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Interpretation of Long-Term Variation of Cosmic Ray Intensity in Terms of the Two-Hemisphere Model

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Abstract: The two-hemisphere model that the interplanetary space is magnetically divided into the away hemisphere and the toward hemisphere by a folded neutral sheet is applied to interpret a long-term variation of cosmic ray neutron intensity. A bending effect of the interplanetary neutral sheet due to the north-south asymmetry of the solar magnetic field intensity is considered to cause a dominance of the polarity of IMF of either away or toward at the earth's orbit. Taking into consideration of the TPD (toward polarity dependence) hypothesis that the diurnal anisotropy of cosmic ray neutron intensity is enhanced while the sector polarity of the magnetic field vector is in the toward direction, the seasonal TPD effect expected from the two-hemisphere model is compared with the TPD effect derived from the observation. It is found that the observed effect $(\Delta R)_{\mathrm{OBS}}$ coincides with the expected effect $(\Delta R)_{\mathrm{EXP}}=0.038\ (R_{\mathrm{N}}\text{-}R_{\mathrm{S}}) \sin\frac{360^\circ}{25}(1958.0-t)+1.13$ with a correlation coefficient of 0.715 and with an accidental probability of occurrence less than only 1%, where R_N, R_S and t indicate the sunspot area in the northern and the southern hemispheres of the sun, and the time given in the unit of years, respectively. A time lag of six months from $(\Delta R)_{\mathrm{EXP}}$ to $(\Delta R)_{\mathrm{OBS}}$ and other clarified characteristics are discussed briefly.

1. Introduction

A high speed spectrum analyzer (HISSA) which was originally designed for dynamic spectral analysis of geomagnetic pulsations (Saito and M. Kuwashima, 1971; Saito, 1973 and 1976) has been utilized for dynamic analyses of diurnal-, semidiurnal-, terdiurnal- and micro-variations of cosmic ray neutron intensity (Kanno, Ishida, et al., 1975; Kanno, Saito, et al., 1975). The analyses have derived a hypothesis that the diurnal anisotropy of neutron intensity is larger in the days of the toward polarity in the interplanetary magnetic field than in the days of the away polarity. This kind of preference of one-sided sector polarity for the cosmic ray anisotropy seems not to be far-fetched, because such a preference has been reported from both the observational and theoretical viewpoints for various geophysical activities, e. g. Dst (Paulikas and Blake, 1967), Cp (Russell and McPherron, 1973), Ci (Saito, 1972a), Kp and AE (Saito, 1972b), and flux of trapped electrons (Paulikas and Blake, 1976). Then, the effect of IMF polarity on the diurnal anisotropy of neutron intensity will be called *TPD* (toward polarity dependence) *hypothesis* on cosmic ray diurnal anisotropy in the present paper.

Kanno, Saito, et al. (1975) pointed out that the TPD effect can be recognized in the analyzed results presented by other researchers, too. They concluded that three-dimensional macroscopic structure of the interplanetary magnetic field should be taken into consideration in order to examine the TPD hypothesis.

As for the three-dimensional structure of IMF, Saito (1975). Saito, Sakurai, et al. (1976), and Saito, Oya, et al. (1976) proposed the two-hemisphere model that the whole interplanetary space is divided into two hemispheres (away and toward) by one folded neutral sheet. From this two-hemisphere model, they proposed further the bending-neutral-sheet effect that a trifle bending of the neutral sheet towards either the northern- or the southern-hemisphere of the interplanetary space causes a drastic change in the observed percentage of the IMF sector polarity.

The purpose of the present paper is to examine the TPD hypothesis based on the two-hemisphere model, which includes the bending-neutral-sheet effect, by analyzing the solar and cosmic ray data for 17 years from 1958 to 1974. When the TPD hypothesis derived from the cosmic ray data obtained in 1973 is physically meaningful and if both the two-hemisphere structure and the bending structure of the neutral sheet do exist really, the TPD hypothesis must be valid for the data during much longer years irrespective of the polarity reversal of the solar magnetic dipole.

In Section 2 the observed percentage of the IMF sector polarity will be checked in terms of the two-hemisphere model which will be used in Section 3 to derive a formula expected from the TPD hypothesis. The observed TPD effect will be explained by the formula in Section 4. Brief discussion and conclusion will be given in the last section.

