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Size of Heliomagnetosphere Derived from Long Term Modulation of Neutron Monitor Intensities

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Abstract

According to the coasting solar wind model, solar activities affecting the galactic cosmic rays in the heliomagnetosphere propagate with solar wind speed from the Sun to the boundary. The cosmic ray intensities are affected by the electromagnetic disturbances from the boundary to the Earth while transporting from galactic space. Therefore, the intensities at the Earth are affected by disturbances being present along the cosmic ray trajectories from the boundary to the Earth. The disturbances at a distance *r* from the Sun at a time *t* can be related to the solar activities at a time *t-r/v*, where *v* is an average solar wind speed. Then, we can relate the intensities at a time *t* and the solar activities during the period from *t-b/v* to *t*, where *b* is the boundary distance from the Sun. We have analyzed the long-term modulation of neutron monitor intensities and solar activities by using multi-regression method, and estimated the size of the heliomagnetosphere at about 150 – 220 a.u..

1 Introduction:

It is well-known that the solar-cycle (11-year) modulation of the galactic cosmic-ray intensity is closely related with the solar activity (Forbush, 1954) and it has a phase lag behind the latter, suggesting that the modulation is controlled by a large magnetically disturbed region (Simpson, 1963; Simpson & Wang 1967). Many studies have been made since then to infer the extent of the region from the phase lag (references therein).

We also studies the influence of the activity to the modulation during 1936-1977 and also during 1953-1992 by using the following regression equation (Nagashima & Morishita 1980a, Morishita & Nagashima 1993) :

$$I_i = I_C + \sum_{j=0}^{j_e} f_j R_{i-j}, \qquad (\, i = 0, 1, 2 \ldots \,), \tag{1}$$

where I_i is the cosmic-ray intensity at the *i-th* month, and the term $f_j R_{i-j}$ is the contribution of the interplanetary magnetic disturbances caused by the delayed effect of the sunspot activity R_{i-j} at the *(i-j)-th* month. We determined the spectrum of f_j within the time interval of about three years. The spectrum, however, might contain some error due to the annual variation of the muon intensity caused by the atmospheric temperature effect, as the analyzed data include those of the ion-chamber at Huancayo. The purpose of the inclusion was to extend the period of analysis as long as possible and also adjust the period to an integer multiple of 22 years. The adjustment was made to eliminate, as much as possible, the influence of the 22-year variation of the comic rays caused by the polarity reversal of the general solar magnetic field, which cannot be simulated by the solar activities with the 11-year periodicity (cf. Jokipii *et al.* 1977; Nagashima & Morishita 1980a,b).

After that time of the analysis, the neutron monitor data have been accumulated and we can now remove the ion-chamber data by adding the neutron monitor data. In the present paper, we make the new set of data from three neutron monitors, Ottawa (Jan. 1953 – Dec. 1967), Deep River (Jan. 1962 – Dec. 1995) and Kiel (Jan. 1964 – Dec. 1997). We normalized those data by using the linear relation between them during overlapping periods. Then, we re-determine the spectrum of f_j by using those data in the period of Jan. 1953 – Dec.1997, which is the integer multiple of 22 years and includes no data of the ion-chamber in the previous analyses.

2 Analysis:

The unknown parameters I_C and $f_0, f_1, \ldots, f_{je}$ in equation (1) were obtained for $j_e = 0, 1, 2, \ldots$ months by using least square method, as the following *RSS* becomes minimum.

$$RSS = \sum_{i=1}^{N} \Delta_i^2 , \quad \Delta_i = I_i^{OBS} - I_i^{SIM} \ , \tag{2}$$

where I_i^{SIM} shows the simulated intensity for f_j-spectrum, I_i^{OBS} the intensity observed by the neutron monitors and *N* the number of data. An example of the spectrum of f_j for $j_e = 38$ is shown in Figure 1. The spectrum is characterized with many peaked groups of the terms with *j* = 0-11, 16-19, 21-22, 25-26 and 29-37. It is noted that the peaks of the spectrum at $j \geq 25$ could not be found in the previous analysis (Nagashima & Morishita 1980a, 1993). This would be due to the influence of the annual variation of the muon intensity caused by the atmospheric temperature effect.

