Using a two-scintillator paddle telescope for cosmic ray flux measurements

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A two-scintillator paddle muon telescope with variable angular acceptance at the earth’s surface was used to study correlations between flux distribution and barometric pressure. The detector was placed in 2 different locations around Georgia State University with varying paddle separations of 0, 7, and 14 inches. Correlation and anti-correlation analyses were conducted by using the muon count from the detector along with the barometric pressure, surface temperature, stratospheric temperature.
and solar activity. It was observed that there was a short and long-term variation relationship between cosmic ray counts and barometric pressure and also cosmic ray counts and temperature. No significant relationship was found between cosmic ray flux and solar activity. A new two-scintillator paddle telescope with larger detecting area was constructed in order to observe a stronger correlation between cosmic ray flux and pressure.

INDEX WORDS: Cosmic ray, Two-scintillator paddle muon telescope, Barometric coefficient
USING A TWO-SCINTILLATOR PADDLE TELESCOPE FOR COSMIC RAY FLUX MEASUREMENTS

by

DAVID L. CAMP

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in the College of Arts and Sciences Georgia State University

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USING A TWO-SCINTILLATOR PADDLE TELESCOPE FOR COSMIC RAY
FLUX MEASUREMENTS

by

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DEDICATION

To my parents, Ronald and Janice Camp
ACKNOWLEDGEMENTS

First and foremost I would like to thank my father and mother, Ronald and Janice Camp, who have been there for me every step of the way through my academic career. They have thoroughly supported me and my studies from the first day of pre-school to the last day of my master’s graduate program. Their love and encouragement fueled me to have high aspirations for myself and to do something significant with my life. It is not enough to say that my parents are the ones who played a vital role in grooming the man I am today. Integrity, perseverance, passion, and drive are some of the core values that have been instilled in me because of my parents. Thanks to you both. I love you!

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LIST OF ABBREVIATIONS

- GSU - Georgia State University
- GCR - Galactic cosmic ray
- SCR - Secondary cosmic ray
- IMF - Interplanetary magnetic field
- PMT - Photomultiplier tube
- hPa - Hectopascal
- ns - Nanosecond
- MeV - Megaelectron volt
- GeV - Gigaelectron volt
- TDC - Time to digital converter
- ADC - Analog-to-digital converter
- TOF - Time of flight
CHAPTER 1

INTRODUCTION

1.1 Introduction to the cosmic ray

There are two types of cosmic rays, galactic cosmic rays (GCR)s and secondary cosmic rays (SCR)s. GCRs are primarily made up of atomic nuclei such as hydrogen or helium, which are stable matter-like protons, while only 1% of the GCR is comprised of electrons. These galactic cosmic rays originate from radioactive decay and stars and supernovae within our galaxy [1]. If the GCRs penetrate our solar system and reach the sun’s solar wind they can be swiped away by the sun’s solar wind. If the GCRs get close to the earth, they will take one of the following path: The cosmic ray particles may be caught in the earth’s magnetic field lines and will be funneled into the north or south poles. As shown in Figure 1.1, if the particle traverses the earth’s atmosphere, it will suffer nuclear interactions with air molecules such as nitrogen or hydrogen which will decay into pions or kaons particles. These further decay into charged particles called muons which reach to the surface of the earth [9],[6]. This is called the secondary cosmic ray flux. The flux of these particles can be measured by detectors at the earth’s surface.
Figure 1.1. The interaction between the incoming proton and air molecule creates a shower of particles such as $\pi_0$, $\pi^-$, $\pi^+$ and $\kappa_0$, $\kappa^-$, $\kappa^+$. These mesonic particles further decay into $\mu^-$ and $\mu^+$ where $\mu^-$ can be detected at the surface of the earth.
CHAPTER 2

TWO-SCINTILLATOR PADDLE TELESCOPE AND EXPERIMENTAL SETUP

2.1 Two-scintillator paddle telescope

A two-scintillator paddle telescope was used to detect secondary cosmic ray particles at the earth’s surface. The detector consists of two paddles made from scintillation material that can either sit directly on top one another or rest above one another separated by some distance. Each scintillator paddle (with dimensions $33 \times 7 \times 1 \text{ cm}$ with a detecting area of $230 \text{ cm}^2$), light guide and cookie are all connected together and wrapped in black tape. The cookie part of the scintillator paddle connects to a photomultiplier tube (PMT). When ionizing radiation traverses the detector paddle and interacts with the scintillation material a flash of light is produced. The light is then reflected down to a light guide which funnels the light to the face of photomultiplier tube. Once the light is detected from the photomultiplier tube an electrical signal via the photoelectric effect is generated. It is essential for the detector to have 2 paddles working together in order to have coincidence. The term coincidence means that two pulses are generated by the two photomultiplier tubes within a short threshold of 10-15 nanoseconds. If both paddles trigger within this extremely small timeframe then a particle is counted and the data is recorded. Each muon that triggers the detector is given a timestamp shown in Table 2.1. The first 8 digits are the month, day, and year respectively. The 6 digits after the '@' are hour, minute, and second respectively.
Table 2.1. Timestamp information for muon events.