2. Interpretation on the observed percentage of the sector polarity by means of the two-hemisphere model

The two-hemisphere model is briefly explained in this section by referring to an illustration of the model for 1954–1955 as shown in Fig. 1C. In the figure the central ball and the large circle indicate the sun and the unit sphere with radius of one astronomical unit, respectively. The folded plane with Archimedean spirals mean the neutral sheet of the magnetic field (or the so-called interplanetary sector boundary) of the inner heliomagnetosphere which separates the interplanetary space into two parts; i.e., away- and toward-hemispheres. The upper and the lower ellipses are the earth's orbits in September and in March, respectively. The neutral sheet is illustrated from IMF data which were obtained actually by satellites near 1AU. (As for the method to illustrate the neutral sheet, see Saito, 1975.)

As seen in the 1954–1955 model, the neutral sheet is bent slightly towards the southern hemisphere so that it does not intersect with the upper ellipse while it does intersect at the four point with the lower ellipse. This means that IMF shows a four-sector structure in the March months while only the away polarity is observable throughout the September months. Such the bending of the neutral sheet can explain well the observations that the sector structure disappeared apparently during the September months of both 1954 and 1955, while the four-sector structure appeared

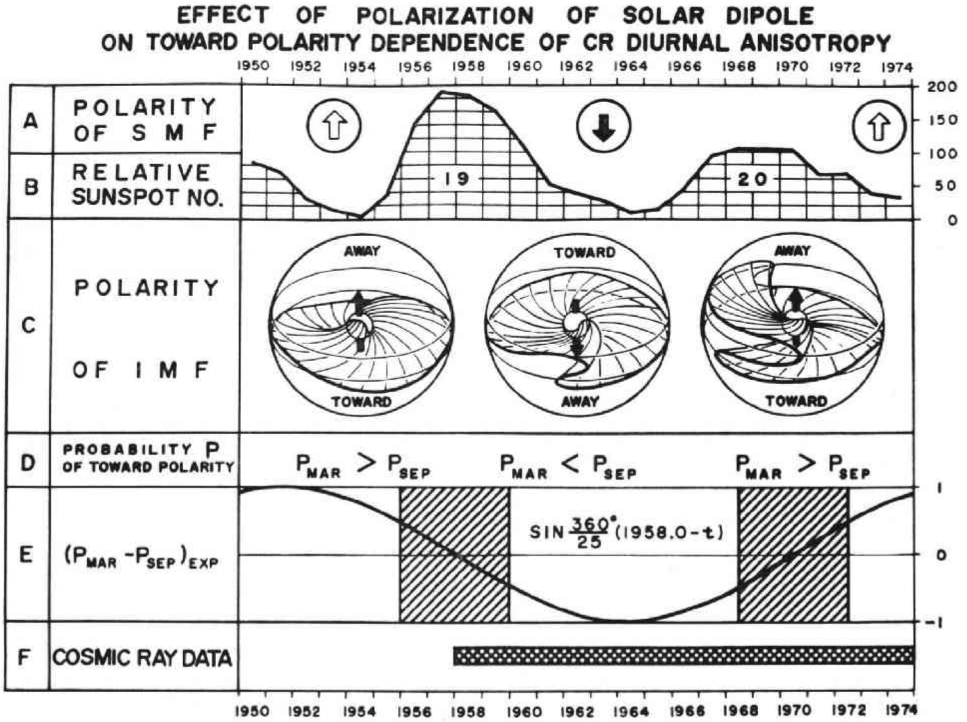

Fig. 1. Effect of polarization of solar dipole on toward polarity dependence of cosmic ray diurnal anisotropy.

(A) Polarity of the general solar magnetic field.

(B) Relative sunspot number.

(C) Polarity of the interplanetary magnetic field as expressed by the two-hemisphere model for the years of 1954–1955 (left), 1967–1968 (middle) and 1970–1971 (right), respectively. The central ball and the large circle mean the sun and the unit sphere with radius of 1 AU. The interplanetary space is always devided magnetically into the away- and the toward-hemispheres by a folded neutral sheet.

(D) Rosenberg-Coleman effect, that is, seasonal dominance of the probability of the time interval when the toward polarity of IMF is observed at the earth's orbit.

(E) The Rosenberg-Coleman effect is expressed here by $\sin \frac{360°}{25}(1958.0-t)$. The hatched intervals indicate the neglected years (see the text).

(F) Cosmic ray data used in the present analysis.

during March months of these years. Such the effect on the variation in the IMF sectors is called the *bending-neutral-sheet effect*.

Percentage of the days per year in which the toward IMF polarity is observed is 40% on an average for the data from 1926 to 1974. The observed percentage does not indicate 50% mainly because of the systematic error in the prehistoric interplanetary magnetic field data obtained from the earth's polar cap stations (Svalgaard, 1974 and 1975). Yearly percentage has fluctuated around the 40% line as will be given in Section 2.3. The deviation of the observed percentage from the mean value can be interpreted by the bending-neutral-sheet effect.

