HELIOSPHERIC CURRENT SHEET NORTH-SOUTH ASYMMETRY SINCE 1926

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ABSTRACT

We extend our earlier analysis of the north-south asymmetry of the heliospheric current sheet (HCS) using a recent data set of heliospheric magnetic field (HMF) sector polarities extracted from ground-based magnetic observations. The solar cycle 19 presents a period of a very curious and exceptional behaviour for the HCS. While the exceptional HMF behaviour in cycle 19 does not contradict with the general rule of the southward HCS shift during the late declining to minimum phase of the cycle, it has probably delayed the appearance of the southward HCS shift in 1960s. Moreover, we find that there is similar southward HCS shift in the early part of the studied data interval (1926-1955), as earlier found for the more recent solar cycles. Accordingly, the ballerina has been bashful at least during the 80 years.

Key words: heliospheric magnetic field, heliospheric current sheet, north-south asymmetry.

1. INTRODUCTION

The heliospheric current sheet (HCS) is the outward extension of the solar magnetic equator, i.e., a surface that separates the two magnetic hemispheres (sectors) with opposite polarities. The 7.2° tilt of the solar rotation axis with respect to the ecliptic and the latitudinal dependence of the dominant polarity of HCS leads to the well known fact, first observed by Rosenberg-Coleman (1969, to be called the RC rule) that one of the two sectors of the heliospheric magnetic field (HMF) dominates at the Earth's orbit in Fall (Spring, respectively) when the Earth achieves its highest northern (southern) heliographic latitudes. During positive polarity solar minima there is a dominance of the away (A) HMF sector in Fall while the toward (T) sector dominates in Spring. The situation is reversed during a negative polarity minima.

The possibility of a north-south displacement of the HCS was studied already in the 1970's and 1980's (see, e.g., Tritakis, 1984) using the concept of an average HMF sector width. However, this method is very sensitive to data gaps and the results led to no definite conclusions. More recently, by calculating the annual differences between the relative occurrences of the two HMF sectors in the 40-year series of hourly in situ HMF observations, it was shown (Mursula and Hiltula, 2003) that the HCS has a clear tendency of being dominantly southward shifted at solar minima. This rule applies at least during the last four solar minima. Accordingly, this property has given the Sun a nickname of a "Bashful Ballerina" as the solar ballerina is pushing her excessively high flaring skirt downward whenever her activity is fading away.

The southward displacement of the HCS was verified by Zhao et al. (2005) using Wilcox Solar Observatory observations of the photospheric magnetic field and the potential field-source surface (PFSS) model. In agreement with the general rule based on HMF observations (Mursula and Hiltula, 2003) they found that the HCS was shifted southward roughly during three years at the last two solar minima covered by WSO observations. The HCS was also found to be shifted southwards during the few months of the first fast latitude scan of Ulysses in 1994-1995 (Simpson et al. 1996, Crooker et al. 1997, Smith et al. 2000).

In order to study the possible asymmetry of the HCS before the in-situ HMF observations we reanalyse here the occurrence of the two HMF sectors at the Earth's orbit for about 80 years using the ground-based derived HMF sector polarities. The paper is organized as follows: In the next section we describe the HMF polarity data sets. Section 3 presents our detailed analysis of the dance of the Bashful Ballerina during the last 80 years. Results of the study are discussed and concluded in the final section.

2. HMF POLARITY DATA SETS

There is a well known relation between the dominant, daily direction of the HMF By component and the daily variation of the geomagnetic field at high latitudes. This relation was found independently by Svalgaard (1968) and Mansurov (1969) and is therefore often called the Svalgaard-Mansurov (SM) effect. The SM effect is best seen in the dayside cusp region, where the sign of By determines the direction of the east-west flowing ionospheric current (so-called DPY current). The horizontal geomagnetic perturbation caused by this current is maximized right beneath the current whereas the vertical perturbation is maximized at the northern and southern edges of the current (Vennerstroem et al. 2001, and references therein). Svalgaard (1968) and Mansurov (1969) derived the HMF polarity using the Z-component or the H-component at a number of stations.

