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North-South asymmetry of cosmic-ray density gradients throughout the epoch 1955-1991

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Summary. — We have computed the magnitude and direction of the asymmetry of cosmic-ray particle density gradient in the heliosphere during the period 1955-1991. Data obtained by twenty-one detectors (neutron monitors, surface and underground muon telescopes) in both terrestrial hemispheres between 1955 and 1991 are analyzed as a function of the sense of interplanetary magnetic field. Their median rigidity of response (R_m) covers the following range: 10 GV $\leqslant R_\mathrm{m} \leqslant$ 185 GV. Significant differences are frequently observed between the diurnal variations measured in toward and away polarity days. The cosmic-ray density gradient displayed insignificant changes near solar maxima and reversed in sign after the reversal polarity periods. The resultant cosmic-ray gradients are: a north-south symmetric gradient which occurred during minima and maxima solar activity epochs, and a N-S asymmetrical gradient which is related to the N-S asymmetry in the activity on the Sun. Northward and southward cosmic-ray latitudinal (or perpendicular) gradients were frequently observed. The solar diurnal phases of toward polarity days north of the HCS (or away) during the period 1981-87 ($qA < 0$) existed a few hours later than those recorded for toward (or away) days south of HCS during the positive IMF period 1971-78, as well as the time shift depends on the rigidity of the particle. In addition, quite a change occurred on phase for the north neutron monitors and muon telescopes than for those located on the southern hemisphere.

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1. – Introduction

The interplanetary magnetic fields (IMF) in the ecliptic plane lie predominantly along an Archimedean spiral angle. The long-scale fields are organized into alternate field

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sectors pointing toward and away from the Sun with relatively sharp sector boundaries at which the field direction reverses in periods of a few minutes to a few hours [1]. The sector structure is believed to result from a solar field pattern in which positive polarity is separated from negative polarity field by a warped, global current sheet. North-south of cosmic-ray asymmetries between the two northern and southern sectors with respect to the neutral sheet has been studied for different periods [2-10]. Also, the correlation of the heliospheric current sheet tilts to galactic cosmic-ray modulations and solar wind speed has been examined [11].

The $B \times \nabla n_{\perp}$ (where B in the IMF vector and $\nabla n_{\perp}$ is the density gradient perpendicular to the ecliptic plane) produces flow in the ecliptic plane perpendicular to B. The flow depends on the sense of the IMF. Studies have shown that a cosmic-ray perpendicular gradient pointed southward (higher cosmic-ray density below the ecliptic plane) when the IMF was directed away from the Sun in the northern hemisphere, and northward when the IMF was directed toward the Sun in the northern hemisphere [2-4, 6, 7, 12-17]. Moreover, there was a very marked correlation between the southward-pointing cosmic-ray density gradient and periods of excess northern activity on the Sun. Results by [15, 18] showed that the solar plasma north of the current sheet was hotter, faster, and less dense than south of it during the epoch of negative polarity (1981-87) and an asymmetry in the averaged magnetic field was absent in solar cycle 21 [19]. The dependence of the cosmic-ray north-south variation upon IMF polarity did not exist [5, 20]. Other [21] found that the bidirectional (or symmetric) gradient is present at all rigidities from 16 GV ($\approx 2\%$ AU^{-1}) to 195 GV ($< 0.5\%$ AU^{-1}). The magnitudes of bi-directional latitudinal density gradient may depend slightly upon the magnetic state of the heliosphere, being smaller during the epoch of $qA > 0$ (IMF points away from the Sun north of the current sheet). The large-scale fields at 1 AU exhibited a persistent north-south asymmetry in the winding angle of the IMF, such that the field north of the current sheet was more tightly wound than the field south of the current sheet [5, 22, 23].

The causes of north-south asymmetry of solar modulations may be due to the N-S asymmetry of winding angle of solar magnetic field [5, 22] or to the N-S asymmetry of the solar activity [2, 4, 24]. Recently, the N-S asymmetry that existed in interplanetary plasma and solar parameters have been examined [19]. Results have shown that the north-south asymmetry of the Sun's activity, together with the north-south asymmetry observed in the geomagnetic disturbances, may provide multiple causes for producing the observed asymmetry in modulation of cosmic rays.

The study of the difference in cosmic-ray modulations between the sectors of opposite polarity provides a means of examining north-south gradients with respect to the current sheet. In the present work, the annual averages of cosmic-ray solar diurnal variation have been determined for both toward and away IMF for the purpose of examining the nature and causes of the perpendicular gradient before and after the reversals the Sun's magnetic dipole. In the following section **2**, data and method of analysis have been clarified. Section **3** discusses the N-S asymmetry observed in the solar activity by using the relative sunspot numbers of the northern and southern hemispheres. In the fourth section, we have experimentally examined the N-S asymmetry of cosmic-ray solar diurnal variations during more than three decades (1955-1991) using eighteen neutron monitors, one surface muon telescope and two underground muon telescopes. The cosmic-ray density gradients have been extended over a wide range of rigidities from 10 GV to 185 GV. In sect. **5**, we studied the N-S asymmetry of cosmic-ray solar diurnal variation during epochs of positive ($qA > 0$) and negative ($qA < 0$) polarities of the Sun's magnetic field. Then, our results have been discussed and summarized.

2. – Data and analysis

In the present work, the method of allocating individual data samples into toward and away data sets is clearly a crucial element. We have used the hourly averages of IMF collected by a variety of spacecraft near 1 AU which were provided by the National Space Science Data Center [25-28], over the time interval 1966-91. The second source is a compilation of daily sector polarities inferred from ground-based magnetograms at high-latitude stations over the years 1955-1965 [29, 30]. The Svalgaard inferred polarity data set provides more valid days each year than does the omnitape. Both polarity data sets gave similar diurnal variations [5]. The field direction is calculated on a daily basis in the geocentric solar ecliptic (GSE) coordinate system. The field direction is then separated into two polarities; away (A) polarity if the solar ecliptic azimuthal angle of the IMF daily average lies between 45° and 225°; otherwise it is considered as toward (T) the Sun. Only the days on which there were 12 or more hourly average field directions were used. Also, days on which the IMF was truly mixed polarity (sector crossing) were removed from our analysis. Data from 1955 to 1991 were then separated into two groups according to away or toward daily average IMF vector.

The period of our analysis covers more than three complete solar cycles (19th, 20th, 21st, and a major part of 22nd covering the period from 1955 to 1991). We classified the former period into two epochs 1955-58 and 1971-79, and 1961-68 and 1981-89. Before the 1969-70 and after the 1980 reversals, the IMF pointed toward the Sun (negative phase $qA < 0$) in the solar northern hemisphere and away from the Sun in the solar southern hemisphere. During 1955-58 and 1971-79, the IMF pointed away from the Sun (positive phase $qA > 0$) in the northern hemisphere and toward the Sun in the southern hemisphere. The relationship between sector polarity and north-south position in the northern and southern hemispheres was reversed.

