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North-South asymmetry of interplanetary plasma and solar parameters

M. A. El-Borie(*)

Physics Department, Faculty of Science, Alexandria University - Alexandria, Egypt

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Summary. — Data of interplanetary plasma (field magnitude, solar wind speed, ion plasma density and temperature) and solar parameters (sunspot number, solar radio flux, and geomagnetic index) over the period 1965-1991, have been used to examine the asymmetry between the solar field north and south of the heliospheric current sheet (HCS). The dependence of N-S asymmetry of field magnitude (B) upon the interplanetary solar polarities is statistically insignificant. There is no clear indication for the presence of N-S asymmetry in the grand-average field magnitude over the solar cycles. During the period 1981-89 ($qA < 0$; negative solar polarity state), the solar plasma was more dense and cooler south of the HCS than north of it. The solar flux component of toward field vector is larger in magnitude than those of away field vector during the $qA < 0$ epoch, and no asymmetry observed in the $qA > 0$ epoch. Furthermore, the sign of the N-S asymmetry in the solar activity depends positively upon the solar polarity state. In addition, we have studied the N-S asymmetry of solar parameters near the HCS, throughout the periods of northern and southern hemispheres were more active than the other. Some asymmetries (with respect to the HCS) in plasma parameters existed during the periods of southern hemisphere predominance.

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1. – Introduction

Most interplanetary plasma parameters are highly variable on time scales ranging from minutes to the solar activity cycle and also vary with heliographic latitude and longitude [1,2]. The solar magnetic field is frozen in the solar plasma and carried outward by the solar wind. When the Sun rotates, the field at equatorial latitudes forms a spiral structure. In addition, a neutral sheet results from this structure, maintaining a

(*) Now at: Physics Department, Teacher College, Riyadh 11491, P.O. Box 4341, Kingdom of Saudi Arabia.

separation between northern and southern regimes. This averaged warped heliospheric current sheet (HCS) separates regions with opposite polarities of the magnetic field. The structure of the HCS changes substantially during the 11-year sunspot cycle [3-5], with a relatively flat sheet at the solar minima years, but neutral sheet waves extend up to 70° heliolatitude at solar maxima epochs. Furthermore, the solar field polarity reverses at each solar maximum giving rise to a 22-year periodicity in the heliomagnetic field.

Observations of large-scale flows in the inner heliosphere have shown two distinct flow regions at solar minimum: one coming from coronal holes and characterized by high speed with low densities, and the other from boundary regions between holes with lower speeds and higher densities. Stronger anticorrelations between ion temperature (T) and density (N) were evident within low-speed regions between streams and was contrasted with more positive correlations between these parameters in high-speed flows [6]. The largest anticorrelation between proton temperature and density were in flows that were between high-speed streams and come from boundary regions between coronal holes. Spectra of SW plasma density and magnetic field fluctuations were observed to evolve as a power law [7]. They showed that the spectrum of small-amplitude density fluctuations follows a power law of $K^{-5/3}$ when the spectrum of field fluctuations has the same shape. The magnetic clouds at sector boundaries have been studied [8]. The expectation that the magnetic clouds should be found at sector boundaries is based upon the view of heliospheric topology where the streamer belt serves as a heliospheric passageway for the coronal mass ejections [9, 10].

The spectrum of large-scale fluctuations in the solar wind ion density has revealed the existence peaks with the solar rotation period (27 days) and broad peak near 1.3 years and the observed variations in ion density appeared to reflect the true variations in the solar wind speed [11]. Studies of long-term variations of solar wind ion density and bulk flow velocity during the period 1965-1986 have shown a negative correlation between the SW speed and the solar activity [12,13]. The existence of the periodic 1.3-year enhancements in SWS from 1987 to 1995 have been reported [14-16], and similar periodicities in Ap (a measure of geomagnetic disturbances) have been observed [17, 16]. Yearly averaged variations in interplanetary plasma (SWS, N, and T), and magnetic-field magnitude (B) over more than two solar cycles were studied in detail [13-18]. Some clear periodicities were evident and some of the observations also showed a solar cycle dependence. The solar wind speed clearly showed an increase at solar maximum and the annual mean of ion density reached its minimum values in 1968 and 1969, which were the years of maximum solar activity. The maximum value of ion density exists in 1977, one year after minimum solar activity [13]. The ion density was not correlated with the other plasma parameters during the three solar cycles (from 20th to 22nd). During the declining phase of solar activity cycles, large values of SWS, plasma T, and IMF magnitude B were observed, with low values of N. The yearly averages of B, SWS, and T have shown separate solar cycle variations [13]. Results by [18] showed that the solar plasma north of the current sheet is 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 is absent in solar cycle 21.

In the present work, we examine the N-S asymmetries in the interplanetary parameters (field magnitude B, ion density N, ion temperature T and solar wind speed SWS). Then we compared the observed results with the asymmetries in the solar indices (sunspot number R_Z, geomagnetic index Kp, and solar radio flux SF). In the next section, we use the superposed epoch analysis to examine the IMF sector-dependence on the plasma parameters near the heliospheric current sheet boundaries. The last section discusses and summarizes our conclusions.

2. – The north-south asymmetry of field magnitude and plasma parameters

It may be useful to compare the north-south asymmetry in the interplanetary plasma and solar parameters with the observed asymmetries in the solar diurnal variations over the period 1965-1991. Detailed discussion of the yearly mean variations of magnetic field and plasma parameters are given elsewhere [13-18]. High cosmic-rays solar diurnal amplitudes coincide with the increase in IMF magnitudes $|B|$, during the descending phase of the solar cycles [19, 20, 13]. This may be due to the large values of upper cutoff rigidity during these periods [21, 20].

