Construction and Characterization of Neutron Monitor at Daejeon, Korea

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Abstract: The amount of cosmic radiation entering the Earth’s atmosphere is determined by, and is therefore an indicator of, the level of solar activity. As the solar activity approaches a maximum, the counts cosmic rays get increased. A NM64-type neutron monitor was installed at the Korea Research Institute of Standard Science in Korea in 2011 with a cutoff rigidity of 11.2 GV. The aim of this study is to analyze the barometric coefficient and the diurnal variation of Daejeon neutron monitor. The barometric coefficient and the diurnal variation are analyzed with data acquired during 2012. A reliable barometric coefficient is determined, -0.6597 ± 0.0004 %/hPa, and the diurnal variation and the Forbush decrease events are observed. Even though the magnitude diurnal variation less than 1 % is hard to measure, the Daejeon neutron monitor is working well. Moreover, some Forbush decrease events are recorded simultaneously at Daejeon neutron monitor.

Keywords: Daejeon neutron monitor, cutoff rigidity, barometric coefficient, diurnal variation, forbush decrease

1 INTRODUCTION

Cosmic rays are divided into galactic cosmic ray (GCR), solar cosmic ray (SCR), and anomalous cosmic ray (ACR) depending on their origins. They are composed of mostly protons and helium particles [1]. Incident high-energy protons or helium particles generate various secondary particles. Typical secondary particles that can reach the Earth’s surface are neutrons, muons, and gammas. Ordinary SCRs, emitted and accelerated by the Sun, cannot reach the ground level due to Earth’s magnetic field and atmosphere. When a transient and strong solar eruption event occurs, SCRs can affect electronics and even humans at the ground level; this phenomenon is called “ground level enhancement” (GLE). Most of secondaries of GCRs can be detected at the ground level because their energies are usually higher than those of SCRs. The count of GCRs is inversely proportional to the solar activity. Accordingly, both GCRs and SCRs are affected by solar activity.

Cosmic radiation has been thought to indicate solar activity and is considered as a type of environmental radiation affecting the Earth. To monitor the fluence of cosmic rays, the IGY neutron monitor was first developed by Prof. John A. Simpson at the University of Chicago in 1948 [2]. At present, the “18-tube” NM64 monitor is the most widely used neutron monitor in the world. The NM64, weighing about 36 tons, is an improved detector system from the IGY neutron monitor. As shown in Fig. 1, the NM64-type cosmic neutron monitor consists of a polyethylene reflector, lead producer, polyethylene moderator, and detection chamber. When incident secondary neutrons reach the lead producer of the NM64 neutron monitor, evaporation neutrons and low-energy neutrons are produced in nuclear reactions. The evaporation neutrons have an energy distribution that shows a maximum at about 2 MeV and reaches energies up to about 15 MeV. The average number of evaporation neutrons per incident nucleon that causes a nuclear interaction in the lead is about 15, so the lead increases the overall detection probability [3].

The cutoff rigidity of the Haleakula neutron monitor in Hawaii, which no longer acquires data, is about 11 GV. Therefore, it is important to research the influence of cosmic rays based on cutoff rigidity in order to replace the conventional neutron monitors. The cutoff rigidity of Daejeon neutron monitor in Korea is similar with Haleakula one in Hawaii.

The 18-tube neutron monitor installed in Daejeon, Korea, was introduced from Bartol Research Institute in November 2011. Its purpose will be to estimate the exposure dose from cosmic radiation that affects the Earth’s surface and to conduct astronomical research on cosmic rays.

This study aims to confirm the reliability of data acquired from the Daejeon neutron monitor and to explore the possibility of further studies. Initially acquired data is used to analyze the correlation between the atmospheric pressure and the count rate. By analysis, the barometric coefficient is determined and applied to correct the count rate. Then, the corrected count rate over time is used to analyze observed diurnal variations and Forbush decreases.