<table>
<thead>
<tr>
<th>Event</th>
<th>Timestamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>03122010@12:11:04</td>
</tr>
<tr>
<td>2</td>
<td>03122010@12:11:49</td>
</tr>
<tr>
<td>3</td>
<td>03122010@12:12:34</td>
</tr>
<tr>
<td>4</td>
<td>03122010@12:13:03</td>
</tr>
<tr>
<td>N</td>
<td>...</td>
</tr>
</tbody>
</table>

Figure 2.1 shows the two-scintillator paddle detector running at Georgia State University (GSU) (33° 44’ 56” N / 84° 23’ 17” W with altitude approximately 320 m above sea level).

Figure 2.1. Two-scintillator paddle detector taking data on the 9th floor of Petit Building.
CHAPTER 3

ANALYSIS OF COSMIC RAY FLUX MEASUREMENTS

3.1 Cosmic ray flux on 5th floor the Natural Science Center

3.1.1 No paddle separation

The two-scintillator paddle detector collected count data from 12/3/2009 - 1/27/2010 on the 5th floor of the Natural Science Center with a 0 inch paddle separation. For easy monitoring, the timestamp information from each count was used to construct muon flux rate plots. It is observed from the bottom plot in Figure 3.1 that the % flux variation from the mean for 12/3/2010 - 12/17/2010 fluxuated only 4-6 % per hour. It is also seen that the flux variation is higher for 12/3/2010 - 12/9/2010 and then decreases for the rest of the time period. To understand the changes in the overall muon flux rate during this time, it was helpful to plot the daily muon flux rate variation as shown in Figure 3.2 where the % daily variation of counts fluxuates 2-3 % per day. Due to the changes in the hourly and daily muon flux, numerous hourly and daily rate plots were made regularly in order to properly monitor the muon flux.

3.1.2 Paddle separation of 7 inches

In order to observe potential changes in muon flux rate, the detector paddles were separated from 0 to 7 inches. After these changes, the detector continued to collect data on the 5th floor of the Natural Science Center from 1/27/2010 - 7/31/2010. The top of Figure 3.2 shows the raw counts as a function of time in hours and the bottom of Figure 3.2 shows the % variation from the mean of the counts as a function of time in hours. When the paddles were separated the raw counts/hr decreased and
the % variation from the mean increased from a 3-6 % to 15-20 %. The decrease in raw counts produced by the increase of the paddle separation is a direct result of the decrease in the angular acceptance of the detector.

3.2 Cosmic ray flux on 9th floor of the Petit Building

3.2.1 Paddle separation of 7 inches

After monitoring, collecting data, and analyzing the cosmic ray muon flux of the detector at the Natural Science Center, it was moved to the 9th floor of the Petit Building at Georgia State University where it collected data from 8/1/2010 - 3/22/2011. The separation of the two-scintillator paddle detector was still 7 inches.

Weather data from http://www.wunderground.com was utilized to make plots of muon counts and the two major contributing atmospheric parameters, barometric
pressure (hPa) and surface temperature (F). Figure 3.3 shows no correlation or anti-correlation between daily muon counts and the surface temperature (F); however, a strong anti-correlation was observed between the daily counts and the barometric pressure (hPa).

The inverse relationship between cosmic ray flux and pressure variations at the surface of the earth have long been observed. As the muon particles traverse the atmosphere, they interact with air molecules; if there are more air molecules for the muon to collide with then lower counts are generally seen at the surface [7]. If there are less air molecules to interact with then the flux rate is higher. This physical process is due to scattering. Upon increasing or decreasing the separation of paddles, the acceptance angle of the cone created above the detector paddles is changed. When
the separation is increased, the cone becomes more narrow, accepting fewer muons. When the separation is decreased, the cone becomes larger, accepting a wider range of muon particles.

Figure 3.5 illustrates the anti-correlation between the % count variation from the mean and barometric pressure (hPa). Figure 3.6 illustrates the anti-correlation with the correlation coefficient $r = -0.76$, and the slope $= -0.95 +/- 0.17 \%$/hPa.

