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The 48 year data analysis of Nagoya muon telescope

— *Discover of (125± 45) day periodicity* —

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We analyzed 48 years of the data from the Nagoya muon telescope without using the East minus West method. The results confirm the existence of (1) one-year periodic oscillations, and (2) winter (4∼10) day variations. (3) A new (125 ± 45) day cycle was also confirmed. Data analysis of the upper atmosphere revealed that (1) and (2) were caused by altitude variations in the upper atmosphere. While, as for (3), it was found that it appears during the active period of solar activity. Quite surprisingly, the 125 day activity appeared also in the lowest time of solar activity. However the rate of occurrence has decreased with the decline in solar activity since 1992.

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1. Introduction

The construction of the Nagoya University Multi-Directional Cosmic Ray Telescope began as a part of Japan's participation in the International Active Sun Year (IASY), which started in the summer of 1968 [1]. Data from October 1970 to December 2018 are publicly available [2]. The purpose of the installation of this instrument was to search for variations in the heliosphere from cosmic-ray muon data. The data obtained from this instrument confirmed that the phase of the daily variation of the cosmic-ray intensity advances during the time of minimum solar activity [3][4] and various other research results that had been presented. In this paper, we have analyzed the data from a different perspective. This is a report of the results of the analysis.

2. Data of the Nagoya Muon Telescope

The Nagoya University Multi-Directional Cosmic Ray Telescope consists of plastic scintillators with an area of 1 m^2 and thickness of 5 cm. The telescope functions through a two-layer structure. A 5 cm thick layer of lead is installed between the first and second layers to remove the electron and gamma-ray components in cosmic ray showers and observe the muon component. The muon flux from multiple directions is observed simultaneously by triggering a combined signal from the plastic scintillators in the upper and lower layers. Details are given in another article [2]. In this article, only vertically incident muon data are analyzed. The effective vertical solid angle is 10m^2 steradian, the average counting rate is 42,000 per one-hour and the effective cut-off rigidity is estimated at 11.5 GV [2].

The published observations data are described in UT and the barometric pressure fluctuation effects have already been corrected. However, temperature fluctuations are not corrected. To remove this variability, for example, the parameter; G=(30°N-30°S)+(30°N-30°E) has been introduced, and data analysis has been carried out [5]. Berkova *et al.* have also proposed to correct the Nagoya muon data for temperature variations in cosmic ray muon flux from meteorological data [6]. Note that the instruments themselves are in the thermostatic chamber and the temperature variation with respect to the trigger rate is negligible. However, still the atmospheric pressure variation associated with the temperature variation is not corrected. Its removal is a challenging task.

We plotted 48 years of public data and found regular one-year variation in the counting rate, reaching a minimum in mid-summer at the end of July and a maximum in winter. The amplitude is approximately ±20 ‰. This phenomenon is caused by the expansion of the atmosphere during the summer season, which increases the altitude that muons are generated. In other words, the expansion of the atmosphere produces pions higher up in the altitude, increasing the muon decay distance and decreasing the number of muons, which is known as a negative temperature effect.

As a first step in the removal process of the temperature effect, we corrected the inter-annual variation due to temperature by approximation using trigonometric functions as; average_flux = $a + bt + p\sin(2\pi t/\tau) + q\cos(2\pi t/\tau)$ where $\tau = 24 \times 365.25$ hour (one solar year). The difference between the corrected value and the original data (difference=flux-average_flux) was analyzed. The results of analysis based on the dataset are reported here.

3. Analysis methods and results

Only one clear GLE (Ground Level Enhancement) event was observed throughout the entire period (Oct. 14, 1970 ~ Dec. 31, 2018); the event was associated with a flare of X9.8 on 29 September 1989 at 11:33 UT. The flare induced a CME (Coronal Mass Ejection) shock that accelerated the protons of warm particles [7] generated at W90° ~ W95° on the solar surface to higher energies and transported them to the Earth[8][9][10]. No other clear GLE events were found in this data base.

