HEMISPHERIC AND LONGITUDINAL ASYMMETRIES OF THE GLOBAL SOLAR MAGNETIC FIELD

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ABSTRACT

Measurements of the heliospheric magnetic field (HMF) since 1960s have recently shown that the heliospheric current sheet (HCS) is systematically coned (or shifted) southward during solar minimum times, leading to the concept of a "bashful ballerina". Recent solar observations in the last two solar cycles verify this HCS asymmetry and show that, during times of persistent HCS coning, the magnetic hemisphere dominant in the northern heliographic hemisphere attains a larger area but weaker intensity than in the south. The multipole expansion reveals a strong quadrupole term which is oppositely directed to the dipole term, implying that the Sun has a symmetric quadrupole S0 dynamo mode that oscillates in phase with the dominant dipole A0 mode. Moreover, HMF has a strong tendency to produce solar tilts that are roughly opposite in longitudinal phase. This implies is a systematic longitudinal asymmetry and leads to a "flip-flop" type behaviour in the dominant HMF sector whose period is about 3.2 years during the recent cycles. This agrees with the observed ratio of three between the activity cycle period and the flip-flop period of sun-like stars.

Key words: heliospheric magnetic field, asymmetries, solar dynamo modes.

1. INTRODUCTION

Several studies during many decennia have examined possible longitudinal and hemispherical asymmetries in various forms of solar activity. However, the observed asymmetries in sunspots or other solar parameters have not formed a conclusive, systematical pattern in their relation to the solar activity cycle or magnetic cycle. Thus, asymmetries observed on solar surface have not been able to provide consistent input to solar theories. On the other hand, recent studies of longitudinal and hemispherical asymmetries in the heliospheric magnetic field have revealed new, systematic features in the global solar magnetic field. Observations during the first fast latitude scan in 1994-95 of the Ulysses probe showed that the heliospheric current sheet was coned southwards at this time (Simpson et al., 1996; Crooker et al.,1997; Smith et al., 2000). Later, using the 40-year series of in situ HMF observations, it was shown (Mursula and Hiltula, 2003; 2004) that the southward HCS coning is a general pattern at least in the last four solar minima. This feature was called the "bashful ballerina" (Mursula and Hiltula, 2003).

HMF sector structure has also a systematic shorter-term repetition pattern (Takalo and Mursula, 2002). There is a tendency for the solar magnetic fields to produce, in successive activations, solar tilts that have a roughly opposite longitudinal phase from one activation to another. This implies a systematic longitudinal asymmetry in open solar magnetic fields and a "flip-flop" type behaviour. The average period of one flip-flop during the last 40 years is about 3.2 years (Takalo and Mursula, 2002), in a good agreement with a more recent finding based on a long series of sunspot observations (Berdyugina and Usoskin, 2003). Here these recent developments in the structure and dynamics of HMF are briefly reviewed (see also Mursula and Hiltula, 2004).

2. HEMISPHERICAL ASYMMETRY

Mursula and Hiltula (2003) studied the HCS structure using the OMNI set. For each hour, the HMF was divided into one of its two sectors, the toward sector (T; southern magnetic hemisphere), or the away sector (A; northern magnetic hemisphere). Two different HMF sector definitions were used: plane division and quadrant division. The total number of T and A sector hours was then calculated for each 3-month season around the two high-latitude intervals (Spring = Feb–Apr; Fall = Aug–Oct) and also for each full year. Also the corresponding normalized ratios T/(T+A) and A/(T+A), i.e., the occurrence fractions of the two HMF sectors were calculated.

