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Bashful ballerina: The asymmetric Sun viewed from the heliosphere ☆

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Abstract

Long-term observations of the heliospheric magnetic field (HMF) at 1 AU have depicted interesting systematic hemispheric and longitudinal asymmetries that have far-reaching implications for the understanding of solar magnetism. It has recently been found that the HMF sector that is prevalent in the northern solar hemisphere dominates the observed HMF sector occurrence for a few years in the late declining to minimum phase of the solar cycle. This leads to a persistent southward shift or coning of the heliospheric current sheet (HCS) at these times, which has been described by the concept of the bashful ballerina. This result was later verified by direct measurements of the solar magnetic field which showed that the average field intensity was smaller and the corresponding area larger in the northern (heliographic) hemisphere than in the southern hemisphere during roughly 3 years in the late declining to minimum phase of the cycle. During these years when the HCS was shifted southwards, the solar quadrupole moment was found to be systematically non-zero and oppositely oriented with respect to the dipole moment. Long-term observations of the geomagnetic field can yield information on the HMF sector structure in the pre-satellite era, showing that the ballerina was bashful since 1930s. In addition to the hemispheric asymmetries, the Sun is systematically asymmetric in longitude. It has been shown that the global HMF has persistent active longitudes whose dominance depicts an oscillation with a period of about 3.2 years. Accordingly, the bashful ballerina takes three such steps per activity cycle, thus dancing in waltz tempo. Stellar observations show that this is a general pattern for sun-like cool stars. We describe these phenomena and discuss their implications.

Keywords: Heliospheric current sheet; North–south asymmetry; Heliospheric magnetic field; Solar magnetic field; Long-term solar variability; Active longitudes

1. Introduction: HCS as the bashful ballerina

The heliospheric current sheet (HCS) is the outward extension of the solar magnetic equator, i.e., a surface that separates the two solar magnetic hemispheres (sectors) with opposite polarities in the heliosphere. 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 and Coleman (1969); to be called the RC rule) that one of the two HMF sectors 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 (e.g., in the 1990s) 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.

The possibility of a systematic north–south displacement of the HCS was studied already in the 1970s and 1980s (see, e.g., Tritakis, 1984) using the concept of average HMF sector width. However, this method is very sensitive to data gaps, leading to partly arbitrary and erroneous results about the HCS asymmetry. Observations during the first fast latitude scan of the Ulysses probe in 1994–1995 found that the heliospheric current sheet was shifted or coned southwards at that time (Simpson et al., 1996; Crooker et al., 1997; Smith et al., 2000).

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In order to study the structure of the heliospheric current sheet, Mursula and Hiltula (2003) used the hourly HMF data of the OMNI data set which covers in situ HMF observations at 1 AU since 1964. For each hour, the observed HMF was divided into one of the two sectors, the T sector (southern magnetic hemisphere) consisting of field lines directed toward the Sun, or the A sector (northern magnetic hemisphere) directed away from the Sun. Two different divisions were used to define HMF sectors: the plane division (e.g., the T sector in GSE coordinates: $Bx > By$) and the quadrant division (T sector: $Bx > 0$ and $By < 0$), and the total number of T and A sector hours was calculated for each 3-month season around the two high-latitude intervals (Spring = February–April; Fall = August–October) and also for each full year. When, e.g., the occurrence fraction of the T sector, the $T/(T+A)$ ratio, is plotted in Fall each year, a clear 22-year variation around the average of one half was found, in agreement with the RC rule, with the T sector dominating during the negative polarity minima and the A sector dominating in the positive minima. Mursula and Hiltula (2003) quantified the RC rule and found that the amplitude of the 22-year variation in the $T/(T+A)$ fraction in Fall is 0.16, implying that the average ratio between the dominant and subdominant sector occurrences in the northern heliographic hemisphere around solar minima is 1.94.