Figure 3.7 illustrates the anti-correlation between the % count variation from the mean and barometric pressure (hPa) for 7/7/2010 - 7/30/2010. Figure 3.8 further illustrates the anti-correlation with the correlation coefficient $r = -0.70$, and the slope $= -0.84 +/- 0.19 \%$/hPa.
Figure 3.4. Cosmic ray muon flux, pressure, and surface temperature variation as a function of time in days for 9/1/2010 - 9/30/2010.

Figure 3.9 illustrates the anti-correlation between the variation from the mean for the barometric pressure (hPa) and the variation from the mean for the cosmic ray flux for 8/1/2010 - 8/26/2010. Figure 3.10 illustrates the count variation against the barometric pressure (hPa) further representing the anti-correlation where the correlation coefficient $r = -0.70$, and the slope $= -1.3 +/-. 0.30 \%$/hPa.

Table 3.1 summarizes the information between the cosmic ray flux and barometric pressure. Each row contains the data period used for analysis, correlation coefficient $r$, and the slope. The average slope for the time periods is 1.03 %/hPa.
Figure 3.5. Daily count and pressure variation as function of time for 6/1/2010-6/25/2010 in the 9th floor of the Petit building.

In Figure 3.11 the cosmic ray flux and the barometric pressure are illustrated as functions of time and their corresponding 10 day running averages for 7/31/2010 - 3/22/2010. Calculating the running average is useful for eliminating some of the statistical fluctuations in the data and also observing long term trends in data. During this period there was a maximum count amplitude at the beginning of August 2010 of 30.0% and a minimum of -10.0% in December 2010. The percent variation of counts was 40% during this time period with maximum and minimum peaks in summer and winter, respectively. The anti-correlation of the percent variation from the mean of the cosmic ray muon counts and barometric pressure can be seen in Figure 3.11.
Figure 3.6. Relative variation of daily count vs. relative variation of daily pressure for 6/1/2010-6/25/2010 in the 9th floor of the Petit building.

For this time period $r = -0.51$ and the slope = $-3.2 \pm 0.1\%$/hPa. Based on the statistical information determined from the data during this period it was observed that this high and low effect in the counts along with change of the pressure indicated a seasonal variation.
Figure 3.7. Daily count and pressure variation as function of time for 7/7/2011-7/30/2011 in the 9th floor of the Petit building.

3.2.2 *Barometric pressure correction*

Using the relationship between counts and pressure

\[
\frac{\delta I}{I} = -\beta \delta P
\]

(3.1)

a derivation of the newly corrected counts is given by

\[
I = I_0 e^{-\beta (P - P_o)}
\]

(3.2)
where \( I \) is the corrected counts, \( I_o \) is the original counts, \( \beta \) is the barometric coefficient given in \%/hPa, \( P \) is the pressure, and \( P_o \) is the average pressure [8]. In order to find of the barometric coefficient, the variances (\( \sigma_P \) and \( \sigma_I \)) must be calculated. They are given as

\[
\sigma_I^2 = \frac{\sum_{i=1}^{N} (I_i - \frac{I}{I_o} - 1)^2}{N} \tag{3.3}
\]

and

\[
\sigma_P^2 = \frac{\sum_{i=1}^{N} (P_i - P_o)^2}{N} \tag{3.4}
\]
Figure 3.9. Daily count and pressure variation as function of time for 8/1/2011-8/26/2011 in the 9th floor of the Petit building.

where $N$ is the total number of data, $I_o$ is the average count, $I_i$ is each count, and $P_i$ is each pressure measurement.

\[
I_o = \frac{\sum_{i=1}^{N} I_i}{N} \quad (3.5)
\]

\[
P_o = \frac{\sum_{i=1}^{N} P_i}{N} \quad (3.6)
\]

The correlation coefficient between the pressure and counts is calculated using

\[
r = \frac{\sum_{i=1}^{N} (I_i - I_o)(P_i - P_o)}{\sigma_I \sigma_P N} \quad (3.7)
\]
and is used along with $\sigma_P$ and $\sigma_I$ to give

$$\beta = r \frac{\sigma_I}{\sigma_P}$$

(3.8)

The barometric coefficient is different for every detector and generally stays within the range of -0.1 to -0.9%/hPa. Numerous factors such as the range of energy the muon has when striking the detector, detector separation, altitude of the detector, and the geomagnetic rigidity contribute to the numerical value for the barometric coefficient [11].
Table 3.1. The different time periods along with corresponding correlation coefficients between pressure and count variation and the slope in (%/hPa).

