom paddle are 0, 57 cm, 99 cm, 145 cm). Because of this large separation between the scintillator paddles, the telescope has very narrow acceptance compared with that of the two paddle telescope. Currently the four paddle telescope is taking data in the basement of the NSC building at GSU as shown in Fig. 3.25 (b).

3.2.3 Mu-II detector

The Mu II scintillator detector is designed to measure cosmic ray flux and its angular distribution. The Mu II detector is made with three barium fluoride (BaF₂) cylindrical scintillators with a diameter and length of 50.8 mm. The detector has a capability of changing its angle orientation. Initially, this detector was used to measure cosmic ray flux in the Natural Science Center building at GSU. Currently, the detector is taking data at Hard Labor Creek Observatory, a facility approximately 50 miles east of Atlanta, GA. A weather station is running at the observatory along with the Mu II detector. Figure 3.25 (c) shows
the Mu II detector setup.

3.2.4 Two paddle telescope at Lanzhou University in China

This is one of the portable detectors (QuarkNet) used for the cosmic ray flux measurements at GSU. The data acquisition board has the dimension of 21 cm long and 13 cm wide. It can analyze signals from one to four photomultiplier tubes. The output data recorded in the detector can be sent to a PC via a standard RS-232 serial interface. Furthermore, an external GPS receiver module provides the position coordinates (latitude, longitude, altitude) and the absolute UTC time of each trigger. Due to its simple mobility, it can be used in travel to record measurements around the world. Currently this detector is taking cosmic ray flux measurements at Lanzhou University in China with two scintillator paddles that have a dimension of 31 cm $\times$ 25.5 cm. Figure 3.25 (d) shows the detector setup.
Figure (3.25) (color online) GSU cosmic ray detectors. Figures (a), (b), (c) and (d) show two paddle telescope running at GSU, four paddle telescope running at GSU, Mu-II detector running at Hard Labor Creek Observatory and two paddle telescope running at Lanzhou University China respectively.
CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Analysis overview

The Nuclear Physics Group at Georgia State University has been monitoring cosmic ray flux variations since 2009 with multiple generations of cosmic ray detectors. The current study is focused on understanding the correlation between cosmic ray particle flux distribution and the atmospheric and space weather observables. Observables such as atmospheric temperature at different altitudes, barometric pressure, humidity, CO\textsubscript{2} concentrations in the air and solar activity could potentially affect the cosmic ray flux variation. On the hand, recent findings show that cosmic ray particles could also influence the variation of atmospheric conditions, for instance by formation of low cloud coverage (< 3.2 km) [10] and depletion of the ozone layer, especially the polar ozone over Antarctica [21]. These cosmic ray effects on atmospheric conditions could indirectly impact the temperature and solar irradiance at the ground level.

Currently this analysis is only focused on understanding the effects of atmospheric and solar parameters on the variation of cosmic ray particles reaching the surface of the earth. This analysis can be divided into three main categories based on the observed effects of atmospheric and solar parameters on our cosmic ray flux measurements at the ground level; (1) influences of atmospheric temperature (Fig. 4.4), (2) influences of atmospheric pressure (Fig. 4.1) and (3) influences of solar parameters (Forbush effect Fig. 4.8). In this research study most of the analysis was done using the data collected using the liquid scintillator detector (Pot detector). Therefore, this Chapter discusses the results obtained by measurements with the Pot detector, done at its present location (9\textsuperscript{th} floor of the Petit building).

As discussed in Chapter 2, the majority of cosmic rays reaching the earth atmosphere come from outside the galaxy. This means that a galactic cosmic ray particle is required to
propagate through the heliosphere as well as the earth atmosphere by the time it reaches the surface of the earth. This leads the cosmic particles to experience both heliosphere disturbances and different thermodynamic processes in earth’s atmosphere during their flight. In order to understand the particle information such as its inherent acceleration mechanism, information about its source and transient modulation effects posed by the sun, it is necessary to know both terrestrial and earth atmospheric influences precisely. The different meteorological effects can alter the actual variation of primary cosmic ray flux and hinder the understanding of dynamics of physical processes in the heliosphere. Thus, it is necessary to know the meteorological effects on the flux of secondary particles reaching the earth surface to recover primary particle flux variations due to heliosphere processes. According to Dorman [27], barometric effects are the major influencing parameter on the cosmic ray secondary particle flux especially on cosmic neutrons. Therefore, as a first step it is necessary to accurately measure the barometric coefficient for a cosmic detector to unfold the solar modulation effects.
4.2 Correlation with atmospheric weather pattern

4.2.1 Influences of atmospheric pressure

The variation of cosmic ray flux at the sea level can be caused by two main atmospheric parameters; (1) atmospheric temperature and (2) atmospheric pressure [27, 57]. As a cosmic ray particle propagates through the atmosphere, the overall path through the atmosphere from the location of origin to the detection is needed to determine the effects of atmospheric temperature. On the other hand, the atmospheric pressure at the detection level is sufficient to calculate the barometric effects since the air density generally is higher close to the surface of the earth. Figure 4.1 shows the short-term (two months) muon flux time profile from November 2010 to January 2011. Also shown in Fig. 4.1 is the barometric pressure variation measured during the same period [58]. Based on this observation it is clear that there is a significant drop of muon flux during higher pressure time periods while higher counting rate is seen in low pressure time periods. This means that the measured muon flux is modulated by the atmospheric pressure. The correlation coefficient between measured counts and pressure during this time period is found to be \(-0.63\), because the high pressure at observation level implies a higher absorption of the muon component in the atmosphere.

The barometric effect can be calculated by considering a linear correlation between cosmic ray intensity \(I\) and corresponding atmospheric pressure \(P\) [27]. The percentage variation of cosmic ray intensity \((dI/I)\) is more meaningful to use here since it is independent of the variation of counts with time (eg: counts/hour, counts/day, counts/month, etc.). Considering the \(dI/I\) of any secondary cosmic ray component varies with a small change in the pressure \(P\) at the level of observation [27];

\[
\frac{dI}{I} \propto dP
\]  

(4.1)

The proportionality constant \((\beta)\) generally called the barometric coefficient (absorption co-
efficient) can be introduced here, and equation 4.1 can then be solved by,

\[ I = I_0 e^{-\beta(P - P_0)}, \] (4.2)

where \( I_0 \) and \( P_0 \) are defined as the mean cosmic ray intensity and the mean atmospheric pressure, respectively.