However, interestingly, the similar amplitude in Spring, i.e., when the Earth is at the highest southern heliographic latitudes, was found to be significantly smaller, about 0.11, implying that in Spring the dominant sector only appears about 56% more often than the subdominant sector. Thus, although the RC rule is separately valid in both solar (heliographic) hemispheres, a systematic difference was found in the latitudinal HMF structure between the two hemispheres so that the dominance of either HMF sector is systematically stronger in the northern than southern heliographic hemisphere. This difference can be demonstrated by plotting the annual $(T - A)/(T + A)$ ratios, i.e., the difference in the annual occurrence of T and A sectors which can reveal the possible dominance of either magnetic hemisphere and, thereby, the possible north–south asymmetry of the HCS during any year.

Fig. 1 depicts this ratio, showing that, despite some scatter (which is mostly not random but due to significant short-term variations), there is a systematic 22-year baseline oscillation in the dominant magnetic hemisphere. Moreover, the results are very similar for different sector definitions and data selections, indicating considerable robustness. Detailed tests also show that the baseline oscillation is statistically significant (Mursula and Hiltula, 2003). Accordingly, the HMF sector prevalent in the northern heliographic hemisphere (the 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 these times. This property has given the Sun the nickname of a bashful ballerina since the solar ballerina pushes her high flaring skirt downward whenever her activity is fading away. A typical amplitude of about 0.09 implies that, on an average, the HMF sector coming from the northern heliographic hemisphere appears about 20% more often around solar minima than the HMF sector from the southern hemisphere.

Further evidence for the southward shift of HCS has been obtained from direct solar magnetic observations at the Wilcox Solar Observatory. Using the source surface model, Zhao et al. (2005) calculated for each solar rotation

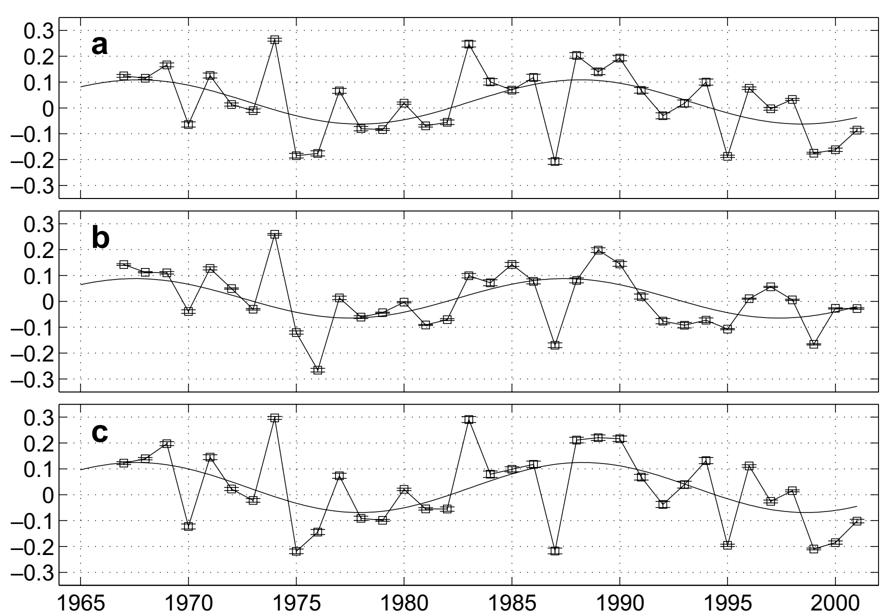

Fig. 1. The $(T - A)/(T + A)$ ratios in 1967–2001 together with the estimated errors and the best fitting sinusoids (Mursula and Hiltula, 2003). (a) Plane HMF division, Fall and Spring data only; (b) plane HMF division, all annual data; (c) quadrant HMF division, Fall and Spring data only.

the total areas and average field strengths of positive and negative polarity regions in 1976–2001. They found that the magnetic hemisphere dominant in the northern solar hemisphere (negative polarity in mid-1980s, positive in mid-1990s) has a systematically larger area than in the south for about 3 years in the late declining to minimum phase of the solar cycle, and that the calculated HCS location is southward shifted during these intervals. These results are in an excellent agreement with the general pattern concluded from the in situ HMF measurements (Mursula and Hiltula, 2003). The average shift during the 3-year intervals was found to be about 3–5°, again in a good agreement with the 7.2° upper limit extracted from HMF observations.