In order to adequately study the N-S asymmetry in the cosmic-ray solar diurnal variations (SDV) and achieve significant insights, a considerable database must be used. We selected twenty-one detectors to carry out the analysis presented in this work. Cosmic-ray data are obtained from neutron monitors as well as surface and underground muon telescopes. They are globally distributed and situated from underground to mountain altitudes. For the muon stations, data from various depths were used. The full epoch of study (1955-1991) includes four periods each of solar activity maxima, minima, and polar field reversals. This length of data coverage should provide a good indication of any relationship with heliospheric parameters and their time variations with solar activity (SA). Smaller subsets of this time span were used for particular analyses due to better coverage during certain time frames.

The characteristics of these detectors are included in table I. Listed are the station symbol, the geographic latitude (λ) and longitude (η), altitude from the sea level (in meters), depth (in meter water equivalent), the threshold (R_0) and median (R_{m}) rigidities. The effective threshold rigidity (R_0) for these detectors lies in the range 0.0 GV $\leqslant R_0 \leqslant$ 13.45 GV, the median primary rigidities of response for these detectors cover the range 10 GV $\leqslant R_{\mathrm{m}} \leqslant$ 185 GV. These data cover a range in latitudes from about 83° N to 90° S. Moreover, their asymptotic latitudes of viewing at R_{m} cover a wide range on either side of the ecliptic plane. For all 21 observations, the hourly count rates have been accurately pressure corrected. Some did not operate throughout the period (for example, Mawson UMT data are not available before 1973, and Hobart UMT data after 1983 were not used). Data from the muon telescopes were not corrected for temperature effects [21,31].

We have eliminated the effects of large Forbush decreases and solar particle events

TABLE I. – *List of data for Neutron Monitors (NMs) and Muon Telescopes (MTs).*

Station			Geographical (degrees)				Rigidity (GV)		Analyzed Period
Name	Symbol	Detector	Lati. (λ)	Long. (η)	Alti. (m)	Depth MWE	Cutoff (R_0)	Median (R_m)	
Alert	ALT	NM	82.5	−62.3	57	-	0.0	17	1966-87
Thule	THU	NM	76.6	−68.7	260	-	0.0	16	1965-91([a])
Apatity	APT	NM	67.6	33.3	177	-	0.65	16	1971-81
Oulu	OUL	NM	65.1	25.47	15	-	0.8	16	1965-87
Deep River	DR	NM	46.1	−77.5	145	-	1.02	16	1965-91
Mt. Washing.	WASH	NM	44.3	−71.3	1909	-	1.38	10	1964-87
Rome	ROM	NM	41.9	12.5	60	-	6.32	22	1967-89
Climax	CLI	NM	39.4	−106.8	3400	-	3.03	11	1955-87([a])
Mt. Norikura	NOR	NM	36.1	137.6	2770	-	11.36	27	1958-88
Tokyo	TOK	NM	35.8	139.7	20	-	11.61	30	1970-91
Nagoya (V)	NAG V	SMT	35.2	137.6	SL	-	12.06	60	1971-91
Huancayo	HUN	NM	−12.0	−75.3	3400	-	13.45	33	1955-91
Potchefstr.	POT	NM	−26.7	27.1	1351	-	6.97	22	1973-87
Hermanus	HER	NM	−34.4	19.23	26	-	4.9	20	1967-88
Mt. Welling.	WEL	NM	−42.9	147.4	725	-	1.89	17	1971-91
Hobart	HOB	NM	−42.9	147.3	0.0	-	1.9	17	1979-90
Hobart (V)	HOB U	UMT	−42.9	147.6	-	36	-	185	1971-83
Mawson	MAW	NM	−67.6	62.9	30	-	0.22	16	1971-91([a])
Mawson (N)	MAW U	UMT	−67.6	62.9	-	30.9	-	165	1973-91
McMurdo	MCM	NM	−78	166.6	48	-	0.01	16	1965-91
South Pole	SOP	NM	−90	0.0	2820	-	0.1	16	1965-91([b])

(V) = Vertical, (N) = North-pointing.
([a]) One year missing.
([b]) Two years missing.

by rejecting days in which the maximum excursion in hourly rates is $\geqslant 4\%$. We also omitted days for which less than 21 h of data were available. The daily linear trend of the hourly average counts has been subtracted from the pressure corrected hourly average counts. This smoothed out long-term trends in the data such as seasonal variations or contributions from the Forbush decreases. The conventional Fourier coefficients for each day were then calculated to determine the solar diurnal amplitude (SDA) and phase for each day. All NMs and muon telescopes (MTs) data have been analyzed according to the IMF polarity sense. So, the daily averaged solar diurnal vectors are separately obtained by taking weights with the numbers of days adopted for the two polarities (toward and away) spanning the period 1955-1991. Within each detector, for each year, the data were further separated into two groups corresponding to away and toward directions of the IMF in a given day. Appropriate correction for the Compton-Getting effect was performed. The yearly averaged vectors in each group were then calculated by simply averaging the vector components (a_m, b_m). Note that the differences of solar diurnal variation across the current sheet were manifested as the differences in amplitudes and phases of the diurnal anisotropy between toward and away sectors [5]. The statistical errors were then derived from the observed scatter of the daily vectors from the annual mean vector for each group, separately. By that analysis, we have analyzed 42% of the total days for toward polarity field and 47% for away IMF polarity field. On average, 11% of days have mixed polarity or no measurement or canceled. Then, the yearly averages of amplitude difference between the two sectors are determined to examine the north-south asymmetry of solar diurnal variations during the epochs of asymmetry in the solar activity, as well as during epochs of positive and negative polarities of the Sun's magnetic field. Error estimates for the difference in variations were determined by the standard technique of

