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Bashful ballerina: Southward shifted heliospheric current sheet

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[1] It is known since long [*Rosenberg and Coleman*, 1969] that one of the two sectors of the interplanetary magnetic field (IMF) observed at the Earth's orbit dominates at high heliographic latitudes during solar minimum times, reflecting the poloidal structure of the global solar magnetic field at these times. Here we find that while this latitudinal variation of the dominant IMF sector around the solar equator is valid for both solar hemispheres during the last four solar minima covered by direct observations, it is systematically more strongly developed in the northern heliographic hemisphere. This implies that the average heliospheric current sheet is shifted or coned southward during solar minimum times, suggesting that the temporary southward shift of the heliosheet found earlier by Ulysses observations in 1995 is a persistent pattern. This also implies that the open solar magnetic field is north-south asymmetric at these times, suggesting that the solar dynamo has an asymmetric component. Accordingly, the Sun with the heliosheet is like a bashful ballerina who is repeatedly trying to push her excessively high flaring skirt downward. However, the effective shift at 1 AU is only a few degrees, allowing the Rosenberg-Coleman rule to be valid, on an average, in both hemispheres during solar minima. *INDEX TERMS:* 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536); 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields. **Citation:** Mursula, K., and T. Hiltula, Bashful ballerina: Southward shifted heliospheric current sheet, *Geophys. Res. Lett.*, *30*(22), 2135, doi:10.1029/2003GL018201, 2003.

1. Introduction

[2] The solar magnetic field experiences a dramatic change over the 11-year solar cycle from a dominantly dipolar form around solar minima to a multi-polar form at maxima. During two successive solar minima the dipolar magnetic field is oppositely oriented which leads to a 22-year cycle of the solar magnetic field. The solar magnetic field during solar minima is dominated by large unipolar magnetic regions of the polar coronal holes [*Newkirk and Fisk*, 1985; *Kojima and Kakinuma*, 1990; *Rickett and Coles*, 1991] that may extend from the poles close to the solar equator. This also leads to the well known fact, first observed by *Rosenberg and Coleman* [1969; to be called the RC rule] that one of the two sectors of the interplanetary magnetic field dominates at the Earth's orbit in Fall (Spring, respectively) when the Earth achieves its highest northern (southern) heliographic latitudes due to the 7.2° tilt of the solar rotation axis with respect to the ecliptic. Accordingly, there is a latitudinal variation of the dominant IMF sector around the heliospheric equator during solar minimum times. During a positive polarity solar minimum there is a dominance of the away (A) IMF sector in Fall while the toward (T) sector dominates in Spring. The situation is reversed one solar cycle later during a negative polarity minimum.

[3] Several studies have reported differences between the northern and southern solar hemispheres (hemispheric asymmetries) in many solar parameters, e.g., in sunspots [*Carbonell et al.*, 1993; *Oliver and Ballester*, 1994] and flares [*Roy*, 1977; *Garcia*, 1990]. However, the north-south asymmetry in sunspots or any other solar parameter has not been found to behave clearly systematically with respect to the 11-year solar activity cycle or to the 22-year solar magnetic cycle. Therefore, the significance of hemispheric asymmetries has not been well understood so far, and has not been able to provide consistent input to theoretical solar models. On the other hand, it was found recently [*Zieger and Mursula*, 1998; *Mursula and Zieger*, 2001; *Mursula et al.*, 2002] that some heliospheric parameters depict north-south asymmetries which are clearly related to the magnetic cycle. In particular, it was shown [*Mursula et al.*, 2002] that the streamer belt is systematically shifted toward the northern magnetic hemisphere during solar minimum times. *Crooker et al.* [1997] verified that the streamer belt was indeed shifted northwards in 1994–1995 during the Ulysses first fast latitude scan. Moreover, *Simpson et al.* [1996], *Crooker et al.* [1997], and *Smith et al.* [2000] found that the heliospheric current sheet (HCS) was shifted or coned southwards at this time.