The bending is further interpreted to be due to the NS-asymmetry in the magnetic field intensity of the sun (Saito, 1975). When the magnetic field is stronger

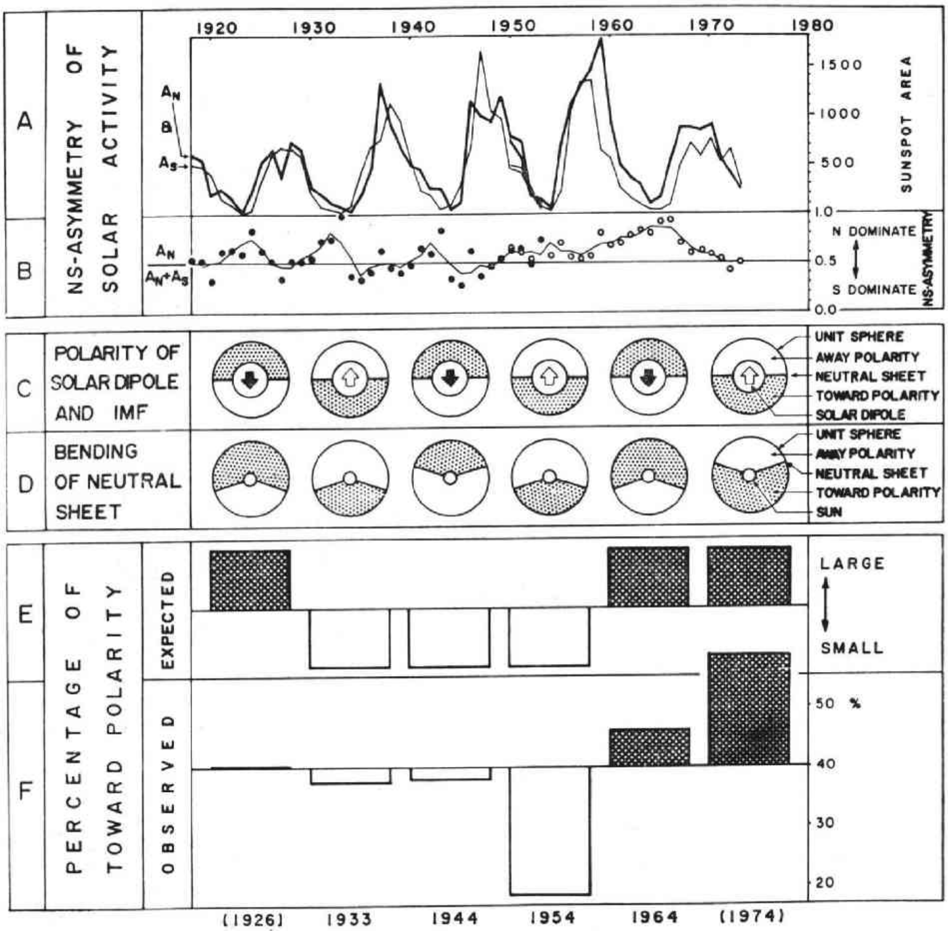

Fig. 2. Deviation from the Rosenberg-Coleman effect due to the bending-neutral-sheet effect.

(A) Solar activity as expressed by the sunspot areas in the northern (A_N) and the southern hemisphere (A_S) of the sun.

(B) North-south asymmetry of solar activity as expressed bi-yearly with $A_N/(A_N+A_S)$.

(C) Polarity of solar dipole and the interplanetary magnetic field when the bending-neutral-sheet effect is not taken into consideration.

(D) The magnetically neutral sheet in the interplanetary space that is bent due to the NS-asymmetry of the solar activity.

(E) Expression of the area of the dotted sectors in (D), that is the expected percentage of toward polarity observed at the earth's orbit.

(F) Observed percentage of toward polarity of IMF during sunspot minimum years. See the coincidence between (E) and (F) in the hatched (larger than the average) and the non-hatched (smaller than the average) year interval in every sunspot minimum. As for the sunspot minima in the solar cycle Nos. 15–16 and 20–21, the 1926 data and the 1974 data, respectively, are used because the PIMF data are not available.

on the northern side of the solar equator than on the southern, for example, the IMF neutral sheet must be bent slightly towards the southern hemisphere of the unit sphere as schematically shown in Figs. 2C and D. The bending angle θ_0 must be only a few degree as a whole, and $\sim 8°$ at most as were analyzed by Rosenberg and

Coleman (1969), Saito (1972b and 1975), Rosenberg and Hedgecock (1976), and Saito and Watanabe (1976), respectively. When $\theta_0 > 7.5°$, the interplanetary sector structure disappears apparently as was explained afore.

Based on the two-hemisphere model including the bending-neutral-sheet effect, the observed long-term variation of cosmic ray intensity will be explained in the next section.

