Long dance of the bashful ballerina

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Received 10 November 2005; revised 21 December 2005; accepted 3 January 2006; published 9 February 2006.

[1] In this letter 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. We find that the heliospheric current sheet is similarly southward coned or shifted during the late declining to minimum phase of the solar cycle in the early part of the studied data interval (1926–1955), as earlier found for the more recent solar cycles. Accordingly, the HCS has been southward shifted; that is, the solar ballerina has been bashful at least during the last 80 years. We also discuss solar cycle 19 which presents a period of a very curious behaviour for the HCS with an exceptionally large HMF toward sector dominance in 1957, the year of cycle 19 maximum, and an equally strong HMF away sector dominance in 1960, the time of final solar polarity reversal. **Citation:** Hiltula, T., and K. Mursula (2006), Long dance of the bashful ballerina, *Geophys. Res. Lett.*, *33*, L03105, doi:10.1029/2005GL025198.

1. Introduction

[2] The heliospheric current sheet 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 the HCS lead 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 dominates at the Earth's orbit in Fall (Spring) when the Earth achieves its highest northern (southern) heliographic latitudes. During the 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 the negative polarity minima.

[3] 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, leading to partly arbitrary results and erroneous conclusions about the HCS asymmetry. More recently, by calculating the annual (and equinoctial) 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 coned or shifted at solar minima. This rule was found to apply at least for the last four solar minima. Accordingly, this property has given the Sun a nickname of a "Bashful Ballerina" since the solar ballerina is pushing her excessively high flaring skirt downward whenever her activity is fading away.

[4] The southward displacement of the HCS was recently verified using Wilcox Solar Observatory observations of the photospheric magnetic field and the potential field-source surface (PFSS) model [*Zhao et al.*, 2005]. In agreement with the general rule based on HMF observations [*Mursula and Hiltula*, 2003] they found that the HCS was consistently shifted southward during some three years at the last two solar minima covered by WSO observations. The HCS was also found to be shifted southward 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].

[5] 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 long dance of the Bashful Ballerina during the last 80 years. Final conclusions of the study are given in Section 4.

2. HMF Polarity Data Sets

2.1. Ground-Based Data

[6] 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 the HMF By component 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 [see, e.g., *Vennerstroem et al.*, 2001, and references therein].

[7] Accordingly, *Svalgaard* [1972] inferred the dominant daily HMF By polarity as a consequence of the SM effect by visually inspecting the magnetograms of Thule and Godhavn stations. More recently, *Vennerstroem et al.* [2001] extracted the daily HMF polarity by a mathematical method based on a linear multiregression between the HMF By component and the average daily perturbations of the three components of the geomagnetic field at three sub-auroral to auroral stations (Sitka, Sodankylä and Godhavn).

[8] Recently, *Echer and Svalgaard* [2004] constructed a combined data set (to be called ES data set) of daily HMF

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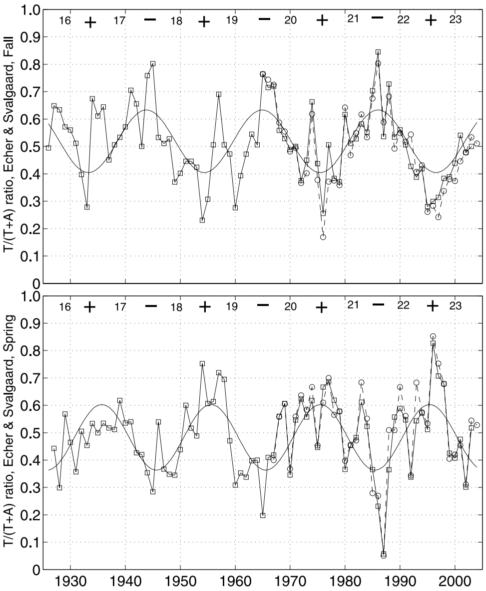

Figure 1. Equinoctial T/(T + A) ratios according to ES data (solid line with squares; least squares sinusoid fit to data) and OMNI-2 data (dashed line with circles). Plus and minus signs show the polarity of the Sun's dipole field around solar minima between the solar cycles indicated by numbers. (top)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

polarity for 1926–2003 as a weighted mean of several data sets. Each data set was given two weights to be called here the p-weight (the relative weight of the daily polarity for each data set; positive for A, negative for T, zero for mixed) and p-number (equal to one for data sets available for any day or half-day, except two for the OMNI data set). The daily polarity is finally defined as a T sector if the daily ratio of p-weight and p-number is less than −0.3 and as a A sector if this ratio is greater than 0.3. The following data sets and p-weights were used in the ES data: daily polarity derived by *Svalgaard* [1972] from various atlases (time span 1947–1975, p-weight 2); Thule and Vostok half-day polarities derived by *Mansurov* [1969] (Thule: time span 1974–1981, both half-day values with p-weight 1; Vostok: time span 1971–1994, both half-day values with p-weight 1); half-day polarities from various atlases derived in Izmiran (time span 1957–2003, both half-day values with p-weight 2); Godhavn and Thule daily polarity inferred by *Vennerstroem et al.* [2001] (Godhavn: time span 1926–1997, p-weight 1, Thule: time span 1932–1997, p-weight 2); HMF daily polarity from the OMNI data set (time span: 1963–2003, p-weight 6). We would like to note that the SM method was strongly criticized soon after its invention because the natural quiet daily variation is biased in favour of the A sector [see, e.g., *Russell and Rosenberg*, 1974; *Fougere*, 1974; *Russell et al.*, 1975]. However, this problem has been removed in the ES data since data from those stations used for the early years has been normalized to the OMNI data set [see, e.g., *Vennerstroem et al.*, 2001].