2 Neutron Monitor at Daejeon

The neutron monitor installed in Daejeon (36.39 N, 127.37 E, 200 m altitude) is a NM64-type detector. This neutron monitor consists of three identical units. Each unit contains six tubes; hence, the designation, “18-tube NM64” neutron monitor. As shown in Fig. 1, the NM64-type cosmic neutron monitor consists of a polyethylene reflector, lead producer, polyethylene moderator, and detection chamber. When incident secondary neutrons reach the lead producer of the NM64 neutron monitor, evaporation neutrons and low-energy neutrons are produced in nuclear reactions. The evaporation neutrons have an energy distribution that shows a maximum at about 2 MeV and reaches energies up to about 15 MeV. The average number of evaporation neutrons per incident nucleon that causes a nuclear interaction in the lead is about 15, so the lead increases the overall detection probability [3].

After these neutrons are moderated in the lead, they are moderated by passing through the polyethylene moderator, a boron trifluoride (BF3) neutron detector, which is sensitive to thermal neutrons, detects the nuclear reaction 10B(n,α)7Li.

For precise cosmic-neutron monitoring, neutron signals should be separated from gamma signals and noise. A pulse-

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height discrimination method is adapted for the separation. In a BF$_3$ detector, pulse heights from gamma rays are generally smaller than the minimum pulse height from neutrons. Therefore, neutron-gamma separation can be used if threshold conditions are set.

Each BP28 counter, 18 channels, is connected in parallel to a DAQ module by using UTP cables. Low voltage is supplied through these cables to data processing circuits at the head of each counter. Each circuit contains a pre-amplifier, pulse-height analyzer, and pulse-height discriminator. Raw signals in detector are sent through these circuits and gathered in the data readout board via UTP cables. The data readout board is connected to the station computer through serial communications links, allowing real-time monitoring. GPS data and barometric information are gathered in the data readout board and transferred to the computer in synchronization with the detector data.

The data acquisition status can be checked with DAG program. A Paroscientific model 216B-102 unit is used for measurement of the atmospheric pressure for later correction, and a GARMIN GA29 GPS module is used for accurate time and location information.

Raw data from the DAQ system has a 1-minute unit data set, which contains the atmospheric pressure, GPS data, and the count rate. The data format is the same as originally developed by Bartol Research Institute. However, the necessity of precisely analyzing multiple time intervals is growing. After data stabilization, we intend to incorporate provisions for the storage of data collected at multiple time intervals into the data format in future studies.

3 Data Analysis

After eliminating initial noises caused by high humidity and other factors, the 1-minute count data are summed for all 18 channels of the Daejeon neutron monitor. Then, 1-minute time series data were summed into hourly time series. These 1-hour time series are presented as percentages. Hourly count rate data during 2012 are used for analysis. Data of abnormal values (because of power failure, maintenance or noisy channel) are eliminated, excluding a total of 70 days.

3.1 Barometric Correction

Atmospheric pressure dominates the count rate of the neutron monitor. Thus the barometric corrected count rate is essential for analysis of primary cosmic ray monitoring. Finding a reasonable barometric coefficient is the first step in data analysis for a newly installed neutron monitor.

The neutron monitor measures secondary cosmic neutrons coming from the extensive air shower, a phenomenon affected by the reaction of cosmic rays and the Earth’s atmosphere. The number of secondary cosmic neutrons decreases with decreasing altitude. The altitude can be changed to the atmospheric depth. Therefore, the thickness of incident material increases as the atmospheric depth increases [7].

In an experiment, the barometric coefficient can be estimated by using the linear correlation between the intensity of cosmic rays $I_i$ and the atmospheric pressure $P_i$ [8]:

$$\beta = r \times \sigma_i / \sigma_P,$$  

where $r$ is the correlation coefficient, $\sigma_i$ is the standard deviation of the count rates and $\sigma_P$ is the standard deviation of the atmospheric pressure. Additionally the correlation coefficient formula follows

$$r = \frac{\sum_{i=1}^{N}(I_i - \mu_i)(P_i - \mu_P)/\sigma_i \sigma_P N}{\sqrt{\sum_{i=1}^{N}(I_i - \mu_i)^2 / \sigma_i^2 N}},$$  

where $\mu_i = \text{mean count-rate}$, $P_0$ is the mean atmospheric pressure, and $N$ is the total number of data points. The error of estimate $\beta$ can be calculated as follow:

$$\Delta \beta / \beta = \pm 1 / r \times \sqrt{1 - r^2 / N - 3}.$$  

Experimentally, the intensity $I$ of any secondary cosmic ray component varies with a small change of the atmospheric pressure $P$ as

$$dI = -\beta dP.$$  

Assuming a constant barometric coefficient in the case of the neutron monitor, Eq. (4) gives

$$I = I_0 e^{-\beta (P - P_0)}.$$  

The influence of the atmospheric pressure is determined using Eq. (5).