<table>
<thead>
<tr>
<th>Time period</th>
<th>cor. factor</th>
<th>slope (%/hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1/11 - 8/26/11</td>
<td>-0.70</td>
<td>-1.3 +/- 0.30</td>
</tr>
<tr>
<td>6/1/10 - 6/25/10</td>
<td>-0.76</td>
<td>-0.95 +/- 0.17</td>
</tr>
<tr>
<td>7/7/10 - 7/30/10</td>
<td>-0.70</td>
<td>-0.84 +/- 0.19</td>
</tr>
</tbody>
</table>

Figure 3.11. The black curve in the left figure is the Raw daily counts vs. Time (in days) for the period 8/1/2010 - 3/22/2011 where the red curve is the 10 day running average of the counts. The black curve in the right figure is the barometric pressure (hPa) vs. Time (in days) for the period 8/1/2010 - 3/22/2011 where the blue curve is the 10 day running average of pressure.
A strong anti-correlation between the cosmic ray flux and barometric pressure was seen on a daily timescale from the two-scintillator paddle detector on the 9th floor of the Petit Building from 8/1/2010 - 3/22/2011. Therefore, it was possible to correct the counts from the detector using the daily pressure. Table 3.2 shows the different time periods that were selected for calculating the barometric pressure coefficient. To ensure an unbiased result for the barometric pressure coefficient, different days where the correlation between cosmic ray counts and pressure were highest were selected. Also, to achieve an unbiased result it was essential to choose time periods during
Table 3.2. The time period, correlation coefficient, and barometric coefficient and error.

<table>
<thead>
<tr>
<th>Time period</th>
<th>cor. factor</th>
<th>barometric coefficient (%/hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/1/11 - 8/15/11</td>
<td>-0.94</td>
<td>-1.0 +/- 0.39</td>
</tr>
<tr>
<td>6/14/10 - 6/17/10</td>
<td>-0.90</td>
<td>-1.5 +/- 0.59</td>
</tr>
<tr>
<td>11/3/10 - 11/6/10</td>
<td>-0.99</td>
<td>-0.62 +/- 0.05</td>
</tr>
<tr>
<td>1/26/10 - 1/30/10</td>
<td>-0.87</td>
<td>-0.17 +/- 0.10</td>
</tr>
<tr>
<td>2/3/11 - 2/6/11</td>
<td>-0.90</td>
<td>-0.39 +/- 0.19</td>
</tr>
<tr>
<td>3/9/11 - 3/10/11 &amp; 3/15/11 - 3/16/11</td>
<td>-0.82</td>
<td>-0.32 +/- 0.22</td>
</tr>
</tbody>
</table>

different months that had a high correlation between counts and pressure while also having minimal variations in solar activity, as solar activity can alter muon flux rates.

3.2.3 Correlation between effective temperature and stratospheric temperature

The atmospheric temperature varies across the seasons as does its density. This change in the density causes variations in the muon rate. As the cosmic ray particles interact with the air molecules they decay into pions or kaons. These particles further decay into muons. During the summer, the atmosphere is warmer, taller, and less dense. After a cosmic ray interaction far above the Earth, pions and kaons propagate through a long stretch of atmosphere which is not very dense. Thus, these pions and kaons are less likely to interact and more often decay into muons. During the winter, the atmosphere is colder, more shallow, and more dense. Cosmic ray interactions happen closer to the earth's surface in a more dense environment. In this dense environment pions and kaons have a larger likelihood of interacting and a lesser likelihood of decaying into muons [6].

In studying the relationship between cosmic ray flux and temperature, the effective temperature was considered due to the lack of an isothermic atmosphere. The effective temperature on average remains fairly constant across several days, although
the temperature at the earth’s surface can change quite drastically on a day to day basis. The higher in the atmosphere the less drastic the change in temperature [6].

Effective temperature depends on pressure and temperature at different heights in the atmosphere. Effective temperature properly represents the temperature of the atmosphere under the assumption that the muons come from the pion contribution and not the kaon contribution. Effective temperature is given as

\[ T_{eff} = \frac{\int_{0}^{\infty} \frac{dX}{X} T(X) (e^{-X/\Lambda_{\pi}} - e^{-X/\Lambda_{N}})}{\int_{0}^{\infty} \frac{dX}{X} (e^{-X/\Lambda_{\pi}} - e^{-X/\Lambda_{N}})} \]  

(3.9)

where \( \Lambda_{\pi} \) and \( \Lambda_{N} \) are the attenuation lengths of the pions and nucleons and \( X \) is the atmospheric depth. It is given as

\[ X = \int_{h}^{\infty} \rho(h)dh \]  

(3.10)

where \( \rho \) is density as a function of height [6].