Considering the linear correlation between intensity of cosmic rays \( I_i \) and their corresponding atmospheric pressure \( P_i \), the linear regression method can be used to calculate the barometric coefficient \( \beta \) [27],

\[ \beta = \frac{\sigma_I}{\sigma_P} \] (4.3)

In general, the unit of \( \beta \) is given in \%/millibar (mb). \( \sigma_I, \sigma_P, I_0, P_0, r \) and the relative error
of $\beta$ are defined as follows,

$$
\sigma_I^2 = \frac{\sum_{i=1}^{N} (I_i - I_0)^2}{N}; \quad \sigma_P^2 = \frac{\sum_{i=1}^{N} (P_i - P_0)^2}{N}; \quad I_0 = \frac{\sum_{i=1}^{N} I_i}{N}; \\
 P_0 = \frac{\sum_{i=1}^{N} P_i}{N}; \quad r = \frac{\sum_{i=1}^{N} (I_i - I_0)(P_i - P_0)}{\sigma_I \sigma_P N}; \quad \Delta \beta = \pm \frac{1}{r} \sqrt{\frac{1 - r^2}{N - 3}}
$$

When calculating $\beta$, a careful selection of primary data is needed, since the reliability of $\beta$ depends strongly on the correct choice of data and method of analysis. Dorman [27] has mentioned some important steps to follow when finding the $\beta$ for a cosmic ray detector.

- It is better to use 3 to 7 days of data for $I$ and $P_0$.

- Low solar activity periods (magnetically undisturbed periods) during which the cosmic ray flux does not have any anomalous variations, should be used.

- If it is applicable, the temperature correction should be applied to the data of ionizing components.

- It is better to use formula (4.2) to determine the $\beta$ for the soft component (low energy cosmic ray particles).

As mentioned previously the Pot detector is sensitive to both cosmic muon and neutron particles. Hence, the dependency of measured counts on pressure is higher than that for the scintillator paddle detectors running at GSU. As shown in Fig. 4.1, there is a $-0.63$ correlation coefficient between atmospheric pressure and counts from the Pot in that period. In order to remove this pressure dependence (to see correlations with other atmospheric and solar parameters), one must first calculate the barometric coefficient corresponding to Pot measurements. For this analysis three different low solar activity time periods were selected in the year of 2010. Figure 4.2 shows the variation of solar parameters in the year of 2010.
The variation of five solar parameters: IMF, plasma speed, Kp index, solar index F10.7 and sunspot number were analyzed in order to obtain the low solar activity period. Among these, IMF and plasma speed are two significant parameters that highly influence the rate of the cosmic rays [12, 13]. The highlighted regions are the time periods selected to calculate the $\beta$. The value of the barometric coefficient for the Pot was found to be $-0.13 \pm 0.01 \%$/mb with $-0.96$ correlation coefficient between counts and atmospheric pressures. This $\beta$ value ($-0.13 \%$/mb) is used to correct the Pot detector counts for pressure using the equation 4.2. As given in equation 4.2, $I$ and $I_0$ are the corrected and the measured counts, respectively. $P$ is the measured atmospheric pressure and $P_0$ is the average atmospheric pressure during the selected time period. The value calculated for $P_0$ is 1015.95 mb. This is the average pressure used for all the pressure correction of the Pot data. The Pot has been taking data in its present location ($9^{th}$ floor of the Petit building) during this analysis period and atmospheric data was taken from the Atlanta Fulton weather station [58]. Figure 4.3 shows correlation coefficients between counts and atmospheric pressures. The top figure shows the pressure
uncorrected counts while bottom figure shows the pressure corrected counts. As presented in Fig. 4.3, the correlation coefficient was dropped from $-0.63$ to $0.03$, indicating that this method can successfully be used to correct the Pot detector data for atmospheric pressure.

Figure (4.3) (color online) Correlation coefficients between counts and atmospheric pressures. The top plot shows pressure uncorrected counts and bottom plot shows the pressure corrected counts. The time period for the data measurements was 11/30/2010 – 01/27/2011.
4.2.2 Influences of atmospheric temperature

The long-term measurements of cosmic ray fluxes on ground level have been carried out by our group since 2009. Our long-term observation of pressure corrected muon flux indicates that there is a seasonal variation as shown in Fig. 4.4. The data were recorded from March of 2011 to January of 2013. Also shown in Fig. 4.4 is the ground temperature recorded during the same period [58]. The data shows that there is an anti-correlation between cosmic muon flux and atmospheric temperature. This trend is also observed by the IceTop [25] and others [26].

![Figure (4.4) Pressure corrected daily muon count percentage variations (red) and temperature (black) measured in Atlanta, Georgia from 2011 to 2013. Temperature data is from Atlanta Fulton weather station [58]. The solid lines are two-week moving averages.](image)

Since the observed muon flux shows a seasonal fluctuation, the main cause for this trend could be the seasonal temperature variation. In order to understand the observed muon
flux trend, the temperature variation profile of the whole atmosphere (from 50 mb level to ground) was analyzed. The highest altitude of temperature variation for this analysis was selected to be the 50 mb level, since the altitude range where primary cosmic ray particles interact with the earth atmosphere is around 100 to 150 mb. The atmosphere was then divided into 50 mb altitude ranges and the correlation between the ground level muon flux and the temperature variation in each altitude range was studied. Results are shown in the Fig. 4.5. As presented in Fig. 4.5, there is a positive correlation (0.63) at the cosmic ray interaction altitude. However closer to the surface of the earth, the correlation coefficient becomes negative and its magnitude is increased.

The results shown in Fig. 4.5 do not directly provide a reason for the observed muon flux variation. Thus it is worth while to look at the atmospheric height variations in different seasons, because as the temperature varies across the seasons, the atmospheric height is also changed, as a result of atmospheric density changes. Figure 4.6 shows the correlation between different atmospheric heights and muon counts recorded at ground level. The correlation coefficient value for all heights is found to be negative indicating that when the atmosphere expands due to a temperature increase, there is a low count rate observed at the ground level and vice versa. Table 4.1 summarizes the correlation between atmospheric heights and ground level muon counts in different atmospheric pressure regions. As presented in Table 4.1 in atmospheric pressure levels 100 – 150 mb and 150 – 200 mb have higher correlation values which implies that fluctuations of the altitude region where the cosmic particle interaction happens (low stratosphere region), influence the ground level muon rate. There is a higher count rate recorded when the interaction occurs at lower altitudes while the higher altitude interaction leads to lower muon flux at ground level.