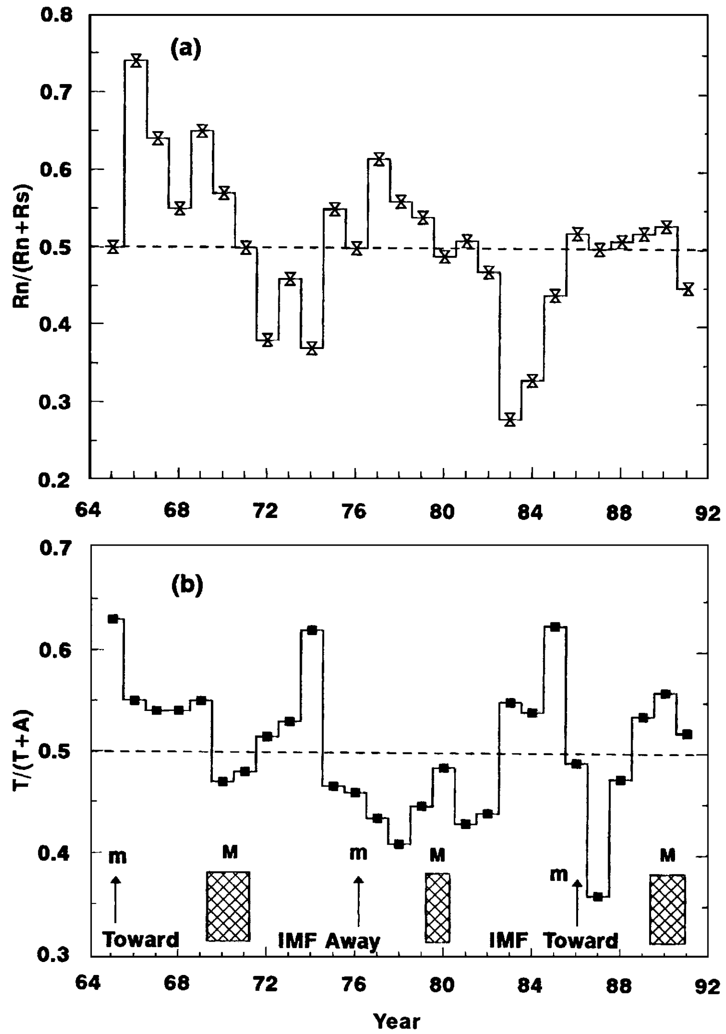

Fig. 1. – a) The long-term variations in the asymmetry of northern (R_n) and southern (R_s) hemispheres of the Sun expressed in terms of $R_n/(R_n + R_s)$, from 1965 to 1991. The horizontal dashed line represents the north-south symmetry. b) The yearly variations of toward (T) and away (A) IMF days, expressed in terms T/(T + A). Epochs of minimum (denoted by m's) and maximum (denoted by M's) solar activity cycles, as well as reversals of the Sun's polar magnetic field are shown in the panel.

error propagation. This kind of latitude gradient was termed "unidirectional gradient", if the cosmic-ray amplitude distribution is north-south asymmetric with respect to the current sheet [5].

3. – The asymmetry of northern and southern solar activities

Firstly, it may be useful to re-examine the long-term variations of the north-south asymmetry in the solar activity. Figure 1, top panel, shows the asymmetry of yearly averages of the sunspot numbers in the northern (R_n) and southern (R_s) hemispheres of the Sun, expressed in the form $R_n/(R_n + R_s)$ (the ratio of northern to total relative sunspot number). These observations of sunspot number from 1965 to 1991 were normalized to the international sunspot relative number (R_i) to obtain R_n and R_s. Periods of excess northern activity are indicated above the dashed line. The bottom panel displays the annual number of days for toward (T) and away (A) IMF groups over the 1965-1991, and also expressed by T/(T + A). Below the dashed line more A days than T days are indicated. Epochs of minimum (denoted by m's) and maximum solar activity (denoted by M's), as well as the reversals of Sun's polar magnetic field, are also expressed. The $qA < 0$ epochs (or $qA > 0$) represent the negative (or the positive) magnetic polarity states in the solar northern hemisphere. It is clear that, although there are large variations in both northern and southern relative sunspot numbers, some cyclic behavior can be noticed in the north-south asymmetry. However, there is a significant peak in excess northern activity following the minimum solar activity years (1965 and 1976). This peaking has been noted previously [32] and it was more pronounced for the even solar cycle.

From the two panels, we find that a symmetry in toward and away days existed. This symmetry may depend slightly upon the magnetic state of the heliosphere. Sometimes equal T and A days have been observed at, or near, the years of maximum and minimum solar activity (1971, 1975, 1980, 1986, and 1991). A corresponding symmetry is observed in the sunspot numbers of the northern and southern hemispheres that occurred in 1965, 1971, 1976, 1980-81, 1986, and 1989-90. These symmetries seemed to attain great magnitudes near times of maxima solar activity [7]. On the other hand, for the five non-reversal epochs, there were more A days than T days (below the dashed-line areas) during the periods 1976-79, 1981-82, and 1987-88, and more T days than A days (above areas) in 1965-69, 1972-74, 1983-85, and 1989-90. This implies that, in general, when the IMF was directed toward the Sun in the northern solar hemisphere, there were more T days than A days (1965-69, 1983-85, and 1989), while on average, our observations reflected more A days when the IMF was away from the Sun. The asymmetry observations of the opposite polarity configurations also fits the Swinson *et al.* [4] model. They have shown that when the neutral sheet was displaced below the Earth (on average) and when the IMF was toward the Sun above the neutral sheet, one should expect more T days than A days on the Earth, while the reverse was true. Note that we have only used the well-defined IMF direction days over the period 1965-1991, and in many cases the spacecraft were not tracked. So, in few years we have only used 250 days or less and the difference between T and A groups was about a few days.

There are, on average, more A days on the Earth than T during the epoch of positive (1971-79) solar polarity. On the other hand, when the Sun's northern hemisphere was more active than the southern hemisphere during the period 1966-69, there were more T days than A days, while during the period 1977-79 (when the Sun's northern hemisphere was more active again), more A days than T days were observed. In contrast, when the Sun's southern hemisphere was active during the epochs 1972-74 and 1983-85, there were more days of toward IMF polarity. Thus, the asymmetries in the number of away and toward IMF days are correlated with the asymmetries in the solar activity [4, 7, 18, 33].

4. – North-south asymmetry of yearly solar diurnal variations

Drift models [34-36] of modulation predict gradients that are sensitive to the sign of the Sun's magnetic polarity. The latitudinal gradient is predicted to reverse sign with the