3. Seasonal TPD effect expected from the two-hemisphere model

The general solar magnetic field changes its polarity with an approximate period of one solar cycle. When the solar dipole is pointing northwards, for example, the IMF tends to be in the toward polarity in March and in the away polarity in September in the two-hemisphere model, since most part of the Kepler orbit of the earth is statistically on the southern (northern) side of the folded neutral sheet, namely, inbedded in the toward (away) hemisphere during March (September). Consequently, if the TPD hypothesis does not contradict with all the observed features, the diurnal anisotropy of cosmic ray neutron intensity must be larger in March than in September when the solar dipole is pointing northwards, and vice versa when the solar dipole is pointing southwards. Then, when we use R_{MAR} and R_{SEP} as the monthly mean amplitude of the diurnal variation of the cosmic ray neutron intensity observed for March and September, respectively,

$$(\Delta R)_{\mathrm{OBS}} = R_{\mathrm{MAR}} - R_{\mathrm{SEP}}$$

must be larger (smaller) statistically when the solar dipole is pointing northwards (southwards). The value ΔR will be called *the seasonal TPD effect* hereafter in this paper. By applying the running reduction method, $(\Delta R)_{\mathrm{OBS}}$ can be expressed for every biannual epoch; for the epochs of 1960.5 and 1961.0, respectively, for example,

$$(\Delta R)_{\mathrm{OBS},\,1960.5} = R_{\mathrm{MAR},\,1960} - R_{\mathrm{SEP},\,1960} \qquad \text{and}$$

$$(\Delta R)_{\mathrm{OBS},\,1961.0} = R_{\mathrm{MAR},\,1961} - R_{\mathrm{SEP},\,1960}\,.$$

The polarity reversal event of SMF is thought not to be instantaneous but to be rather gradual from the physical point of view (Babcock, 1959; Howard, 1974; Saito, Sakurai et al., 1976). The functional form of the axial dipole intensity is, therefore, given by a sinusoidal function instead of a delta function with respect to the time t. Let us denote t_0, t_1, and m for the epoch of a reversal of the solar dipole, the epoch of the next reversal, and the interval of these reversals, i.e., $m = t_1 - t_0$, respectively. Then ΔR can be expected to be dependent on $\sin \frac{360°}{2m}(t_0 - t)$, where t is the year in A.D. The solar magnetic field changed its polarity in 1957–1958 (Babcock, 1959) and in 1969–1971 (Howard, 1974), respectively, then we put;

$$t_0 = 1958.0$$

$$t_1 = 1970.5$$

$$m = 12.5 \qquad \text{and}$$

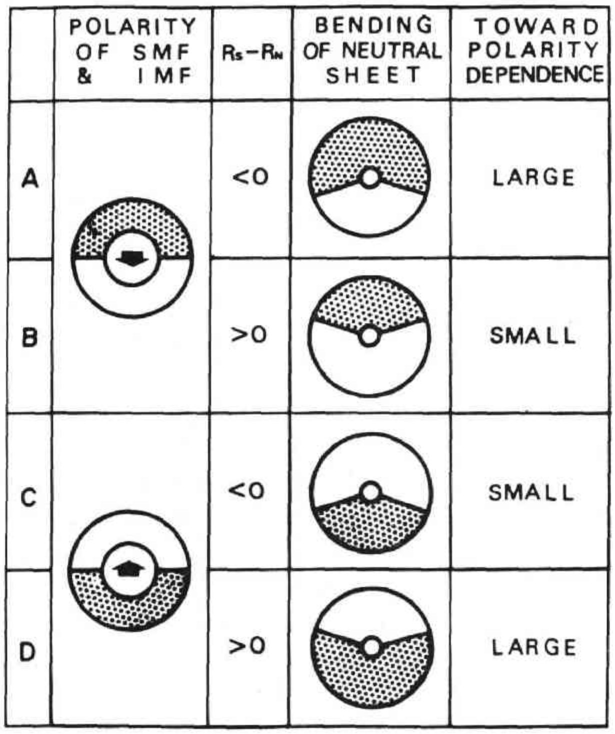

Fig. 3. The bending-neutral-sheet effect (or θ_0-effect) on toward polarity dependence of cosmic ray diurnal anisotropy for four cases of the positive and the negative polarities of the solar and the interplanetary magnetic fields and of the positive and the negative value of R_N-R_S. Cf. Fig. 2.

$$\Delta R = f(t)\cdot\sin\frac{360^\circ}{25}(1958.0-t)+C\,. \tag{1}$$

The seasonal TPD effect ΔR can be assumed to be dependent also on an asymmetry of the solar magnetic fields between the northern and the southern hemispheres of the sun because the asymmetry gives rise to the bending of the neutral sheet. When the northern SMF is more intense than the southern, the neutral sheet is bent southwards. The southward bending of the neutral sheet should give rise to increase the toward polarity in September when the solar dipole points southwards and then ΔR decreases as shown in Fig. 3A.