In this section, we have used the hourly averages of IMF magnitude B and plasma parameters (solar wind speed SWS, ion density N, and ion temperature T), taken near 1 AU by a variety of spacecraft which were provided by the National Space Science Data Center "omnitape" [22-25], over the time interval 1965-1991. These parameters have been analyzed according to the IMF sector to examine the presence of the north-south asymmetry. A day is considered in our analysis only if it has at least 12 hourly averages of IMF magnitude and 12 or more hourly averages of either plasma parameters available for that day. The field direction is calculated on a daily basis in the geocentric equatorial coordinated system. So, we have separated the field direction into two polarities; away (A) polarity if the solar ecliptic azimuthal angle of the IMF daily averages lies between $45\,^\circ$ and $225\,^\circ$; otherwise it is considered as toward (T) the Sun. We have removed days on which the IMF was truly mixed; and we have then separated the considered data into two groups according to away or toward daily average IMF vector, over the 1965-91 epoch.

Figure 1 displays from the top the yearly difference variations of field magnitude B, solar wind speed SWS, and ion density N, between the positive and negative polarity days (Toward-Away days). Curves indicate the centered 3-year running averages over the period 1965-91. Estimated error is shown for each year, for each parameter. Times of magnetic-field reversal at the Sun's north (N) and south (S) poles are noted at the top of the figure. A persistent north-south asymmetry of the field magnitude is clear over the considered period. From the top panel, $[B(\mathrm{T}) - \mathrm{B(A)}]$, there are three obvious negative N-S asymmetries in the averaged magnetic field occurring in 1970, 1983, and 1984, and a positive asymmetry one in 1966. In addition, there are four weak positive asymmetries that occurred in 1969, 1972, 1976, and 1990. Note that toward sectors occur north of the current sheet during negative solar polarity and south of the current sheet during positive polarity. In general, the average behavior of field magnitude differences (see the curve) is large (positive peak) north of the current sheet during the first negative solar polarity (1965-68), while we find a negative peak in the second negative polarity period (1981-85). The N-S asymmetry in magnetic field displayed a tendency to be positive prior to the solar magnetic dipole reversal that occurred near 1970, and negative following the next reversal in 1980.

Tables I and II display the averages of field magnitude, plasma and solar parameters for toward and away polarity days, respectively, as well as the differences between the two groups over the epochs of positive (1971-78) and negative (1981-88) IMF polarity years. The total number of days north and south of the current sheet as calculated from each parameter is listed in the tables. The grand average differences of field magnitude north and south of HCS are $0.03 \pm 0.09\,\mathrm{nT}$ for $qA > 0$ epoch and $-0.29 \pm 0.23\,\mathrm{nT}$ for $qA < 0$ epoch. This is statistically insignificant. There is no remarkable N-S asymmetry in the field magnitude over the former epochs. No magnetic solar cycle dependence is evident. However, in general the dependence of N-S asymmetry in the averaged B upon the asymmetry of the solar northern and southern hemispheres is not apparent. The