2.2. Satellite Data

[9] The in situ HMF observations by several satellites are collected in the OMNI (and more recently in the OMNI-2) database [*King*, 1977]. We use here the average daily HMF values as given in the OMNI-2 database (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. Because of the roughly 45° winding angle of the HMF (Parker) spiral at 1 AU, we divided the daily HMF values into toward (T) and away (A) sectors by the plane division where the T sector (A sector) is defined by Bx > By (By > Bx).

3. Results

[10] 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 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.

3.1. Rosenberg-Coleman Rule

[11] Figure 1 presents the equinoctial fractions of the T sector days, i.e., the T/(T + A) ratios for the ES data set separately for Spring and Fall. The near-coincidence of the dashed and solid traces indicates that the ES data follows very closely the observed OMNI-2 HMF polarity since 1960s, as expected from the strong weight of the latter in the combination. We have also fitted a simple sinusoid to the data. (In each case the best-fitting sinusoid has a period of about 20 years). 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.

[12] 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 as found earlier in OMNI data set [*Mursula and Hiltula*, 2003] where the Fall amplitude is larger than the Spring amplitude. Leaving out solar cycle 19 (see later), the RC amplitudes for the ES data set in 1926–1955 are 0.095 in Spring and 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

[13] The annual (T − A)/(T + A) ratios of the ES data depicted in Figure 2 also follow closely the corresponding OMNI-2 ratios during the overlapping period 1967–2003. The southward shift of the HCS is seen as a dominantly negative (positive) (T − A)/(T + A) ratio during the declining to minimum phase of an even (odd) 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

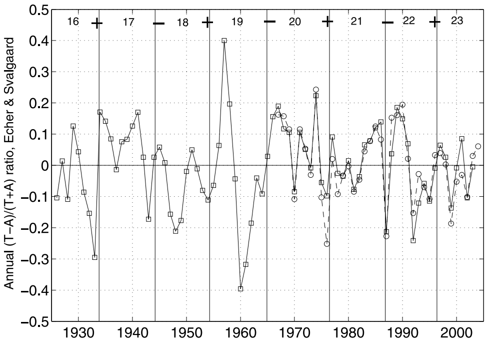

Figure 2. Annual (T − A)/(T + A) ratios according to ES data (solid line with squares) and OMNI-2 data (dashed line with circles). Plus and minus signs and numbers as in Figure 1. Vertical lines denote the NGDC sunspot minima.

+ A) ratio prior to the minima in 1990s and 1970s and as a positive deflection in 1980s.

[14] 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 (leaving out cycle 19 again; see later) are fitted with a sinusoid, to a roughly 20-year variation with an amplitude of 0.075. We have 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 latter period has an amplitude of 0.077 and is significant at least at the level of 97%.

[15] 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. We have divided the data of each time interval 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]. 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 HCS shift rule is valid.

3.3. Solar Cycle 19

[16] 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 HCS behaviour was very exceptional during solar cycle 19, the greatest sunspot cycle so far. Figure 2 shows that there was an exceptionally large T sector dominance in late 1950s, with a maximum in 1957, coinciding with the sunspot maximum of cycle 19. Thereafter, the T sector dominance quickly changed to A sector dominance, reaching a maximum in 1960. Interestingly, the deflections to either direction were almost exactly equally large, and roughly twice as large as in all other times.

[17] Figure 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 was particularly well organized in the southern heliographic hemisphere at this time. (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).

[18] 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 Figure 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 the (T − A)/(T + A) ratio in Figure 2.

[19] The exceptional dominance of the T sector (against the RC rule) in Fall, 1957, indicates that the solar polarity was temporarily changed in the northern hemisphere, leading to the T sector dominance in both hemispheres during the maximum year of solar cycle 19. This is in agreement with direct solar observations where multiple field reversals were observed in the northern hemisphere between 1958 and 1960 [*Makarov and Makarova*, 1996]. The observed HMF sector behaviour in cycle 19 was unique during the 80-year time interval included in the study. It also led to an exceptional HCS structure, perhaps including 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 HMF evolution in cycle 19 delayed the appearance of the southward HCS shift in 1960s where it is observed only at the minimum year and years thereafter.

4. Conclusions

[20] 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. We find that the heliospheric current sheet is similarly southward shifted during the late declining to minimum phase of the solar cycle in the early part of the

studied data interval (1926–1955), as found earlier for the more recent solar cycles. Accordingly, the solar ballerina has been bashful at least during the last 80 years.

[21] We have shown that 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 final solar polarity reversal. 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 this 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.

[22] **Acknowledgments.** We are grateful to L. Svalgaard for providing the ground-based data set and to NSSDC for the OMNI data (for a complete list of data and providers, see omniweb.gsfc.nasa.gov). Financial support by the Finnish Academy of Science and Letters, Vilho, Yrjö and Kalle Väisälä Foundation and the Academy of Finland is gratefully acknowledged.

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