Accordingly, Svalgaard (1972) inferred the dominant daily HMF polarity as an extension of the SM effect by visual inspection of the magnetograms of Thule and Godhavn stations. Later on Vennerstroem et al. (2001) calculated the daily HMF polarity by a mathematical method based on a linear multiregression between the HMF By component and the average daily perturbations of all the three components of the geomagnetic field at three subauroral to auroral stations (Sitka, Sodankylä and Godhavn).

Recently, Echer and Svalgaard (2004) constructed a combined data set of daily HMF polarity for 1926-2003 as a weighted mean of following data sets: daily polarity derived by Svalgaard (1972) from various atlases (time span 1947-1975, weight = 2); Thule and Vostok half day polarities derived by Mansurov (1969) (Thule: time span 1974-1981, both halves of days have weight = 1, Vostok: time span 1971-1994, both halves of a day have weight = 1); half day polarities from various atlases derived in Izmiran (time span 1957-2003, both halves of days have weight = 2); Godhavn and Thule daily polarity inferred by Vennerstroem et al. (2001) (Godhavn: time span 1926-1997, weight = 1, Thule: time span 1932-1997, weight = 2); HMF daily polarity from OMNI data set (time span: 1963-2003, weight $\approx$ 3).

The in situ HMF observations by several satellites are collected in the OMNI (and more recently in the OMNI-2) data base (King, 1977). We use here the average daily HMF values as given in the OMNI-2 data base (in GSE-coordinate system). There is a good data coverage all through the year since 1967. In 1965-1966 the coverage is good only in Fall and we have included these years for Fall as well. Using the daily HMF values, we divided HMF into toward (T) and away (A) sectors by the plane division, where T sector (A sector) is defined by Bx>By (By>Bx).

3. RESULTS

Following the method presented in our earlier paper (Mursula and Hiltula, 2003), we have calculated the total number of T and A sector days for the full years and for each 3-month season around the two high-latitude intervals (Spring=Feb-Apr; Fall=Aug-Oct). The annual (or equinoctial) average of the (T-A)/(T+A) ratio reveals the possible annual dominance of either magnetic hemisphere and thus the possible asymmetry of the heliospheric current sheet, i.e., the heliomagnetic equator, at 1AU. Moreover, studying the T/(T+A) ratio separately in Spring and Fall one can study the RC rule, i.e., the latitudinal dependence of the dominant HMF sector in the two heliographic hemispheres (Spring=south; Fall=north), and its possible hemispherical difference.

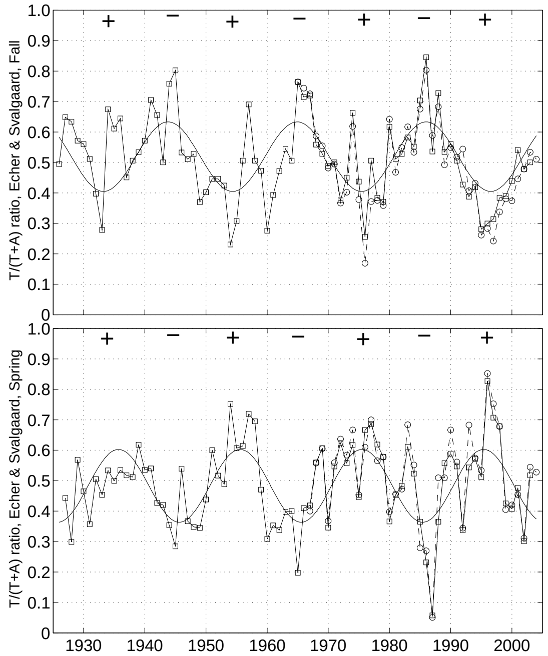

Figure 1. Equinoctial T/(T+A) ratios according to ES data (solid line with squares; least squares sinusoid fit to data) and OMNI-2 data (dashed line with circles). Plus and minus signs show the polarity of the Sun's dipole field around solar minima. Top panel: Fall; bottom panel: Spring.

3.1. Rosenberg-Coleman rule

Fig.1 represents the fraction of the T sector days, i.e., the T/(T+A) ratio for the Echer and Svalgaard (ES) data set in Spring and in Fall. The ES data follows very closely the observed OMNI-2 HMF polarity, as expected from the strong weight of the latter in the combination. The sinusoid is the least squares fit to the data. Plus and minus signs show the polarity of the Sun's dipole field. The ES data depicts the RC rule quite clearly both in Spring and Fall with sinusoid amplitudes 0.120 and 0.114, respectively, for the whole data interval.