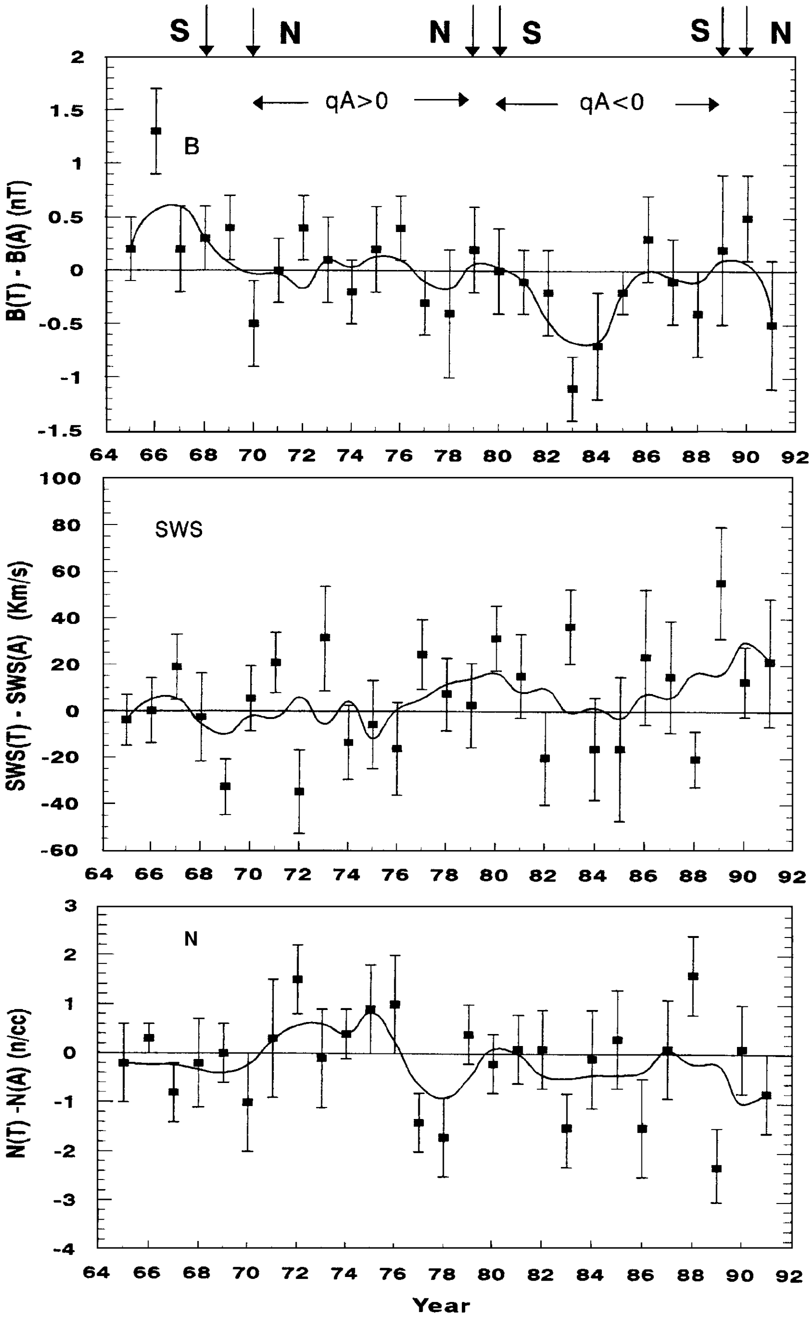

Fig. 1. – (Top) The differences between the yearly averages of field magnitude north $B(\mathrm{T})$ and south $B(\mathrm{A})$ of the current sheet. Middle panel displays the solar wind speed difference $SWS(\mathrm{T}) - SWS(\mathrm{A})$, over the 27-year period. Bottom, the differences between the values of solar wind ion density north $N(\mathrm{T})$ and south $N(\mathrm{A})$ of the current sheet. Curves represent the centered 3-year moving averages of the magnitude difference. Arrows above the top plot show when the Sun's north (N) and south (S) pole reversal magnetic polarities.

TABLE I. – *Averages of IMF field magnitude, plasma and solar data for toward and away polarity days, as well as the differences between the two sectors during the epoch of positive polarity of the polar solar magnetic field 1971-78 ($qA > 0$). The total number of days north and south of the current sheet as calculated from each criterion is listed.*

IMF and solar parameters	Toward days		Away days		T-A
	no. of days	average	no. of days	average	average
B (nT)	1070	6.24 ± 0.14	1078	6.21 ± 0.22	0.03 ± 0.09
SWS (km/s)	1082	459 ± 13	1046	424 ± 13	35 ± 10
N (n/cc)	1066	9.03 ± 0.3	1027	8.88 ± 0.4	0.15 ± 0.3
$T(10^3\,\mathrm{K})$	1055	88.2 ± 2.6	1025	90.5 ± 2.5	-2.3 ± 2
Kp	1258	23.7 ± 1.0	1265	23.6 ± 1.0	0.1 ± 1.1
R_Z	1258	45.7 ± 8	1265	46.4 ± 7	-0.7 ± 1.1
SF	1258	99 ± 8	1264	100 ± 7	-1 ± 5

magnitude of asymmetry as computed from the yearly averages exceeds $\approx 1.2\,\mathrm{nT}$ in 1966 and 1983, but it is generally closer to $0.3\,\mathrm{nT}$.

In the middle panel of fig. 1, when we take the error bars into account, there are 10 random years out of 27 with north-south asymmetry in the yearly average of SWS. Seven clear positive asymmetries with $SWS(\mathrm{T}) > SWS(\mathrm{A})$ happened in 1967, 1971, 1973, 1977, 1980, 1983, and 1989, most of which occurred during or near the positive polarity period. In contrast, three clear negative N-S asymmetries occurred in 1969, 1972, and 1988. The largest positive N-S asymmetry occurred in 1989 ($55.4 \pm 24\,\mathrm{km/s}$), in contrast with the largest negative one obtained in 1972 ($-35 \pm 18\,\mathrm{km/s}$). One can see that during the periods when the northern sunspots predominate over the southern sunspots (1965-68 and 1975-79), north-south symmetry in the averaged SWS was observed. In contrast, during the periods of the Sun's southern hemisphere were more active than the Sun's northern hemisphere (1971-74 and 1981-84), the N-S asymmetry in SWS was observed. From tables I and II, we find that the $SWS(\mathrm{T})$ for toward days south of the current sheet is larger in magnitude than those for away polarities north of the current sheet $SWS(\mathrm{A})$ during the positive polarity epoch (1971-78), while the north-south asymmetry is absent during the epoch of negative polarity (1981-88) of the solar polar magnetic field. This confirms the existence of a weak N-S asymmetry in the averaged SWS during the epoch of positive solar polarity and a N-S symmetry during the epoch of negative polarity of the solar polar magnetic field. Also, we find that the asymmetry in SWS exhibited well at the times of maximum solar activity. The moving average curve shows prominent asymmetries near the maxima solar activity years (1969, 1980, and 1988-89). The computed toward-away sector SWS asymmetry has a tendency to be positive at, or slightly near, the times of solar polar reversals in 1979-80 and 1989. Furthermore, the SWS are faster by about 35 km/s for toward polarity days (see tables I and II) than for away days when the IMF points away from the Sun north of the current sheet and toward the Sun south of it. The present results confirmed earlier results [26, 18], that the observed asymmetry in the solar wind speeds was not the source of the observed asymmetry in the IMF winding angles at 1 AU [27]. Note that the SWS was high during the declining phase of the solar cycle (1973-75 and 1982-84). This coincides with the time of enhancements in the amplitude of solar diurnal variation and the SWS reaches its highest value in 1974 [20, 28, 29, 26, 13].

TABLE II. – *Averages of IMF field magnitude, plasma and solar data for toward and away polarity days, as well as the differences between the two sectors during the epoch of negative polarity of the polar solar magnetic field 1981-88 ($qA < 0$). The total number of used days (for toward and away sectors) is listed for each parameter.*

IMF and solar parameters	Toward days		Away days		T-A
	no. of days	average	no. of days	average	average
B (nT)	970	7.01 ± 0.27	1030	7.3 ± 0.3	-0.29 ± 0.23
SWS (Km/s)	939	458 ± 8	1011	456 ± 10	2 ± 7
N (n/cc)	902	10.25 ± 0.3	978	9.1 ± 0.3	-1.15 ± 0.3
T (10^3 K°)	890	82.1 ± 2.7	970	73.4 ± 2	8.7 ± 1.7
Kp	1284	25.1 ± 0.9	1401	26.1 ± 1.2	-1.0 ± 1.1
R_Z	1284	67.9 ± 12	1401	65.9 ± 11	2.0 ± 3
SF	1283	120 ± 12	1401	120.9 ± 10	-0.9 ± 5

