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HMF sectors since 1926: Comparison of two ground-based data sets

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Abstract

In this paper, we compare two recent long-term data sets of daily HMF sector polarities since 1926 based on ground-based geomagnetic measurements: the combined data set by Echer and Svalgaard [Echer, E., Svalgaard, L. Asymmetry in the Rosenberg–Coleman effect around solar minimum revealed by wavelet analysis of the interplanetary magnetic field polarity data (1927–2002). Geophys. Res. Lett. 31, 12808, 2004] (ES data set) and a three-station data set derived by Vennerstroem et al. [Vennerstroem, S., Zieger, B., Friis-Christensen, E. An improved method of inferring interplanetary sector structure, 1905–present. J. Geophys. Res. 106 (15), 16011–16020, 2001] (VZF data set). The Rosenberg-Coleman rule is consistently valid in the ES data during the last 80 years, but fails in the VZF data set in the early cycles. There is a clear bias (T sector dominance) in the VZF data that is not observed in satellite measurements collected in the OMNI-2 data set, or in the ES data. Also, there is a difference on the success rates between the two sectors in the VZF data. Therefore, we conclude that the ES data set is more reliable, especially in cycles 16–18, in reproducing the HMF sector structure. Both data sets reproduce the southward shift of the heliospheric current sheet during the OMNI-2 interval. However, only the more reliable ES data set depicts this systematically also during the early cycles 16–18.

Keywords: Heliospheric magnetic field; Heliospheric current sheet; North–south asymmetry

1. Introduction

The solar magnetic equator extends into the heliosphere as the heliospheric current sheet (HCS), i.e., as a curved surface that separates the heliospheric magnetic field (HMF) into two magnetic hemispheres with opposite polarities. The HMF field lines directed away from the Sun form the away (A) sector, i.e., the northern magnetic hemisphere in the heliosphere. Similarly, the HMF field lines directed toward the Sun form the toward (T) sector, i.e., the southern magnetic hemisphere. This leads to a latitudinal organization of HMF sectors with respect to the heliomagnetic latitude which, together with the 7.2° tilt of the solar rotation axis with respect to the ecliptic, yields the well known Rosenberg–Coleman (RC) rule (Rosenberg and Coleman, 1969) that one of the two HMF sectors dominates at the Earth's orbit in Fall (Spring, respectively) when the Earth achieves its highest northern (southern) heliographic latitudes. Accordingly, there is a latitudinal variation in the dominant HMF sector around the heliographic equator during most of the solar cycle, especially around solar minima. During positive polarity minima there is a dominance of the A sector in Fall while the T sector dominates in Spring, and the situation is reversed during negative polarity minima.

The possible north–south displacement of the HCS was already investigated in the 1970s and 1980s (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. Instead, by calculating the annual differences in the relative occurrence of the two HMF sectors in the 40-year series of hourly in situ HMF observations, we have recently shown (Mursula and Hiltula, 2003) that the HCS has a systematic tendency to be dominantly southward shifted around solar minima. The persistent southward displacement of the HCS

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(the "bashful ballerina") in the late declining phase of the solar cycle was verified by Zhao et al. (2005) using Wilcox Solar Observatory (WSO) measurements of the photospheric magnetic field and the potential field source surface 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 around each of the two solar minima covered by WSO observations. Even earlier, the HCS was found to be coned southwards for a few months during the first fast latitude scan of Ulysses in 1994–1995 (Simpson et al., 1996; Crooker et al., 1997; Smith et al., 2000). The WSO observations also showed that, at the time of the HCS shift, there was a quadrupole moment in the Sun which was oppositely directed to the dipole moment. These results imply that a large scale quadrupole term, the so called S0 dynamo mode, must be taken into account in solar dynamo modeling, in addition to the dominant dipole (A0) mode (Mursula and Hiltula, 2004).

We have recently studied the southward shift of the HCS in 1926–2003 using the daily HMF sector polarities extracted from ground-based magnetic observations Hiltula and Mursula, 2006. HCS was found to be shifted southward (so, the ballerina was bashful) during the last 80 years, perhaps excluding the solar cycle 19 when the HCS was seen to behave in a very exceptional way, depicting largest annual variations from equal distribution. Here we study and compare the occurrence of the two HMF sectors at the Earth's orbit since 1926 in two different HMF polarity data sets obtained from ground-based measurements.