2. Longer dance of the bashful ballerina

The ground-based observations of the geomagnetic field can be used to extract information about the dominant daily HMF polarity for the pre-satellite era. There is a well known relation, so called Svalgaard–Mansurov (SM) effect Svalgaard, 1968; Mansurov, 1969, between the dominant daily direction of the HMF By component and the daily variation of the geomagnetic field at high latitudes. Recently, Echer and Svalgaard (2004) constructed a combined data set (ES data set) of daily HMF polarity for 1926–2003 as a weighted mean of several different ground-based extracted HMF polarity data sets and the OMNI data set. Hiltula and Mursula (2006) used this data set to study the HCS properties in the early part of the last century. They showed that the ES data depicts the RC rule throughout the whole time interval separately in Spring and Fall, thus giving evidence for the validity of the data set. When using only the more recent years since 1965, the RC amplitudes for the ES data set are 0.122 in Spring and 0.155 in Fall, i.e., closely similar and depicting the same difference (Fall amplitude larger) as the OMNI data set. Leaving out the time interval of solar cycle 19 (see later), the RC amplitudes for the ES data set in the early period 1926–1955 are 0.095 in Spring and 0.114 in Fall. Thus, although the sinusoid amplitudes are overall smaller in the early period, the Fall amplitude is larger than the Spring amplitude both in the early and in the later period of the ES data set.

The annual $(T-A)/(T+A)$ ratios of the ES data set and the OMNI data set are depicted in Fig. 2. The two curves follow closely each other during the overlapping period 1967–2003. The southward shift of the HCS is seen both in the ES and OMNI 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 (leaving out cycle 19) are fitted with a sinusoid, to a roughly 20-year variation with an amplitude of 0.075. This variation was found to be significant at least at the level of 91% (Hiltula and Mursula, 2006). As a comparison, a similar sinusoid fit to the ES (OMNI) data in the later time interval 1967–2003 has an amplitude of 0.053 (0.077, resp) and is significant at least at the level of 93% (97%). Accordingly, the HCS seems to be shifted southward both in the early (1926–1955) and later (1967–2003) part of the ES interval.

As seen in Fig. 2, the HCS depicts an exceptional behavior during solar cycle 19, the greatest sunspot cycle so far. There was an exceptionally large T sector dominance in

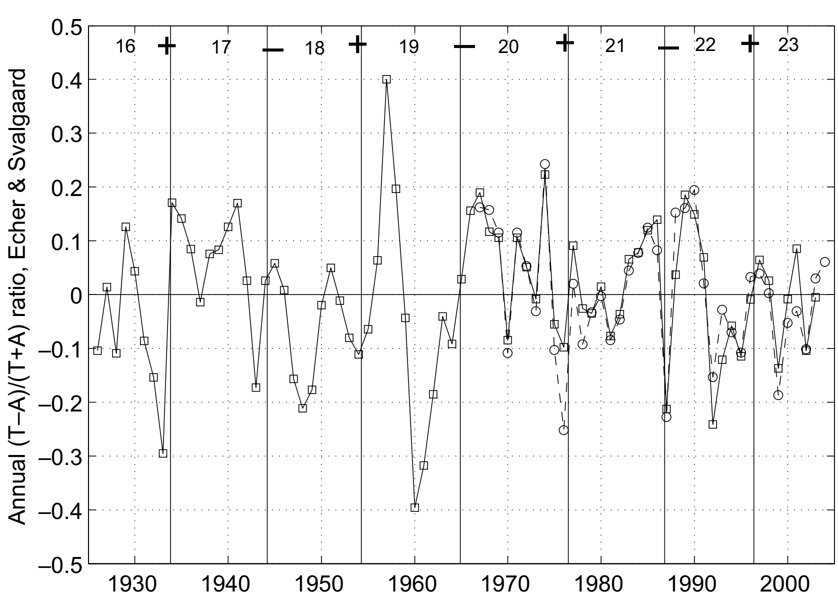

Fig. 2. Annual $(T-A)/(T+A)$ ratios according to ES data (solid line with squares) and OMNI data (dashed line with circles). Plus and minus signs denote the solar polarity and numbers indicate the solar cycle number. Vertical lines denote the NGDC sunspot minima (Hiltula and Mursula, 2006).