[4] In order to study the long-term north-south behavior of the HCS at 1 AU, we reanalyse here the RC rule and study the occurrence of the two IMF sectors, i.e., the two solar magnetic hemispheres, at the Earth's orbit for nearly 40 years. We find that while the latitudinal variation of the dominant IMF sector is, as suggested by the RC rule, valid on an average for both solar hemispheres and all studied solar minima, there is a systematic difference between the northern and southern heliographic hemispheres. The latitudinal dominance of one IMF sector is systematically more strongly developed in the northern heliographic hemisphere, irrespective of solar magnetic polarity. This implies that, over the annual orbit of the Earth, there is an overall dominance of that IMF sector (magnetic hemisphere) which is prevailing in the northern heliographic hemisphere. Accordingly, the annually averaged HCS is systematically shifted or coned toward the heliographic south at solar minimum times.

2. Rosenberg-Coleman Rule in the Two Hemispheres

[5] We have used here the hourly IMF data (in the GSE coordinate system) collected in the OMNI data set [*King*, 1977]. For each hour, the IMF was divided into one of the

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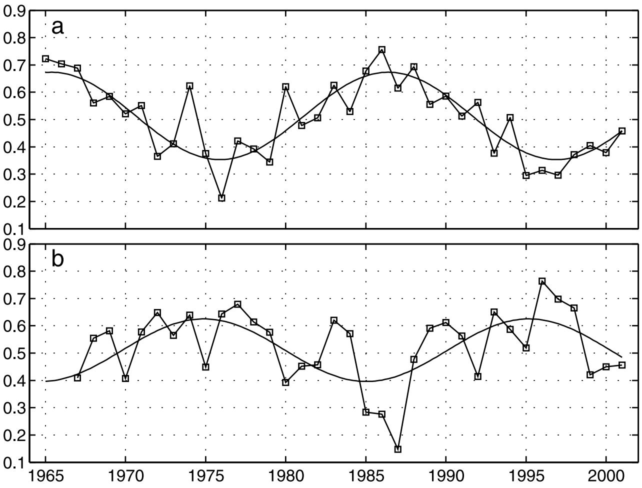

Figure 1. The 3-month T-sector occurrence fractions T/(T + A), together with the best fitting sinusoids; a: Fall seasons in 1965–2001; b: Spring seasons in 1967–2001.

two sectors. (We have used here both the plane division, Bx > By defining the T sector, and the quadrant division, Bx > 0 and By < 0 defining the T sector, as the sector definition. However, since all results remained very similar for both divisions we mainly present here results obtained using the plane division.) Then we calculated the total number of T and A sector hours for each 3-month season around the two high-latitude intervals (Spring = Feb–Apr; Fall = Aug–Oct) and also for each full year. These numbers reflect the occurrence of the two IMF sectors in the respective time intervals. Since the IMF data coverage varies considerably over the nearly 40 years studied (see discussion below) we have used the normalized T sector occurrence ratios T/(T + A) rather than the absolute numbers.

[6] Figure 1a depicts the T sector occurrence ratios in Fall, i.e., when the Earth is at the highest northern heliographic latitudes during its annual orbit. Despite some scatter, there is a clear 22-year variation in the dominant IMF sector so that the T sector dominates in Fall during the negative polarity minima in the 1960s and 1980s, while the A sector dominates in the positive minima in the 1970s and 1990s. Accordingly, the northern heliographic hemisphere closely follows the Rosenberg-Coleman rule over the studied time interval in 1965–2001. Note that the average level of the observed T/(T + A) ratio is about 0.49, i.e., very close to the expected value of 0.50. This shows that there is no large overall observational bias in favor of either sector either due to the data set or due to any possible natural asymmetry. We have also plotted in Figure 1a the best fitting sinusoid whose period was found to be 21.0 years and amplitude ±0.16, implying that, on an average, the ratio between the dominant and subdominant sector occurrences is 1.94 during solar minima. Thus the dominant sector appears nearly twice as often as the subdominant sector in Fall at these times. Note also that during each minimum the extremal values of the T/(T + A) ratio deviate from the overall average by more than 0.2 at least in one year.