Figure 1 (bottom panel) shows the yearly differences between the ion density north and south of the current sheet. Yearly averages of plasma ion density (for toward and away IMF days) systematically increase from a lower value in 1970 to a maximum value in 1977 [13, 18]. The average north-south asymmetry of the plasma proton density is absent during the positive period of the Sun's polar magnetic field (see table I), while the existence of a negative north-south asymmetry is confirmed during the negative polarity period 1981-88 (see table II). The average ion plasma density for away polarity days south of the HCS during the 1981-88 epoch is 1.15 ± 0.3 n/cc more dense than those of toward polarity days north of HCS. So, the solar plasma is more dense south of the current sheet than north of it during the negative solar polarity epoch ($qA < 0$). Six out of 27 years show negative asymmetry with the average N of the northern heliospheric densities smaller than the average of the southern heliospheric densities which occurred in years (1967, 1977, 1978, 1983, 1986, and 1989). The largest negative asymmetry occurred in 1989 (-2.3 ± 0.7 n/cc) and two nearly equal positive asymmetries happened in 1972 and 1988 ($\approx 1.8 \pm 0.8$ n/cc). Most of the asymmetries occurred during the period of negative IMF polarity (1967, 1983, 1986, 1988, and 1989). Curves of the computed T-A polarity sectors of asymmetry in ion density are usually negative prior to the solar magnetic reversal in 1969, changed to positive from 1971 to 1976, and are mostly negative from 1977 to 1986. In addition, larger N-S asymmetries in ion density happened during the period 1966-69, 1975-78, and 1986-89, when the Sun's northern hemisphere was more active.

The variation of plasma temperature for toward and away days has been extensively studied [13, 16, 18]. Almost no negative N-S asymmetry in proton temperature was obtained, while seven positive asymmetries occurring over the considered period (not shown here). This means that the ion plasma is hotter for toward polarity days than for away days. In tables I and II, a positive N-S asymmetry is detected ($8.7 \pm 1.7 \times 10^3$ K) for the epoch 1981-88, while the asymmetry of T is absent during 1971-78. Therefore, the plasma density north of the current sheet is less dense and hotter than south of it during the negative IMF polarity period 1981-88. In contrast, the solar wind speed was faster for toward polarity days than away days, when the IMF pointed away from the Sun north of the current sheet. Large asymmetries in B, T, N, and SWS have been observed in 1983. Moreover, significant changes in the N-S asymmetries have been correlated with the N-S asymmetries of the solar activity in the northern and southern hemispheres.

3. – The north-south asymmetry of solar indices

In this section, we have examined the asymmetry that exists between the very large-scale properties of the toward and away sectors of solar parameters. The asymmetry between the northern and southern hemispheres sunspot activity is well known to solar observers and is one of the features used in the morphological descriptions of the solar activity. The northern and southern active periods are generally quite different when long-term activity is considered. Throughout the period of solar cycles 12-21 (1878-1988), the N-S asymmetry of the sunspot numbers with respect to the solar equatorial plane has been studied [30]. This asymmetry revealed an 11-year periodicity with the phase of the maximum in earlier half or in the later half, occurring alternatively in each four solar interval, thus exhibited an 88-year variation as pointed out by [31,32]. On the other hand, the relationship between solar and geomagnetic activity has been investigated [33]. The results clearly indicated that the geomagnetic activity represented by the Kp index revealed two maxima for each single maximum in solar activity as represented by sunspot numbers and indicated also that the geomagnetic activity had two discrete components attributed to solar flare effects and corotating streams. Studies by Rangarajan [34] revealed that the sun's northern hemisphere is, almost always, geomagnetically more active, on average about 20%, than the southern hemisphere. This enhanced activity may be attributed to the inverse relationship between the geomagnetic activity and the strength of the magnetic field. The N-S asymmetry of aa-index with respect to the solar equatorial plane showed a variation with a 22-year period in solar cycles 17-21 (1933-1988) [30].

Figure 2 displays the yearly differences in R_Z, SF, and Kp between toward and away polarity days for the 27-year interval 1965-91. The notations are the same as in fig. 1. The solid curve is the 3-year moving averages. These daily data were provided by the National Geophysical Data Center, Colorado, USA. The records of international sunspot number contain the Zurich number through the end of 1980, and the international Brusels number thereafter. The solar radio flux (10.7 cm) adjusted to 1 AU and measured at 1700 UT daily and expressed in units of 10–22 Watts/m^2/Hz. We have separated the daily averaged data into two groups corresponding to away and toward IMF polarities. The yearly averages of these parameters have been calculated for away and toward groups, separately. Only hours when both magnetic field and solar indices were available were used throughout this analysis. Error estimates in the averages are calculated for each group. In top panel, only 10 of 27 years have asymmetry with magnitude more than the estimated error (the years 1965, 1966, 1968, 1983, and 1988 have positive asymmetry, and years 1967, 1970, 1974, 1982, and 1991 have negative asymmetry). Most of the asymmetries occurred when the solar northern hemisphere has toward polarity during the negative polarity epoch (1965-68 and 1981-88). Two asymmetries occurred in years of IMF mixed polarities (1970 and 1991) and one year (1974) during the year of high-speed solar wind streams. It is interesting to note that the sign of the average N-S asymmetry depends upon the solar magnetic polarity. It is generally positive in negative solar magnetic polarity years (see the curve) and negative in positive polarity years. The toward-away difference in the R_Z has a tendency to be positive prior to the solar magnetic reversal occurring in 1969, nearly negative from that time until near the reversal of 1980, and again positive from 1983 to 1989. During years of negative solar polarity (1965 through 1968 and 1981 to 1988) toward sector measurements correspond to northern hemispheric fields and away sector measurements correspond to southern hemispheric field. During years of positive solar polarity (1971 through 1979) the association is reversed. There is