Every 12 hours a weather balloon descended from a weather monitor station in Peachtree City, GA collecting data on pressure, temperature, humidity, and density at various heights in the atmosphere. This data was used to calculate the effective temperature from 0-1000 hPa, the part of the atmosphere that ascends from the ground to the top of the troposphere. It has been long observed that there is also a correlation between the cosmic ray flux and the bottom region of the stratosphere (40-80 hPa). Using the data from Peachtree City and equations 3.9 and 3.10 the effective temperature for this region was calculated.

Figure 3.13 shows the pressure corrected muon flux rate decreasing from 8/1/2010 - 3/22/2011. Figure 3.14 and Figure 3.15 show a decrease in effective temperature and stratospheric temperature, respectively, during the same time period. Figure 3.16
shows a strong correlation between the cosmic ray flux, effective temperature and stratospheric temperature. The strength of correlation between counts and effective temperature is 0.75 and strength of correlation between counts and stratospheric temperature is 0.43. A seasonal variation in the cosmic ray muon flux is also observed with a maximum count rate of 150-170 count/day in the summer and a minimum count rate of 110-120 counts/day in the winter.

Figure 3.13. Pressure corrected daily counts as a function of time for 8/1/2010 - 3/22/2011.
Figure 3.14. Effective temperature as a function of time for 8/1/2010 - 3/22/2011.

3.2.4 Forbush decrease

There are numerous solar parameters that can potentially modulate the cosmic ray flux seen at earth’s surface. One in particular is the interplanetary magnetic field (IMF). The IMF is part of sun’s magnetic field carried by the solar winds. As the sun becomes extremely violent its magnetic field lines can snap sending out streams of particles carried by the solar winds into space. This process is called a Coronal Mass Ejection (CME). These highly energetic particles emitted by the sun through CMEs deflect many GCRs that arrive from other parts of the solar system. A highly
active sun with a highly disturbed IMF can negatively modulate the muons detected at the surface of the earth. This process is known as a Forbush decrease.

Most of the cosmic ray muons at the earth’s surface are modulated by the barometric pressure. In order to pull out the Forbush decrease, the cosmic muon data was corrected for pressure effects. Figure 3.17 shows the hourly cosmic ray muon flux along with the hourly IMF as a function of time. For nearly 60 hours (1.5 days) the cosmic ray flux stayed fairly constant and at 19:00 on 8/2/2010 there was a decrease in the muon flux rate. Using the equation for relative amplitude variation of the

Figure 3.15. Stratospheric temperature (40-80 hPa) as a function of time for 8/1/2010 - 3/22/2011.
Figure 3.16. The figure on the left is the pressure corrected daily counts vs. effective temperature (K) with correlation factor 0.75 and the figure on the right is the pressure corrected daily counts vs. stratospheric temperature (K) with correlation factor 0.43.

The cosmic ray flux

\[ A = \frac{r_b - r_{fb}}{r_b} \]  \hspace{1cm} (3.11)

\( r_b \) being the flux rate before the forbush event, \( r_{fb} \) being the rate just after the forbush event takes places, and \( A \) the amplitude a decrease of -29.7\% in the flux rate occurred with a 120\% increase in the IMF. Although the flux rate tended to increase and decrease within a 10-15 \% margin on the hourly timescale a drop close to 30\% was significant and the cosmic ray flux observed by the detector was effected by this large increase in the IMF.

3.2.5 Correlations between corrected counts and solar activity

It has been observed that the cosmic ray muon flux changes as the sun becomes more or less active. Solar weather parameters such as the sun’s plasma speed, the KP index (planetary magnetic field strength), and the IMF are measures of the sun’s activity. If the sun’s activity increases the incoming particles can be swept away
Figure 3.17. Counts/hr and hourly IMF (nT) as function of time for 8/1/2010 - 8/5/2010.

causing a decrease in the secondary cosmic ray flux. A decrease in the sun’s activity allows for more incoming particles and a higher muon flux can be observed at the earth’s surface [10].

Figure 3.18 shows the daily muon count variation (black line), the daily pressure corrected count variation (red line), and the daily plasma speed variation. Figure 3.19 shows the daily muon count variation, the daily pressure variation, and the daily KP index variation. Figure 3.20 shows the daily muon count variation, the daily pressure corrected muon variation, and the daily IMF variation. The detector configuration consists of scintillator paddles separated by a distance of 7 inches. Based on the data
shown in the figures for these periods no apparent pattern is observed between the
cosmic ray muon flux variation, the corrected cosmic ray flux muon variation, plasma
speed, KP index or IMF index.