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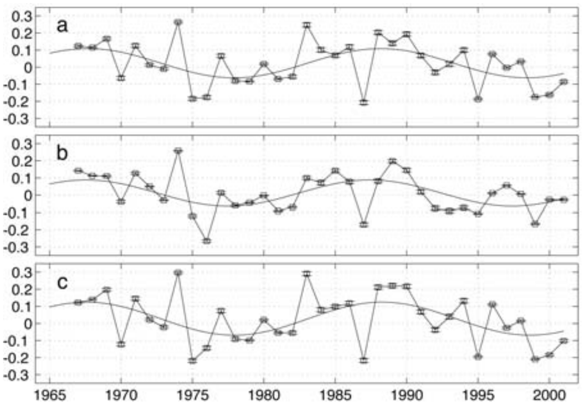

Figure 1. (T-A)/(T+A) ratios in 1967-2001 together with estimated errors and best fitting sinusoids (Mursula and Hiltula, 2003). a) Plane HMF division, Fall and Spring; b) Plane HMF division, full years; c) Quadrant HMF division, Fall and Spring.

When, e.g., the fraction of the T sector in Fall (when the Earth is at the highest northern heliographic latitudes) is plotted each year, a clear 22-year baseline variation around the average of one half is found. This indicates that the T (A) sector dominates in Fall (Spring) during the negative polarity minima (e.g., in the 1960s and 1980s), while the A (T) sector dominates in Fall (Spring) during the positive minima (e.g., in the 1970s and 1990s). This reflects the dipolar structure of the solar magnetic field around solar minima with dominant field polarity in either hemisphere alternating from one cycle to another (Rosenberg and Coleman, 1969). Mursula and Hiltula (2003) quantified this R-C rule and found that the amplitude of the 22-year variation in the T/(T+A) fraction in Fall is ±0.16, which implies an average ratio of 1.94 between the dominant and subdominant sector occurrences in the northern heliographic hemisphere around solar minima. However, the similar fraction in Spring was 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 R-C rule is separately valid in both heliographic hemispheres, there is a systematic difference in the latitudinal HMF structure between the two hemispheres so that the dominance is systematically stronger in the northern than southern heliographic hemisphere. This difference can be studied by the normalized ratio (T−A)/(T+A). The annual (or equinoctial) average of this ratio can reveal the possible dominance of either magnetic hemisphere during one year (or only at high heliographic latitudes) and, thereby, the possible north-south asymmetry of the HCS. Fig. 1 depicts this ratio for a number of choices and shows that, despite some scatter, there is a systematic 22-year baseline oscillation in the dominant magnetic hemisphere. 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, coned (or shifted) toward the southern heliographic hemisphere during these times. A typical amplitude of about 0.09 implies that the HMF sector coming from the northern heliographic hemisphere appears typically 20% more often around solar minima than the HMF sector from the southern hemisphere. Since the R-C rule is, on an average, valid both in Fall and Spring, the average HCS southward coning angle must be less than the 7.2° tilt of the solar rotation axis. However, coning can temporarily be much larger than this, as can also be seen in Fig. 1.

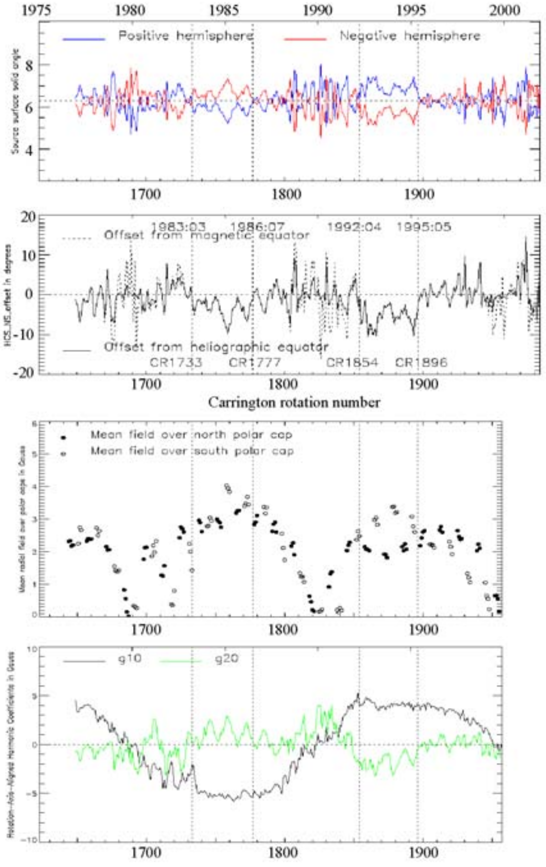

Figure 2. Solar magnetic field observations at WSO in 1976-2002 (Zhao et al., 2005). a) Source surface areas of the two magnetic hemispheres; b) Calculated HCS shift from heliographic (solid) and magnetic (dashed) equator; c) Mean radial field in the northern (full dot) and southern (open dot) polar cap; d) Rotation axis aligned dipole (g10; dark line) and quadrupole (g20; gray line) magnetic components.