Based on the results presented in Fig 4.4, Fig. 4.5 and Fig. 4.6, the following conclusion can be obtained in order to understand the temperature effects on the cosmic ray muon flux variation. The primary cosmic ray particles interact with the stratospheric nuclei at an altitude range between 12 and 15 km. The mesons produced in these cosmic showers have a both chance of interacting with atmospheric molecules like oxygen or nitrogen, or decaying
Figure (4.5) (color online) Correlation between stratospheric temperature in different pressure regions and ground level muon counts. Muon counts were measured at GSU while atmospheric temperature measurements were measured by the Peachtree City observations station [60]. Measurements were taken in the period of 03/10/2011 − 12/31/2011.
Figure (4.6) (color online) Correlation between stratospheric altitudes in different pressure regions and ground level muon counts. Muon counts were measured at GSU while atmospheric temperatures were measured by the Peachtree City observations station \cite{60}. Measurements were taken in the period of 03/10/2011 – 12/31/2011.

into muons. It is known that the temperature in the troposphere can fluctuate considerably within a day while the stratospheric temperature usually varies seasonally unless there is a sudden stratospheric warming \cite{15}. During the summer time due to the expansion of the atmosphere (consequently the atmosphere is taller and less dense) cosmic ray showers occur at higher altitudes. This means, muons from the meson decays travel further to reach the surface of the earth increasing the probability that low energy muons will decay. This leads to observe a lower muon rate in summer time. On the other hand, during the winter time, when the earth’s atmosphere is colder and thus more dense the cosmic ray interactions occur closer to the earth’s surface. In this environment the muons are produced closer to ground level and that have a larger likelihood of reaching to the ground before decaying. This leads to the observed higher rate of muons in the winter time. Note that this conclusion is only valid for experiments that have ground level detectors with threshold energies in the MeV
Table (4.1) The correlation coefficients between atmospheric heights and ground level muon counts in different atmospheric pressure regions

<table>
<thead>
<tr>
<th>atm pressure level (mb)</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 - 100</td>
<td>-0.33</td>
</tr>
<tr>
<td>100 - 150</td>
<td>-0.58</td>
</tr>
<tr>
<td>150 - 200</td>
<td>-0.65</td>
</tr>
<tr>
<td>200 - 250</td>
<td>-0.51</td>
</tr>
<tr>
<td>250 - 300</td>
<td>-0.28</td>
</tr>
<tr>
<td>300 - 350</td>
<td>-0.39</td>
</tr>
<tr>
<td>350 - 400</td>
<td>-0.50</td>
</tr>
<tr>
<td>400 - 450</td>
<td>-0.42</td>
</tr>
<tr>
<td>450 - 500</td>
<td>-0.30</td>
</tr>
<tr>
<td>500 - 550</td>
<td>-0.31</td>
</tr>
<tr>
<td>550 - 600</td>
<td>-0.25</td>
</tr>
<tr>
<td>600 - 650</td>
<td>-0.30</td>
</tr>
</tbody>
</table>

region [26]. On the other hand, for a case where a muon detector located deep underground is sensitive to energies in the GeV and TeV regions and they observe an opposite trend of muon rates in two seasons [15, 25, 26]. In this case, during the winter time due to more dense environment, pions and kaons produced in the hadronic interactions have a higher chance of interacting with atmospheric molecules and lesser chance of decaying into muons. While during the summer time, these pions and kaons are less likely to interact with air and more likely to decay into muons. To further verify our seasonal muon flux observation, a Monte Carlo simulation software was developed based on the Geant4 package [61] and studied the influences of seasonal temperature variation on cosmic ray flux. More details of the simulation study are discussed in chapter 5.

In order to evaluate the temperature influence on the observed seasonal muon flux variation, the effective temperature ($T_{eff}$) was calculated for the Pot detector measurements. As mentioned in experiments [15, 25, 62, 63], to determine the $T_{eff}$, the overall profile of the atmosphere where from the location of primary cosmic ray interactions to the detection level is needed. The $T_{eff}$ can be calculated using the following equation 4.4.

$$
T_{eff} = \frac{\int_0^\infty \frac{d(X)}{X} T(X)}{\int_0^\infty \frac{d(X)}{X}},
$$

(4.4)
where $X$ is the atmospheric depth and $T(X)$ is the temperature at atmospheric depths. The parameter $X$ is defined as follows:

$$X = \int_{h}^{\infty} \rho(h) d(h),$$

where $\rho(h)$ is the atmospheric density as a function of height $(h)$ above the earth. The atmospheric depth has the unit of g/cm$^2$. Therefore the $T_{eff}$ is the weighted average atmospheric temperature over the different atmospheric depths. As discussed in [15, 62, 63], considering the constant detector configuration, acceptance and location over the time, the relationship between the variation of the rate of counts and the variation of effective temperature can be written as,

$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}, \quad (4.5)$$

where $R$ is the rate of variation of the counts, $\langle R \rangle$ and $\langle T_{eff} \rangle$ are the mean count rate and the mean $T_{eff}$ over the time period of observation. $\Delta R = R - \langle R \rangle$ and $\Delta T_{eff} = T_{eff} - \langle T_{eff} \rangle$. $\alpha_T$ is the temperature coefficient.

The temperature coefficient $\alpha_T$ was calculated for the Pot detector measurements using equations 4.4 and 4.5. Pressure corrected Pot data measured during the time period of 03/10/2011 – 12/31/2011 were used. The barometric coefficient used for correcting the data for pressure was $-0.13\%/mb$. Weather data were taken from the Peachtree City observations station [60]. Note that these weather data were measured at 12Z time, thus the $\alpha_T$ was calculated for both daily average counts and average counts in between 9 am – 12 pm of each day to check the consistency of results. Table 4.2 summarizes the correlation coefficients found between different atmospheric altitudes and $T_{eff}$ values.