In a similar logic ΔR is estimated for every three other cases of the combination of the polarity and the NS-asymmetry of the solar magnetic field as listed in Fig. 3. Actually it is difficult to calculate the monthly mean value of the NS-asymmetry of the solar magnetic field for many years, so it will be replaced by another available data, R_N–R_S, which is the NS-asymmetry of the sunspot area compiled by Murayama.

In conclusion, we may derive from the two-hemisphere model the following formula for the expected ΔR.

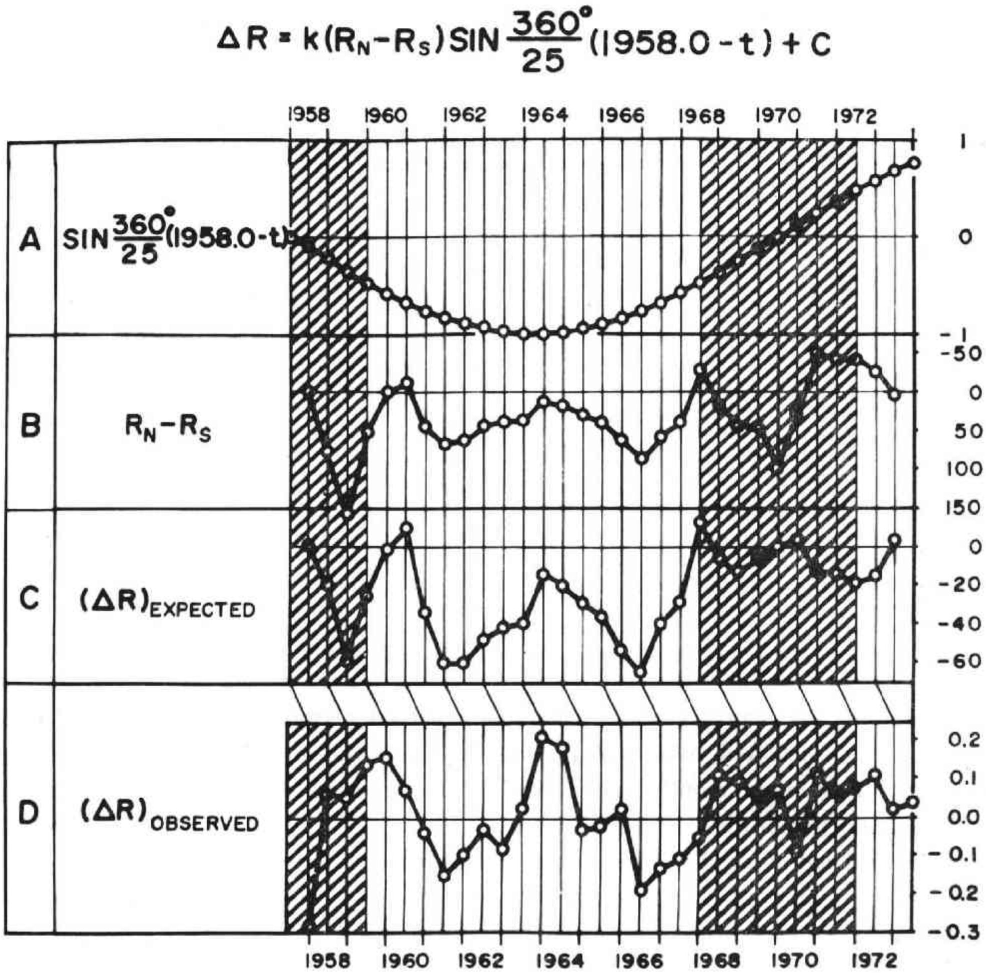

Fig. 4. Comparison of the seasonal TPD effect expected from the two-hemisphere model ($(\Delta R)_{\mathrm{EXP}}$) with that derived from the observation ($(\Delta R)_{\mathrm{OBS}}$).
(A) Effect of the polarity of SMF and IMF (cf. Fig. 1E).
(B) Effect of the bending of the neutral sheet (cf. Fig. 3).
(C) The expected seasonal TPD effect $(\Delta R)_{\mathrm{EXP}}$ obtained by producting (A) with (B).
(D) The observed seasonal TPD effect $(\Delta R)_{\mathrm{OBS}}$ obtained by averaging the data from Deep River, Ottawa, and Rome, respectively (cf. Fig. 5). The observed ΔR is lagged by six months behind the expected ΔR (see the text and Table 1). Note a striking coincidence between $(\Delta R)_{\mathrm{EXP}}$ and $(\Delta R)_{\mathrm{OBS}}$.