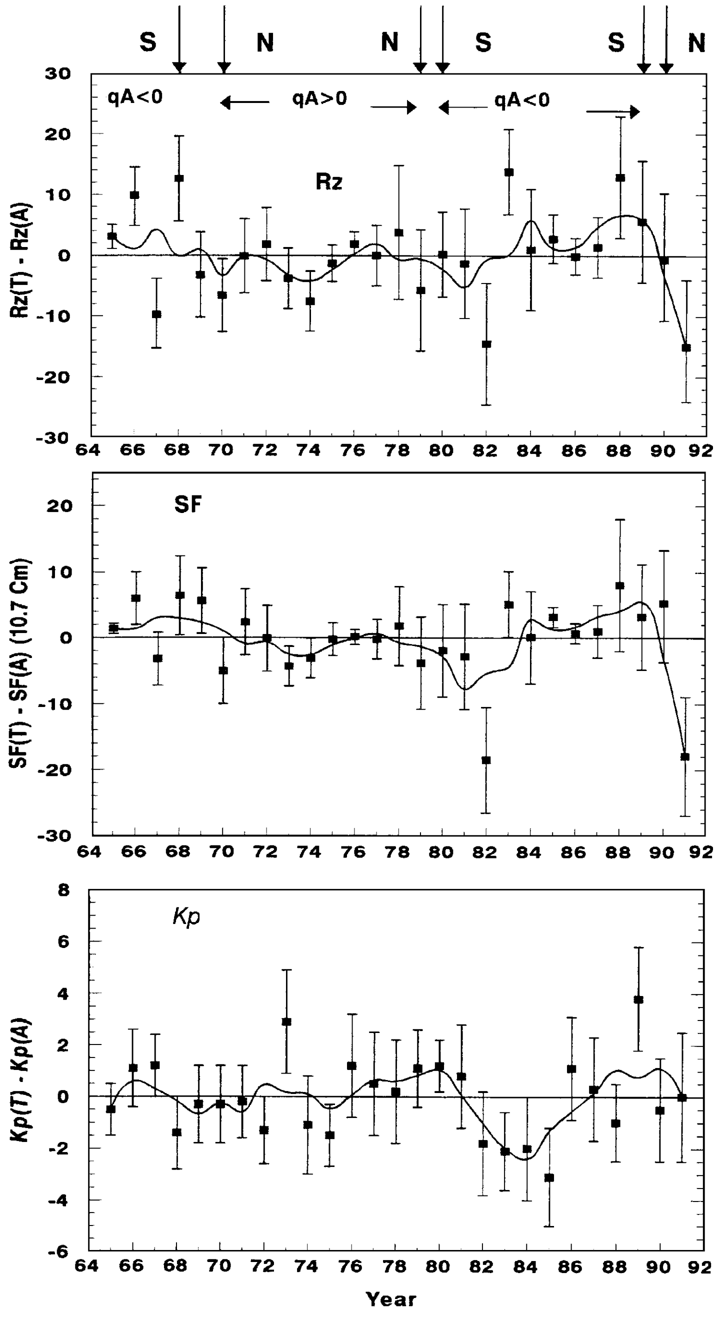

Fig. 2. – Comparison of yearly difference of the north-south asymmetries in the sunspot numbers R_Z, solar radio flux SF, and geomagnetic index Kp during the 1965-91 period. Times of Sun's north (N) and south (S) pole reversal magnetic polarities are displayed by arrows in the top panel.

no observable difference between the sunspot numbers of grand averages during the two IMF polarities epochs $qA > 0$ and $qA < 0$ (see tables I and II). In contrast, the annual magnitudes of N-S asymmetry depend positively on the solar magnetic cycle, whereas great asymmetries occurred during the negative solar epochs (1965-68 and 1981-89).

The asymmetry of the solar radio flux during 1965-91 is displayed in the middle panel of fig. 2. The two curves of R_Z and SF have nearly the same behavior. The north-south asymmetry in SF is confirmed over the former period. We get 6 years (1965, 1966, 1968, 1969, 1985, and 1988) out of 27 with larger solar flux component north of the current sheet and 3 years (1973, 1982, and 1991) with larger component south of the current sheet. In other words, the solar flux component of toward field vector is larger in magnitude than those of away field vector during the negative polarity epochs (1965-1968 and 1981-88). Three of these nine years (1965, 1973, and 1985) have insignificant difference. While nearly no north-south asymmetry was observed during the positive IMF period (1971-78). Again, we should note that the toward (away) sectors occur north (south) of the current sheet during the negative solar polarity epoch, and the IMF directions reverse during the positive polarity period. The grand average of the solar flux is -1 ± 5 for the $qA > 0$ epoch and -0.9 ± 5 for $qA < 0$ epoch (see tables I and II).

In the bottom panel, during the former period we see that out of 27 years there are 6 years with differences more than estimated errors (ΔKp is more than 1σ during the years 1973, 1980, and 1989 with positive asymmetry and years 1975, 1983, and 1985 with negative asymmetry). Two of these six years (1980 and 1989) occurred during the years of polarity reversals of IMF. The results shown in this panel are qualitatively consistent with those observed in the top panel of fig. 1. Finally, we think that the north-south asymmetry of the Sun's activity, together with the north-south asymmetry observed in the geomagnetic index Kp, may provide multiple causes for producing the observed asymmetric modulations of cosmic rays. Multiple factors may give rise to north-south asymmetric modulations. The observed cosmic-ray modulations were related to a corresponding N-S asymmetry of solar activity as indicated by sunspot numbers. Large asymmetries in R_Z, SF, and Kp have been observed in 1982, 1983 and 1991. Other [35] suggested that the geomagnetic activity is high during the passage of the interaction regions from both corotating and flare-associated streams because both the negative southward component of the interplanetary magnetic field and the fluctuations of magnetic field are high in the interaction regions. The Kp index values were high in the trailing part of corotating streams due to the presence of large fluctuations of magnetic field there. The maximum speed values of corotating streams accumulated around small values of geomagnetic index and the high speed values of flare generated streams were extended around greater values of Kp-index [36]. The most of the geomagnetic activity (85%) of the occurring activity is of solar wind origin [37]. So, any increase or decrease of such geomagnetic activity is related to the rotation with the Sun of alternate sources and in turn, it appears to be related with the active region (geomagnetically) on the Sun (northern or southern hemispheres). This may support our previous suggestion.