As shown in Table 4.2, there is a negative correlation between the Pot data and the
Table (4.2) The correlation coefficients between atmospheric altitudes and $T_{eff}$ values

<table>
<thead>
<tr>
<th>atm altitude</th>
<th>Pot measurements</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full atm (from ground to ~30km)</td>
<td>daily mean count</td>
<td>-0.18</td>
</tr>
<tr>
<td>Full atm (from ground to ~30km)</td>
<td>mean count(9am − 12pm)</td>
<td>-0.18</td>
</tr>
<tr>
<td>atm pressure&lt;700mb (from ground to ~3km)</td>
<td>daily mean count</td>
<td>-0.63</td>
</tr>
<tr>
<td>atm pressure&lt;700mb (from ground to ~3km)</td>
<td>mean count(9am − 12pm)</td>
<td>-0.65</td>
</tr>
</tbody>
</table>

effective temperature values. In addition the muon intensity is highly correlated with the $T_{eff}$ calculated in the altitude range of ground to $\sim 3$ km. Also there is no significant difference of correlation values calculated using the daily mean count and the average count in the time period of 9 am − 12 pm. Therefore the daily average counts with $T_{eff}$ found in the altitude range of ground to $\sim 3$ km were used to calculate the temperature coefficient for Pot measurements. The $\alpha_T$ was found to be $-0.26\%/^\circ C$ for the Pot data. Figure 4.7 (a) shows the correlation between temperature uncorrected counts and effective temperatures while Fig. 4.7 (b) shows the correlation between temperature corrected counts and $T_{eff}$ values. As shown in Fig. 4.7 (a) and Fig. 4.7 (b) the correlation coefficient value dropped from $-0.63$ to $-0.01$, indicating that influence of atmospheric temperature on cosmic ray counts was removed and the calculated $\alpha_T$ value can be used to correct the Pot measurements for temperature.
Figure (4.7) (color online) (a) percentage variation of temperature uncorrected daily counts as a function of the variation of effective temperatures. (b) percentage variation of temperature corrected daily counts as a function of the variation of effective temperatures. Data collected time period was from March 2011 to December 2011. The temperature coefficient used to correct the data was $-0.26\%/{}^\circ C$. 
4.3 Correlation with space weather pattern

Figure 4.8 shows the variation of observed muon flux during a higher solar activity period. On the y-axis is the percentage variation of muon counts, interplanetary magnetic field (IMF), solar proton density, solar plasma speed and plasma pressure and on the x-axis is the number of hours in a day. The higher solar activity time period is indicated by the enhancement of solar parameters, especially the IMF and plasma speed. In addition to the IMF and plasma speed are two significant parameters that highly impact the variation of GCR with energies below 15 GeV [2, 12, 13]. As shown in Fig. 4.8 during the higher solar activity hours, there is \( \sim 1.5\% \) drop of measured counts while \( \sim 1\% \) enhancement in the counts shows about four hours before the beginning of solar activities. In addition, the variation of cosmic data clearly show two step decrements in this time period. A gradual recovery (nearly exponential) of cosmic flux after its decreases is another prominent feature shown in the Fig. 4.8. This effect is also observed in cosmic ray neutron flux measurements by the Sodankyla Geophysical Observatory in Oulu, Finland [24] and others [11, 64]. This short term cosmic ray flux decrease is called a Forbush decrease. Earlier it was thought that Forbush decreases are associated with geomagnetic storms. However from the spacecraft measurements, currently it is found that the Forbush decrease is a result of disturbing the path of the primary cosmic ray flux by massive burst of solar plasma wind and magnetic fields from the sun that reached the vicinity of the earth [12].

Coronal mass ejections (CMEs) are currently identified as the responsible agent for short term cosmic ray flux drops as presented in Fig. 4.8. A CME is a massive eruption of solar plasma wind and magnetic fields from the sun into space. Following a CME event there is a rapid decrease in low energy (below 15 GeV [2]) GCR flux caused by sweeping some of the GCR particles away from the earth by the solar plasma wind and its magnetic fields. These CME events happen due to magnetic reconnection processes in the sun. Magnetic reconnection is the process of disconnecting and reconnecting oppositely directed magnetic field lines in a plasma. As a result of this process, the magnetic field energy is converted
Figure (4.8) (color online) Forbush decrease event observed in the year of 2011. The percentage variation of pressure corrected muon flux (magenta) was measured at GSU. The percentage variation of solar parameters; interplanetary magnetic field (blue), solar proton density (green), solar plasma speed (brown) and plasma pressure (red) were taken from OMNI solar weather station [59].
into thermal and kinetic energy of the plasma. Scientists believe that magnetic reconnection drives every dynamic process in the sun including solar flares.

According to analysis by Cane [11], a Forbush decrease is caused by two different physical mechanisms of a CME event; the interplanetary shock wave associated with CME and the ejecta of a CME event. Figure 4.9 can be used to understand the responses of GCR as they pass through the large structure of a CME ejecta and its associated shock wave [11]. As shown in Fig. 4.8, a two step cosmic ray decrease can be observed if the GCR particles encounter the shock and its associated ejecta. Note that less energetic ejecta do not produce a shock wave, thus as the GCR pass by ejecta only a one step cosmic ray flux decrease is registered in the cosmic ray monitors. As shown by the path B of Fig. 4.9 there is a higher chance of intercepting GCR particles with a shock wave, since shocks have longer longitudinal extent than ejecta. In this case, there is one step cosmic flux decrease registered in the monitor. Figure 4.10 shows some examples of one step Forbush decrease events registered in Pot measurements.
Figure (4.10) (color online) Forbush decrease events registered in the Pot detector. Percentage variation of pressure corrected cosmic data (magenta) was measured at GSU. Interplanetary magnetic field (green) and solar wind speed (brown) were measured by Advanced Composition Explorer [65]. The events in the top and bottom figures were observed in 2011 and 2012.
Therefore, in general there are three basic types of CME associated with cosmic ray decreases: (1) decrease caused by shock and ejecta, (2) decrease caused by ejecta only and (3) decrease caused by shock only. In fact, the majority greater than 80% of the CME-related cosmic decrease observations are one-step, short term decreases while > 4% are of the two-step types decreases [66]. Experimental studies [12] show that the depth of a Forbush event depends on the strength of the associated magnetic field. A magnitude of one nT (nano Tesla) increase in IMF, produces $\sim 2\%$ decrease in cosmic ray intensity [13]. It is also confirmed that the depth of a Forbush event not only depends on magnetic field but also on the speed of the solar plasma wind [12]. Our observations shown in Fig. 4.8 and Fig. 4.10 also confirm these features. In addition, Cane et al. found that the location of the heliolongitude from which the CME was ejected is another significant parameter to determine the depth of a Forbush decrease [66]. A larger depth of Forbush event can be observed if the associated CME originates near the solar meridian. However many Forbush events happen if its CME arises within 50 degrees of 0 degrees heliolongitude [12]. On the other hand, the recovery time of a Forbush event is found to be independent of the strength of the magnetic field but is dependent upon the decay rate and speed of plasma wind after it passes the earth [12]. The recovery time can be used to probe the structure of CME at radial locations, since it is dependent upon the strength of plasma wind as it passes the earth. Early studies done on recovery times showed that the rate of the recovery time is higher for the stations with higher cut-off rigidity. However later it was suggested that the rate of the recovery time has no or little dependence on the energy [67]. Thus there are still have some mysteries in the Forbush recovery time although it has been studied for more than half a century.