Thus, the ES data set has fairly similar sinusoid amplitudes for the RC rule in Spring and Fall for the full data set. This is contrary to the OMNI-2 data set where the amplitude in Spring (in 1967-2004) is 0.116 and in Fall (in 1965-2004) 0.177. However, when using only the more recent years in ES data set (1965-2003 for Fall, 1967-2003 for Spring), the RC amplitudes are 0.122 in Spring 0.155 in Fall. These amplitudes are much closer to the OMNI-2 values, and indicate the same difference

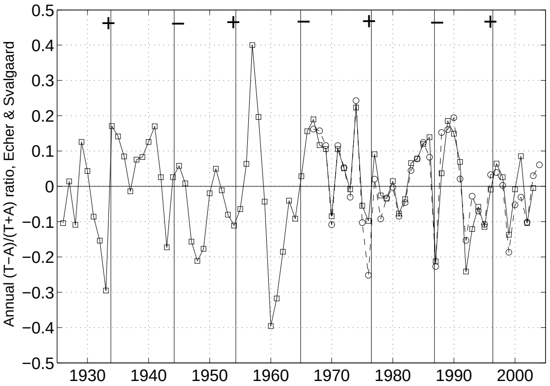

Figure 2. Annual (T-A)/(T+A) ratios according to ES data (solid line with squares) and OMNI-2 data (dashed line with circles). Plus and minus signs as in Fig.1. Vertical lines denote ("official") NGDC sunspot minima.

as found earlier in OMNI data set (Mursula and Hiltula, 2003) where the Fall amplitude is larger than the Spring amplitude. Leaving out the solar cycle 19 (see later), the RC amplitudes for the ES data set in 1926-1955 are 0.095 in Spring 0.114 in Fall. Accordingly, the Fall amplitude is larger than the Spring amplitude both in the first (1926-1955) and last (1965-2003) decennia of the full ES data set.

3.2. Annual (T-A)/(T+A) ratio

The annual (T-A)/(T+A) ratios of the ES data (see Fig.2) also follow closely the OMNI-2 ratios during the overlapping period 1967-2003. The southward shift of the HCS is seen as a dominantly negative (positive) the (T-A)/(T+A) ratio during the declining to minimum phase of an even (odd, respectively) solar cycle (Mursula and Hiltula, 2003). This is seen both in the ES and OMNI-2 data as a negative deflection of the (T-A)/(T+A) ratio prior to the minima in 1990s and 1970s and as a positive deflection in 1980s.

Similarly, in the ES data there is a negative deflection prior to the positive minimum in 1930s and 1950s. There is also a long period of positive (T-A)/(T+A) deflection during most of the declining phase of cycle 17, although the year before the minimum is oppositely deflected. These intervals lead, when the annual (T-A)/(T+A) ratios in 1926-1955 are fitted with a sinusoid, to a roughly 20-year variation with an amplitude of 0.075. We have also tested the significance of this variation by the Stellingwerf (1978) method and found that the variation is significant at least at the level of 91%. Correspondingly, a similar sinusoid fit to the later time interval 1967-2003 has an amplitude of 0.053 and is significant at least at the level of 93%. OMNI-2 data for the same period has an amplitude of 0.077 and is significant at least at the level of 97%.

We have also performed a binomial analysis of the distribution of (T-A)/(T+A) differences for the ground-based data in 1926-1955 and 1967-2003 separately, by dividing each into two sets, those where the observed and modelled values were on the same side from the average and those where they were on opposite sides (see Mursula and Hiltula, 2003, for more information). In 1967-2003, 27 out of the 37 annual values followed the HCS shift rule, 10 opposed it. The probability of having 10 or less of 37 values in one set is less than 1.5×10^{-3}. Similarly, for the early period, 22 out of 30 annual values followed the rule while 8 opposed it. Having 8 or less of 30 values in one set has a probability less than 8×10^{-4}. Accordingly, this gives further strong support for the fact that the 22-year cycle organizes the differences and that the found HCS shift rule (Mursula and Hiltula, 2003) is valid.