late 1950s with a maximum in 1957, coinciding with the sunspot maximum of cycle 19. Thereafter, *T* sector dominance quickly changed to *A* sector dominance, reaching a maximum in 1960. The deflections to either direction were almost equal, and roughly twice as large as in all other times. As discussed in more detail in Hiltula and Mursula (2006), the exceptional HCS evolution indicates that the solar polarity was temporarily changed in the northern hemisphere, in agreement with direct solar observations of multiple field reversals in the northern hemisphere between 1958 and 1960 (Makarov and Makarova, 1996).

The HMF sector behavior and the HCS structure in cycle 19 were unique during the last 80 years, perhaps due to long-lasting multiple sheets between the cycle maximum in 1957 and the final polarity reversal in 1960. While this maximum time behavior does not contradict with the southward HCS shift during the late declining to minimum phase of the cycle, it may have delayed the appearance of the southward HCS shift in 1960s where it is observed only in the minimum year and thereafter.

We note that the sunspot maximum in 1957 started a long period of strong northern dominance in sunspot activity (see Fig. 3). The related sunspot asymmetry was strongest from 1957 until 1960, i.e., exactly during the time when the HCS depicted the large dipolar oscillation. The northern dominance lasted unbroken until 1970, the period from 1957 to 1970 marking the longest time interval of northern dominance in sunspot activity. The unique HCS oscillation and the large northern dominance in sunspots are probably related but, so far, in an unknown way.

3. Centennial evolution of solar global asymmetry

It is known that, in addition to the HCS, also the solar wind distribution (the streamer belt) depicts a clear, systematic north–south asymmetry (Zieger and Mursula, 1998; Mursula and Zieger, 2001; Mursula et al., 2002).

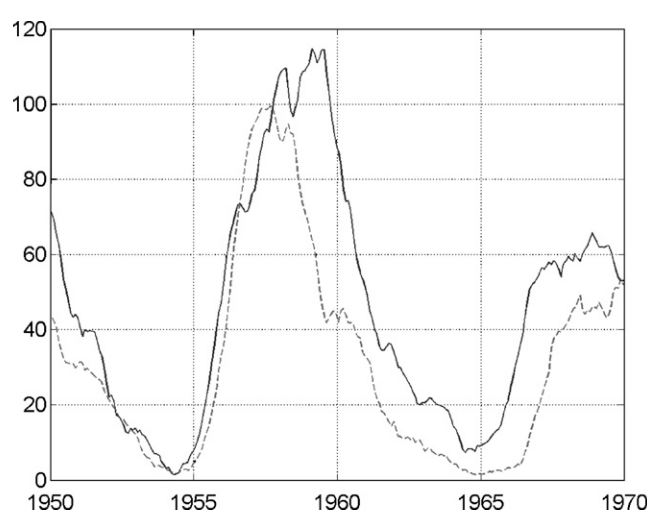

Fig. 3. Monthly sunspot numbers in the northern (solid line) and southern (dashed line) hemisphere in 1950–1970.

Although the in situ solar wind observations only exist since early 1960s, the hemispheric asymmetry can be studied over a much longer time interval using the correlation with geomagnetic activity (Zieger and Mursula, 1998). Extending the well known aa index of geomagnetic activity (Mayaud, 1973) by early geomagnetic observations in Helsinki since 1844 (Nevanlinna and Kataja, 1993), Mursula and Zieger (2001) could study the streamer belt asymmetry during the last 160 years. The asymmetry of the streamer belt leads to an annual variation of solar wind speed and geomagnetic activity (GA) with a maximum in Spring or Fall, depending on the direction of the asymmetry.