Due to variations in solar activity (11-year solar cycle), the properties of CME (amount of solar wind, magnetic field) are not constant. Therefore, the amount of cosmic ray modulation changes with the solar activity. However understanding the short-term cosmic ray modulations lead us to understand influences of long-term solar modulations. Since these Forbush decrease events are well correlated with various interplanetary, solar and geophysical parameters, our current ground level cosmic flux observation leads us to understand the
temporal behavior of space weather.
CHAPTER 5

MODELING EARTH ATMOSPHERE

5.1 Simulation overview

As discussed in chapter 4 our cosmic ray flux measurements show an anti-correlation with both atmospheric pressure and temperature variations. It is known that these atmospheric parameters eventually vary the air density at different altitudes which is the main cause for our observed cosmic ray flux patterns. It is therefore important to precisely understand how both the muon and neutron flux is attenuated in different layers of the atmosphere. Numerical simulations of muon and neutron flux variations at the surface of the earth have been carried out with varying air densities in the troposphere and stratosphere. A Monte Carlo simulation software is developed based on the Geant4 package [61] to study cosmic ray flux in the atmosphere. Geant4 has been used in nuclear and particle physics research for over 40 years to simulate radiation and its effect on matter and has wide applications in space radiation and medical physics. Results are presented in this chapter.

5.1.1 Simulation setup

In the simulation setup, a column of air with dimension 100 km in height and 50 km in diameter is configured. The air column is composed of 70% of Nitrogen and 30% of Oxygen. The atmospheric air densities in each altitude are parameterized as the realistic air density variation described in section 5.1.2. The atmosphere is then divided into 99 layers of varying air densities that ascend in magnitude from the upper atmosphere to the bottom of the atmosphere near the surface of the earth. Each of the layers has a height of 1 km. It is possible to launch different types and numbers of particles having different energies from the top of the atmosphere and study their trajectories as the cosmic ray shower particles travel and scatter through various layers in the atmosphere. It is also possible to read off
the various energy losses in each layer of the atmosphere and the total energy loss at the end of simulation. In addition, a 10 cm thick scintillator paddle is placed near the bottom atmosphere layer (1.5 km from the surface) in order to study the number of secondary cosmic particles reaching the ground and their total energy loss.

Figure 5.1 shows several screen captures of our simulation display window which were taken during cosmic ray particle interactions with the earth’s atmosphere. Note that for each simulation run one cosmic ray particle was initially launched vertically downwards from the 100 km altitude. Figure 5.1 (a), (b), (c) and (d) show the cosmic ray interactions for initially launched 5 GeV protons, 10 GeV protons, 5 GeV $\mu^-$s and 20 GeV $\mu^+$s respectively. The particle trajectories are color coded; blue, red and green color trajectories represent the positively charged, negatively charged and charge neutral particles, respectively. As mentioned previously, the total height of the air column is 100 km and one can thus estimate in Fig. 5.1 that the altitude of particle interactions mainly occurs is at about 20 km from the ground. As shown in Fig. 5.1 (a) and (b) both 5 GeV and 10 GeV protons interact with air molecules and produce air showers at around 20 km altitude. Note that these types of interactions produce lots of gamma rays as shown in green trajectories, whereas, muon particles propagate through the air with fewer interactions, especially for the high energy muons as shown in Fig. 5.1 (d).

The primary cosmic particles impinging on the top of the earth’s atmosphere consist of 79% protons and a small fraction of alpha particles and heavier nuclei [36]. In the present work of studying the atmospheric influence on cosmic flux variation, only primary protons are included in the simulation. The primary protons are launched vertically downward at the top of the air column with an energy distribution as described in [36]. The intensity of the primary protons used in this simulation is given by equation 2.1.

Figure 5.2 shows the energy distribution of primary protons relevant to our simulation study. The lowest energy of the primary proton is set to 4.0 GeV, since the vertical geomagnetic cutoff rigidity in Atlanta is 3.6 GV [38]. This energy distribution is consistent with the primary cosmic ray energy distribution given by the Particle data group [36].
Figure (5.1) (color online) Screen captures of the simulation event display window. Initially launched particle for corresponding (a), (b), (c) and (d) figures are 5 GeV proton, 10 GeV proton, 5 GeV $\mu^-$ and 20 GeV $\mu^+$ respectively. For each simulation run one particle was launched vertically downwards from the 100 km altitude. Trajectories of blue, red and green color represent the positively charged, negatively charged and charged neutral particles respectively.

The simulation study focuses on understanding the observed atmospheric effects on the variation of cosmic ray particles as illustrated in Fig. 1.7 and Fig. 4.4. This study can be divided into two main categories; (1) understanding influences of the troposphere and (2) understanding influences of stratosphere on cosmic ray flux. Several Monte Carlo simulations have been done by changing atmospheric densities at different altitudes. This air density variation is modeled in the simulation by scaling the air density to match the realistic air density fluctuation discussed in the section 5.1.2. Table 5.1 summarizes the different air density configurations used in the simulation to study troposphere and stratosphere effects.

In each simulation run, 100,000 protons were launched vertically down at an altitude of 100km from the ground. The primary protons will then interact with atmospheric molecules and produce showers of secondary particles. The number of secondary particles reaching to the ground is recorded in the simulation. Some additional information recorded during the simulation is: (1) energy loss and total track length in each layer of the atmosphere, (2) total
Figure (5.2) (color online) Primary cosmic ray proton energy distribution used for our simulation study. The lowest energy of the primary proton is set to 4.0 GeV, since the vertical geomagnetic cutoff rigidity in Atlanta is 3.6 GV.
Table (5.1) Different air density configurations used in the simulation to study troposphere and stratosphere influences.

<table>
<thead>
<tr>
<th>Study troposphere effects</th>
<th>Study stratosphere effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>scaled the troposphere density (altitude &lt; 11 km) from 98% to 102% relative to the yearly average.</td>
<td>scaled the stratosphere density (altitude &gt; 11 km) from 90% to 110% relative to the yearly average.</td>
</tr>
<tr>
<td>low densities (98%) represent summer time while high densities (102%) represent winter.</td>
<td>low densities (90%) represent winter and high densities (110%) represent summer time.</td>
</tr>
<tr>
<td>kept stratosphere density as constant (100%).</td>
<td>kept troposphere density as constant (100%).</td>
</tr>
</tbody>
</table>

energy loss when the particle reached the ground, (3) momentum, total energy and position of the particle at ground level, (4) pions and muons produced at altitude and their kinetic energies, and (5) total energy of the primary particle.