4. – North-south asymmetry of plasma parameters near the heliospheric current sheet

We have examined the north-south asymmetries of plasma parameters (B, SWS, and N) near the heliospheric current sheet (HCS). Periods when the Sun's northern hemisphere was more active (1965-68 and 1975-78) and those when the Sun's southern hemisphere was more active (1971-74 and 1981-84), have been studied. A thin warped

HCS (sometimes called the neutral sheet) separates the two hemispheres of the IMF [38-40]. Since the Sun rotates every 27 days, and the HCS corotates with it, the Earth will be located above (north of) the sheet for about half of each solar rotation. The passage of the HCS at the Earth (or at any nearby spacecraft) is interpreted as a "sector boundary crossing", during which the Earth experiences a reversal of IMF polarity (either T-A or A-T). The effect of HCS crossings on related geophysical phenomena has been studied (*e.g.* [41, 42]). Negative gradients in cosmic-ray intensities were obtained for both magnetic polarity states (maximum intensity at the neutral sheet, with intensity decreasing with distance from the neutral sheet when the Earth has moved away from it). Strong correlations were found between the inclinations of the HCS and solar wind speeds during different short periods [43]. Other excellent correlations were obtained between R_Z and the tilts of the HCS, and it was dependent on the reversal of the Sun's magnetic field.

We sorted the daily average of IMF according to the field polarity sense; away polarity if the solar ecliptic azimuthal angle of the IMF daily average lies between 45° and 225°, and toward polarity otherwise. These data were further subdivided according to state of the Sun's northern hemisphere activity. The day of the HCS crossing the Earth was used as the zero epoch day for Chree superposed epoch analyses using data extending for five days before and after the zero day. Periods containing another HCS crossing within the studied five days of the zero day were rejected. We used 206 T-A HCS crossings (97 during the $qA > 0$ epoch and 109 during the $qA < 0$ epoch), and 189 A-T crossings (84 during the $qA > 0$ epoch and 105 during the $qA < 0$ epoch). For each crossing, each plasma parameter was first averaged for the full 11 days. The percent deviation from the average was then calculated for each day. The standard error ($\pm 1\sigma$) of the mean was derived for each day from the actual scatter of the individual percent deviations. The weighted estimated error was then determined for all days. The computed error is ranging from 8 to 12 km/s for SWS, 0.3–0.5 nT for field magnitude B, and from 0.5 to 0.7 n/cc for the plasma ion density N.

Figure 3 clearly demonstrates the characteristics signatures of HCS crossings in B, SWS, and N for the periods 1965-68 (top panels a and b) and 1975-78 (bottom panels c and d), for T-A and A-T HCS crossings, respectively. These selected periods are corresponding to epochs when the Sun's northern hemisphere was more active than those of the southern hemisphere. We should note that the north-south asymmetries of the Sun's activity may provide a possible explanation for the observed asymmetries in interplanetary and plasma parameters. The behavior of B (triangles) shows that there is no consistent changes in the field magnitude B near the HCS crossings either T-A or A-T. The plots show no statistically significant north-south asymmetry effect in B related to boundary crossings in either $qA > 0$ or $qA < 0$ epochs. On the other hand, for both polarity changes, the maximum magnitude of ion density (circles) is at or slightly after the HCS crossing. A gradual increase in N starts 1–2 days before crossings. On the average, the total increase in ion density is $\approx 25\%$, independent of the IMF changes from T-A or from A-T. In general, away polarity days have larger N magnitudes than those of toward days during the $qA < 0$ epoch, and the reverse existed during the $qA > 0$ epoch. This leads us to the conclusion that the ion densities south of the HCS are persistently larger than those north of it, and independent of the IMF polarity state. This procedure is based on the fact that the magnetic field north of the current sheet points away from the Sun during positive solar magnetic polarity ($qA > 0$) and toward the Sun during negative polarity ($qA < 0$), while the magnetic field south of the current sheet points toward the Sun during positive solar polarity ($qA > 0$) and away from the Sun during