$$(\Delta R)_{\mathrm{EXP}} = K(R_N - R_S) \sin \frac{360^\circ}{25} (1958.0 - t) + C \tag{2}$$

where both of K and C are constants. The values, $\sin \frac{360^\circ}{25}$ (1958.0–t), R_N–R_S, and $(\Delta R)_{\mathrm{EXP}}$ are calculated and plotted separately with respect to the time in Figs. 4A, B, and C, respectively. Then let us obtain $(\Delta R)_{\mathrm{OBS}}$ in the next section to compare it with $(\Delta R)_{\mathrm{EXP}}$.

4. Calculation of the observed seasonal TPD effect

Hourly value of cosmic ray neutron intensity is collected for available years from 1958 to 1974 from 12 world-distributed stations with different cutoff rigidity (see Table 1). The first harmonic dial vector $\vec{R}$ is calculated from the monthly values

Table 1. Location and cutoff rigidity of the 12 stations referred to in Fig. 5.

Station	Geographic		Altitude (m)	Cutoff rigidity (GV)
	Latitude	Longitude		
Alert	82°.50N	62°.33W	57	0.00
Resolute Bay	74°.68N	94°.90W	17	0.00
Inuvik	68°.35N	133°.72W	21	0.18
Goose Bay	53°.27N	60°.40W	46	0.52
Deep River	46°.10N	77°.50W	145	1.02
Ottawa	45°.40N	75°.60W	57	1.08
Leeds	53°.80N	1°.50W	*	2.20
Rome	41°.90N	12°.50E	60	6.32
Norikura	36°.11N	137°.55E	2770	11.39
Tokyo	35°.75N	139°.72E	40	11.61
Hermanus	34°.42S	19°.22E	42	4.90
Mawson	67°.60S	62°.88E	0	0.22

*) 100 m is from Jan. to Aug., 72 m is from Sep. to Dec.

averaged from the hourly values. Then the observed seasonal TPD effect $(\Delta R)_{OBS}=R_{MAR}-R_{SEP}$ is calculated, where R_{MAR} and R_{SEP} are the amplitude of $\vec{R}$ for every March and September months, respectively. The calculated result is illustrated in Fig. 5. Even though the stations are far from each other in terms of both geographical longitude and cutoff rigidity, these curves show a remarkably common tendency of variations in minima at the vicinity of 1961, 1966, and 1970, respectively, and in maxima at the vicinity of 1960, 1964, 1968, and 1972, respectively. This characteristic implies that even if we may derive a curve obtained from an average of an any few curves out of the 12 curves, the deviation of the curve from the general tendency is not large.

When the 12 curves are simply averaged, the general tendency is altered by a peculiarity of the curve with the largest amplitude. On the other hand, inhomogeneous errors are derived when curves with different data periods are averaged over. Then the three stations with the similar periods of observation, Deep River, Ottawa, and Rome, are selected. The three curves from the three stations are then averaged over the period.

It is natural that a change in the macroscopic interplanetary magnetic structure affects the observed cosmic ray anisotropy with a general time lag of n months. Then the curve $(\Delta R)_{EXP}$ which was obtained in Section 3 is compared with the averaged curve $(\Delta R)_{OBS}$ with various n values, 0, 6, 12, 18, etc. Figures 4C and D indicate the curves $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$, respectively, for the case of $n=6$. A striking smilarity between the two curves is evident in these figures.

5. Discussion and conclusion

The similarity between $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$ as obtained in the previous section is