5.1.2 Realistic air density variation

The atmosphere of the earth is composed of 78% nitrogen, 20% oxygen and the rest with small amounts of other gases. It is a very thin sheet of gases extending from the surface of the earth to the edge of the space. This air sheet varies due to various reasons and it is primarily influenced by activities of the sun. The sun heats the atmosphere as well as the ground and some of heat from the ground warms air near the ground. This heated air is then convected or diffused above through the atmosphere leading to various physical properties at different altitudes. The air density of the atmosphere is one of the important physical properties for cosmic ray particle interactions. As given by the atmospheric model from NASA [68], the atmospheric air density can be parameterized in the following equation 5.1,

\[
\rho = \frac{P}{0.2869(T + 273.1)},
\]  

(5.1)
where \( \rho \) is the air density in kg/m\(^3\), \( P \) is the pressure in kPa, and \( T \) is the temperature in celsius. As shown in the equation 5.1, the atmospheric density can be calculated as long as the atmospheric temperature and pressure are known in different altitudes. The temperature dependent atmospheric pressures for different layers of the atmosphere are given in the Table 5.2.

Table (5.2) Temperature dependent atmospheric pressures for different layers of the atmosphere [68].

<table>
<thead>
<tr>
<th>Altitude ( h(m) )</th>
<th>Temperature ( T(\degree C) )</th>
<th>Pressure ( P(kPa) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>For upper stratosphere ( (h &gt; 25000m) )</td>
<td>(-131.21 + 0.00299h)</td>
<td>(2.488 \left(\frac{T+273.1}{216.6}\right)^{-11.388})</td>
</tr>
<tr>
<td>For lower stratosphere ( (11000m &lt; h &lt; 25000m) )</td>
<td>(-56.46)</td>
<td>(22.65e^{1.73-0.000157h})</td>
</tr>
<tr>
<td>For troposphere ( (h &lt; 11000m) )</td>
<td>(15.04 - 0.00649h)</td>
<td>(101.29 \left(\frac{T+273.1}{288.08}\right)^{5.256})</td>
</tr>
</tbody>
</table>

As shown in the Table 5.2, the atmospheres is divided into three different regions: troposphere (altitude < 11 km), lower stratosphere (11 km < altitude < 25 km) and upper stratosphere (altitude > 25 km). According to the atmospheric model, the variation of atmospheric temperature, pressure and density in different altitudes are shown in Fig. 5.3 (a). The variation of empirical atmospheric temperature, pressure and density in different altitudes is shown in Fig. 5.3 (b), for the comparison with the results from the atmospheric model. The empirical data were taken from the Peachtree City observation station [60]. As shown in Fig. 5.3, the results from the atmospheric model are consistent with the empirical data and thus the model was used in order to construct a realistic air density variation in our simulation program.

To understand the seasonal atmospheric effects on the variation of cosmic ray particles, it is necessary to know how the air density in three regions (troposphere, lower stratosphere
and upper stratosphere) change during different seasons. Figure 5.4 shows the percentage variation of densities of the atmosphere during winter and summer times in 2012. The data was provided by the NASA model [69]. As shown in Fig. 5.4 the densities in months of January and July were used to represent winter (blue curve) and summer (red curve) seasons, respectively, in Atlanta. The average density of the full year of 2012 was used to calculate the percentage difference. The air density in the stratosphere is larger in summer time and smaller in the winter, which is opposite to the air density variation in the troposphere. Figure 5.4 shows a $\pm 2.5\%$ maximum variation in the troposphere density between winter and summer while around $\pm 5\%$ fluctuation in the stratosphere density. This air density variation was modeled in our simulation by scaling the air density to match the seasonal variation in order to study its effect on cosmic neutron as well as muon flux changes measured at the surface of the earth.
Figure (5.3) Variation of atmospheric pressure (blue), temperature (red) and density (green) as a function of the altitude. (a) shows the variation of atmospheric parameters obtained by the NASA atmospheric model [68]. (b) shows the variation of empirical data from the Peachtree City observation station [60].
Figure (5.4) (color online) Percentage variation of the atmospheric density in months of January (blue) and July (red) 2012, as a function of the altitude. The data were provided by NASA model [69]. The dashed line represents the average density of the full year of 2012.
5.2 Results and discussion

5.2.1 Troposphere effects

The troposphere extends from the ground to 11 km altitude in the earth’s atmosphere. It contains \( \sim 80\% \) of the mass of the atmosphere and \( \sim 99\% \) of water and aerosols [70]. Hence, the troposphere holds the greatest air density in the atmosphere. The density of the troposphere undergoes \( \pm 2.5\% \) maximum variation during winter and summer seasons as shown in Fig. 5.4. This variation in density was modeled in our simulation by scaling the troposphere density from 98\% to 102\% relative to the yearly average while keeping the stratosphere density constant. In each density level 100,000 protons were launched vertically down from the altitude of 100 km with the energy distribution shown in Fig. 5.2. At the end of each run, the number of secondary muons and neutrons were recorded at the ground level. The upper panel of Fig. 5.5 shows the percentage variation of simulated neutron (black squares) and muon (blue triangles) counts variation as a function of the percentage variation of densities. Also shown in the bottom panel of Fig. 5.5 is the measured neutron counts variation (red circles) as a function of the percentage variation of the atmospheric pressure from Oulu observation in 2012. The variation of measured neutron counts (bottom Fig. 5.5) is shown only for the qualitatively comparison with simulated results.

The simulated neutron results show a very consistent trend with the data. This indicates that the neutron flux variation is primarily influenced by the modulation of the air density in the troposphere. One should not expect a perfect correlation between the measured data and the simulated results for three reasons: (1) the simulation does not include the Oulu detector acceptance and efficiency; (2) a constant primary cosmic ray flux is used in the simulation, (3) the primary cosmic ray particles are only launched vertically down. The observed trend can be understood by the following argument. During the summer time due to the expansion of the atmosphere the troposphere density is lower compared to the troposphere density in the winter season. This implies that number of air molecules in the troposphere is higher during the winter time than in the summer. Therefore as cosmic neutrons traverse the air in
Figure (5.5) (color online) Top figure shows the simulated percentage variation of ground level neutron (black) and muon (blue) counts as function of the percentage variation of the troposphere density. Bottom figure shows the daily percentage variation of neutron counts as a function of the atmospheric pressure from Oulu (red). Neutron measurements were done at Sodankyla Geophysical Observatory in Oulu, Finland in 2012.
winter time, there is a higher chance of their interacting with air molecules and leading us to observe lower count rate at the ground level. Thus as shown in Fig. 5.5, the simulation and the measured results show a lower neutron rate as the atmosphere cools (winter) compared with the time when it is warmer (summer).