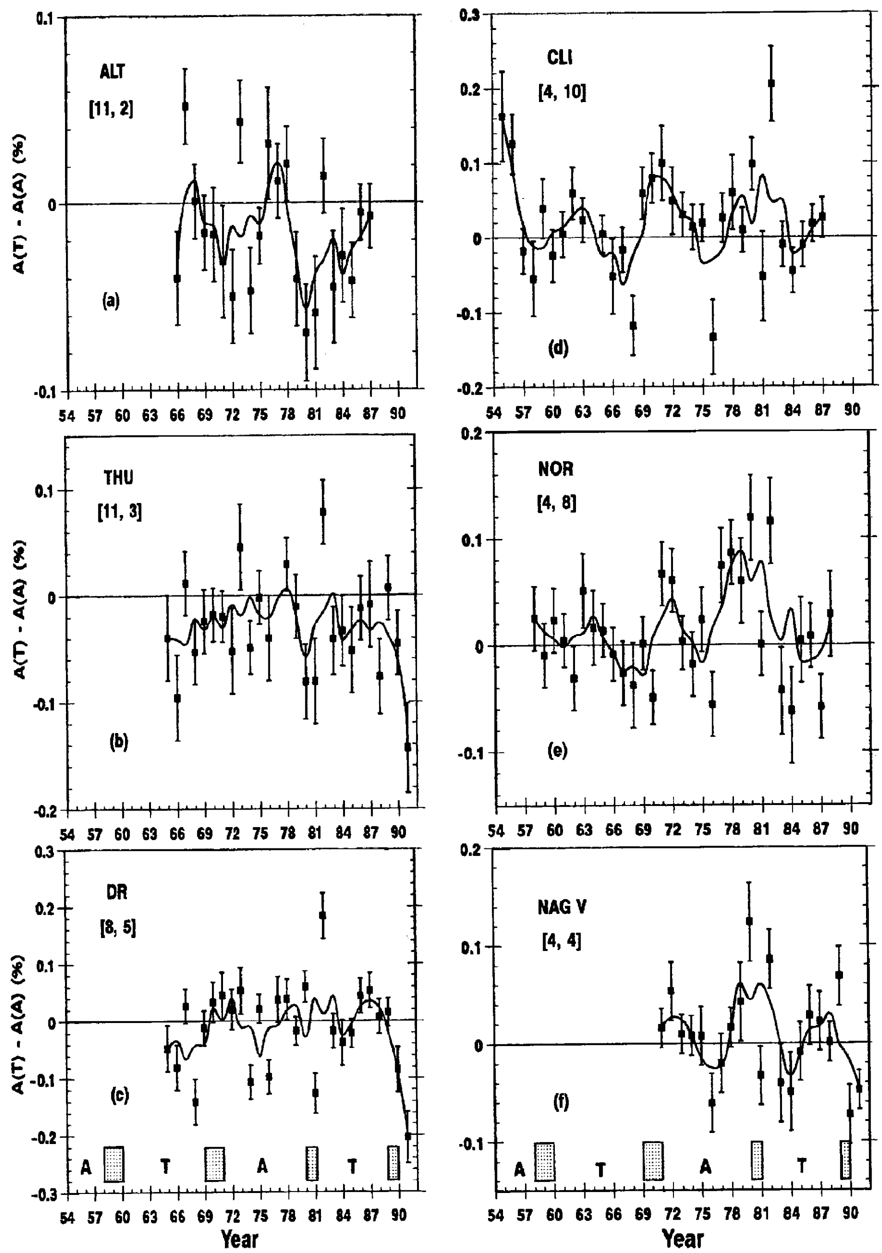

Fig. 2. – Yearly amplitude differences of cosmic-ray diurnal variations between the two sectors, for the north stations (ALT, THU, DR, CLI, NOR, and NAG V) during the period 1955-1991. These observations cover a range in latitudes from about 83° N to 35° N. Plots (from a to f) are arranged from the most northerly at the top (left) to less latitude at the bottom (right). Number of clear southward and northward gradients for each station are noted between square brackets. The estimated statistical error for each year is indicated. Curves represent the centered 3-year moving averages of the amplitude difference between the two sectors. In the bottom panels, the reversals of the Sun's polar magnetic field are also indicated with the IMF orientations above the heliospheric current sheet.

solar polarity reversal, with positive latitudinal gradients (cosmic-rays density increasing towards high latitudes) predicted for the positive solar polarity (outward magnetic fields in the Sun's northern hemisphere), and negative latitudinal gradients predicted during negative polarity state. On the other hand, two possible mechanisms for producing a north-south asymmetry of solar modulation have been proposed. One is related to the north-south asymmetry of the IMF winding angle [5, 22], and the other is related to the north-south asymmetry of the solar activity as indicated by sunspot numbers [2, 4, 33]. Figure 2 shows the annual amplitude differences of the cosmic-ray solar diurnal variation between the two sectors, for ALT, THU, DR, CLI, NOR, and NAG V during the period 1955-91. Numbers of clear southward and northward density gradients over the considered period for each station, are noted between square brackets. Plots (from a to f) are arranged from the most highest to lowest observatory latitudes. Curves represent the centered 3-year moving averages of the amplitude differences $(A(\mathrm{T})-A(\mathrm{A}))$ between the two sectors. Yearly error bars are shown with the same scale as the diagram. In the bottom panels (c and f), the reversals of the Sun's polar magnetic field are also displayed with the IMF directions above the neutral sheet. The difference in phases between the data for the two sets of IMF polarities will be discussed later. The notations noted in fig. 2 are the same in fig. 3 for the southern detectors (HUN, HER, WEL, HOB U, MAW U, and SOP). The amplitudes from the most equatorial to the most southerly detector are plotted (panels a-f). The main results are the followings:

1) In general, most of stations in both hemispheres (at 8 of 12 stations) indicated more southward amplitudes than northward, in keeping with previous observations [2-4, 7, 18, 37-39]. The most northerly (ALT and THU in plots 2a and 2b) and southerly observations (HOB U, MAW U, and SOP in plots 3d to 3f) show a more frequent occurrence of southward gradients. As the latitudes become less northerly (panels 2d and 2e), on average a predominance of northward latitudinal gradients is observed.

2) Lower amplitude differences occur at solar minima and high values near solar maxima, the rest of intermediate times do not display a dependence on solar activity. Within experimental errors, at or near the years of IMF reversal (1958-59, 1969-70, 1980, and 1989) asymmetric southward or northward or sometimes equal amplitudes were obtained in both hemispheres, implying that the N-S asymmetry seems to change its sign during these epochs. The direction of the asymmetric particle density gradient changed after each solar polar field reversal. Note that at solar maximum the IMF is so confused that the sectorisation on the Earth can have little meaning. The neutral sheet can even approach 90° meaning that the gradients are normally considered perpendicular to the neutral sheet. Studies by [40] found that the bi-directional latitudinal gradients of surface muon telescopes showed significant changes in sign at solar polarity reversal and most latitudinal values obtained from underground muon telescopes were not statistically significant. On the other hand, near times of minimum solar activity (1964-65, 1975, and 1986) the annual diurnal amplitudes of T and A days have nearly the same values (symmetry gradients). The density gradient displayed the same values both north and south of HCS. The minima solar activity periods were not associated with clear north-south asymmetries of solar activity, in accordance with the results reported before [7].