[7] The similar T sector occurrence ratios in Spring, i.e., when the Earth is at the highest southern heliographic latitudes, are shown in Figure 1b. Again, the Rosenberg-Coleman rule is valid and illustrated by the overall dominance of the T (A) sector during the positive (negative) solar minima, leading to a roughly 22-year variation with a phase opposite to Figure 1a. However, there is more scatter to the RC rule in Spring than in Fall, and the amplitude of the best fitting sinusoid in Figure 1b is somewhat smaller, at about ±0.11, implying that, on an average, the dominant sector appears about 56% more often than the subdominant sector in Spring during solar minima. The period of the best fitting sinusoid, 20.3 years, is close to that in Fall. Note that, although the average amplitude is smaller in Spring, the extrema of the T/(T + A) ratio attain roughly similar values as in Fall and that the largest deviation is found in Spring in 1987. (The overall average in Spring is 0.53).

[8] We also note that since the HCS is not always sinusoidal but often contains warps and other complicated structures, the 22-year variation of the RC rule does not necessarily have to be sinusoidal and may also contain significant temporal fluctuations around the trend. Nevertheless, Figure 1 shows that the trend of the 22-year variation is surprisingly close to a sinusoidal behaviour, especially in Fall. The largest deviations from the sinusoidal pattern in Figure 1 occur in the form of bipolar type fluctuations which include a short interval of opposite dominance just before the actual, RC favoured extremum at solar minimum. This is best seen in Fall in 1974 and in Spring in 1983–1984. Such bipolar fluctuations (lasting mostly 3–4 years) are probably related to the recently observed 3.2-year "flip-flop" periodicity in IMF sector structure [*Takalo and Mursula*, 2002]. The largest bipolar fluctuation is observed in mid-1980s in Spring. This is probably due to the fact that the HCS was exceptionally thin during this minimum [*Richardson and Paularena*, 1997], making such fluctuations and other temporal variations more dramatic and easily observed at 1 AU.

3. Shifted Heliospheric Current Sheet

[9] The above observation that the latitudinal variation of the dominant IMF sector is systematically stronger in the northern heliographic hemisphere leads to interesting consequences. We have calculated in Figure 2 the normalized ratios (T − A)/(T + A), i.e., the differences in the fractional occurrence of T and A sectors. This difference reveals the possible average dominance of either magnetic hemisphere during one year as observed at 1 AU and, thereby, the possible average north-south asymmetry of the heliospheric current sheet around the solar equator during the respective year.

[10] Figure 2 shows that, despite considerable scatter, there is a systematic 22-year oscillation in the dominant magnetic hemisphere. This directly follows from the fact that the amplitude of the 22-year variation in Fall (Figure 1a) is larger than in Spring (Figure 1b). Accordingly, the IMF sector prevalent in the northern heliographic hemisphere (A sector during positive polarity minima and T sector during negative polarity minima) is dominating during all solar minima. This implies that the heliosheet at 1 AU is, on an average, shifted or coned toward the southern heliographic hemisphere during all solar minimum times.

[11] Figure 2a presents the (T − A)/(T + A) ratios using the plane division and data from the equinox seasons (Fall and Spring) only while Figure 2b uses all annual data.