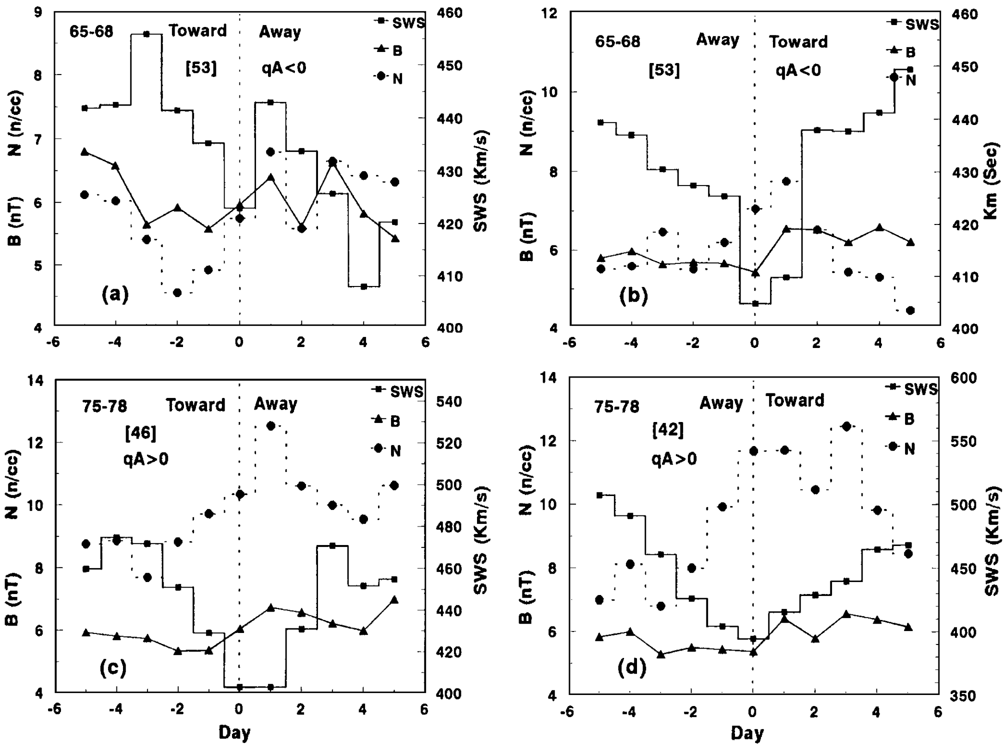

Fig. 3. – Eleven days superposed epoch analyses for the plasma parameters (B, SWS, and N) during the periods 1965-68 ($qA < 0$) and 1975-78 ($qA > 0$). Zero epoch day is the day of HCS crossing the Earth. The polarities of the IMF before and after the HCS crossing are also shown. The number of events studied during each period is given in square brackets.

negative polarity ($qA < 0$). In addition, near the HCS crossing, the negative gradients in N existed (higher densities near the neutral sheet and decreases with distance from it). The differences between T-A and A-T crossings provide evidence for an additional, small, asymmetry during the two epochs when the Sun's northern hemisphere was more active.

The profile of SWS (the squares in fig. 3) as the Earth crosses the HCS shows a minimum at, or slightly after, the crossing in both $qA > 0$ and $qA < 0$ epochs. A clear minimum in SWS values exists near the HCS boundaries. This implies that the passage of the HCS was not associated with the high-speed solar wind streams (HSSWS). The depression in solar wind speed starts 1–2 days before the crossing and the recovery time is similar. The low SWS meet high-density flows. Following the crossings either from T-A or A-T, positive gradients in SWS have been observed (lower magnitudes of SWS at the neutral sheet and then increasing with distance from the neutral sheet on either side of the sheet). Larger depressions in SWS are observed in the $qA > 0$ epoch (25% and 30%, for T-A and A-T during the period 1975-78, respectively), than in the $qA < 0$ epoch (9% and 11%, respectively). Within experimental errors, the measurements of SWS near the Earth are the same on both sides of the HCS independent of the Earth's location (above or below the neutral sheet). We find that there is no obvious large difference among them, near the HCS. Thus, no N-S asymmetry in solar wind speed measurements was apparent at or near the heliospheric current sheet boundaries, during the periods when

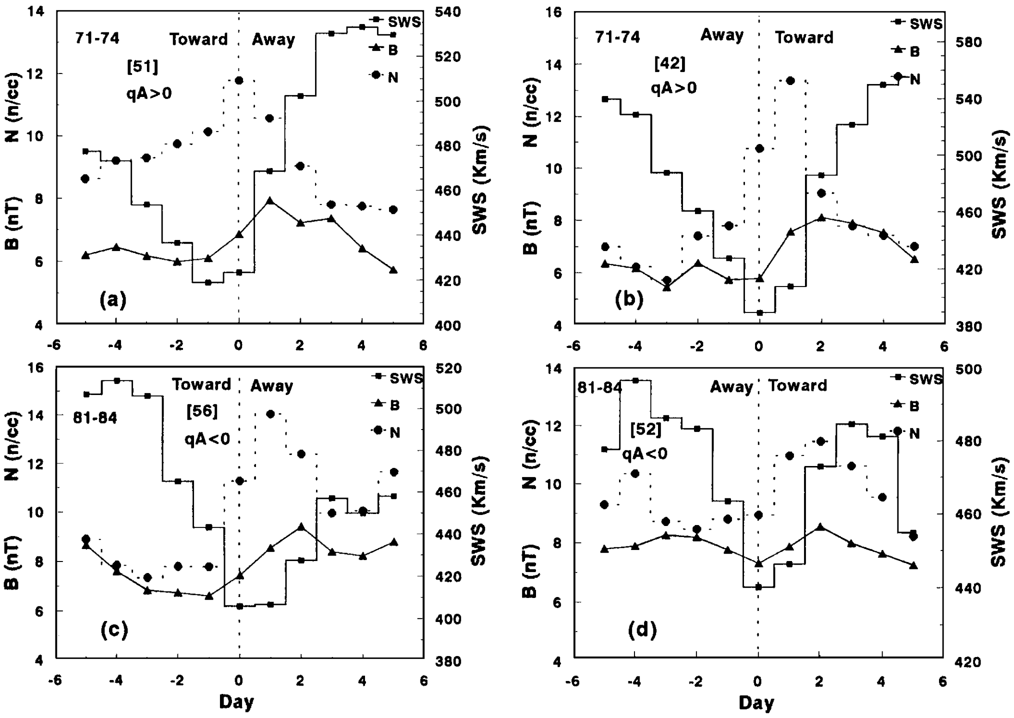

Fig. 4. – Superposed epoch analysis results of the solar wind speed, IMF field magnitude and ion density with epoch IMF sector boundary crossing for periods 1971-74 ($qA > 0$) and 1981-84 ($qA < 0$). The analyzed events are noted between square brackets.

the Sun's northern hemisphere was more active. Therefore, we can definitely say that during the two epochs when the solar northern hemisphere was more active, as the sector boundary neared the Earth a systematic behavior was observed in the magnitude of the interplanetary magnetic field and the solar wind speed. No north-south asymmetries in B and SWS were observed as a reference of the HCS passage. We find a small but significant N-S asymmetry in plasma ion density for both directions of HCS crossing.