In order to find out the necessary and sufficient parameters, we used the Akaike's Information Criterion called 'AIC' which is defined as a function of the number (*M*) of unknown parameters in a regression equation (Akaike 1973; Sakamoto *et al*. 1986), as

$$AIC(M) = N\{\ln(2\pi) + 1\} + N\ln(RSS) + 2(M+2) \ . \tag{3}$$

The *AIC* tells us that if it is increased by the introduction of an additional parameter into the regression equation, the introduction is not appropriate even if *RSS* becomes smaller.

We obtained $AIC(j_e + 2)$ of the present simulation for j_e = 38, i.e. *M* = 40. And then, we select the f_j which has the smallest F-Value from among the parameters as shown in Figure 1. Next, we re-obtain the new set of f_j s for reduced number of parameters, i.e. *M* = 39. Thus and so, we tried to reduce *AIC* by eliminating some f_j s, which do not effectively contribute to the modulation, and found finally that the minimum *AIC* can be obtained by the series of f_j s with *j* = 0-1, 3, 5, 7, 10-11, 19, 32 and 37. In Figure 2, we show the *AIC* depending on the number of parameters *M* and its minimum at *M* = 11. The most appropriate f_j-spectrum thus obtained is shown in Figure 3. It is clear that the eliminated parameters f_j s from original series (*j* = 0, 1, …, 38) are those of small absolute values in Figure 1. This certifies the effectiveness of the criterion.

The simulated intensity I_i^{SIM} for the best f_j-spectrum in Figure 3 is shown in Figure 4, together with the observed intensity I_i^{OBS}, the sunspot number R_i and the residual Δ_i. The observed and simulated intensities are considerably different from each other, as can be seen by the residual in the figure. The main cause for the large residuals cannot be attributed to the incomplete simulation, as they show a systematic variation of 22 years rather than 11years. The variation is positive in the period of the away magnetic field (+) from the Sun in the northern hemisphere (N) observed every two solar cycles. Then it can be interpreted as being due to the difference of the latitudinal drift motion of the cosmic rays in the solar magnetic field with different polarity (Jokipii et al. 1977). This implies that the analysis using equation (1) is effective not only for the simulation of the solar-cycle modulation but also the derivation of the 22-year variation, as has been pointed out in the previous papers (Nagashima & Morishita 1980a,b; Morishita & Nagashima 1993).

3 Discussion and Conclusion:

(1) As far as the present analysis period is concerned, the solar-cycle modulation of the galactic cosmic rays can be most appropriately simulated by the series of parameters shown in Figure 3. The selection of the parameters was made purely from the statistical point of view, and the eliminated parameters would become necessary for the simulation with the increase of the statistical accuracy due to the extension of the analysis period.

(2) The term $f_j R_{i-j}$ in equation (1) expresses the contribution to I_i, of the interplanetary magnetic disturbances caused by the delayed effect of the sunspot activity R_{i-j} at the *(i-j)-th* month. During *j*-months, the activity propagates in the heliosphere with the solar wind velocity (*v*) to the radial distance (jv) from the sun, disturbing the magnetic field on the way. If we assume the velocity of 400 km/s, the radial distances corresponding to the representative lag times (11, 19 and 32-37 months) are 77 a.u., 153 a.u. and 220-260 a.u., respectively. The galactic cosmic rays would be modulated successively with their respective boundary radii given above.

(3) As a by-product of the present analysis, the 22-year variation of the galactic cosmic-cosmic ray intensity due to the polarity reversal of the general solar magnetic field can be clearly seen in the residual of the simulation of the solar-cycle modulation over the period of four solar cycles (cf.Fig.4)