Fig. 4 (middle panel) displays the filtered annual variation of the extended aa index as an intensity map where 1 year is depicted along the vertical axis so as to demonstrate the phase of the annual variation. The bottom panel of Fig. 4 depicts the annual variation in the solar wind speed, showing great similarity with GA during the overlapping time. Fig. 4 shows that there was a strong asymmetry in streamer belt since the 1930s. This happens to coincide with the time interval covered by the ES data. If the streamer belt asymmetry and the HCS asymmetry are, as expected, related, this would imply that the ballerina was not bashful in the first decennia of the last century.

Fig. 4 also shows that the streamer belt was asymmetric even earlier, in the mid-19th century. It is interesting to note that these two time intervals of a large asymmetry coincide with the intervals of fairly high-activity solar cycles. On the other hand, around the turn of the 19th and 20th century, during low-activity cycles, the asymmetry was weak or even vanishing. This indicates a profound connection between the overall solar activity and the solar hemispheric asymmetry.

Studying the phases of annual maxima in more detail Mursula and Zieger (2001) noted that while the annual maxima since 1930s occurred in Spring during positive polarity times and in Fall during negative polarity times (see color version of Fig. 4), the situation was reversed in mid-19th century. Accordingly, the streamer belt asymmetry experienced a phase shift, being oriented toward the southern magnetic hemisphere in mid-1800s and toward the northern magnetic hemisphere since 1930s. Assuming that a similar phase change also occurred in the HCS asymmetry, the HCS must have been shifted northward in the 19th century. Alas, the ballerina was not bashful but rather, perhaps, permissive at that time.

As noted earlier (Mursula and Zieger, 2001), the change of the solar asymmetry between mid-1800s and since 1930s implies a new form of long-term oscillation in the solar magnetic field with a period of about 200–300 years. The only known solar periodicity in this period range is the 205- to 210-year long deVries cycle (also sometimes called Suess cycle) which appears in many time series of cosmogenic isotopes (see, e.g., Raspopov et al., 2005). Although the asymmetry cycle is not a solar activity cycle, the two halves of this cycle may still affect cosmic rays differently and, thereby, lead to the observed deVries cycle in