As the resolution would be reduced if a plot of whole period of one-hour value is presented in a figure, the difference data during 2006 and 2018 is first shown in Figure 1, and the results of the Fourier analysis of the data are shown in Figure 2. In Figure 1, there are two examples of events that swing significantly downwards, which correspond to Forbush Decrease (FD). The FD events have not been removed in the current analysis. The Fourier analysis was also carried out for the events at the time of the missing events with a difference of 0. Note that the abscissa of Figure 2 is presented by the logarithmic scale. The sharp peak near 3.68 on the abscissa corresponds to a 24-hour variation, while the peak near 3.98 corresponds to a 12-hour variation. Several peaks are concentrated near 2.25 and a wide peak is recognized near 1.6, corresponding to a 27-day and 125-day cycle, respectively.

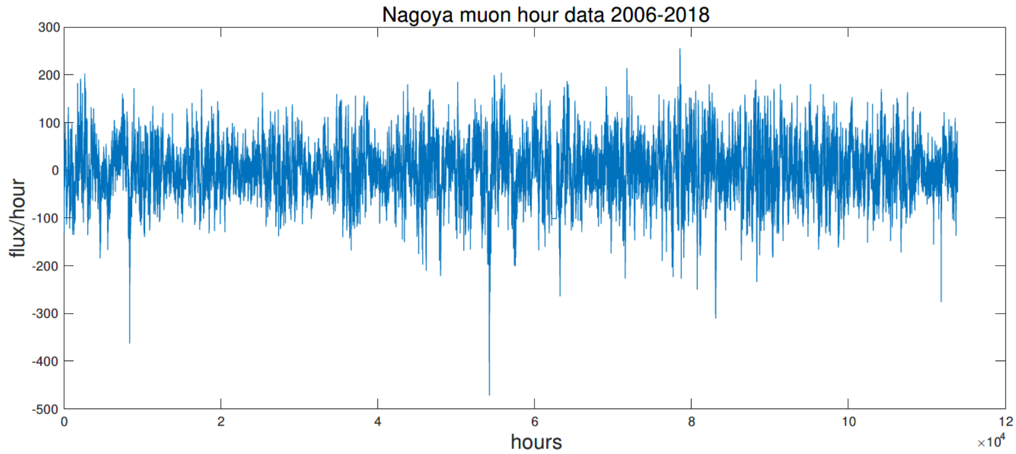

Figure 1: The Nagoya muon difference intensity data (ΔI) during 2006.1.1 and 2018.12.31. Two downward spikes correspond to Forbush Decreases.

To further clarify the presence of these peaks, wavelet analysis was carried out, using the software of Matlab[11]. The results are shown in Figure 3. The vertical and horizontal axes are given by "hour values". Four major features can be recognized: (1) Black dots are concentrated near the 24-hour vertical axis. This is due to solar diurnal variation associated with the rotation of the Earth. Oscillations of this period are present over the entire period of 1970-2018. (2) Next, there is a strong amplitude region near 120 hr. An explanation on this amplitude is given later. (3) Furthermore, peaks corresponding to 27-day variations are discretized around 640 vertical. (4) Then, the presence of a (125 ± 45) day $(125 \times 24 = 3000$hours) cycle is seen in the first half of the period, which appears between 1 January 2006 (left end of Figure 3) and 30 June 2013 (end of June). This period corresponds to the 24th to 25th solar cycles.