2. HMF polarity data sets

The daily variation of the geomagnetic field at high (cusp and polar cap) latitudes is affected by the daily averaged direction of the HMF By component. This relation is called the Svalgaard–Mansurov (SM) effect (Svalgaard, 1968; Mansurov, 1969). The SM effect is strongest in the dayside cusp region, where the sign of the HMF By determines the direction of an east-west flowing ionospheric current (so-called DPY current). The horizontal magnetic perturbations caused by this current are maximized right beneath the current whereas the vertical perturbations are maximized at the northern and southern edges of the current (Vennerstroem et al., 2001). The SM effect allows to determine the dominant daily (or half-daily) value of HMF sector polarity from the observed daily variation of the various components of the geomagnetic field at high latitudes.

Exploiting the SM effect, Vennerstroem et al. (2001) calculated the daily HMF polarity data set by linear multiregression between the hourly HMF By component and the hourly perturbations of all the three components of the geomagnetic field. They derived several polarity datasets using different combinations of the (subauroral) Sitka and Sodankylä stations, the (cusp) Godhavn station and the (polar cap) Thule station. The most reliable data set since 1926 was obtained by the combination of Sitka, Sodankylä and Godhavn stations (the VZF data set to be used here) which was calculated until 1992. From the point of view of the SM effect, the best station would be Thule but, unfortunately, its data exist only since 1947.

More recently, Echer and Svalgaard (2004) constructed a combined data set of daily HMF polarities for 1926–2003 (the ES data set to be used here). They calculated the HMF polarity as a weighted mean of several other, earlier data sets, e.g., those by Svalgaard (1972) and Mansurov (1969), Vennerstroem et al. (2001) (where only Godhavn data is used), and OMNI data (for more details on the ES data set, see Hiltula and Mursula, 2006). The in situ HMF observations by several satellites are collected in the OMNI (updated to OMNI-2 in 2003) data base (King, 1977). This data was used to calibrate both the ES and VZF data sets.

3. Success rates and occurrence fractions

Following the method presented in our earlier papers (Mursula and Hiltula, 2003; Hiltula and Mursula, 2006), 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 1 AU. 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.

The success rate (i.e., relative percentage of successful predictions) of the daily HMF polarity estimates is 95.4% for the ES data set (in 1967–2003; we do not use the early OMNI years because of large, systematic data gaps) and 86.6% for the VZF data set (in 1967–1992) when comparing with the polarity derived from the OMNI-2 data set using the plane division for the HMF sector definition (plane perpendicular to the 45° average HMF direction). However, taking into account the fact that the HMF sector derived from ground-based observations is based on the ionospheric effect of the HMF By component, we have also calculated the success rates when the OMNI-2 HMF sector is defined by the value of this component. Then the success rates are increased to 97.0% for ES and to 88.7% for VZF. The overall agreement between the ES and VZF data sets (only when both data sets had a definite polarity value) is about 90.2% in 1967–1992 and 87.5% in 1926–1966. Note that the ES data set has a better overall agreement with OMNI-2 than the VZF data set. This is probably because the OMNI data is explicitly included in the ES data set with a rather large weighting, while the VZF method uses the OMNI data set only to find the best fitting values for the regression parameters. Note also that the maximum attainable accuracy for the ground-based method was estimated to be about 88% (Russell and Rosenberg, 1974), i.e., very close to that reached by the VZF data set.

We have also calculated the separate success rates for the two magnetic hemispheres. Using the plane division, the success rate for the A sector is 95.0% and for the T sector 95.8% in the ES data set, and 83.8% for A and 89.1% for T in the VZF data set. Using the By division, the ES success rates are 96.6% for A and 97.4% for T, and the VZF success rates are 86.0% for A and 91.2% for T. Note that, while the ES data set is roughly equally successful in estimating both magnetic hemispheres, the VZF data set is clearly asymmetric and estimate the T sector clearly better than the A sector. However, even the T sector in the VZF data set is considerably less successful than either sector in the ES data set.

Note also that the T/A sector ratio in the OMNI-2 data set is 1.007, i.e., practically equally distributed, in 1967–2003 and 1.080 in 1967–1992. For ES data the T/A ratio is 1.028 in 1967–2003 and 1.070 in 1967–1992, and for VZF data 1.143 in 1967–1992. Accordingly, while the OMNI-2 and ES data sets are roughly equally distributed between the two sectors over the longer time interval (when the two solar polarities occur roughly equally), they depict a surplus of T sector in the shorter interval which is dominated by negative solar polarity. This is in agreement with the southward shifted HCS leading to a T sector dominance at this time. However, the VZF data set depicts an even larger T dominance, suggesting that it is biased in favor of the T sector despite the fit to the OMNI data. This is supported by the fact that the T/A ratio in 1926–1966 is 0.964, fairly close to equal distribution, for the ES data set but 1.061 for the VZF data set, clearly favoring the T sector.