Count rate data are analyzed for atmospheric pressure by using Eq. (4), and the barometric coefficient is determined to be 0.6597% hPa$^{-1}$. The correlation coefficient was calculated as 0.92 by using Eq. (2). The error of estimation, calculated by using Eq. (3), is $\pm 0.0004$.

To verify barometric corrections, we fit a 2D correlation graph by using a linear regression, as shown in Fig. 2. The value of $r^2$ is 0.84, which can be determined that fitting is correctly done. Because the calculated barometric coefficient shows reliable, this coefficient is adapted to correct for the effect of the atmospheric pressure by using Eq. (5).

3.2 Diurnal Variation

The shortest cycle of the cosmic ray is the solar time variation, which depends on the rotation of the Earth. The solar time variation is called “diurnal variation” in the field of neutron monitor analysis. The diurnal variation is the result of complex phenomena involving the interplanetary
magnetic field (IMF) and the Earth’s internal magnetic field; in addition, it depends on the latitude and the longitude \[^9\]. In brief, because the intensity of the Earth’s magnetic field, which is one of the factors that impede the progress of incident cosmic rays, varies diurnally, the number of incident cosmic neutrons also shows a diurnal variation.

To analyze the diurnal variation, hourly pressure-corrected data from neutron monitors at Daejeon, Newark, and Nain are used. The pressure-corrected count rate can be fitted as a sinusoidal function \[^10\]. Distributions of the phase and the amplitude of the diurnal variation are obtained by following Eq. \(^6\) fitted with the harmonic approximation function \[^11\].

\[
f(t_i) = A + B \cdot \cos(\omega t_i + C).
\] (6)

Here, \(A\) is the daily average relative count rate, \(B\) is the amplitude of the diurnal variation, \(C\) is the phase of the diurnal variations, and \(\omega\) is the angular frequency. The phase is directly connected to solar time.

The quality of fit, i.e., the measure of deviation from the ideal case, is characterized by the dispersion

\[
d^2 = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} (Y_i - f(t_i))^2,
\] (7)

where \(Y_i\) is the relative count rate for each data point. This value is same with \(1 - r^2\) value. In the case of the Daejeon neutron monitor, we decide to present the fitting of the yearly averaged curves of daily variations, which are found to be more illustrative. Daily data are summed and presented as percentages. Thereafter, averaged daily curves are fitted by using the cosine function of Eq. \(^6\). The amplitude and the phase of the curve are estimated, and the quality of the fit calculated by using Eq. \(^7\). Also, the chi-square value is calculated for each neutron monitor station to confirm the reliability of the fit.

Observation of the diurnal variation confirms the DAQ status and the barometric coefficient. Thus the diurnal variation can be observed only after all the monitoring systems work and the pressure-corrected count rates are calculated correctly. The amplitude of the diurnal variation for the cosmic neutron is less than \(1\%\).

The diurnal variation of the Daejeon neutron monitor presented is in Fig. \[^3\] and is fitted by using Eq. \(^6\). Mean values of the count rates are calculated for each day. Fig. \[^3\] shows that the amplitude of variation is about \(0.24\%\) and that the maximum phase appears at \(16:44\) in local time.

The amplitudes of diurnal variation should be larger at higher latitude stations because of high sensitivity to low energy primary cosmic rays at a low cutoff rigidity. A primary particle’s trajectory is expected to be bent less at high altitude. On the other hand, at low latitude, because of low sensitivity to low energy primary cosmic rays, a tendency exists for low latitude monitors to show lower amplitudes. Additionally, because of the anisotropic shape of the magnetosphere, from interactions between the IMF and the Earth’s magnetic field, the diurnal variation is observed based on local time, not on universal time.