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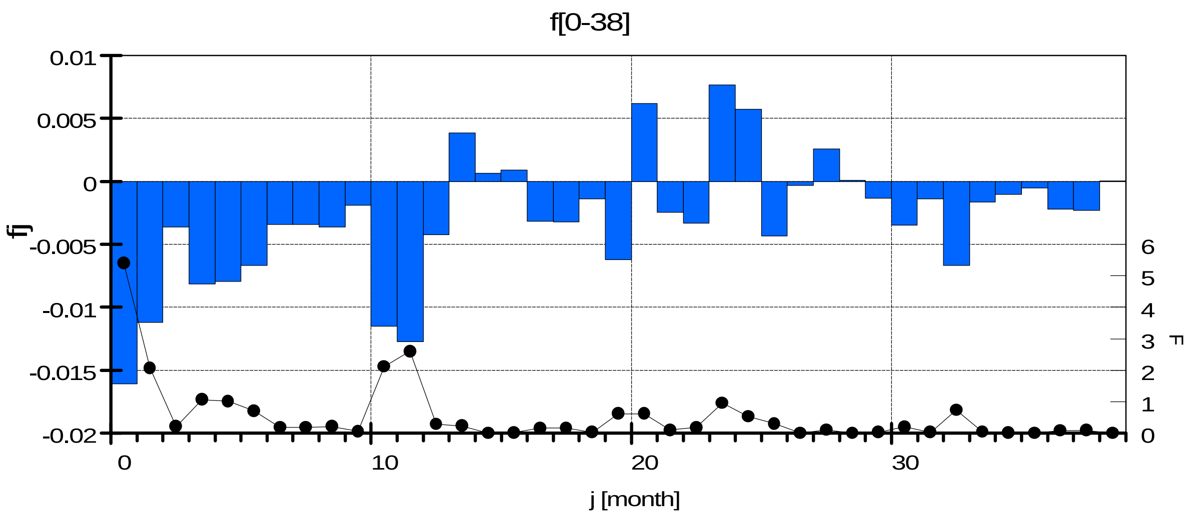

Fig.1 f_j-spectrum for $j_e = 38$. The solid line with black dots show the F-values, which mean the significance of the parameters.

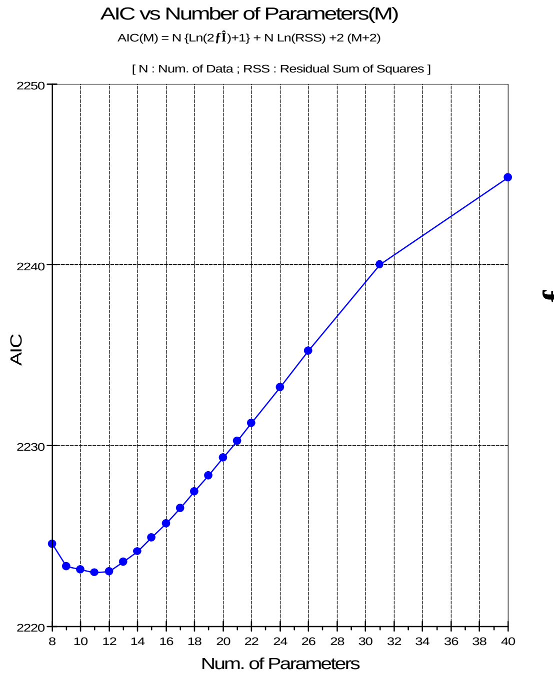

Fig2. *AIC* dependence on the number of the parameters, M.

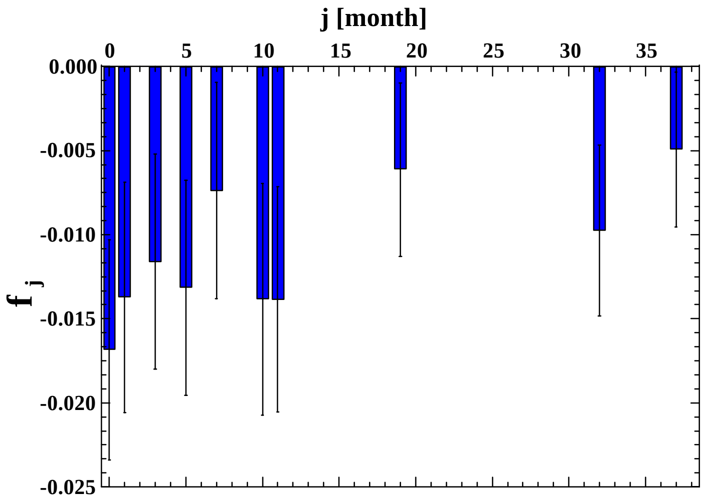

Fig.3 The best f_j -spectrum derived from minimum *AIC*. The error bars show one sigma.