Figure 3.18. The daily muon count variation and plasma speed variation for

3.3 Paddle separation of 14 inches

After observing the anti-correlation between the cosmic ray muon count variation
and the barometric pressure variation, the two-paddle detector was then raised from
7 inches to 14 inches to further test the relationship between the count variation and
pressure variation. By raising the scintillator paddles, an even more narrow cone is
produced above the detector, allowing the two-scintillator paddles to detect particles
traversing the cone. By increasing distance between the paddles, an even greater anti-correlation is expected to be observed in the data from the detector.

It was observed that the hourly and daily muon flux rate, barometric pressure, and temperature fluctuated a significant amount during the time period 3/22/2010 - 7/31/2011. No pattern or trend was seen in the data. After the results for this time period were observed, there was no conclusion evident, therefore, the paddles were placed back to a 7 inch separation and continued running.
Figure 3.20. The daily muon count variation and IMF index for 11/1/2010 - 11/30/2010.
CHAPTER 4

NEW PROTOTYPE TELESCOPE

4.1 Two-scintillator paddle prototype telescope

A second two-scintillator paddle telescope was constructed which measures 30.5 x 15.2 x 0.95 cm and has a detecting area of 464 $cm^2$, which is double that of the previous two-scintillator paddle detector. One of the goals for this detector is to provide a larger detecting surface area which allows for a higher count statistics when studying the correlation between variations in cosmic ray flux and barometric pressure.

The acrylic light guide was constructed by using Snell’s Law, the critical angle for the light guide was calculated as

$$\theta_c = \theta_i = \arcsin\left(\frac{1.00}{1.50}\right) = 41.8^\circ$$

where the acrylic medium has an index of refraction of 1.50 and its interface air has an index of refraction of 1.00. The light guide’s critical angle is 50° and was designed so that its critical angle was above 41.8°. If the light incident on the border is less than 41.8° the light is internally reflected and lost. If the critical angle is above 41.8° then the light stands a better chance to be reflected towards the bottom of the light guide and captured through a cylindrical piece called a cookie. A visual of the light guide and the attached cookie is shown in Figure 4.1.

A new prototype cookie was constructed by implanting two LED lights, one red and one yellow, into the side of each cookie as shown in Figure 4.2. Using this set-up, a function generator was used to control the frequency of the the LED light. At the
same time, an oscilloscope was used to look at the output pulse of the photomultiplier tube. If the oscilloscope and function generator had pulses of the same frequency then it was concluded that the photomultiplier tube was in proper working condition.

Figure 4.2. Cookies with a yellow and red LED infused into each upper side.

Once the cookie, light guide, and scintillator were cut to design they were lightly sanded by hand using medium to hard grade sandpaper shown in Figure 4.3. After
sanding, a clear optical cement resin mixture was used to fuse the scintillator, light
guide and cookie together. The cement was mixed by parts. The mixture was placed
in a vacuum for 15-20 minutes, as shown in Figure 4.6, so that the air could be
removed from the cement. The process of removing the air from the mixture allowed
for the light to be more easily transmitted to the surface of the photomultiplier tube
instead of being reflected back and losing light when passing through an air bubble.

Masking tape was applied to the sides of the scintillator paddle, cookie, and light
guide. After the mixture was ready and the pieces were cleaned and taped, a small
amount of optical cement was applied to the surface inside the light guide, on the
roughed edge of the scintillator and to the inside of the cookie. One scintillator paddle
was then placed faced down on top of the cookie inside of a box taped down and left
to set and harden for 24 hours. The next day the second scintillator underwent the
same treatment.

Once the two paddles were ready, a methanol treatment was applied again to
each paddle to assure a clean scintillator. Regular aluminum foil was used to wrap
the scintillator. The aluminum foil was cut into sheets and washed with detergent and cleaned again with methanol as shown in Figure 4.7.

Each scintillator was double wrapped with the aluminum foil. Optical grease was then applied to the face of each photomultiplier tube and then pressed gently to the face of each paddle’s cookie. Four metal hooks were placed onto the edge of each cookie. The flat parts of the hook were taped to the photomultiplier tube in order to secure the cookie and photomultiplier tube together. Teflon tape was then used to wrap around the side area of the cookie and then black electrical tape was used to ensure a secure connection between cookie and photomultiplier tube. This tape was also important in order to keep outside light from entering the face of the tube. The procedure mentioned above is shown in Figure 4.8. Lastly, each detector was then inserted into a cutout piece of PVC pipe and attached securely with electrical tape as shown in Figure 4.9. The completed two-scintillator paddles are shown in Figure 4.10.