Zhao et al. (2005) have recently presented further evidence for the southward coning of HCS using Wilcox Solar Observatory observations of the solar magnetic

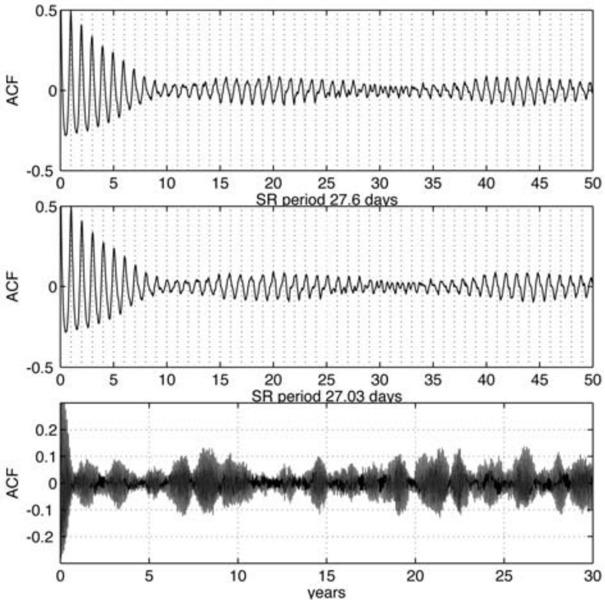

Figure 3. ACF of HMF Bx component for lags up to 50 solar rotations with a) multiples of 27.6 days marked with vertical dotted lines; b) multiples of 27.03 days marked with vertical dotted lines.

field since 1976. They calculated for each solar rotation the total areas and average field strengths of positive and negative polarity regions. Fig. 2 shows 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 three years around the two solar minima included in the study. There are also several shorter intervals of a few solar rotations where either of the two magnetic hemispheres is temporarily dominating. This shows that while a temporary north-south asymmetry in magnetic hemispheres is a quite typical situation, a long-term asymmetry only appears in the late declining to minimum phase of the solar cycle and always depicts a larger area for the magnetic field of the northern heliographic hemisphere. As required by the equality of the total flux of either polarity, the average magnetic field intensity is stronger in the southern heliographic hemisphere at these times (see Fig. 2c).

Fig. 2 also shows that there is a systematic southward shift in the calculated HCS location during the above mentioned intervals, in a good agreement with the general pattern concluded from HMF measurements (Mursula and Hiltula, 2003). Even the magnitude estimated from the HMF observations agrees very well with those depicted in Fig. 2. While the shift occasionally attains as large values as 10° or even more, the average shift during the three-year intervals is about $3^\circ - 5^\circ$.

A magnetic quadrupole term aligned with the solar rotation axis has the same polarity in both polar regions contrary to the dipole term where the field at the two poles is oppositely oriented (e.g., Bravo and Gonzalez-Esparza, 2000). Thus, a significant quadrupole term can enhance the dipole term at one pole and reduce it at the other pole, thus leading to a north-south difference in field strength, area and the related HCS asymmetry. In order explain the observed higher field strength in the southern hemisphere (and the related larger area in the north and the southward shifted HCS), the quadrupole term must be oriented opposite to the dipole term. Moreover, the quadrupole term must change its polarity in phase with the leading dipole term over the solar cycle since the north-south asymmetries and the HCS shift remain oriented in the same direction from one cycle to another. A symmetric quadrupole term is called the S0 mode in solar dynamo theory. The present observations require that this mode must coexist with the dominant dipole (A0) mode.