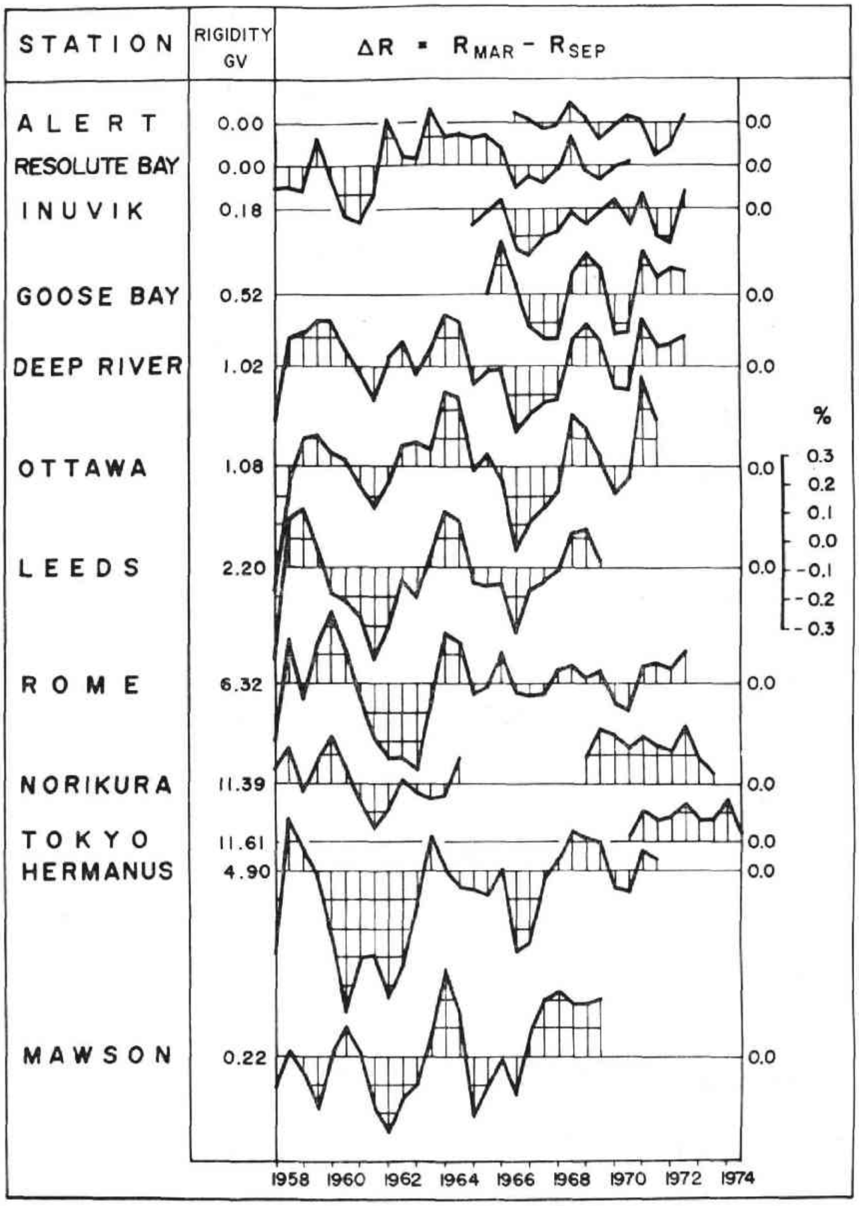

Fig. 5. Difference between the March value (R_{MAR}) and the September value (R_{SEP}) of the diurnal anisotropy of cosmic ray neutron intensity observed at 12 stations. Note a common tendency of the 12 curves in the years of maxima and minima.

further expressed by the 31 points plotted on the $(\Delta R)_{EXP}$-versus-$(\Delta R)_{OBS}$ diagram in Fig. 6. The number above each point means the year corresponding to $(\Delta R)_{EXP}$. In order to compare $(\Delta R)_{EXP}$ with $(\Delta R)_{OBS}$, the following two points have to be taken into consideration.

(1) During the transition from the north-seeking solar dipole to the south-seeking