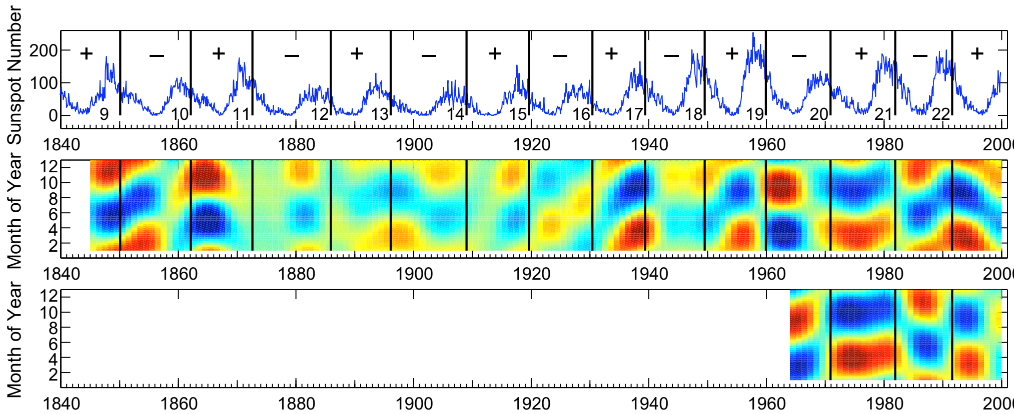

Fig. 4. Monthly sunspot numbers with solar polarity denoted by + and − signs (top panel). Filtered annual variation of the extended aa index in 1845–1999 (middle panel), and of the solar wind speed in 1964–1999 (bottom panel) in intensity coding. The dark grey regions (red and blue in color code) represent large (positive and negative) values of annual variation, while white (yellow and green in color) denotes a small amplitude. The scale of the intensity code is ±3.5 nT for the aa index and ±25 km/s for the solar wind speed. Vertical lines denote the approximate times of polarity reversal 2 years after sunspot maxima (Mursula and Zieger, 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cosmogenic isotopes. The different effect of the opposite orientations of the solar hemispheric asymmetry to cosmic rays is expected to take place mostly in the distant heliosphere and, especially, in the inner heliosheath where the orientation of the asymmetry has an important effect upon the three-dimensional structure of the heliopause. This possible identification of the deVries cycle as the solar asymmetry cycle would imply that the deVries cycle would not be a solar activity cycle at all (unless the amplitude of asymmetry oscillates with the same period). Moreover since, as discussed above, the strength of the hemispheric asymmetry is related to solar activity and the Gleissberg cycle is a roughly centennial cycle of solar activity, it is tempting to suggest that the solar asymmetry cycle, i.e., the deVries cycle, would consist of two Gleissberg cycles with opposite solar asymmetry. Thus, the roughly 200-year deVries (asymmetry) cycle consisting of two centennial Gleissberg (activity) cycles would be analogous with the well known 22-year Hale (magnetic) cycle consisting of two 11-year Schwabe (activity) cycles.

4. Longitudinal asymmetry in HMF: steps of the bashful ballerina

The solar wind and the HMF components have often a strong tendency to repeat their current values after the solar rotation period of about 27 days. This repetition reflects the existence of persistent, longitudinally asymmetric structures, such as, e.g., polar coronal holes with equatorial extensions. Such structures also determine the inclination of the heliospheric current sheet (the solar tilt) and, thereby, the HMF sector structure observed, e.g., at 1 AU.

In order to study the solar rotation related repetition in HMF Takalo and Mursula (2002) calculated the autocorrelation function (ACF) of the HMF Bx component up to lags of several tens of solar rotations. Fig. 5 shows that there is a strong tendency for HMF Bx to repeat its value with a decreasing probability (ACF amplitude) for about nine solar rotations. This can be understood in terms of a slow decrease of the solar dipole tilt after some reconfiguration (tilt activation) produces the initial tilt value. However, after the node at about 10–11 rotations, the ACF amplitude (i.e., rotation periodicity) recovers again and reaches an antinode at a lag of about 20–22 solar rotations. Moreover, after this first antinode the ACF amplitude decreases to the next node at a lag of about 35 rotations and increases again to the next antinode at about 42–43 rotations, i.e., after some 3.2 years. The long-term repetition of nodes and antinodes continues even thereafter, as depicted in Fig. 5 (bottom panel).

There are some important consequences of this node–antinode structure. First, the subsequent tilt activations are not random, but depict a considerable amount of phase coherence. In particular, it implies that after one activation has died out, the second activation develops, at a considerable probability, so that its phase (longitude) is nearly opposite to the phase of the first activation. Moreover, the third activation has again a considerable probability to attain a tilt phase in the direction opposite to the second one, i.e., roughly reproducing the phase of the first activation.

The second consequence of this node–antinode structure relates to the average rotation period of the large scale magnetic structures that produce the HMF. Fig. 5 depicts multiples of the 27.6-day rotation period which match very well to the first 10 ACF maxima and, after the first node, to the ACF minima (not maxima), reflecting the reversed phase in solar rotation periodicity (and solar tilt). The original phase is recovered again at the second antinode. This alternation of phase also continues with subsequent nodes. Takalo and Mursula (2002) showed that such a node–antinode structure of the ACF can be reproduced if the 27.6-day rotation periodicity is phase/frequency modulated by