3. LONGITUDINAL ASYMMETRY

The solar wind and the heliospheric magnetic field have 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. Persistent large scale magnetic fields also determine the inclination of the heliospheric current sheet (the tilt of the solar magnetic field) and, thereby, the HMF sector structure observed, e.g., at 1 AU. It is known that the HMF sector structure typically prevails roughly the same for several solar rotations (e.g., Mursula and Zieger, 1996).

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. 3 shows that there is a strong tendency for HMF Bx to repeat its value with a decreasing probability (ACF amplitude) for about 9 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, as first noted by Takalo and Mursula (2002), after the node at about 10-11 rotations, the ACF amplitude 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. 3c.

This node-antinode structure can not be produced if the subsequent tilt activations are random. Rather, it requires a considerable amount of phase coherence between such activations and implies that after one activation has died out, the second activation develops at a high probability so that its phase (longitude) is nearly opposite to the phase of the first activation. Moreover, the third activation has again a high probability to attain a tilt with a phase in the direction of the phase of the first activation. This implies that there is a persistent, asymmetric pattern in the large scale solar magnetic fields that cause such "active" longitudes in the tilt direction, 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 reminds of 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).

Takalo and Mursula (2002) found the flip-flop period of about 42-43 rotations, i.e., about 3.2 years, using the HMF observations. The flip-flop period in sunspots was recently estimated to be about 3.6-3.8 years (Berdyugina and Usoskin, 2003). However, this sunspot analysis was based on a much longer record which includes many weak and long cycles at the turn of the 20th and 21st centuries, while the HMF study only includes data from the recent highly active and short cycles. Thus, in fact, such a difference in the flip-flop period between the two studies is expected. This difference can be validated even more quantitatively. Stellar observations suggest that the ratio between the stellar activity cycle and the flip-flop cycle for sun-like stars is typically three (Berdyugina, 2004). Thus, the observed, shorter HMF flip-flop period is indeed close to the average cycle length during the recent decennia and the longer sunspot flip-flop period close to the long-term averaged sunspot cycle length. These results strongly suggest that the active longitudes and their dynamics (flip-flops) have the same origin both for the large scale solar magnetic structures responsible for solar tilt and HMF, as well as for those producing sunspots. These results also clearly demonstrate the need in the Sun for a non-axisymmetric dynamo mode and thereby give another important constraint for solar dynamo modelling.

4. CONCLUSIONS

The HMF observations since 1960s show that the heliospheric current sheet is systematically coned (or shifted) southward during solar minimum times (Mursula and Hiltula, 2003). This result has been verified by WSO observations of the solar magnetic field for the last two solar cycles (Zhao et al., 2005) who found prolonged asymmetric periods of about three years in the late declining to minimum phase of the solar cycle. During both minima included in WSO study, the magnetic areas in the northern solar hemisphere were larger and the intensities weaker at these times. The calculated HCS was coned southwards by an average angle of about $3° - 5°$. A multipole expansion of the field shows that a strong quadrupole opposite to the dipole field exists during times of HCS asymmetry. Accordingly, there is a need in solar dynamo theory for a symmetric quadrupole (S0) mode which is in anti-phase with the main dipole (A0) mode.

We have also shown that the large scale magnetic fields producing the heliospheric magnetic field are systematically asymmetric in longitude. They have a strong tendency to produce, in successive activations, magnetic tilts that are always roughly opposite in longitudinal phase to the previous tilt. This leads to a "flip-flop" type behaviour for the repetition of HMF sectors. The period of such a flip-flop is about 3.2 years during the last 40 years (Takalo and Mursula, 2002). This agrees very well with the similar flip-flop period found later in sunspots (Berdyugina and Usoskin, 2003), and supports the ratio of three between the activity cycle period and flip-flop period found for sun-like stars. Obviously, these results require the inclusion of a non-axisymmetric mode in realistic dynamo theories, in addition to the symmetric A0 and S0 modes.

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