The Newark and the Nain neutron monitors are selected to investigate latitude and longitude effects of the diurnal variation. Maximum phases in local time and the quality of fit values are presented also in Table \[^1\]. Table \[^2\] shows the cutoff rigidity, latitudes and amplitudes of the Newark, Nain, and Daejeon neutron monitors. Variations in the count rates are indicated by local time. As expected, the amplitude is lower at a lower latitude, and the phase coincides with others in local time. Consequently, the diurnal variation of the Daejeon neutron monitor match the general tendency of diurnal variation.
Table 1: Results of sinusoidal fit for the diurnal variations at the Daejeon, Newark and Nain neutron monitors. Data are gathered from Spaceship Earth.

<table>
<thead>
<tr>
<th>station</th>
<th>maximum phase (LT)</th>
<th>quality of fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daejeon</td>
<td>14:19</td>
<td>8.68E−3</td>
</tr>
<tr>
<td>Newark</td>
<td>13:07</td>
<td>7.04E−3</td>
</tr>
<tr>
<td>Nain</td>
<td>14:21</td>
<td>5.93E−3</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of the diurnal variations at the Daejeon, Newark and Nain neutron monitors.

<table>
<thead>
<tr>
<th>station</th>
<th>cutoff rigidity</th>
<th>latitude</th>
<th>amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daejeon</td>
<td>11.2 GV</td>
<td>36.4N</td>
<td>0.24 %</td>
</tr>
<tr>
<td>Newark</td>
<td>2.4 GV</td>
<td>39.7N</td>
<td>0.27 %</td>
</tr>
<tr>
<td>Nain</td>
<td>0.45 GV</td>
<td>56.6N</td>
<td>0.31 %</td>
</tr>
</tbody>
</table>

3.3 Forbush Decrease

The Forbush decrease (FD) is one of remarkable variation phenomena of cosmic ray intensity. This phenomenon consists of sudden drop and slow recovery. Typically the recovery phase takes a week. The interplanetary (IP) shock caused by coronal mass ejection (CME) could occur a FD event. FDs are usually observed by particle detectors on the Earth such as the neutron monitor, within a few days after CME.

When a sudden decrease recorded on neutron monitor is observed and a IP shock is also observed at the same time, it can be confirmed as a FD event. The IP shock is identified by Advanced Composition Explorer (ACE) satellite at the Lagrangian point, L1. As the location of L1 point is much close from Earth than Sun, there is almost no time gap between IP shock and FD observation on the Earth.

A bright and fast eruption (halo CME) with an intense solar X-ray flare (X5.4) occurred on 7 March 2012 at 00:15 UT in active sunspot AR1429, facing the Earth. The effect of the CME was reached on 8 March 2012 at 10:53 UT. As shown in Fig. 5, Daejeon neutron monitor observed a sudden change simultaneously with the ACE satellite. Its drop rate in percent is 4.83 %. From the starting time at 10:53 UT during about half a day, the decrease was continued and then the recovery phase started. On 12 March 2012, there was another IP shock. Therefore incident cosmic ray intensity could not be fully recovered. However second FD event didn’t show simultaneous property, it is rare event that another FD event occurs during recovery phase. To account for this second effect, further study should be needed.

4 CONCLUSIONS

A NM64-type neutron monitor was installed in Daejeon, Korea in November 2011 with a cutoff rigidity of 11.2 GV. In order to reliability of data acquired from the Daejeon neutron monitor, we analyzed the barometric corrected count rates recorded at 2012. As the results, the diurnal variation with the small amplitude was observed. Its maximum phase and amplitude were verified by the comparison with other neutron monitors. Some FD events were also identified by the IMF and solar wind data. Thus the process of barometric correction is reasonable to use the data observed by the Daejeon neutron monitor. Furthermore, as the steady-state operation of the neutron monitor ensues, it will be possible to estimate exposure doses due to cosmic rays over the atmosphere in Korea as the contribution to environmental radiation research.

References


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