Long-term variation of galactic cosmic ray intensity observed with the Nagoya multidirectional muon detector

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We analyze long-term variations of galactic cosmic ray intensity observed with the Nagoya multidirectional muon detector during a period between 1970 and 2016 which covers four solar activity cycles. We particularly analyze the rigidity spectrum of the modulation in 16-107 GV rigidity range by using the data recorded in 17 directional channels of Nagoya muon detector together with 6 neutron monitor data. This paper reports very preliminary results of our analysis.

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1. Introduction

We have recently developed a method of correcting the atmospheric temperature effect on the ground level muon count rate by analyzing the data collected with the GMDN (Global Muon Detector Network), which is a global network consisting of four multidirectional muon detectors [1, 2]. This is a significant step, because it makes possible for the first time to analyze the long-term variation (such as 11-year and 22-year variations) of cosmic ray density (i.e. isotropic intensity) in 50-100 GV rigidity range, which has been possible only for cosmic rays around $\sim$10 GV observed by neutron monitors. In this report, we analyze the long-term variation observed with Nagoya multidirectional muon detector (MD) during a period between 1970 and 2016 which covers four solar activity cycles. We particularly analyze the rigidity dependence of variations in $\sim$10-100 GV range by using the data recorded in 17 directional channels of Nagoya-MD together with neutron monitor (NM) data.

2. Data used for analysis

We use muon count rates recorded in 47 years between 1970 and 2016 in 17 directional channels of Nagoya-MD. These count rates are corrected for the atmospheric effects (pressure and temperature effects) and for the instrumental discontinuities in the count rate. For the correction of the temperature effect, we use the mass-weighted atmospheric temperature calculated from the meteorological data provided by the Global Data Assimilation System (GDAS) maintained by the NOAA's Air Resources Laboratory (ARL). It is verified that the large amplitude seasonal variation due to the temperature effect is successfully removed from the observed count rate by our correction method [1, 2].

We also use the pressure corrected data recored by 6 NMs at McMurdo, Thule, Rome, Tokyo, Tibet and Doi Inthanon during the same period. By using Nagoya-MD data together with these NM data, we can analyze the intensity variation in a wide range of the median primary rigidity (P_m) between 16 and 107 GV. We estimate P_m by using the so-called Nagashima's response function for NMs [3] and Murakami's response function for Nagoya-MD [4].

3. Analysis and Result

The lower panel of Figure 1 shows long-term variations of muon count rate recorded in three directional channels of Nagoya-MD and corrected for the atmospheric effects (bottom three colored curves), together with variations recorded by two NMs (top black and gray curves). The variation in each curve is multiplied by an indicated factor to plot all curves on the same vertical scale and is shifted from each other to avoid overlapping. It is seen that all variations recorded by Nagoya-MD and NMs show a common feature of the intensity varying in a clear anti-correlation with the solar activity represented by the sunspot number and the heliospheric current sheet tilt-angle in the upper panel. It is also seen that the variation amplitude is approximately proportional to $1/P_m$ decreasing with increasing P_m. Unknown "seasonal variation" within one year is also notable particularly