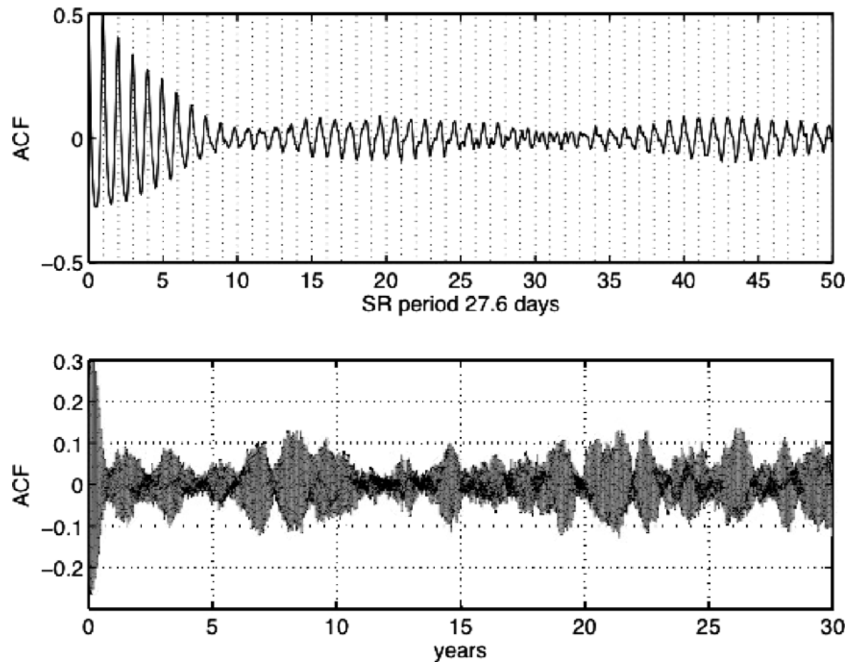

Fig. 5. ACF of HMF Bx component for lags up to 50 solar rotations with multiples of the 27.6-day period marked with vertical dotted lines (top panel) (Takalo and Mursula, 2002); the same ACF for lags up to 30 years (bottom panel).

the solar magnetic cycle. On the other hand, other rotation periods, like the 27.03-day period suggested by Neugebauer et al. (2000) or Carrington's 27.2753-day period, cannot explain the observed nodal structure or the phase change. Accordingly, 27.6 days is the most persistent rotation period of those solar magnetic structures responsible for the HMF.

As noted earlier (Mursula and Hiltula, 2004), the systematic preference of the solar tilt to repeat with opposite phase implies that there are two persistent "active longitudes" that cause such an asymmetric pattern in the large scale solar magnetic fields, in a quite similar way as has been found in the occurrence of starspots (see, e.g., Berdyugina (2004)). Moreover, the back and forth alternation of the tilt phase is analogous to the alternation (so called "flip-flop") of the relative intensity of the two active longitudes first found in starspots (Jetsu et al., 1991), and later in sunspots (Berdyugina and Usoskin, 2003). As first found by Takalo and Mursula (2002), the period of such a full flip-flop in the Sun takes about 42–43 rotations, i.e., about 3.2 years.

The flip-flop period in sunspots was estimated to be about 3.6–3.8 years (Berdyugina and Usoskin, 2003), i.e., slightly longer than the HMF flip-flop period. However, the sunspot analysis was based on a much longer record which includes many weak and long cycles at the turn of the 19th and 20th centuries, while the HMF study only includes data from the recent active and short cycles. In fact, such a difference in the flip-flop period between the two studies is expected since stellar observations suggest that the ratio between the stellar activity cycle and the flip-flop cycle for sun-like stars is 3:1 (Berdyugina, 2004). Using this rule, the observed HMF flip-flop period gives about 10 years, close to the average cycle length during the recent decennia, while the longer sunspot flip-flop period gives 11 years, close to the long-term averaged sunspot cycle length. The detailed understanding of the 3:1 ratio remains for future studies, but one can perhaps note that, calling the flip-flop cycles the "steps" of the bashful ballerina, it seems that she is dancing in the waltz tempo or, counting each half of the flip-flop cycle as one step, tarantella or gigue.

5. Discussion and conclusions

It is known by now that the Sun is systematically asymmetric both in the hemispheric and longitudinal direction. The global solar magnetic field is, during a few years in late declining to minimum phase of the solar cycle, hemispherically asymmetric so that the field in the northern solar hemisphere is weaker than in the south and, correspondingly by flux conservation, the area of the northern field is larger than in the south. This asymmetry leads to the observed southward shift of the heliospheric current sheet (Mursula and Hiltula, 2003). It is also known that this asymmetry is related to a global quadrupole moment which is phase locked but oppositely oriented with respect to the dipole moment (Zhao et al., 2005). An oppositely oriented quadrupole term reduces the field intensity at the northern pole and enhances it at the southern pole. Accordingly, these observations require that a global symmetric quadrupole moment (called the S0 mode in solar dynamo theory) must coexist in the Sun with the dominant dipole (A0) moment.