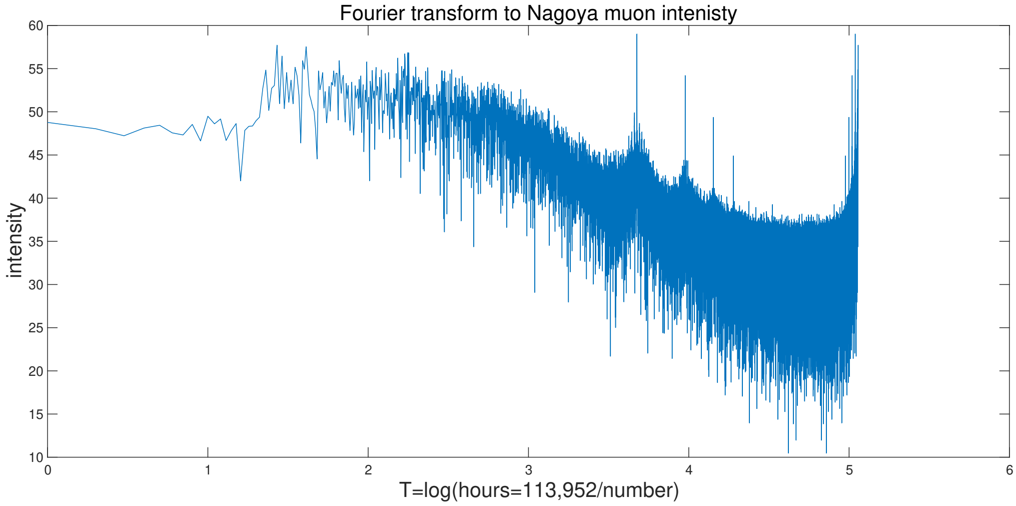

Figure 2: The results of Fourier analysis for the data presented in Figure3. The peak around 3.68 and 3.69 correspond to the 24 hours (one day) and 12 hours periodicity. On the other hand the group of peaks around 2.25 and a wide peak around 1.6 correspond to 27 day periodicity and 125 day periodicity respectively.

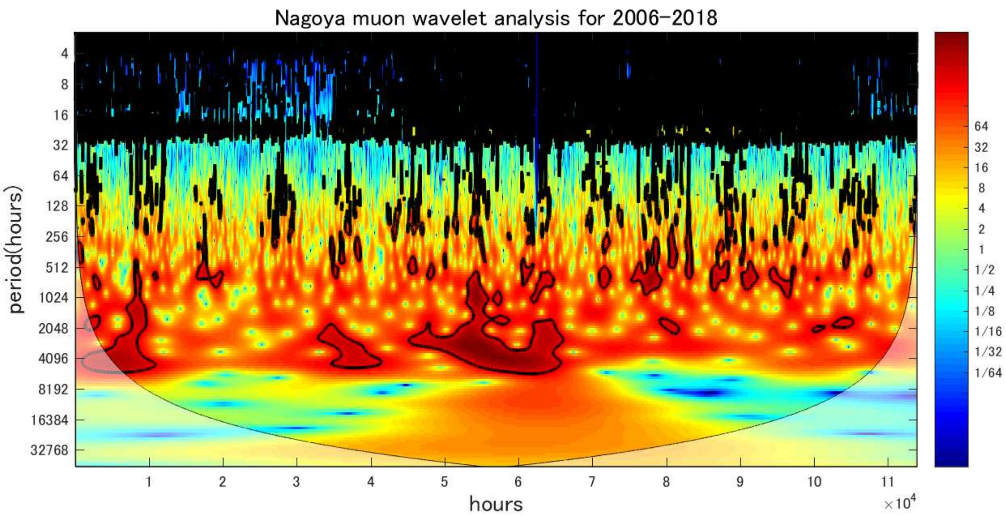

Figure 3: The results of the wavelet analysis by using the Morlet wavelet function to the data set during 2006-2018. Clear periodicity is recognized at 24 hours of the vertical axis. In addition another periodicity can be recognized around 120 hours, but they appear with a half year no active time. Furthermore around 640 h (=27 days) and 3000 h (=125 days), another bump can be recognized. The right-side color bar represents the continuous wavelet transform coefficients where large coefficients are presented by red and small by blue.

Here, in order to see in detail the 24-hour and 12-hour variations in Figure 2, we present the results of the periodic analysis using wavelets for the one-year data set from 2018.1.1 to 2018.12.31 in Figure 4. Strong amplitudes are observed throughout the year with the 24-hour variation. The 24-hour and 12-hour oscillations are highly significant in the statistical analysis, while the 6-hour oscillation is insignificant. On the other hand, the 120-hour oscillations are observed in the first and second half of the period. This corresponds to the winter in Japan.