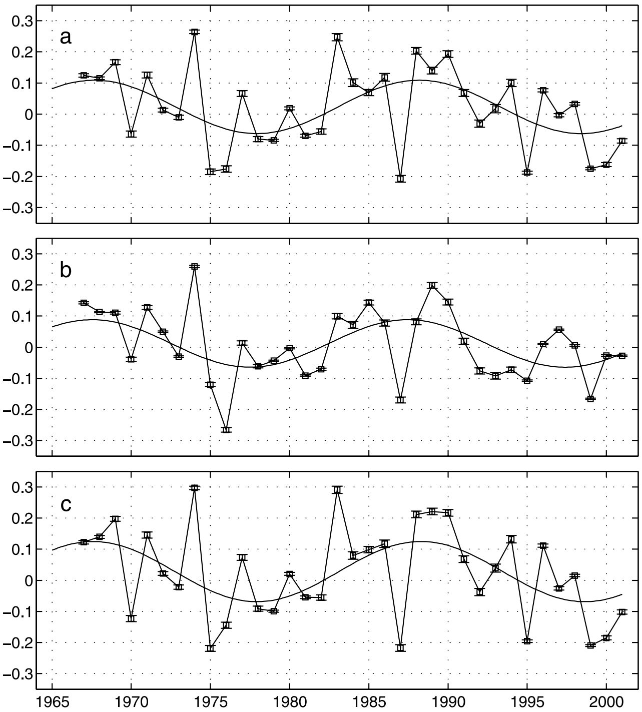

Figure 2. Differences between T- and A-sector occurrence fractions (T − A)/(T + A) for 1967–2001 together with the estimated errors and the best fitting sinusoids; a: Plane IMF division, Fall and Spring data only; b: Plane IMF division, all annual data; c: Quadrant IMF division, Fall and Spring data only.

Figure 2c depicts the result for the quadrant division using data from equinox seasons. All the three treatments (and some others used but not shown) give the same basic result. The amplitude of the 22-year oscillation in Figure 2a is about 0.09, implying that, on an average, the IMF sector coming from the northern heliographic hemisphere appears about 20% more often in solar minima than the IMF sector from the southern heliographic hemisphere. Note also that the the quadrant division yields the largest 22-year amplitude (0.10) in Figure 2. This is most likely due to the fact that this IMF definition rules out the most disturbed HCS situations and emphasizes time intervals when the IMF sector structure is most developed. Accordingly, it suggests that the observed asymmetry is indeed the property of the normal, quiet IMF and not only due to abnormal or disturbed conditions.

[12] As mentioned above, a similar southward shift of the HCS was found [*Simpson et al.*, 1996; *Crooker et al.*, 1997; *Smith et al.*, 2000] in 1994–1995 outside 1 AU using Ulysses observations during its first fast latitude scan. The present results verify that the asymmetry is a persistent structure at least during the last four solar minima. Note also that the average southward shift of the heliospheric current sheet must be less than the 7.2° tilt of the solar rotation axis since otherwise the RC rule would not be observed both in Fall and Spring.

4. Statistical Analysis

[13] The data coverage of the OMNI IMF data set in 1965–2001 is about 66% but for many years (or shorter periods) it is considerably smaller. When discussing the annual differences of the two IMF sectors, an important question is how large a data coverage, e.g., in the 6-month equinoctial interval is needed in order to have a certain confidence level for the observed dominance of one IMF sector. It is natural that the smaller the data coverage is, the more there is random scatter due to statistical fluctuations. We have studied this question in the following way. First we generated a random 6-month sample of hourly IMF data (to be called test data) with a roughly equal number of T and A sectors. (We used both an exactly equal distribution and a slightly T sector dominated distribution, as seen in data, but the results were very similar in both cases). Then, we took a random sample of the test data corresponding to a certain data coverage percentage and calculated the fraction of either IMF sector in this sample. We repeated this random sampling several times using the same data coverage percentage for the sample. Using this set of samples with the same data coverage we calculated the standard deviation for the sectorial fraction around the average. (We studied the values of standard deviations as a function of the number of samples and found that 100 samples is a sufficient set in order to obtain a close estimate of the final asymptotical value). Finally we repeated the sampling for different data coverage percentages (in steps of 2% from 2% to 20% and of 10% above that) and thereby obtained the standard deviation as a function of data coverage.

[14] Figure 3 depicts the values of the calculated standard deviations as a function of data coverage percentage, together with the best fitting curve (exponential of a fourth order polynomial) superimposed. E.g., at the 20% coverage level the standard deviation in the sectorial fraction is only about 0.015, while beyond 40% level it is less than 0.01. Since, after 1966, all seasons have a data coverage better than 30% and the typical coverage is about 60%, the typical statistical fluctuation in the sectorial occurrence is less than 0.007. This value has to be compared with the differences in Figure 2. E.g., the average amplitude, 0.09, of the difference in Figure 2a is more than 12 typical standard deviations away from equal distribution, giving strong support for the