3) The 3-year moving average of amplitude difference (see the curves) tends to be negative during the declining phase of the solar activity and positive one (∇n points northward) during the ascending phase. A clear oscillation in the north-south asymmetry has been observed with the solar cycle (ALT, THU, CLI, NOR, NAG V, HUN, HER, WEL, HOB U, MAW U, and SOP). Positive peaks in N-S asymmetry occurred in 1955-56 (CLI and HUN), 1963-64 (CLI, and NOR), 1971-72 (CLI, NOR, NAG V, HUN, WEL,

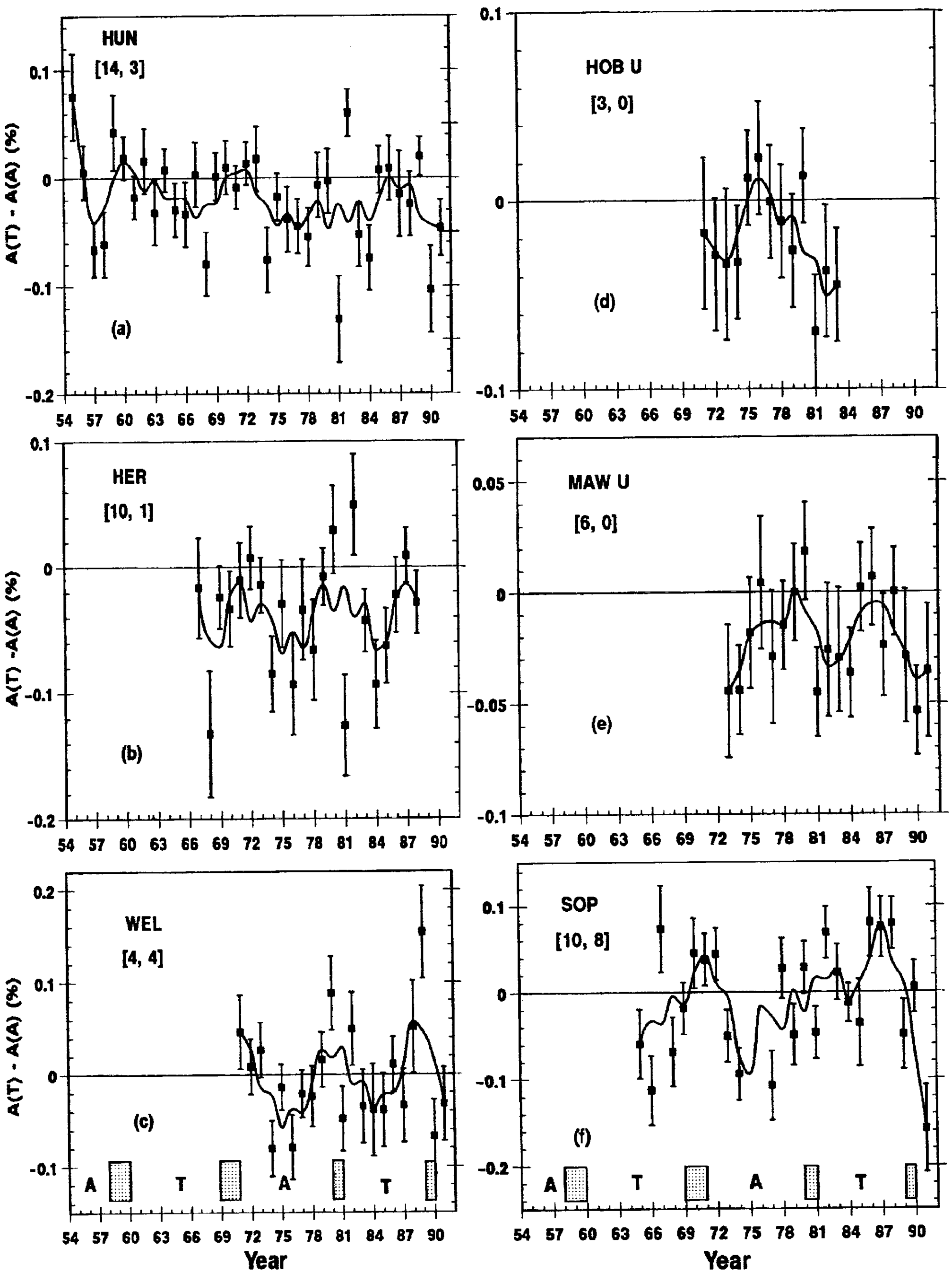

Fig. 3. – Annual amplitude differences between the IMF toward and away days of solar diurnal variation, for the south detectors (HUN, HER, WEL, HOB U, MAW U, and SOP). These observations cover a wide range in latitudes from 12° S to 90° S. Plots (from a to f) are arranged from the most southerly at the bottom (right) to less one at the top (left). The notations are the same in fig. 2.

and SOP), 1977-79 (ALT, DR, CLI, NOR, NAG V, and WEL), and in 1987-88 (DR, NAG V, WEL, and SOP). In contrast, negative peaks (negative N-S asymmetries) occurred in 1958-59, 1967-68, 1975-76, 1984, and 1990-91. In addition, most of the detectors have shown a negative latitudinal gradient in 1974, a year of high-speed solar wind streams. In 1974 and 1984, the two-sector structure of the IMF gave rise to extended periods of enhanced cosmic-ray solar diurnal variation [12]. In 1991, the enhancement of the two sectors pattern has recurred.

4) The north-south asymmetries of the Sun's activity may give a possible explanation for the observed N-S asymmetry modulation of cosmic rays. The periods of the Sun's northern and southern activity have been carefully studied as follows:
i) During the period 1965-68 (a predominance of northern sunspots on the Sun), the average amplitude of diurnal variations for away polarity days is larger than those of toward days (the average cosmic-ray gradient points southward) for the detectors in both hemispheres (THU, DR, CLI, HUN, HER, and SOP). In contrast, during the period 1977-1979 (the Sun's northern hemisphere was again more active), a dominance southward gradient is observed for the southern observations (HUN has A, A, A, one equal; HER has A, A, A, one equal; WEL has A, A, A, HOB U has T, one equal, A, A; MAW U has one equal, A, A), while the northern detectors reflected no discernible asymmetric gradients. Thus, during periods when northern hemisphere activity on the Sun predominated over that in the southern hemisphere, significant changes are frequently observed between the average diurnal amplitudes measured in toward and away days.
ii) During the period 1971-74 (a predominance of southern hemisphere activity on the Sun), the average amplitude for toward days is larger than those for away days (inferring the presence of a northward perpendicular cosmic-ray density gradient), for the northern detectors (DR has T, T, T, A; CLI has four toward directions; NOR has T, T, one equal, A; and NAG V has four toward directions). On the other hand, during the period of the Sun southern hemisphere was again more active (1981-84), most of the north and south stations have shown a predominance of southward gradients.

5) One should note that the average behavior of amplitudes differences has a tendency to 2-year oscillations (see curves of ALT, THU, DR, NOR, HUN, HER, WEL, and SOP). This effect was observed before [5].

6) There is no obvious evidence for dependence of the rigidity of particles on the cosmic-ray unidirectional latitudinal gradient.