We have shown that the HCS has been shifted southward (during the late declining phase of solar cycle) since the 1930s (Hiltula and Mursula, 2006). Moreover, there is strong evidence that a related north–south asymmetry has existed in the solar wind even in the mid-19th century, during an earlier period of high solar activity, while the asymmetry has been weak or vanishing during the low-active cycles at the turn of the 19th and 20th century. Thus, the more active the Sun is, the more asymmetric it is, implying that the solar dynamo itself is north–south asymmetric. In fact, this suggests that the quadrupole moment is not only phase locked but also proportional to the dipole moment, leading to a larger (absolute) asymmetry during high activity. Of course, relative asymmetry may be very large during extreme low activity, such as the Maunder minimum (Ribes and Nesme-Ribes, 1993).

The north–south asymmetry in the solar wind has also changed its orientation between the mid-1800s and the recent period since 1930s. Since a close connection between the asymmetries in the solar wind and HCS is expected, this would indicate that the HCS was shifted oppositely, i.e., northward at that time. Then, obviously, at that time the solar ballerina was not bashful but rather, perhaps, permissive or even loose. Mursula and Zieger (2001) noted that the change of the solar asymmetry between mid-1800s and since 1930s implies a new form of long-term oscillation in the solar magnetic field with a period of about 200–300 years. This periodicity can be identified with the 205- to 210-year long deVries cycle known in cosmogenic isotopes, since the opposite orientations of the solar hemispheric asymmetry are expected to modulate cosmic rays differently in the distant heliosphere, in particular in the heliosheath where the orientation of the asymmetry has an important effect upon the three-dimensional structure of the heliopause. Moreover, the solar asymmetry cycle, i.e., the deVries cycle, may consist of two Gleissberg cycles with opposite solar asymmetry. Then the deVries (asymmetry) cycle would consist of two Gleissberg (activity) cycles analogous to the Hale (magnetic) cycle consisting of two Schwabe (activity) cycles.

As to the longitudinal asymmetry, it has been shown that the large scale magnetic fields producing the heliospheric magnetic field are systematically asymmetric in longitude. A certain HMF sector structure, i.e., one tilt activation, has a tendency to persist for about 8–10 solar rotations, reflecting the typical lifetime of coronal holes and other large scale phenomena. Interestingly, subsequent tilt activations do not have a random phase but depict a considerable tendency to produce tilts that are roughly opposite in longitudinal phase to the previous tilt. This leads to a "flip-flop" type behavior for the dominant HMF sector. The period of such a flip-flop is about 3.2 years during the last 40 years (Takalo and Mursula, 2002). This agrees well with the similar flip-flop period subsequently found in sunspots (Berdyugina and Usoskin, 2003), and supports the 3:1 ratio between the activity cycle period and flip-flop period found for sun-like stars. Active longitudes of differentially rotating sunspots have recently been explained in terms a stretched, stationary magnetic structure by a stroboscopic effect (Usoskin et al., in this issue), in an analogy with the quasi-rigidly rotating large scale magnetic structures. While the detailed understanding of the origin of active longitudes, and their flip-flop oscillation remains yet unsolved, these results demonstrate the need for a non-axisymmetric dynamo mode in addition to the symmetric A0 and S0 modes, and thereby give another important constraint for solar dynamo modelling.

Finally, we would like to note that these systematic asymmetries in the solar magnetic field are not of purely academic interest and only important for a better understanding of the Sun. They also have significant practical consequences for the Earth, by allowing for possibilities for a better forecasting of both long-term solar activity (Space Climate) and short-term activity (Space Weather). While a more detailed discussion must be left for subsequent studies, we note that the bashful ballerina times are fairly well predictable and modify, e.g., the HMF interaction with the geomagnetic field via the Russell–McPherron effect (Russell and McPherron, 1973), and reduce the semi-annual variation but increase the annual and 22-year variations in geomagnetic activity. Also, taking the active longitudes into account will increase the success of short-term predictability.

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