in Nagoya-MD data, but we suspect the possibility that this is due to insufficient correction of Nagoya-MD data for atmospheric effect because we see similar variations also in NM data. The origin of this seasonal variation will be analyzed in detail in separate paper.
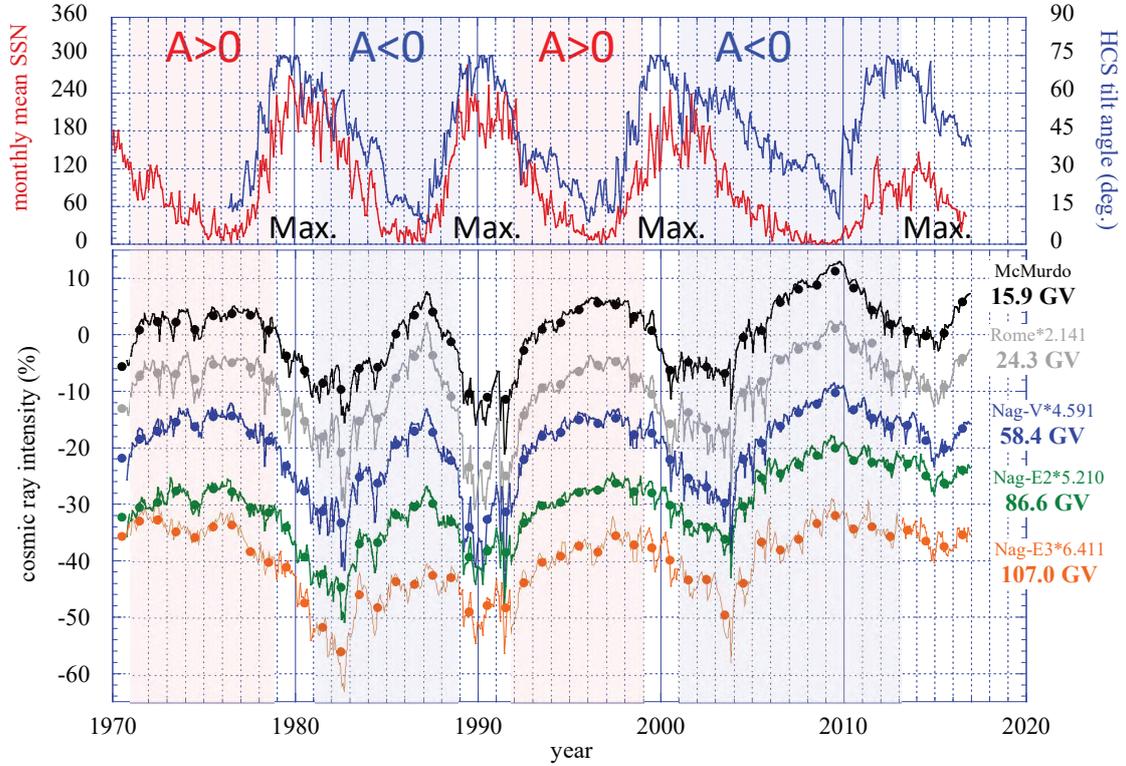
Figure 1: The long-term variation of cosmic ray intensity observed with NMs and Nagoya-MD in a period between 1970 and 2016. Upper panel displays temporal variations of monthly mean sunspot number (red curve) on the left vertical axis and Carrington rotation average of the heliospheric current sheet tilt-angle (blue curve) on the right vertical axis. The polarity (A>0 or A<0) of the solar magnetic dipole and the solar activity maximum and minimum (Max. and Min.) are indicated in the figure. The lower panel shows cosmic ray intensity variations in % observed by two NMs (top black and gray curves) and by Nagoya-MD (bottom three colored curves). Solid circles in each curve show yearly mean intensity, while thin curves with the same color show the Carrington rotation mean intensity. Each curve in the lower panel is multiplied by a factor indicated in the figure to plot all curves on the same vertical scale and is shifted from each other to avoid overlapping.

An interesting feature of variations in Figure 1 is seen in the difference between intensities in A>0 solar minimum around 1976 and in A<0 solar minimum around 1987. The intensity by NMs is higher in A<0 solar minimum than in A>0 solar minimum, but this correlation with the solar magnetic dipole polarity (A>0 or A<0) tends to reverse in high P_m intensity monitored by the Nagoya-MD, implying that the rigidity spectrum of the solar modulation is also time dependent. To analyze the temporal variation of the rigidity spectrum, we first convert the yearly mean intensity ($I_i^{obs}(t)$) observed by the i-th component of total 23 components (6 NMs plus 17 directional channels of Nagoya-MD) in a year t to the intensity ($\Delta I_i^{obs}(t)$) relative to $I_i^{obs}(2009)$ in 2009 when

the McMurdo NM recorded the highest count rate in 1970-2016, as

$$\Delta I_i^{\text{obs}}(t) = 1 - I_i^{\text{obs}}(t)/I_i^{\text{obs}}(2009) \tag{3.1}$$

By assuming a simple power-law spectrum for the modulation, we model the relative intensity, as

$$\Delta I_i^{\text{fit}}(t) = 1 - \int_{P_{ci}}^{\infty} c(t)(p/10\text{GV})^{\gamma(t)} R_i(p) dp / \int_{P_{ci}}^{\infty} R_i(p) dp \tag{3.2}$$

where p is the rigidity of primary cosmic rays in GV, $R_i(p)$ and P_{ci} are the response function and the geomagnetic cut-off rigidity for the i-th component, respectively [3, 4]. We obtain the best-fit parameters $c(t)$ and $\gamma(t)$ in a year t minimizing,

$$S(t) = \sum_i \left(\Delta I_i^{\text{obs}}(t) - \Delta I_i^{\text{fit}}(t)\right)^2 / \sigma_i^2 \tag{3.3}$$

where σ_i is the error of $\Delta I_i^{\text{obs}}(t)$ deduced from the dispersion of hourly count rates in the corresponding year.