In conclusion, the heliospheric magnetic field has a great effect on the direction (or sign) of cosmic-ray N-S asymmetry (pre- and post-reversal field configuration). Conversely, the magnitude of N-S asymmetry is shown to be only weakly dependent on solar activity and to be independent of the magnetic polarity of the solar dipole which is the source of the IMF. The cosmic-ray density gradients reversed sign through the epochs of the solar polar field reversals. The north-south asymmetries of cosmic-ray latitudinal gradients are correlated well with the relative frequency of the Sun's activity in the northern and southern hemispheres. Furthermore, southward gradients were observed on both hemispheres during the active periods of the northern hemisphere. The N-S asymmetry changes its sign with the polarity reversal on the Sun.

5. – North-south asymmetries of solar diurnal amplitude and phase during the $qA > 0$ and $qA < 0$ epochs

To examine the dependence of the N-S asymmetry of solar diurnal variations (SDV), at different rigidities and latitudes, on the IMF polarities ($qA > 0$ and $qA < 0$), we

TABLE II. – *Amplitudes and phases of solar diurnal variations for north and south of heliospheric current sheet with the variation differences between the two sectors, during the epoch of positive IMF polarity 1971-1978 ($qA > 0$)([a]).*

IMF Direction	Toward-Days		Away-Days		T-A Days	
Station	A (%)	Phase (h)	A (%)	Phase (h)	A (%)	Phase (h)
ALT	0.043 ± 0.005	15 ± 0.12	0.048 ± 0.007	14.1 ± 0.3	−0.005 ± 0.009	0.9 ± 0.3
THU([b])	0.1 ± 0.008	15.8 ± 0.3	0.11 ± 0.009	14.9 ± 0.3	−0.01 ± 0.01	0.9 ± 0.4
APT	0.28 ± 0.02	14.9 ± 0.6	0.25 ± 0.008	14.9 ± 0.6	0.03 ± 0.02	0 ± 0.8
OUL	0.28 ± 0.02	13.6 ± 0.13	0.27 ± 0.01	13.84 ± 0.2	0.01 ± 0.02	−0.24 ± 0.2
DR	0.31 ± 0.02	13.75 ± 0.12	0.31 ± 0.01	13.45 ± 0.1	0 ± 0.025	0.3 ± 0.15
WASH	0.35 ± 0.02	13.6 ± 0.2	0.36 ± 0.02	13.44 ± 0.2	−0.01 ± 0.03	0.18 ± 0.3
ROM	0.2 ± 0.02	12 ± 0.3	0.2 ± 0.015	11.8 ± 0.3	0 ± 0.02	0.2 ± 0.4
CLI	0.28 ± 0.01	14.6 ± 0.3	0.25 ± 0.01	13.2 ± 0.2	0.03 ± 0.01	1.4 ± 0.36
NOR	0.2 ± 0.01	12 ± 0.2	0.17 ± 0.01	11.6 ± 0.2	0.03 ± 0.01	0.4 ± 0.3
TOK	0.23 ± 0.01	12.55 ± 0.1	0.17 ± 0.02	12.22 ± 0.2	0.06 ± 0.02	0.33 ± 0.2
NAG V	0.19 ± 0.01	10.5 ± 0.3	0.16 ± 0.01	9.9 ± 0.2	0.03 ± 0.01	0.6 ± 0.3
HUN	0.17 ± 0.01	9.7 ± 0.2	0.2 ± 0.01	10 ± 0.2	−0.03 ± 0.01	−0.3 ± 0.2
HER	0.19 ± 0.01	12.9 ± 0.2	0.15 ± 0.01	13.26 ± 0.2	−0.04 ± 0.01	−0.36 ± 0.2
WEL	0.25 ± 0.01	12.9 ± 0.25	0.27 ± 0.01	13 ± 0.3	−0.02 ± 0.01	−0.1 ± 0.4
HOB U	0.05 ± 0.004	10 ± 0.2	0.063 ± 0.004	11.5 ± 0.2	−0.013 ± 0.005	−1.5 ± 0.3
MAWU([d])	0.044± 0.004	13.1 ± 0.4	0.069 ± 0.005	14.8 ± 0.3	−0.025 ± 0.006	−1.7 ± 0.5
MAW([b])	0.22 ± 0.01	16.8 ± 0.2	0.3 ± 0.02	17.2 ± 0.2	−0.08 ± 0.002	−0.4 ± 0.2
MCM	0.058 ± 0.005	9 ± 0.2	0.061 ± 0.003	7.2 ± 0.2	−0.003 ± 0.006	1.8 ± 0.2
SOP([c])	0.16 ± 0.01	17.6 ± 0.2	0.19 ± 0.009	16.9 ± 0.2	−0.03 ± 0.01	0.7 ± 0.2

([a]) Averaged over complete epoch.
([b]) One year missing (1977 at THU and 1973 at MAW NM).
([c]) Two years missing (1975-76).
([d]) Averaged over 1973-78.

TABLE III. – *Amplitudes and phases of cosmic rays solar diurnal variations for north and south of heliospheric current sheet as well as the variation differences between the two sectors, during the epoch of negative IMF polarity 1981-88 ($qA < 0$)([a]).*

IMF Direction	Toward-Days		Away-Days		T-A Days	
Station	A (%)	Phase (h)	A (%)	Phase (h)	A (%)	Phase (h)
ALT([b])	0.032 ± 0.005	14.2 ± 2.1	0.057 ± 0.006	15 ± 0.7	−0.025 ± 0.008	−0.8 ± 2.2
THU	0.086 ± 0.01	16.2 ± 0.2	0.11 ± 0.01	16 ± 0.2	−0.028 ± 0.001	0.3 ± 0.2
OUL([b])	0.28 ± 0.02	14.8 ± 0.2	0.27 ± 0.02	15 ± 0.1	0.01 ± 0.03	−0.21 ± 0.2
DR	0.31 ± 0.01	15.1 ± 0.13	0.3 ± 0.02	15 ± 0.2	0.01 ± 0.02	0.1 ± 0.24
WASH([b])	0.33 ± 0.02	14.7 ± 0.1	0.325 ± 0.03	14.9 ± 0.2	0.03 ± 0.03	−0.2 ± 0.2
ROM	0.2 ± 0.03	13.7 ± 0.2	0.22 ± 0.02	14.25 ± 0.1	−0.02 ± 0.03	−0.55 ± 0.2
CLI([b])	0.32 ± 0.02	15.5 ± 0.1	0.3 ± 0.03	15.26 ± 0.1	0.02 ± 0.03	0.26 ± 0.12
NOR	0.236 ± 0.02	14.2 ± 0.1	0.237 ± 0.02	14.26 ± 0.2	0 ± 0.03	−0.06 ± 0.2
TOK	0.217 ± 0.01	14.3 ± 0.1	0.218 ± 0.01	14.28 ± 0.2	0 ± 0.01	0.036 ± 0.2
NAG V	0.17 ± 0.01	13.5 ± 0.2	0.17 ± 0.01	13.1 ± 0.2	0 ± 0.01	0.4 ± 0.2
HUN	0.18 ± 0.01	12.5 ± 0.2	0.21 ± 0.01	12.16 ± 0.2	−0.03 ± 0.01	0.35 ± 0.2
HER	0.21 ± 0.02	14.7 ± 0.3	0.25 ± 0.02	15.66 ± 0.2	−0.04 ± 0.02	−1.1 ± 0.3
WEL	0.278 ± 0.02	14.6 ± 0.2	0.288 ± 0.02	14.8 ± 0.2	−0.01 ± 0.02	−0.18 ± 0.2
HOB U([c])	0.068 ± 0.006	15.92 ± 0.2	0.12 ±.003	16.38 ± 0.2	−0.052 ± 0.007	−0.69 ± 0.2
MAW U	0.065 ± 0.006	17.9 ± 0.3	0.084 ±.005	18.33 ± 0.2	−0.019 ± 0.007	−0.44 ± 0.3
MAW	0.27 ± 0.02	17.77 ± 0.2	0.253 ± 0.01	18.05 ± 0.2	0.02 ± 0.02	−0.3 ± 0.3
MCM	0.07 ± 0.003	9.07 ± 0.5	0.045 ± 0.004	10.34 ± 0.2	0.025 ± 0.004	−1.3 ± 0.5
SOP	0.2 ± 0.006	18.45 ± 0.2	0.17 ± 0.01	18.33 ± 0.15	0.03 ± 0.01	0.11 ± 0.2