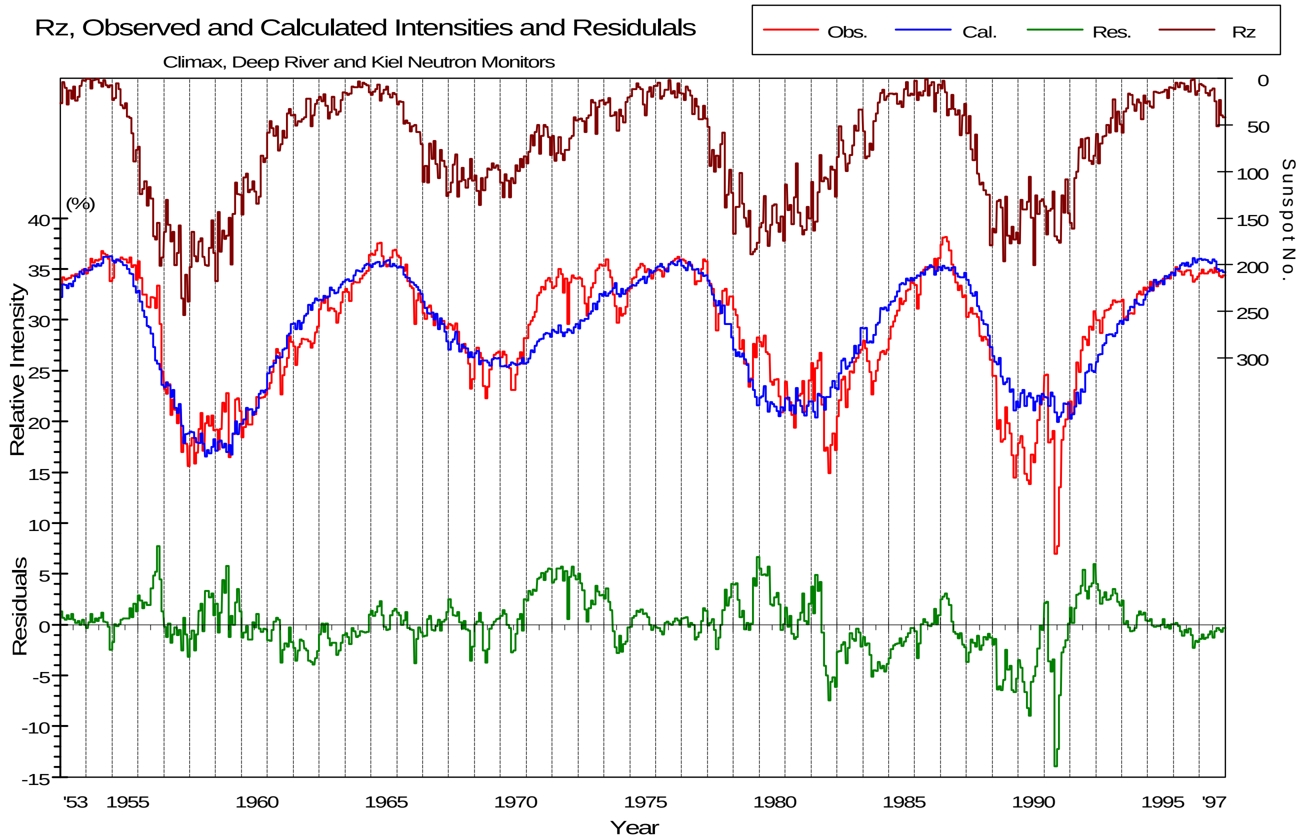

Fig.4 Most appropriate simulation of solar-cycle modulation of cosmic ray. From the top, the sunspot number, simulated and observed cosmic-ray intensities and the residuals.