Figure 4.4. Methanol is applied to the detector pieces for cleaning before they are all cemented together.
After the paddles were completed, they were placed directly above one another with approximately a 6 inch distance between the two. Voltage was supplied to each photomultiplier tube and each signal was read out by an oscilloscope. The signals of the photomultiplier tubes were positive dynode signals as shown in Figure 4.11. The dynode signal in contrast to the anode signal has a much larger width measuring 5-6 microseconds compared to 10-15 nanoseconds. The integral of the generated pulse, also referred to as the ADC value, is proportional to energy lost in the scintillator. It was of interest to have the photomultiplier tubes with a dynode signal because the pulse widths are much larger than the anode signals. A more accurate ADC value could be integrated with a larger pulse width; thus, a more accurate description of the energy lost in the scintillator could be determined due to their direct proportionality.

4.2 Time of flight (TOF) measurement

Four scintillator detectors all measuring 12 cm x 12 cm were placed on a rack with spacing in between the detectors with the distance between the first and fourth paddles being 245 cm. When a muon particle strikes the scintillator a light pulse is
Figure 4.6. A vacuum pump is used to remove as much air from the mixture as possible.

sent to the photomultiplier tube and generates an electronic signal. Each signal is fed into a discriminator with a delay of 42 ns. The setup requires 4-fold coincidence meaning that each detector signal is fired at the same time. This helps to ensure that the cosmic ray particle seen by the detector is indeed a muon particle and not a random misfire. The coincidence signal is fed into the TDC start. The delayed 42 ns cable from each of the 4 paddles are fed into each of the channels of the TDC. These delayed signals allow for stopping of the TDC so that the TDC values can be read.

Muons arrive at the surface of the earth in particle showers and at various angles. If a muon particle strikes the top scintillator and another separate muon particle simultaneously strikes another paddle the machine measures a triggered event. This is not the true particle track. When taking the time of flight measurements a read out of the TDC values for all the channels is made. If the TDC values are out of increasing order then that event is neglected in the analysis because it is not the same particle and has a different track.
Figure 4.7. The aluminum foil is being cleaned and decrinkled with an application of methanol and paper towel.

Table 4.1. A sample of the different events and their corresponding TDC values.

<table>
<thead>
<tr>
<th>N</th>
<th>TDC 1</th>
<th>TDC 2</th>
<th>TDC 3</th>
<th>TDC 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>179</td>
<td>311</td>
<td>352</td>
<td>394</td>
</tr>
<tr>
<td>2</td>
<td>237</td>
<td>316</td>
<td>388</td>
<td>390</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
<td>192</td>
<td>307</td>
<td>370</td>
<td>394</td>
</tr>
<tr>
<td>5</td>
<td>239</td>
<td>271</td>
<td>401</td>
<td>374</td>
</tr>
</tbody>
</table>

Table 4.1 illustrates the sequential increase of the sample muon TDC values for the experiment. Note that for the 4th event the TDC values are out of order and must be eliminated when doing the analysis.

The data was collected from 9/29/2011 - 9/30/2011 accumulating 400 triggered events and of those 400 events only 139 were selected for analysis. The raw TDC values were then converted to time values by multiplying each TDC value by the resolution of the TDC module, 50 picoseconds/count. Using the simple formula

$$v = \frac{d}{t}$$

(4.2)
the velocities for each event is trivially calculated. Once the velocity of each particle is determined, the equation

$$\beta = \frac{v}{c}$$  \hspace{1cm} (4.3)

can be used to determine what the ratio of $v$ to the speed of light the particle moved. The energy of each muon is then calculated using

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$  \hspace{1cm} (4.4)

where $m$ is the rest mass of the muon, 105.7 MeV/$c^2$, and $v$ is the velocity of the muon particle.

The purpose behind using the new two-scintillator paddle detectors was to be able to measure a large width dynode pulse and gain an accurate ADC value. Also, by calculating the velocity of the particle the energy of the particle was obtained. A distribution of the counts and each of their corresponding times was created with the
mean at 9.6 ns shown in Figure 4.12. A distribution of each particle’s energy was also made with the mean at 262 MeV shown in Figure 4.13.