While there is a strong anti-correlation between the troposphere air density and the neutron flux, there is little effect on the muon flux from the troposphere air density variations as shown in Fig. 5.5 in blue triangle points (except a noticeable effect on muon flux changes at the higher troposphere air density range). This is consistent with the results reported in [14] and led us to believe that the stratospheric air density may play a significant role in modulating the muon flux variation as seen in Fig. 4.4.

5.2.2 Stratosphere effects

Using the same simulation framework, we also modeled the seasonal air density variation in the stratosphere and studied its effects on the muon flux variation at the surface of the earth. In order to make a realistic simulation, we modeled the stratosphere density variation according to the data provided by NASA [69]. In our simulation, stratosphere density is varied from 90% to 110% relative to its average while the troposphere density is kept constant. The main reason of keeping the troposphere density constant is to study effects only from the stratospheric density on the GCR as well as on the seasonal variation of the secondary muon flux. In the simulation lower stratosphere densities (90%) represent the winter time while higher densities (110%) reflects the summer. When the atmosphere is warmer, air molecules in the troposphere convect or diffuse up through the atmosphere. This leads to higher stratospheric densities in summer and lower stratospheric densities in the winter. As described in section 5.1.2, the measured maximum stratosphere density variation is about ±5% between winter and summer, however, we extended the density ±10% variation limits in our simulation in order to check the consistency of the results. At each density level 100,000 protons are launched vertically down from the altitude of 100 km with the energy distribution given in Fig. 5.2. At the end of each run the number of secondary muons
Figure (5.6) (color online) Ground level muon flux percentage variation as a function of percentage variation of the stratospheric air density. The red-circle data points are from GSU measurement and the stratosphere air densities are from the Peachtree City observation station [60]. The black-square are the simulated results. Note that the error bars in the figure are statistical only.

were recorded at the ground level. The results are shown in Fig. 5.6. The red-circle data points are from GSU measurements and the stratosphere air densities are calculated using the equation 5.1 from the data taken from [60]. The black-squares are the simulated results. Note that we only sampled muon particles with kinetic energy ≥ 1 GeV at the ground level which corresponds to the detector threshold. A significant reduction in the muon flux is clearly seen with increasing stratospheric air density, which is very consistent with our measurements at GSU. Based on the results in Fig. 5.5 and Fig. 5.6, it is clear that the effect of density fluctuation in the stratosphere region is dominant on the muon flux variation compared to the modulation effect from the troposphere region.
A remark has to be made about the simulated results and the measurements at the higher densities in Fig. 5.6. The simulated results in Fig. 5.6 are obtained by only varying the stratospheric density and keeping a constant tropospheric density. However, empirical atmospheric data [69] show that the stratospheric and tropospheric densities vary inversely during summer and winter. The measured muon rate is higher compared to the simulated muon rate in summer times as a result of less modulation by the low troposphere density. This trend is also consistent with our muon simulation results shown in Fig. 5.5.

The modulation of muon flux by the variable stratospheric air density can be further understood by studying the cosmic ray shower maxima distributions in altitude. The maximum shower altitude is where the most of the primary cosmic ray particles interact with atmospheric nuclei. The primary cosmic ray particles interact with the stratospheric nuclei at about 12 - 15 km altitude where the shower occurs. That is the maximum number of primary cosmic ray interactions occur where the atmospheric pressure in between 100 and 250 hPa which is the same region that the maximum particle flux is observed in the atmosphere (Pfotzer maximum) [29]. To understand the variation of empirical shower maxima altitudes, the data taken by the Peachtree City observation station (2011 - 2013) were analyzed [60]. Figure 5.7 shows the variation of the mean altitude (black) of the pressure range of 100 to 250 hPa from March of 2011 to January of 2013. Also shown in Fig. 5.7 is the pressure corrected ground level muon counts (red) measured at GSU during the same period. The data shows a significant drop of muon counts during the periods of higher mean altitudes while higher muon counts are recorded during the lower mean altitude periods. This indicates that the rate of secondary muons mainly depends on the altitude distribution of the shower maxima.

The mesons produced in this hadronic interaction can either further interact with the atmospheric molecules or decay into muons. According to our simulation study about \( \sim 99\% \) of pions decay into muons. This indicates that very few pions interact further with atmospheric nuclei without decaying to muons. It is imperative to look at these muons and their parent pion production altitude distributions in order to study the cosmic ray
Figure (5.7) (color online) Percentage variation of pressure corrected muon daily counts (red) measured in Atlanta, Georgia from 2011 to 2013. The black data points represent the mean altitude of the pressure range of 100 to 250 hPa. The solid lines are two-week moving averages.
Figure (5.8) (color online) Pions (top) and muons (bottom) produced location distribution as a function of atmospheric heights. Atmospheric height zero is the ground level. Brown, magenta and blue curves represent 90%, 100% and 110% stratospheric density levels set in the simulation respectively. The troposphere density is the same for all different stratospheric densities.

Particle shower maxima distribution during the seasonal changes. Our simulation is capable of obtaining the number of particles and their total energies in each layer of the atmosphere. It is clearly seen in Fig. 5.8 that the simulated shower maxima occur at the altitude range of 12 - 15 km, which is consistent with the theory [29]. Also, illustrated in Fig. 5.8, the location of maximum number of pion and muon production shifts to the upper altitudes as stratospheric density increases. This shifting of shower maxima to higher altitudes as the stratospheric density rises shows that the primary particle interactions happen at higher altitudes in the summer time compared to that in the winter time.