4. Rosenberg–Coleman rule

The left panels of Fig. 1 present the equinoctial fractions of the T sector days, i.e., the T/(T + A) ratios, for the VZF data set for Fall (upper panel) and Spring (lower panel). The rough agreement of the dashed OMNI-2 and solid VZF traces indicates that the VZF data follows the observed OMNI-2 HMF polarity fairly closely during the overlapping time. We have also fitted a simple sinusoid to the VZF data over the whole interval 1926–1992. (In each panel the best-fitting sinusoid has a period of about 20 years). Over the whole data interval, the RC rule in the VZF data set is more clearly valid in Spring than in Fall. The sinusoid amplitudes in Spring (0.128) and in Fall (0.083) are quite different for the VZF data, whereas in the ES data set (depicted in the right panels of Fig. 1) they are roughly similar (0.120 and 0.114) (Hiltula and Mursula, 2006). In agreement with the above mentioned overall T sector dominance, the VZF data set shows a strong T sector dominance in Fall whereas there is only a weak A dominance in Spring: sinusoid fits have offsets of 0.049 (0.014) in favor of T (A) sector dominance in Fall (Spring).

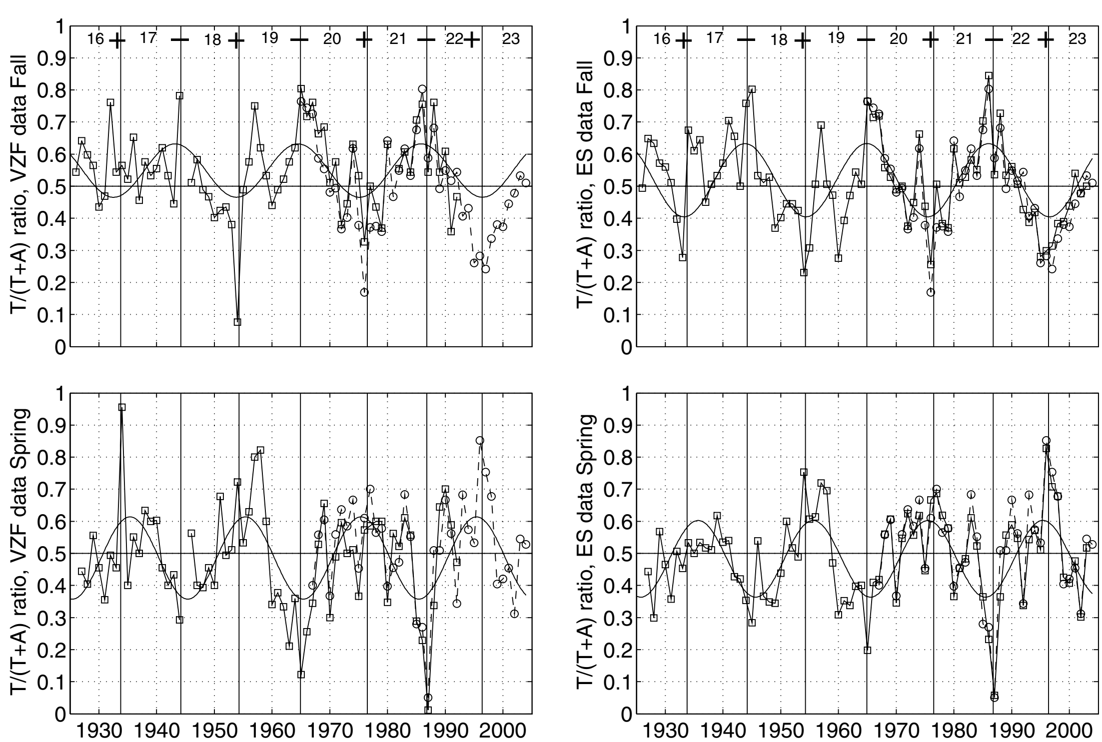

Fig. 1. The T/(T + A) ratios in the VZF data (left panels, solid line with squares) and ES data (right panels, solid line with squares) with least squares sinusoid fits and in the OMNI-2 data (dashed line with circles). Plus and minus signs indicate solar polarity and vertical lines sunspot minima. Top panels: Fall. Bottom panels: Spring.

Instead, the offsets in ES data were roughly similar in Fall (0.019 in favor of T sector) and in Spring (0.014 in favor of A).

Note that despite the smaller overall sinusoid amplitude in Fall in VZF data, the amplitude is larger in Fall for the more recent cycles (0.135 in Fall and 0.113 in Spring in 1965–1992), in agreement with the OMNI and ES data sets (Hiltula and Mursula, 2006). On the other hand, in the early part in 1926–1955, the average amplitude in Spring is still quite large (0.094) but the 20-year RC variation is not observed at all in Fall at this time. This is contrary to the situation with the ES data where, as shown in Hiltula and Mursula (2006), the sinusoid amplitude was larger in Fall than in Spring both for early and more recent cycles.