Accordingly, the HCS seems to be shifted southward both in the early (1926-1955) and later (1967-2003) part of the ES interval. However, we find that the behaviour of the HCS was very exceptional during solar cycle 19, the greatest sunspot cycle so far. Fig.2 shows that there was an exceptionally large T sector dominance in late 1950s, with a maximum in 1957, thus coinciding with the sunspot maximum of cycle 19. Thereafter, the T sector dominance quickly changed to A sector dominance, with a maximum in 1960. Interestingly, the deflections to either direction were almost exactly equally large, and roughly twice as large as in other times.

Fig.1 shows that the RC rule is roughly valid both in Spring and Fall over the whole depicted time interval, including the period of the exceptional HCS behaviour. This is particularly true in Spring (southern heliographic hemisphere) where the T/(T+A) ratio forms a very smooth curve indicating that the latitudinal variation of the dominant magnetic hemisphere is particularly well organized in the southern heliographic hemisphere. (We note in passing that this not only supports the expected latitudinal distribution but also gives strong support for the reliability of the data set).

While the same is roughly true in Fall (northern heliographic hemisphere) overall, there is an interesting difference in the latitudinal evolution in Fall which leads to the observed exceptional HCS behaviour. Amidst the expected southward deflection in 1950s, there is a period of a few years of opposite deflection around 1957. At this time both Spring (following the RC rule) and Fall (against the RC rule) depict T sector dominance, leading to the observed maximum T sector dominance in Fig.2. After 1957, the T/(T+A) ratio starts to decrease both in Spring and Fall, both ending with a local maximum of A dominance in 1960, the former slightly too early, the latter too late for its RC rule expected evolution. This behaviour leads to the observed minimum in (T-A)/(T+A) ratio in Fig.2.

The positive deflection in the RC rule in Fall around 1957 allows the exceptionally large T sector dominance even though the RC amplitudes remain roughly normal. This deflection indicates that the field polarity was changed temporarily in the northern hemisphere, leading to T sector dominance in both hemispheres. This is in agreement with direct solar observations where multiple field reversal was observed in the northern hemisphere between 1958 and 1960 (Makarov and Makarova, 1996). The observed HMF sector behaviour during cycle 19 was unique during the 80-year time interval included in the study. It also led to an exceptional HCS structure (perhaps, e.g., with long-lasting multiple sheets) between the cycle maximum in 1957 and the interval of final polarity reversal in 1960. While this behaviour does not contradict with the general rule of the southward HCS shift during the late declining to minimum phase of the cycle (i.e., the bashful ballerina), the exceptional MHF evolution in cycle 19 probably delays the appearance of the southward HCS shift in 1960s where it is observed only at the minimum year and years thereafter.

4. CONCLUSIONS

In this paper, we have extended our earlier analysis (Mursula and Hiltula, 2003) of the north-south asymmetry of the heliospheric current sheet in 1965-2001 which was based on satellite HMF observations collected in the OMNI data set. We have used here a recent data set of HMF sector polarities by Echer and Svalgaard (2004) which is obtained by combining the OMNI data set with various series of daily HMF polarity extracted from ground-based magnetic observations.

The largest solar cycle measured so far, cycle 19, presents a period of a very curious and exceptional behaviour for the HCS. During this cycle, the HMF observations indicate an exceptionally large T sector dominance which maximizes in 1957, the year of cycle 19 maximum. During the following three years, the T sector dominance turns into an equally strong A sector dominance with a maximum in 1960, i.e., close to the time of solar polarity reversal in the southern hemisphere. The HMF observations in Fall depict a temporary reversal of field polarity in the northern hemisphere at cycle maximum, in agreement with the observed triple reversal of field polarity in the northern hemisphere during this cycle (Makarov and Makarova, 1996).

While the exceptional HMF behaviour in cycle 19 does not contradict with the general rule of the southward HCS shift during the late declining to minimum phase of the cycle, it has probably delayed the appearance of the southward HCS shift in 1960s. Moreover, we find that there is similar southward HCS shift in the early part of the studied data interval (1926-1955), as earlier found for the more recent solar cycles. Accordingly, the ballerina has been bashful at least during the 80 years.

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