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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

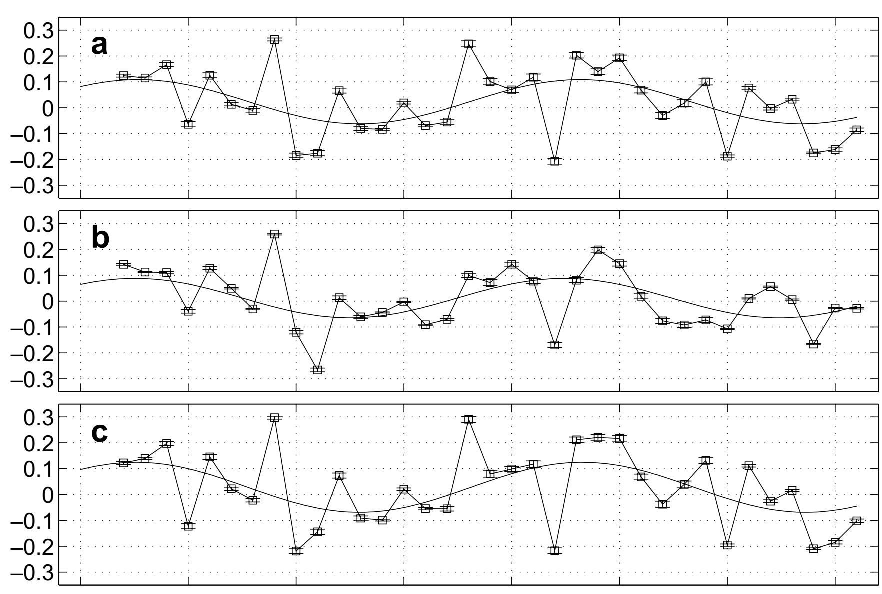

Fig. 1. The $(T-A)/(T+A)$ ratios in 1967–2001 together with the estimated errors and the best fitting sinusoids (Mursula and Hiltula, 2003). (a) Plane HMF division, Fall and Spring data only; (b) plane HMF division, all annual data; (c) quadrant HMF division, Fall and Spring data only.