Both ES and VZF data sets show a small overall T sector (A sector, respectively) dominance in Fall (Spring) even if there are more of positive polarity years in the data which could produce a small A sector (T sector) dominance in Fall (Spring) for a southward shifted HCS. The OMNI-2 data set does not show such an unexpected preference. This suggests that this effect is due to the ground-based method of finding the sector polarity. Note that the Russell–McPherron mechanism (Russell and McPherron, 1973) leads, by enhancing the southward HMF component in the GSM coordinate system, to a larger disturbance level during the A sector days in Fall and T sector days in Spring. It is very likely that the success rate for predicting the more disturbed days is lower in the SM method. This would reduce the correct interpretation of a A (T) sector days in Fall (Spring), leading to the observed preference of T (A) sector in Fall (Spring). However, this does not explain the excessive T sector dominance of the VZF method in Fall.

5. Annual (T − A)/(T + A) ratio

The annual $(T - A)/(T + A)$ ratios of the ES data (upper panel of Fig. 2, see also Hiltula and Mursula, 2006) follow closely the corresponding OMNI-2 ratios during the overlapping period 1967–2003. The southward shift of the HCS is seen both in the ES and OMNI-2 data as a negative deflection of the $(T - A)/(T + A)$ ratio prior to the positive polarity minima in 1990s and 1970s and as a positive deflection around the negative minimum in 1980s. Similarly, in the ES data there is a negative deflection prior to the positive minima 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) are fitted with a sinusoid, to a 20-year variation with an amplitude of 0.075 whose significance was demonstrated in Hiltula and Mursula (2006).

The $(T - A)/(T + A)$ ratios in the VZF data (bottom panel of Fig. 2) also follow the OMNI-2 data rather closely. However, the differences to OMNI-2 results are much larger than in case of the ES data. The largest differences occur around 1980 when the ratio for VZF data is even opposite to that in the OMNI-2 data. Note also that the overall T sector dominance of the VZF data discussed above leads to the non-zero average value of the $(T - A)/(T + A)$ ratio of 0.04. In the ES data, the average value of this ratio is −0.004.

In the last few cycles before the OMNI-2 data, the overall pattern of the $(T - A)/(T + A)$ ratio in the VZF data is fairly similar to that in the ES data. In particular, cycle 19 has a quite similar odd behaviour as in the ES data (Hiltula and Mursula, 2006), depicting an exceptionally large T sector dominance in 1957, i.e., in the sunspot maximum year, and a large A sector dominance in 1960, at the final turn of the solar polarity. As seen in Fig. 2, this behavior is quite symmetric around zero in the ES data and has an amplitude roughly twice larger than typical deflections in other cycles (Hiltula and Mursula, 2006). However, in the VZF data, the maximum in 1957 is even larger than in the ES data, but the minimum in 1960 is weaker which is very likely due to the effect of the overall T sector dominance in the VZF data set.

The agreement in the $(T - A)/(T + A)$ ratio between the VZF and ES data sets is still quite reasonable in cycle 18. The annual fluctuations of this ratio show a rather similar