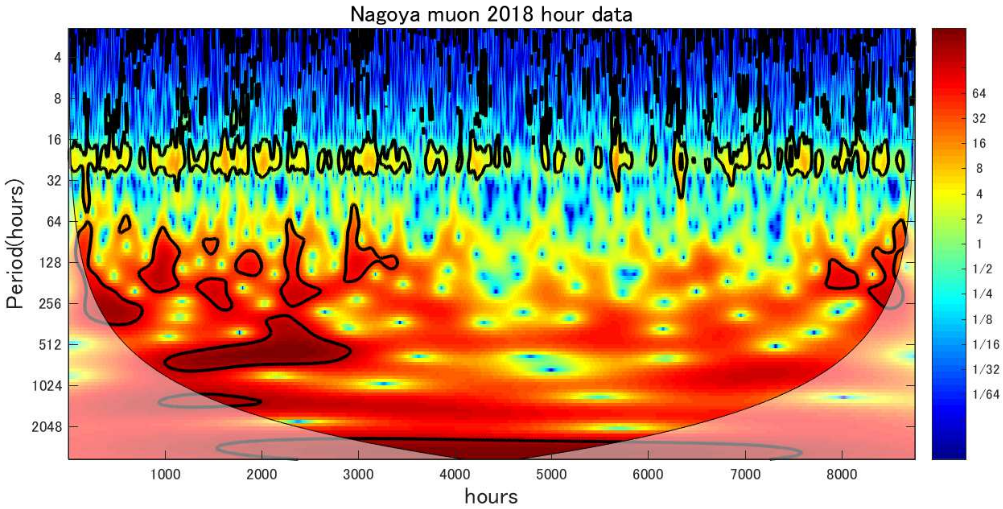

Figure 4: The wavelet analysis for one year data of 2018. We can recognize a clear periodicity along the horizontally line with 24 hours periodicity. Furthermore along the horizontal line from January to April with 120 hours, an interesting periodicity can be recognized.

Finally, the plot for the entire period of analysis is shown in Figure 5. This plot was created for the daily average, so the 24-hour variation has been eliminated. Note that the vertical and horizontal axes are all in the unit of day. The presence of (125 ± 45) diurnal periods is observed. The periods of pronounced 125-day oscillations can be recognized through the 21st, 22nd, 23rd and 24th periods of solar activity.

Quite surprisingly, the 125 day activity appeared in the lowest time of solar activity during 1976 and 1986. However, it does not appear in the subsequent minimum periods, which may be a key to elucidate the phenomenon of decreasing trend of solar activity and an extension of the 11-year cycle. These periods are summarized in Table 1.

4. Discussion

The 24-hour variation in cosmic-ray intensity arises from the Earth's rotation and the 27-day variation (= 648 hours) is associated with the Sun's rotation. They are observed in the data. The 24-hour variation is well known as the solar diurnal variation and has been the subject of numerous studies, so it is not discussed here. The 27-day variation is thought to be due to the effect of the Sun's magnetic field structure on the intensity of cosmic rays traveling near the Earth as the Sun rotates, but we leave the discussions to other papers [12][13].

Here, we will discuss the variation with 125-day period (= 3,000 hour variation), which has yet to be well discussed in the cosmic ray research field to date. First of all, present discussion