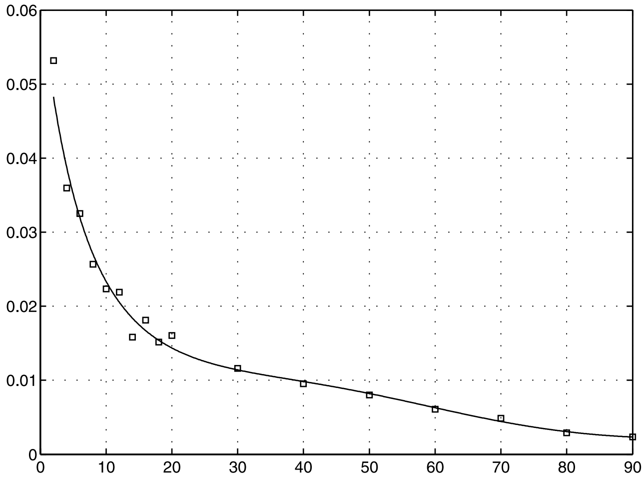

Figure 3. Estimated values of the standard deviation for sectorial nonequality due to random scatter as a function of data coverage percentage together with the best fitting curve.

statistical significance of the 22-year oscillation in this difference. (Note also that we have used the standard deviations given by the best fitting curve in Figure 3 as error bars in Figure 2 and as weights when fitting the observed data points in Figure 2 to the 22-year sinusoid. However, the results without such weighting do not differ much from those presented here).

[15] In order to further test the significance of the main result of the 22-year oscillation of the differences (T − A)/(T + A) (Figure 2), we have made two additional tests. First, we made a binomial analysis of the distribution of these differences by dividing them 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. For example in Figure 2b, out of the 35 annual values only 6 were in the latter set. The probability of having 6 or less values in one set is less than 3×10^{-5}, giving strong support for the fact that the 22-year cycle organizes the differences. As a second test, we have tested the significance of 22-year variation by the *Stellingwerf* [1978] method according to which the 22-year oscillation in Figure 2b is significant at least at 93% confidence level.

5. Discussion and Conclusions

[16] We have shown in this paper that while the Rosenberg-Coleman rule of the latitudinal variation of the dominance of one IMF sector at 1 AU is valid for both solar hemispheres separately, it is more pronounced in the northern hemisphere. This implies that the heliospheric current sheet is systematically shifted or coned southward during solar minimum times. We note that the average southward HCS shift must be less than the 7.2° tilt of the solar rotation axis with respect to the ecliptic plane since otherwise the Rosenberg-Coleman rule would not be valid both in Fall and Spring.

[17] A temporary southward shift or coning of the HCS in 1995 was earlier found from Ulysses observations during its first fast latitude scan [*Simpson et al.*, 1996; *Crooker et al.*, 1997; *Smith et al.*, 2000]. The present observations verify the shift at this time (see Figure 2) and generalize this observation by showing that the average HCS is systematically shifted or coned southward during all the four last solar minima covered by direct IMF observations. As an amusing analogy, one might say that the Sun with the heliosheet is like a bashful ballerina who is repeatedly trying to push her excessively high flaring skirt downward every 11 years. This also implies that the open solar magnetic field is north-south asymmetric at these times, suggesting that the solar dynamo has an asymmetric component.

[18] We also note that the observed behavior of the HCS is different from the recently found north-south asymmetry of the streamer belt [*Zieger and Mursula*, 1998; *Mursula and Zieger*, 2001; *Mursula et al.*, 2002] which is systematically shifted toward the northern magnetic hemisphere. So, during negative solar minima the HCS and the streamer belt are both shifted toward the heliographic south. However, during positive solar minima they are oppositely shifted, HCS southward, streamer belt northward. This separation of the streamer belt and HCS during positive polarity minima is another unexpected and new phenomenon which needs to be expained in more detail. Moreover, it gives another dramatic demonstration of how different the two halves of the 22-year magnetic cycle are. Note also that the Ulysses observations in 1994–1995 have shown that the HCS was shifted downward while the streamer belt was simultaneously shifted northward [*Crooker et al.*, 1997], verifying the general pattern found here. It will be interesting to see if, during the coming minimum, both the streamer belt and HCS will indeed be shifted downward. It is obvious that these observations present new important constraints which have to be implemented by realistic solar dynamo models.

[19] **Acknowledgments.** Financial support by the Academy of Finland is gratefully acknowledged. We are also grateful to NSSDC for OMNI data.

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