The middle panel of Figure 2 shows the best-fit $\gamma(t)$ as a function of year, while the bottom panel shows the bset-fit $1 - \Delta I_i^{\text{fit}}(t)$ (i.e. the second term on the right side of 3.2 representing the modulation magnitude at P_m=10 GV and 100 GV by blue and red curves, respectively. Note that the vertical axis of this panel is reversed for representing the intensity variation instead of the modulation magnitude. It is seen that the modulation spectrum is significantly harder in 1987 than in 1976, resulting in the observed feature in Figure 1 that the intensity at lower (higher) P_m is higher (lower) in A<0 solar minimum than in A>0 solar minimum.

4. Discussion

By using yearly mean intensities observed by 17 directional channels of the Nagoya-MD and by 6 NMs, we analyzed the rigidity spectrum of the GCR intensity modulation in a range of the median primary rigidity between 16 and 107 GV. It was shown that the modulation spectrum is significantly harder in 1987 than in 1976, resulting in the observed intensity at lower (higher) P_m being higher (lower) in A<0 solar minimum than in A>0 solar minimum. This implies that there is a "cross-over" of two spectra in 1976 and 1987 at around 30 GV, in addition to that at ∼7 GV reported from the latitude survey using NMs [5]. Such a pair of two cross-overs at low and high rigidities has been actually predicted by the drift model calculation [6]. While the long-term observation with Nagoya-MD is very important for accurately deducing the modulation spectrum and its temporal variation, our analysis still has to be improved to reduce possible systematic errors arising from incomplete data corrections.

5. Acknowledgment
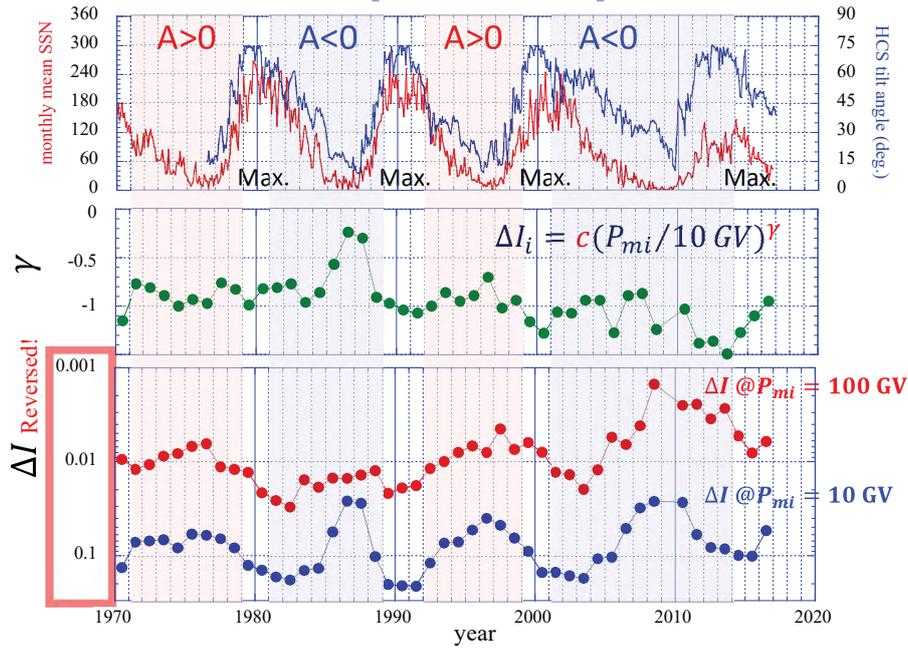
Figure 2: The temporal variation of the rigidity spectrum parameters obtained from best-fitting the power-law spectrum to the observed yearly mean cosmic ray intensity (see text). Middle panel shows the power-law index $\gamma(t)$, while bottom panel displays magnitude of the modulation at 10 GV (blue curve) and at 100 GV (red curve), each as a function of year. Note that the vertical axis of the bottom panel is reversed to represent variation of the intensity instead of the magnitude of modulation. Top panel displays temporal variations of monthly mean sunspot number (red curve) and Carrington rotation average of the heliospheric current sheet tilt-angle (blue curve) in the same manner as Figure 1.

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