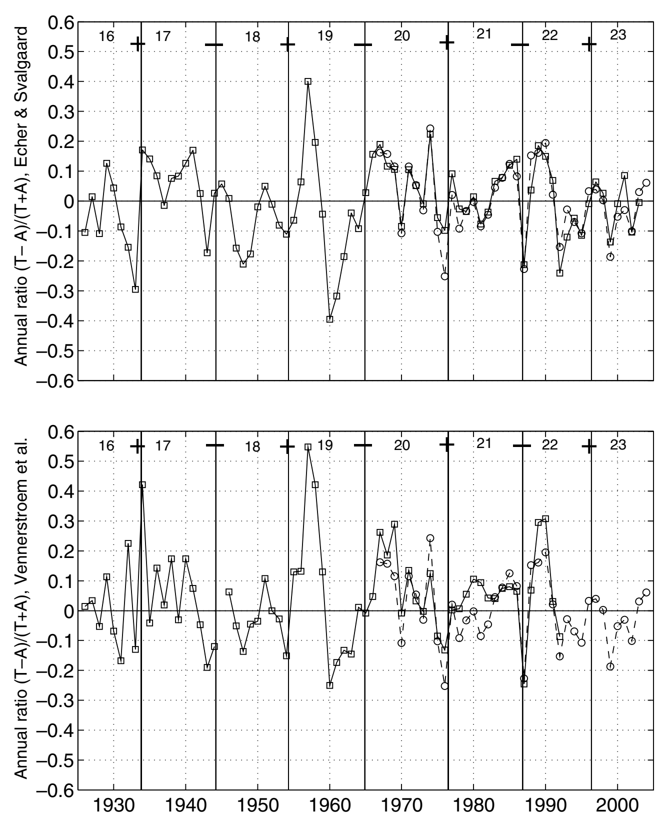

Fig. 2. Annual $(T - A)/(T + A)$ ratio. The OMNI data is denoted with dashed line with circles. Plus and minus signs show the polarity of the Sun's dipole field around solar minima and the vertical lines denote the sunspot minima. Top panel: the ES data (solid line with squares). Bottom panel: the VZF data (solid line with squares).

pattern but the overall level of the ratios is shifted slightly higher in the VZF data set, again in agreement with the T sector dominance of this data set. However, the agreement between the two data sets gets quite poor at the beginning of the data sets in cycle 16 and part of cycle 17. The (T − A)/(T + A) ratios in the VZF data set vary almost randomly during the first 10–15 years and, contrary to the ES data, do not depict the clear southward shift in 1930s (negative values in 1931–1933) and 1940s (positive values in 1938–1941) found in the ES data set.

6. Discussion and conclusions

In this paper, we have studied the long-term evolution of HMF sector polarities in 1926–2003, using two recent data sets by Echer and Svalgaard (2004) and Vennerstroem et al. (2001) that use ground-based geomagnetic observations to determine the HMF sector polarity by the Svalgaard–Mansurov effect. The purely ground-based VZF data set reaches a success rate with the OMNI-2 data set which is close to the theoretical maximum attainable for a ground-based method (Russell and Rosenberg, 1974), yet considerably lower than the success rate of the ES data set which combines OMNI data with several ground-based data sets. Also, the success rates of the VZF data set are asymmetric between the two HMF sectors, yielding a lower success rate for the A sector. There is no such difference in the success rates of the two sectors in the ES data set. While the two data sets agree quite well with each other during the OMNI data time, they differ more in early part of the interval studied.

Both data sets depict the Rosenberg–Coleman rule during the high-latitude intervals (Fall, Spring) for most of the interval studied. This is particularly true for the OMNI-2 time interval when both data sets show slightly larger RC amplitudes in Fall than in Spring, in agreement with the southward HCS shift (Mursula and Hiltula, 2003, 2006).

Both data sets show a small overall T sector dominance in Fall and an A sector dominance in Spring. Since this is not observed in the OMNI-2 data set, it suggests that this effect is due to the ground-based method used to determine the sector polarity. In fact, this is likely due to the Russell–McPherron effect (Russell and McPherron, 1973), which leads to a larger disturbance level during the A sector days in Fall and T sector days in Spring, reducing their correct interpretation and leading to the observed preference of T sector in Fall and A sector in Spring.

However, this does not explain the fact that there is an excessively large T sector dominance in Fall in the VZF data which is considerably larger than the A sector dominance in Spring. The sinusoid fit to the T/(T + A) ratio in Fall depicts an offset which is nearly three times larger in the VZF data than in the ES data. In Spring the corresponding offsets are roughly similar.

The excessive T sector dominance in Fall in the VZF data set is also reflected in the fact that the VZF data set includes an overall T sector dominance, even during the OMNI-2 interval when the OMNI data was used to find the best fit parameters of the VZF method. The T sector dominance in Fall is particularly strong in the early years of the VZF data set (cycles 16 and 17), even so that the RC rule breaks at this time. This also lead to a smaller overall sinusoid amplitude in Fall than in Spring in the VZF data, against the OMNI-2 interval and to the ES data set. Also, the breaking of the RC rule in the VZF data set in these early years leads to the disappearance of the HCS shift in the VZF data set in cycles 16 and 17.

While the VZF data set reproduces most of the essential features in the long-term occurrence of HMF sectors, especially in the latter part of the studied time interval (e.g., the exceptional behaviour of the HCS during cycle 19 and the southward HCS shift since 1950s), it deviates from the ES data set significantly in cycles 16 and 17. However, the above results suggest that the ES data set gives a more reliable estimate of the early HMF sector polarities than the VZF data set. This may be due to the fact that while in the ES data the early values were based only on the cusp latitude Godhaven station, the VZF data included also the subauroral Sodankylä and Sitka stations. This may well be the case since the SM method is expected to be applicable only when the cusp currents make an essential contribution in the local ionosphere, which may not be the case below the auroral oval.

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