([a]) Averaged over complete epoch.
([b]) Averaged over 1981-87.
([c]) Averaged over 1981-83.

classified the former period into two subsets; one set for positive (1971-78) and the other set (1981-88) for negative magnetic polarity. Thus, each subset contains 8 years, after removing the years during which the Sun's polar field was reversing. Tables II and III show the average solar diurnal amplitude and phase of toward and away days, as well as the variations (amplitude and phase) difference between the two sectors during the epochs of positive (1971-78) and negative (1981-88) polarity of the solar polar magnetic field. Results are arranged from the most northerly at the top (ALT) to the most southerly at the bottom (SOP). We concluded the followings:

1) During the period of positive IMF polarity 1971-78 (the IMF points away from the Sun north of current sheet and toward the Sun south of it), there is no obvious N-S asymmetry in solar diurnal amplitudes (SDA) for NMs at the most northerly latitudes (ALT and THU). Note that a clear asymmetry is considered when the SDA difference $> 2\sigma$. Detectors of lower latitude (CLI, NOR, TOK, and NAG V) reflected asymmetry gradients, while a negative N-S asymmetry existed in SDA for detectors in the southern hemisphere (HUN, HER, HOB U, MAW U, MAW, and SOP). In case of solar diurnal phases, the phases of negative polarity days (means toward days) are larger than those of positive days for detectors in the northern hemisphere (THU, DR, CLI, NOR, TOK, and NAG V), while for south observations (HUN, HER, HOB U, MAW U, and MAW) the reverse is true. At the most southerly NMs, an obvious positive N-S asymmetry in SD phases were revealed (MCM and SOP). Larger positive N-S asymmetry in phases was observed in CLI (1.4 ± 0.36 h LT) in the northern hemisphere and MCM (1.8 ± 0.2 h LT) at the most southerly latitude. In contrast, larger negative phases were observed for underground muon telescopes HOB U and MAW U (1.5 ± 0.3 and 1.7 ± 0.5 h LT, respectively).

2) During the period of negative IMF polarity 1981-88 (the direction of IMF was reversed toward the Sun north of the current sheet and away from the Sun south of it), a negative N-S asymmetry in SDA existed in the north only at ALT and THU. Most of northern stations (at 8 of 10 observation sites; OUL, DR, WASH, ROM, CLI, NOR, TOK, and NAG V) showed no N-S asymmetries. On the other hand, positive asymmetries were obtained for the most southerly NMs at MCM and SOP. Other southern stations expressed negative N-S asymmetries (HUN, HOB U, and MAW U). A weak asymmetry in solar diurnal phases was observed for the north detectors (THU, ROM, CLI, and NAG V). For most south detectors, the phases of toward days (north of the HCS) were shifted to earlier hours than those for away days (south of HCS). Larger negative asymmetries in phases were recorded in HER, HOB U, and MCM.

3) In general, northern results showed that the diurnal amplitude of T days in both polarities of IMF (1971-78 and 1981-88) were the same, within experimental errors. Moreover, that was not true for the away days. We found consistent changes in the cosmic-rays solar diurnal amplitudes between A (or T) groups, during the two epochs $qA > 0$ and $qA < 0$. Furthermore, the magnitudes of observed cosmic-ray north-south asymmetry in SDA are found to be independent of the IMF polarity epoch.

4) The diurnal phases of T days during the epoch of negative IMF polarity ($qA < 0$ epoch) shifted $\approx 1.8 \pm 0.2$ h earlier than those during the positive IMF polarity ($qA > 0$ epoch), for the northern observations, and $\approx 3 \pm 0.2$ h earlier in the southern hemisphere. To display that we have plotted in fig. 4a the time-shift (TS h) of toward days for the northern (squares points) and southern stations (crosses), as a function of the median primary rigidity. The best-fit lines to the data are shown; the equation of the best-fit and the regression coefficient, r, are also shown. This time-shift is dependent on the rigidity of the particles. There is a well positive correlation between TS and the rigidity of the