Similarly, fig. 4 (plots a to d) shows the results obtained for the epochs 1971-74 and 1981-84 (predominance of the southern sunspots). Significant changes in B, SWS, and N were frequently observed. Following the HCS crossings, we found large increase in SWS, N, and B. Some N-S asymmetries existed. The B measurements are quantitatively not similar on either side of the HCS passage (plots a, b, and c). The B reaches a minimum at or just before the HCS crossings. The subsequent maximum occurs at or slightly after the crossings (when, on average, the Earth has moved further from the HCS). Small but significant N-S asymmetries were observed in B in later days after the crossings (negative asymmetries in panels a and c, and positive one in panel b).

A north-south asymmetry (within $\pm 1\sigma$) in N occurred near the sector boundaries of the HCS (see panels b, c, and d). The asymmetry of N depends upon the solar magnetic field polarity during these studied periods (when the Sun's southern hemisphere was more active than the northern one). The largest increase in N measurements was observed one day after the HCS moved away from Earth. Therefore, the plasma became more dense with the passage of the HCS (north and south). In panel a, the measurements of N near the HCS are the same, within experimental error. In contrast, the N-S asymmetry in SWS has been revealed (see panels a, b, and c). It is interesting to note that near the HCS, the sign of the N-S asymmetry in the SWS depends upon the solar magnetic polarity. The asymmetry is generally negative in positive solar magnetic polarity years (panels a and b during the period 1971-74), and positive in negative solar magnetic polarity years (plot c during the period 1981-84). Systematic decreases in SWS in the days before the crossings are observed. Thus, the results indicate that there is little differentiation for the mechanism of energy transport at the sector boundaries and inside sectors.

5. – Conclusions

This work has analyzed magnetic-field data from the various spacecraft near 1 AU over the period 1965-91, to examine the large-scale structure of the IMF parameters, as well as the asymmetry that exists between the field north and south of the current sheet. By separating the hourly average values of interplanetary magnetic-field data according to the field polarity sense (away or toward), we have calculated the daily averages of field magnitude B, plasma parameters (speed, temperature, and ion density), and solar indices (sunspot number R_Z, solar radio flux SF, and geomagnetic index Kp). Only days with more than 12 hours of data were used in this study, except for the solar indices data since the daily values were available. Our principle conclusions are the followings:

1) We find that the N-S asymmetry in the field magnitude occurred in years (1966, 1970, 1983, and 1984). The dependence of N-S asymmetry of B upon the IMF solar polarities is statistically insignificant. There is no clear indication of the presence of north-south asymmetry in the grand-average field magnitude during the solar cycles.

2) Over the $qA > 0$ epoch, the solar wind speed of toward polarity days south of HCS was faster with $\approx 35 \pm 10$ km/s than those of away polarity days north of HCS. The N-S asymmetry in SWS were exhibited well with the periods of predominance of southern sunspots on the Sun (1971-74 and 1981-84). Over the 1981-89 years, the N-S asymmetry in SWS was absent. On the other hand, during the negative solar polarity epoch ($qA < 0$), the solar plasma was more dense and cooler south of the neutral sheet than north of it, and the north-south asymmetry in N over the $qA > 0$ epoch was not apparent. Furthermore, more asymmetries in N have been observed during the active times of the northern hemisphere. The ion plasma temperature was hotter for toward polarity days over the $qA < 0$ period. However, significant changes in the observed asymmetries of plasma parameters have been correlated with the asymmetry of solar activity levels in the northern and southern hemispheres. Large asymmetries in B, SWS, T, and N occurred in 1983.

3) The sign of the N-S asymmetry in the solar activity as indicated by sunspot number depends positively upon the state (or the sign) of the solar IMF polarity. It was generally positive in negative epoch ($qA < 0$) and negative in positive polarity years (1981-88). In addition, the annual magnitude of N-S asymmetry depends on the orientations of IMF polarity. High asymmetries have occurred during the epoch $qA < 0$.

4) The solar flux component of toward field vector is larger in magnitude than those of away field vector during the $qA < 0$ epoch, and no asymmetrical observed in the $qA > 0$ epoch. We get six years (1965, 1966, 1968, 1969, 1985, and 1988) out of 27 with larger solar flux component north of the current sheet and three years (1973, 1982, and 1991) with larger component south of the current sheet.

5) Large asymmetries in geomagnetic index Kp have been observed in years 1973, 1983, 1985, and 1989.

6) The north-south asymmetries of the Sun's activity may provide a possible explanation for the observed asymmetries in interplanetary and plasma parameters. So, we have studied the N-S asymmetries of SWS, N, and B near the HCS (five days before and after the HCS crossings from T-A and A-T), throughout the periods of northern and southern hemispheres were more active than the other;

i) During the periods of predominance of northern hemisphere, there was no evidence for significant variations in B around the crossings in either $qA > 0$ or $qA < 0$ epochs. The proton densities south of HCS are persistently larger than those north of it, and it independent of the polarity state of IMF. A little evidence for an asymmetry in N has been presented around the boundaries of HCS. The measurements of SWS near the Earth are the same on both sides of the HCS independent of the Earth's location (above or below the neutral sheet). No N-S asymmetry in solar wind speed measurements was apparent at or near the heliospheric current sheet boundaries, during the periods when the Sun's northern hemisphere was more active.

ii) During the periods of predominance southern hemisphere and near the HCS boundaries, some asymmetries in plasma parameters existed. The B measurements are quantitatively not similar on either side of the HCS passage. The B reaches a minimum at or just before the HCS crossings. The subsequent maximum occurs at or slightly after the crossings (when, on average, the Earth has moved further from the HCS). Small but significant N-S asymmetries were observed in B in later days after the crossings (negative asymmetries in panels 4a and 4c, and positive one in panel 4b). Excess of plasma density was associated with the HCS crossings. The asymmetry in N is generally negative in positive solar magnetic polarity years (panels 4a and 4b during the period 1971-74), and positive in negative solar magnetic polarity years (plot 4c during the period 1981-84). The sign of N-S asymmetry in SWS near the HCS depends upon the state solar magnetic polarity.

* * *

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