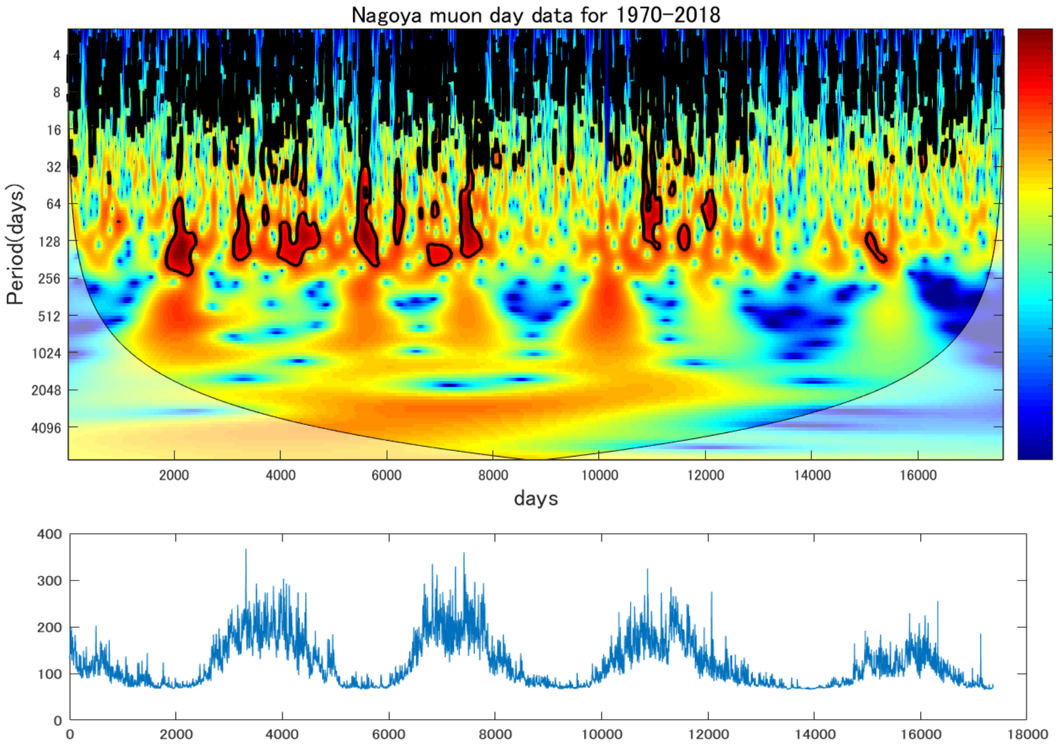

Figure 5: The Matlab-plot shows the results of the wavelet analysis during October 1970 and December 2018 (total duration). The vertical and abscissa are presented by the unit of day. Along the line of vertical value 125 days, several spots are appeared. We confirmed that the enhancements around 125-day have the statistical significance over 5 sigma. The number 16 in the color-bar corresponds to around 3 sigma excess. In order to compare with the solar activity, the 10.7cm solar radio wave intensity data during October 14, 1970 and April 30, 2018 are shown in the under part.

will be compared with the results of various wavelet analyses published in the Katsavrias-Preka-Papadema-Moussas paper [14]. According to the KPM paper, the existence of the 125-day cycle was first noticed by Rieger *et al.* [15]. They found the existence of the cycle from the analysis of solar gamma rays, which they claimed to be a 154-day cycle. Bai and Sturrock also interpreted its origin [16].

KPM paper performed a periodic analysis of a number of solar and geomagnetic parameters, using the NASA OMNI web database obtained by the ACE satellite and other satellites from 1966 to 2006. Among them, we selected the physical quantities in which the 125-day cycle appears, including solar wind velocity and temperature, plasma pressure and density, interplanetary magnetic field strength, Alfven Mach number and plasma beta. However, the 125-day cycle is only noticeable in two specific seasons; mid-1982 and 1989, but not in the other periods. On the other hand, in the cosmic-ray data, 125-day cycles appear around the peak of active solar time. It continues for quite a long time, as shown in Figure 5 [17].

5. Summary

We have analyzed 48 years of observations without using the East minus West method [18]. The results show that the effect of temperature fluctuations on the intensity of cosmic rays can be removed throughout the year, but that the amplitude of the cosmic rays exceeds the effect of temperature fluctuations during the winter season. The variation with (4~10)day periodicity is due to arrival of the Siberian cold air mass to Japan in winter time. On the other hand, the existence of an effect on the intensity of ~ 20 GeV cosmic rays with a periodicity of (125 ± 45) days was confirmed. It was found that it appears both during the peak and quietest periods of solar activity.

This may be a key to understanding the origin of this oscillation. If the oscillations only appear during the periods of high solar activity, it may be possible to assume that a large number of energetic particles are produced on the solar surface during the active period, however if they also appear during the quiet period, it may be necessary to consider another origin. For example, there could be magnetic field oscillations in the heliosphere that we do not know about, which could affect the intensity of cosmic rays. Anyway, the origin of 125 day periodicity is still a matter for future investigation.

Table 1: The number of abscissa represents the day from October 14th, 1970.

Abscissa (days)	**Calender year**	**Solar activity**	**Solar cycle**
1700-2200	1975.6.7-1976.10.19	minimum	
3000-3200	1978.11.28-1979.7.16	maximum	21st solar cycle
4000-4700	1989.9.23-1983.8.24		
5400-5800	1985.7.24-1986.8.28	minimum	
6800-7000	1989.5.24-1989.12.10	maximum	22nd solar cycle
7300-7700	1990.10.06-1991.11.10		
11000	2000.11.22	maximum	23rd solar cycle
11600	2002.7.15		
12000	2003.8.26		
15000	2011.11.5	near maximum	24th solar cycle

6. Acknowledgments

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