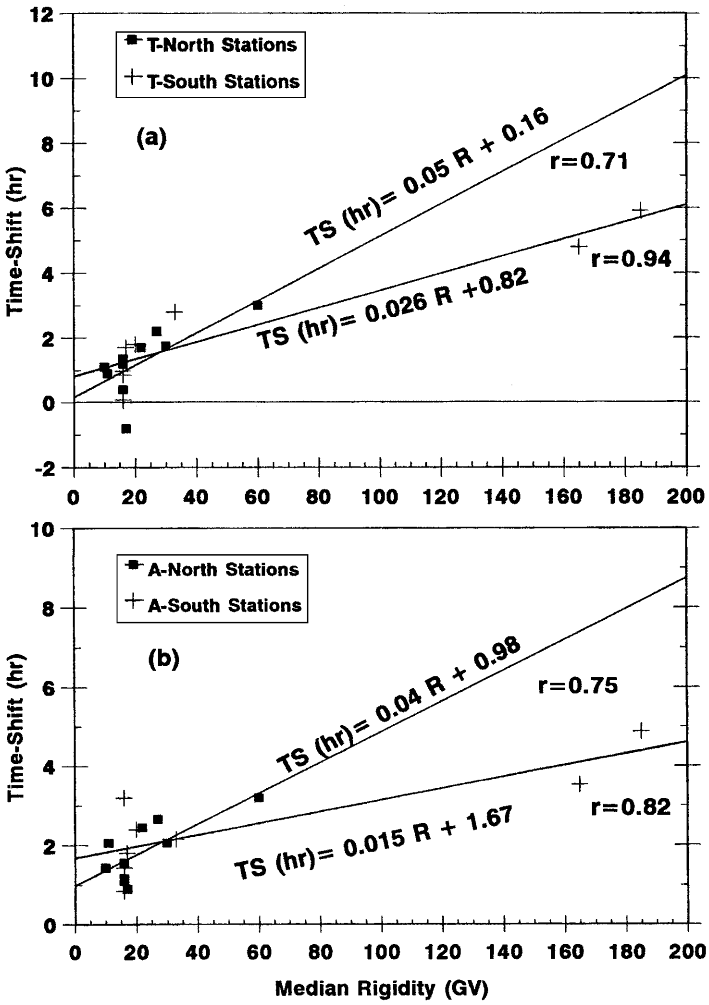

Fig. 4. – a) shows the time-shift (TS) of toward polarity days for northern (squares) and southern (crosses) observations. The best-fit lines to the data, the equation of the best-fit and the regression coefficient (r) are noted. b) The same notations noted in the top panel but for away polarity days.

particles. Furthermore, it is clear that the slope (a measure of sensitivity of time-shift of toward days to the changing of $R_{\rm m}$) of the best-fit straight line to the northern stations is steeper than for southern stations, a factor of two larger.

5) The diurnal phases for A days during the negative IMF polarity ($qA < 0$ epoch) also shifted to earlier hours than during the positive polarity epoch, by $\approx 2.2 \pm 0.2$ h for the northern detectors and $\approx 3.3 \pm 0.3$ h for the southern ones. The notations noted in fig. 4a are the same for fig. 4b for the away polarity days. As in fig. 4a, we notice that the sensitivity of TS of away days to the changing in $R_{\rm m}$ for the northern stations is larger than for the southern stations by a factor of about three. Strong correlations between TS and $R_{\rm m}$ are seen. Therefore, the solar diurnal phases of toward days north of the HCS

(or away) during the period 1981-88 ($qA < 0$) were a few hours later than those recorded for toward (or away) days south of the HCS during the positive IMF period 1971-78; the time-shift depends on the particle rigidity. Moreover, the change in phase for the northern NMs and MTs was larger than for those located on the southern hemisphere. These results are consistent with and confirm the results of El-Borie *et al.* [6, 7, 15, 18].

Thus, during the negative period ($qA < 0$) and at the most northerly latitudes (ALT and THU), the results indicated the presence of a negative N-S asymmetry, while at the most southerly latitudes (MCM and SOP), positive asymmetries were observed. Most of northern observations reflected a N-S symmetry gradient. Moreover, the two underground muon observations (HOB U and MAW U) revealed that the cosmic-ray density gradients pointed southward. Conversely, during the positive period ($qA > 0$), the most northerly observations have not clearly displayed a latitudinal gradient. The northern (CLI, NOR, TOK, NAG V) and southern (HUN, and HER) equatorial observations indicated northward (existed later) and southward density gradients (existed earlier), respectively. At high southerly latitude (MAW U, MAW, and SOP) we find a southward latitudinal density gradient. Results of [4] explained that cosmic rays with high rigidities that are detected by the most northerly (or southerly) pointing seem to be arriving from a region of the north (or south) pointing gradient well above (or below) the current sheet. This will result in cosmic-ray diurnal variations in which toward (or away) amplitudes exceed away (or toward) amplitudes and give rise to the higher northward (or southward) gradients.

6. – Conclusions

We have analyzed data obtained with 21 globally distributed detectors, with median primary rigidity of response (R_{m}) in the range 10 GV $\leqslant R_{\mathrm{m}} \leqslant$ 185 GV over the period 1955-1991. The time interval covers several epochs of solar activity maxima, minima, and polar field reversals. Observations from neutron monitors and muon telescopes (surface and underground) have been used. Typical gyroradii for neutron monitor primaries are about 0.1 AU, while those for muon telescopes primaries are 0.5 AU or greater. The annual average cosmic-ray solar diurnal variations were separated into toward and away sectors of the IMF. Our principle conclusions are the followings:

1) A symmetry in toward and away IMF days existed. This symmetry may depend slightly upon the magnetic state of the heliosphere. Sometimes equal T and A days have been observed at, or near, the years of maximum and minimum solar activity. A corresponding symmetry was observed in the sunspot numbers of the northern and southern hemispheres.

2) The annual number of A and T polarity days indicated a good correlation with the level of solar activity. It has been found that when the IMF was directed toward the Sun in the northern hemisphere ($qA < 0$) there were more toward days (north of HCS) than those of away days. Furthermore, there were an additional T days during the epochs 1971-74 and 1982-85 when the northern hemisphere was less active than the southern one. These periods coincide with times of declining phase of solar activity cycle.

3) The density gradients existed near times of maximum solar activity. Within experimental errors, near the years of IMF reversal (1958-59, 1969-70, 1980, and 1989) asymmetric southward or northward or sometimes equal amplitudes were obtained in both hemispheres, implying that the N-S asymmetry seems to change its sign during these epochs. It nearly disappeared near times of minimum solar activity.

4) The north-south asymmetries of cosmic-ray gradients are correlated well with the

relative frequency of the Sun's activity in the northern and southern hemispheres. Significant changes between the diurnal amplitude of toward and away days are frequently observed, implying the existence of southward and northward density gradients. Moreover, the directions of the N-S asymmetry are dependent on the IMF polarity states.

5) The running average of N-S asymmetry in cosmic rays has a tendency to be negative (∇n density points southward) during the declining times of solar activity cycle, and to be positive (∇n density points northward) in the recovering phase of solar cycle. The magnitude of N-S asymmetry of cosmic ray displayed a weak correlation with the solar activity and it is independent of the magnetic polarity of the IMF. In addition, the N-S asymmetry of cosmic-ray solar diurnal variations existed for particle rigidities from 10 GV to 185 GV.

6) The study of the average N-S asymmetries during the epoch $qA < 0$ confirmed the presence of a northward gradient at the most southerly latitudes and a southward gradient at the most northerly latitudes. Moreover, most of northern observations reflected a N-S symmetry gradient. In contrast, during the period $qA > 0$, the most northerly observations have not clearly displayed N-S gradients. We found significant changes in the N-S asymmetry of the solar diurnal amplitudes and phases are frequently observed.

7) The solar diurnal phases of toward polarity days north of the HCS (or away) during the period 1981-87 ($qA < 0$) existed a few hours later than those recorded for toward (or away) days south of HCS during the positive IMF period 1971-78, as well as the time shift depends on the rigidity of the particle. In addition, quite a change occurred on phase for the north NMs and MTs than for those located on the southern hemisphere.

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