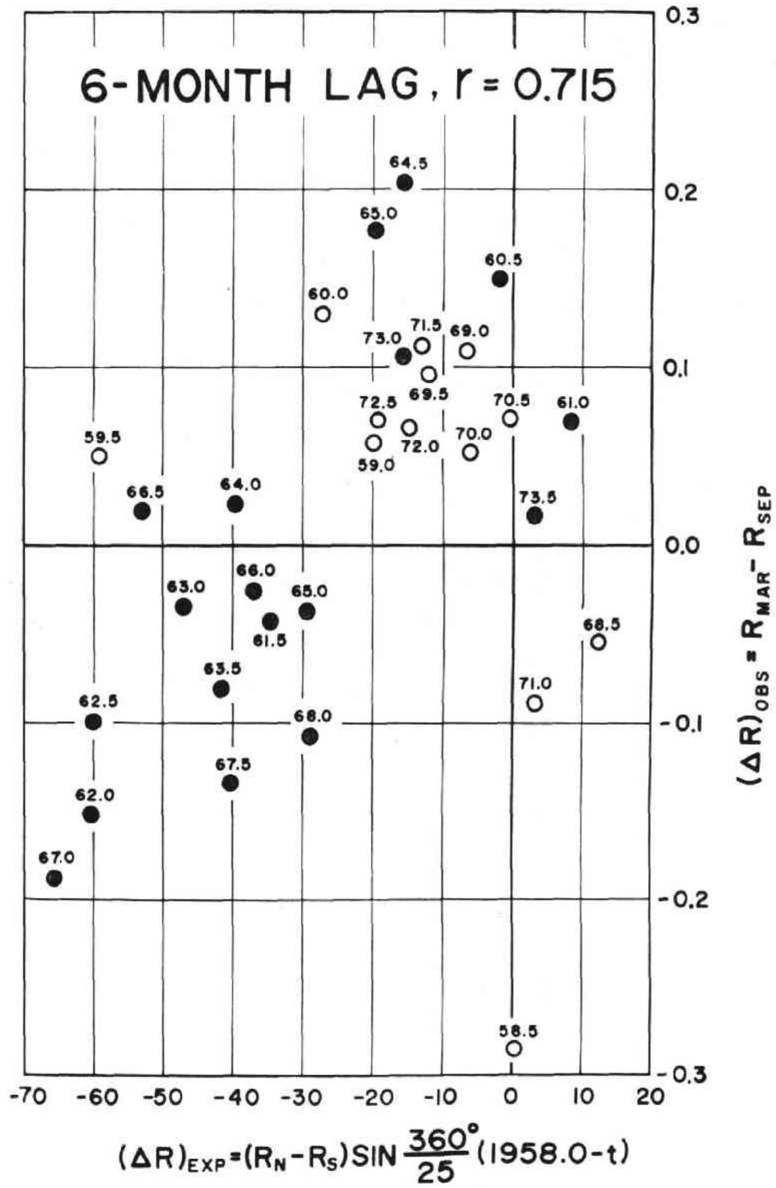

Fig. 6. Typical example of the coincidence between $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$ for $n=6$ months. The hollow circles correspond to the years of neglection. The number above each circle indicates the analyzed year. Cf. Fig. 4.

one, or vice versa, the neutral sheet of the inner heliomagnetosphere transfers from the parallel condition with respect to the earth's orbital plane as seen in Figs. 1C and 2C to the perpendicular condition (Antonutti, 1974; Saito, 1975; Saito, Sakurai, et al., 1976) and enters into the so-called perpendicular stage (Saito and Watanabe, 1976). Consequently the validity of the formula (3) cannot be expected any more during the perpendicular stage.

(2) The reversal of the solar dipole is not instantaneous, but is taking place fluctuatedly during a certain interval of years (Babcock, 1959; Howard, 1974). Even two discrepant epochs of the polarity reversal of the solar dipole were reported: an epoch which is applied in the present paper, is from 1969 to 1971 (Howard, 1974) and the other is from 1970 to 1971 (Moriyama, 1972). Taking into consideration of these two points, the comparison between $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$ is physically meaningless during the transition stage of the polarity reversal of the solar dipole field. Then, assuming a four-year duration, the transition stages of the polarity reversal are determined to be 1956.0–1960.0 and 1968.5–1972.5, respectively. Thus, for the remained 18 data points except for the transition stage, the correlation coefficient r between $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$ is calculated to be 0.715 for $n=6$. According to the Fischer's test, accidental probability of occurrence β for $r=0.715$ is only less than 1%. Since K and C are calculated to be 0.038 and 1.13, respectively, the resultant $(\Delta R)_{EXP}$ is finally given as,

$$(\Delta R)_{EXP} = 0.038(R_N - R_S) \sin \frac{360^\circ}{25} (1958.0 - t) + 1.13\,. \tag{3}$$

Correlation coefficients for $n=0$, 6, 12, 18, and 24 are listed in Table 2.

Table 2. Correlation coefficients between $(\Delta R)_{EXP}$ and $(\Delta R)_{OBS}$ for various lags n.

Time lag (n)	Correlation coefficient	Accidental probability
0-month	0.437	<7%
6	0.715	<1%
12	0.630	<1%
18	0.299	—
24	−0.013	—

As seen in the table the correlation coefficient exhibits the highest value for $n=6$. This tendency implies that it takes a time lag of about half a year to yield a sufficient amount of the density gradient that causes a diurnal anisotropy of the cosmic ray neutron intensity.

The analyzed result that $(\Delta R)_{OBS}$ and $(\Delta R)_{EXP}$ are related with high correlation and with low accidental probability derives a possibility to conclude that *all the TPD hypothesis, the two-hemisphere model, and the bending-neutral-sheet effect are acceptable for the interpretation.*

Swinson (1976 and 1977) reported that the diurnal anisotropy of cosmic ray variation is larger in days of away IMF polarity. He suggested a possibility that there would be some reversal of the effect between the results for the relatively lower energy neutron monitor data and the relatively higher energy underground muon data (Swinson, private communication).

We used the two-month data of every March and September in the present analysis. By using all the 12-month data, the sidereal effect on the seasonal variation (Swinson, 1976) will further be examined in the future.

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