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

Very Preliminary Results

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• Correction of the atmospheric temperature effect.
• Long-term intensity variation observed with Nagoya-MD in 1970-2016 (47 years).
  • Variation spectrum of yearly mean intensity
  • Temporal variation of yearly mean modulation spectrum in $16 \text{ GV} < Pm < 107 \text{ GV}$

⇒ “high-energy” cross-over of spectra in 1976 $A>0$ and 1987 $A<0$ solar minima.
Correction of GMDN data for the atmospheric temperature effect

Mass Weighted Method:
\[
\Delta I_T = \alpha_{MSS} \Delta T_{MSS} \quad \alpha_{MSS}(\%/K) < 0
\]

\[
T_{MSS} = \sum_{i=0}^{n} w[h_i] \cdot T[h_i] \quad w[h_i] = \frac{x[h_i] - x[h_{i+1}]}{x[h_0]}
\]

We use Global Data Assimilation System (GDAS) by NOAA’s Air Resources Laboratory (ARL).
- SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on board the TIMED
- Integrated Global Radiosonde Archive, NOAA/ESRL Radiosonde Database

Nagoya-V

Original (pressure corrected)

After removing gaps

After temp. correction
## Data analyzed

<table>
<thead>
<tr>
<th>detector</th>
<th>Geographic lat. ; long. (°)</th>
<th>Alt. (m)</th>
<th>Geomag. cutoff rigidity Pc (GV)</th>
<th>Median primary rigidity Pm (GV)</th>
<th>Data period</th>
</tr>
</thead>
<tbody>
<tr>
<td>McMurdo NM</td>
<td>-77.95; 166.60</td>
<td>48</td>
<td>0.01</td>
<td><strong>16.2</strong></td>
<td>1970-2016</td>
</tr>
<tr>
<td>Thule</td>
<td>76.50; -68.70</td>
<td>26</td>
<td>0.01</td>
<td><strong>16.5</strong></td>
<td>1970-1976, 1978-2016</td>
</tr>
<tr>
<td>Rome NM</td>
<td>41.90; 12.52</td>
<td>60</td>
<td>6.32</td>
<td><strong>20.8</strong></td>
<td>1970-2016</td>
</tr>
<tr>
<td>Tokyo NM</td>
<td>35.75; 139.72</td>
<td>20</td>
<td>11.61</td>
<td><strong>29.3</strong></td>
<td>1970-1996</td>
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<tr>
<td>Tibet NM</td>
<td>30.11; 90.53</td>
<td>4300</td>
<td>14.1</td>
<td><strong>29.6</strong></td>
<td>1999-2016</td>
</tr>
<tr>
<td>PSNM</td>
<td>18.59; 98.49</td>
<td>2565</td>
<td>16.8</td>
<td><strong>35.5</strong></td>
<td>2008-2016</td>
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<tr>
<td>Nagoya MD (17 directions)</td>
<td>+35.15; 139.97</td>
<td>77</td>
<td>8.91 - 17.76</td>
<td><strong>58.4 - 107.0</strong></td>
<td>1970-2016</td>
</tr>
</tbody>
</table>
Long-term variations

- Monthly mean SSN
- Cosmic ray intensity (%)
- HCS tilt angle (deg.)

Year:
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020

A>0
A<0
Max.

McMurdo:
- 16.2 GV

Rome:
- 20.8 GV

Nag-V:
- 58.4 GV

Nag-E2:
- 86.6 GV

Nag-E3:
- 107.0 GV
Variational spectrum

Regression coefficient (Beta)

\[ y = 7.9055 \times x^{-0.86162} \]

Correlation coefficient (R)

\[ y = 0.20562 + 0.467034x \quad R = 0.97 \]
\[ y = 0.086933 + 0.21782x \quad R = 0.95 \]
\[ y = -0.09596 + 0.19198x \quad R = 0.89 \]
\[ y = -0.016844 + 0.15599x \quad R = 0.80 \]
Long-term variations

We normalize the intensity to 2009

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<th>Year</th>
<th>monthly mean SSN</th>
<th>HCS tilt angle (deg.)</th>
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<td>1970</td>
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A>0 A<0 A>0 A<0

Max. Max. Max. Max.
Rigidity spectra relative to 2009

Observed GCR intensity modulation relative to 2009:

\[ \Delta I_i^{obs} (t) = \{ I_i^{obs} (2009) - I_i^{obs} (t) \} / I_i^{obs} (2009) \]

\( i \) : component (1~23)  
\( t \) : year

Simple power-law model:

\[ \Delta I_i^{fit} (t) = \int_{P_c}^{\infty} c(t) \left( \frac{p}{10 \text{GV}} \right)^{\gamma(t)} R_i(p) dp / \int_{P_c}^{\infty} R_i(p) dp \]

\( R_i(p) \) : Response function (RF) of \( i \)-th component to primary GCRs with rigidity \( p \) (Nagashima’s RF for NM, Murakami’s RF for MD)

We obtain \( c(t) \) and \( \gamma(t) \) every year minimizing...

\[ S = \sum_i \{ 1 - \Delta I_i^{obs} (t) - \Delta I_i^{fit} (t) \}^2 / \sigma_i^2 \]

We compare \( f(t) \Delta I_i^{obs} (t) \) with \( \Delta I_i^{model} (t) = c(t) \left( \frac{P_{mi}}{10 \text{GV}} \right)^{\gamma(t)} \)

...where \( f(t) = \Delta I_i^{model} (t) / \Delta I_i^{fit} (t) \)
Variation of spectrum parameters

\[ \Delta I_i = c \left( \frac{P_{mi}}{10 \text{ GV}} \right)^\gamma \]

-\( A>0 \) A\(<0 \) A\( >0 \) A\(<0 \)

Max. Max. Max. Max.

\[ \Delta I \]

Reversed!

\[ \text{HCS tilt angle (deg.)} \]

\[ \text{monthly mean SSN} \]

\[ \text{year} \]

\[ \text{1970} \quad 1980 \quad 1990 \quad 2000 \quad 2010 \quad 2020 \]

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Rigidity spectra relative to 2009

\[ \Delta I_i = c \left( \frac{P_{mi}}{10 \text{ GV}} \right)^\gamma \]

Sol. Max.

Reversed!

Sol. Min.

A>0

A<0

A>0

A<0

32.0 GV

25.1 GV

Fit in previous Min.
Drift model predicts cross-overs (COs)

Reinecke & Potgieter (JGR, 1994)

- Low-P COs predicted at A>0
- High-P COs also predicted

Moraal+ (JGR 94 1989)

- Low-P COs by lat. surveys
- High-P COs predicted but never observed so far


- Low-P COs by lat. surveys
- High-P CO is also predicted but never observed so far
Summary and conclusion

- Based on observations with GMDN, we develop a correction method for the atmospheric temperature effect on the ground-level muon count rate.

- The corrected Nagoya MD data with NM data clearly show the rigidity dependence of long-term intensity variation in $\sim 10$-100 GV.
  - Overall, the variational spectrum of yearly mean data is consistent with $p^\ (-0.9)$.
  - CR rigidity spectra in $A>0$ and $A<0$ minima show high-rigidity counterpart of the “cross-over” reported from NM latitude survey and predicted by the drift model.

- The long-term observation with Nagoya MD is very important for CR modulation study.