The average muon particle which strikes the surface of the earth is on the average 1 GeV. The muon particles detected at the Natural Science Center according to the results are on average 25% of what has been observed by others. One reason for this result could depend on the material the muon is passing through before it reaches the detector. The detector is in the basement of a 6 story building which could effect the results. Through the use of GEANT4, a simulation could be constructed to see how much muon energy could be lost in concrete or metals before reaching the detector.
Figure 4.10. The completed detector paddles.

Figure 4.11. Pulses of the two detectors.
Figure 4.12. Distribution of counts vs. time of flight (ns) for 9/29/2011 - 9/30/2011.
Figure 4.13. Distribution of counts vs. energy (MeV) for 9/29/2011 - 9/30/2011.
CHAPTER 5

CONCLUSIONS

In conclusion, a two-scintillator paddle detector was used to measure hourly, daily, and monthly cosmic ray flux distributions. On 4 different occasions the paddles were separated and on 2 different occasions the location of the detector was changed.

The first detector setup had a 0 inch paddle separation and the detector location was on the 5th floor of the Natural Science Center. During this time period the counts were very high due to the large angular acceptance produced by the paddles sitting directly on top one another. During this specific configuration, the hourly counts over the course of a couple weeks vary by a 3-4% and the daily counts vary by 2-3%.

The second detector setup had a paddle separation of 7 inches and the detector location was on the 5th floor of the Natural Science Center. With the scintillator paddles being apart, the geometric acceptance cone that forms above the detector becomes smaller allowing for fewer muon counts. The muon counts go from approximately 2900 counts/hr with no separation to approximately 130 count/hr with a 7 inch separation between the scintillator paddles. It was observed from the 7 inch separated paddle detector that the counts fluctuate much more going from an average of 3-4% variation from the mean per hour to 10-20% variation from the mean per hour.

The detector was then moved the 9th floor of the Petit Building and collected cosmic ray muon data with a 7 inch separation. Plots of daily muon count rates in relationship to barometric pressure and to surface temperature were now made. It was observed from Figure 3.4 that there is no correlation between cosmic ray muon flux and surface temperature with the configuration of the paddles at 7 inch sep-
oration during short term daily measurements. From the same figure there is an anti-correlation between cosmic ray flux and barometric pressure which has been known for some time now. After this observation was seen with this current detector setup and location, other plots of cosmic ray flux variation and barometric pressure variation were made. Various time periods where the correlation factor was high, approximately -0.90, were used to determine the barometric coefficient of -0.62+/−0.70. The error for the barometric coefficient was extremely high meaning that there are other parameters affecting the contribution of the value for the barometric coefficient. Future work can be done to look at all the other contributions of different parameters to the cosmic ray flux which can allow for a more accurate calculation of the barometric coefficient for this detector. After finding the barometric coefficient for the detector, daily counts over the course of a few months were corrected and then plotted along with daily surface and stratospheric temperatures. A seasonal variation of the cosmic ray flux with stratospheric and surface temperature was observed. The warmer months showed a higher count rate and colder months showed a lower count rate. Figure 3.17 shows an intermittent spike where the IMF (nT) increased by approximately 30.0% and the counts/hr decreased by approximately 30.0%. This type of behavior observed by the detector is called a Forbush decrease. Plots of the pressure corrected muon flux variations along various solar activity parameters such as IMF (nT), plasma speed (km/hr), and Kp index were made but no correlation or anti-correlation was observed.

The detector was then raised to a 14 inch separation expecting that there would be an even stronger correlation between the cosmic ray flux and the barometric pressure variations. Hourly plots of the flux variation, pressure variation, and temperature variation was made but there was no observed relationship among these parameters.
A new two-scintillator prototype telescope with double the detecting area of the previous two-scintillator paddle detector was created to increase the detecting area without compromising the separation between the paddles. By doubling the counting area of the new two-scintillator paddle telescope the statistics are increased; the paddles can then be separated and an even stronger anti-correlation between the cosmic ray muon count and barometric pressure can be observed. Before the paddles were used to look at the pressure and cosmic ray flux correlations, there were used in determining the energy of muons. This resulted because of the dynode pulses of the PMTs. A time of flight experiment was conducted with the 2 new paddles and 4 detector generating anode signals. ADC values were used to find time of flight, velocity, and then lastly energy of the particle. It was determined that the average muon energy was 262 MeV. This is much smaller than what has been observed. Simulations should be done to find out what may have affected the particle’s energy in such a way.

The new two-scintillator paddle detector is now currently taking muon count data in the Natural Science Center. The correlation between the muon counts and barometric pressure should be studied to see if there is a strong anti-correlation with using the new paddle detector. Other possible correlations and anti-correlations between muon counts with temperature, cloud coverage and solar activity should be studied as well.
REFERENCES