In order to find out the exact altitude of the simulated shower maxima, the shower peak was fitted with Gaussian fit in the atmospheric region of 10 - 18 km. For instance, Fig. 5.9 shows the simulated pion production location distribution as a function of atmospheric height from the ground. The peak altitude given by the Gaussian fit is 14.47 km for the 110% stratosphere density. As shown in Fig. 5.9 the simulated shower maxima altitude
Figure (5.9) (color online) Pions ($\pi^+, \pi^-$) produced location distribution as a function of the atmospheric heights. Atmospheric height zero is the ground level. Stratospheric density is 110% set in the simulation while the troposphere density is 100%.

was obtained using the Gaussian fit for all stratospheric densities from 90% to 110%. Figure 5.10 shows the altitudes of the simulated shower maxima (black squares) as a function of the stratospheric densities. Also shown in Fig. 5.10 is the variation of mean altitude (red circles) of the stratospheric pressure range of 100 to 250 hPa from March 2011 to January 2013. The empirical atmospheric data were taken from the Peachtree City observation station and the stratospheric density was calculated using equation 5.1. Note that the larger error bars at low densities are due to low statistics. A remarkably good agreement is seen between the simulated shower maximum altitude distribution and the extrapolated altitudes of the 100 to 250 hPa pressure region. It is clearly seen in Fig. 5.10 that the position of the shower peak appears at higher altitudes for high stratospheric densities (summer time) while it occurs at lower altitudes for low stratospheric densities (winter time).
Figure (5.10) (color online) Simulated cosmic ray shower maximum altitude (black square) distribution as a function of the percentage variation of the stratosphere air density. The red circle data points represent the mean altitude of the pressure range of 100 to 250 hPa, which are taken from the Peachtree City observation station (2011 - 2013) [60].
As shown in Fig. 5.5, the simulated muons flux is little affected by the troposphere density. However, the density modulation on the muon flux is significant at the troposphere density of 102%. Thus, it is imperative to check whether the observation of seasonal muon flux variation is due to the shower maxima altitude variation or due to the stratosphere density modulation effect. Therefore, further simulations studies were done to understand influences from these two effects on the muon flux variation. If there is a modulation effect, then the density of the lower stratosphere (11 - 25 km) is the density region that contributes to muon flux fluctuations since the troposphere density was kept constant for all stratospheric density variation in our simulation. To understand the lower stratospheric modulation effect, 10,000 $\mu^-$ particles were launched at 20 km altitude while changing the stratospheric densities from 90% to 110%. The troposphere density was kept constant. Figure 5.11 shows the schematic diagram of the simulation setup. The simulation results were obtained for four different energies (3 GeV, 4 GeV, 5 GeV and 10 GeV) of $\mu^-$ particles launched at each stratospheric density level. The number of $\mu^-$ particles reaching the ground level with energy greater than 1 GeV, was compared at different stratospheric densities.

The results are shown in Fig. 5.12. The number of muons particles with a given energy value is same for all stratosphere densities. Thus density of the lower stratosphere does not modulate the cosmic ray muon particles reaching the ground with energies greater than 1 GeV.

To determine the effect of shower maxima altitude variations, a simulation study was done by launching 10,000 $\mu^-$ particles from different altitudes as shown in the schematic diagram of Fig. 5.13. The launching altitude was varied from 12 to 20 km with the step size of 1 km. Three different energies (10 GeV, 8 GeV and 5 GeV) of $\mu^-$ particles were launched from each altitude. In addition, both troposphere and stratosphere densities were set to 100% in each simulation run. At the end of each simulation run, the number of $\mu^-$ particles were recorded at the ground level with energy greater than 1 GeV.

As shown in Fig. 5.14, for a given energy of $\mu^-$ particle, the counts recorded at the ground level is increased with decreasing launched altitudes. This implies that some of $\mu^-$
particles launched at higher altitudes decayed before reaching the ground. On the other hand, $\mu^-$ particles launched at lower altitudes have shorter path to cross the atmosphere to reach the ground and thus their probability of surviving at ground level will be increased. This leads us to observe higher $\mu^-$ counts at the surface of the earth.

Based on the results in Fig. 5.12 and Fig. 5.14, it is clear that the effect of shower maxima fluctuation in the stratosphere region is dominant on the muon flux variation comparing the modulation effect from the lower stratosphere region.

Overall, the seasonal variation of muon flux as shown in Fig. 4.4 can be understood based on the results of this simulation study as follows. It is known that the temperature in the troposphere can fluctuate considerably within a day while the stratospheric temperature only varies seasonally unless there is a sudden stratospheric warming [15]. The primary cosmic ray particles mainly interact with the stratospheric nuclei and generate secondary cosmic ray particles at an altitude between 12 and 15 km. The mesons produced in these
Figure (5.12) (color online) Number of muons reached to the ground with energy greater than 1 GeV as a function of the percentage variation of the stratospheric densities. Energies of initially launched $\mu^-$ particles are 3 GeV (brown), 4 GeV (green), 5 GeV (blue) and 10 GeV (magenta).

Figure (5.13) (color online) Schematic diagram of the simulation setup to study the effects of the shower maxima altitude variation. 10,000 $\mu^-$ particles from different altitudes (from 12 to 20 km with the step size of 1 km) were launched. 10 GeV, 8 GeV and 5 GeV of $\mu^-$ particles were launched from each altitude. Both troposphere and stratosphere densities were set to 100% in each simulation run.
Figure (5.14) (color online) Number of muons reached to the ground with energy greater than 1 GeV as a function of the launched altitude. Energies of initially launched $\mu^-$ particles are 5 GeV (green), 8 GeV (blue) and 10 GeV (magenta).

cosmic showers can either interact with the atmosphere or decay into muons. During the summer time due to the expanding atmosphere cosmic ray showers occur at higher altitudes. This means that the muons travel further to reach the surface of the earth and are more likely to decay leading to a lower muon rate in summer and a higher rate during winter.
CHAPTER 6

CONCLUSIONS

Our ground level cosmic ray flux measurements show the modulation effects from both atmospheric and space weather parameters. Atmospheric influence is first removed in order to understand the solar modulation effect. Short-term cosmic flux measurements show an anti-correlation with atmospheric pressure and the barometric coefficient was found to be $-0.13 \pm 0.01 \%/\text{mb}$. This barometric coefficient was used to correct the Pot detector data for pressure. Pressure corrected cosmic data shows a seasonal variation with a significant drop of muon counts during the summer time while a higher counting rate seen in winter. This count variation occurs due to the fluctuation of primary particle interaction altitude as a result of seasonal temperature changes. The temperature coefficient for the Pot data was found to be $-0.26\%/\circ C$. Pressure corrected muon data also show the effect of solar modulation due to coronal mass ejections.

To understand the atmospheric influence (effects of the tropospheric and stratospheric density variations) on cosmic flux, numerical simulations of cosmic muon and neutron flux variations at the surface of the earth have been carried out. Our simulation results show that the density variations in the troposphere mainly influence the neutron flux while its influence on the muon flux is relatively insignificant. On the other hand, variation of the stratospheric density dominates the muon flux which is in remarkably good agreement with observed seasonal variation of muon flux. It is, therefore, very important to have a long-term simultaneous monitoring of both cosmic ray muon and neutron flux on a global scale in order to study the dynamical change of the atmosphere. These results pave a new path for systematically studying the global temperature evolution using worldwide cosmic ray data.
REFERENCES


