STREAMER BELT NORTH-SOUTH ASYMMETRY AND ITS LONG-TERM EVOLUTION

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ABSTRACT

The average solar wind (SW) speed at 1 AU is known to be faster (slower) in Spring than in Fall around positive (negative, respectively) helicity sunspot minima (*Zieger and Mursula*, 1998). While the average speeds from the two magnetic hemispheres are roughly equal, the effective latitudinal gradients of the SW speed in the two magnetic hemispheres around the heliographic equator at 1 AU are dramatically different (*Mursula et al.*, 2002a). There is a large effective gradient of about 5-10 km/s/deg in the southern magnetic hemisphere around each solar minimum but no statistically significant effective gradient in the northern magnetic hemisphere. Similarly, there is a large effective gradient in SW temperature of about 2700-5400 K/deg in the southern magnetic hemisphere while no significant gradient exists in the northern hemisphere (*Mursula et al.*, 2002b). Accordingly, the streamer belt at 1 AU is systematically displaced toward the northern magnetic hemisphere. This displacement implies a new, persistent north-south asymmetry related to the solar magnetic cycle which needs to be explained by realistic solar dynamo models. We also discuss the long-term evolution of this asymmetry and show that the north-south asymmetry depicts a century-scale oscillation, being strong during high solar activity. Thus, the solar dynamo is the more asymmetric the stronger it is.

1. INTRODUCTION

Solar wind can be roughly divided into two main components: the slow, cool and dense solar wind and the fast, hot and sparse solar wind. The former is related to closed solar magnetic field lines and the heliospheric current sheet, while the latter originates from the open magnetic field lines of solar coronal holes (*Krieger et al.*, 1973; *Sheeley et al.*, 1976). Polar coronal holes start growing after solar maxima and attain their largest extension towards the heliographic equator during the declining phase of the solar cycle (*Newkirk and Fisk*, 1985; *Rickett and Coles*, 1991). Simultaneously, large latitudinal gradients in SW speed arise close to the equator between the fast, hot SW of coronal holes and the slow, cool SW of the streamer belt. Then, if the heliospheric current sheet (HCS) is sufficiently tilted, the high SW streams from coronal holes can be observed even at the Earth's orbit. Accordingly, the SW speed and temperature at 1 AU are maximized during the late declining phase of the solar cycle (*Gosling and Bame*, 1972; *Bame et al. 1976*; *Mursula and Zieger*, 1996).

Due to the tilt of the solar rotation axis with respect to the ecliptic, the Earth achieves its highest northern (southern) heliographic latitudes in September (March, respectively), enhancing the fraction of fast, hot SW at these times. Thus, two semiannual maxima are expected in SW speed and temperature. However, it was found earlier (*Zieger and Mursula*, 1998) that the two semiannual maxima in SW speed are systematically unequal, leading to a dominant annual (rather than semiannual) variation around solar minima. Moreover, the phase of the annual variation changes from one solar minimum to another so that the annual SW speed maximum is observed in Spring, i.e., at the highest southern heliographic latitudes, during solar minima with a positive magnetic polarity and in Fall during negative minima. The same has been shown to be true for SW temperature for which the resulting effective 22-year variation has an average amplitude of about 15000 K, implying a roughly 20 % fluctuation around the overall average (*Mursula et al.*, 2002b).

2. SOLAR WIND IN THE TWO MAGNETIC HEMISPHERES

During a positive polarity minimum there is a dominance of the away (A) sector of the interplanetary magnetic field (IMF) in Fall while the toward (T) sector dominates in Spring (*Rosenberg and Coleman*, 1969). The situation is reversed one solar cycle later during a negative polarity minimum. This leads to the idea that the polarity dependent Spring-Fall difference in SW properties might perhaps result from an intrinsic north-south difference so that the southern magnetic hemisphere (T sector) would always

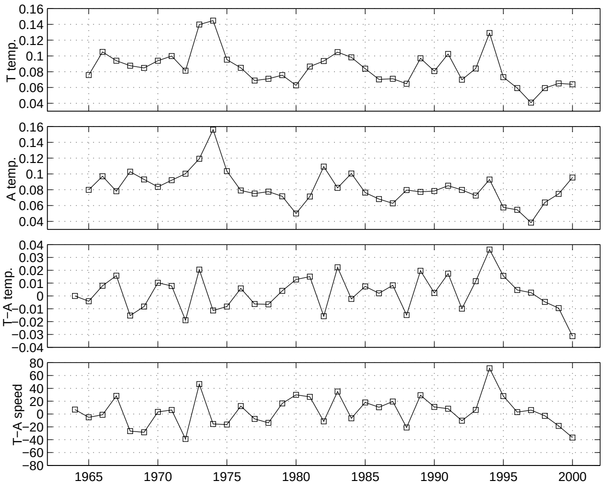

Figure 1. Annual SW temperatures (in million K); top: toward sector; second: away sector; third: toward-away difference. Bottom: toward-away difference for SW speed (in km/s).

produce a faster and hotter solar wind than the northern magnetic hemisphere (A sector).

However, we have shown that there is no systematic difference between the two magnetic hemispheres in the average SW speed (*Mursula et al.*, 2002a) or in SW temperature (*Mursula et al.*, 2002b). This is also demonstrated in Fig. 1. We divided the SW data into two groups according to the direction of the simultaneously measured IMF. (We used the plane division of IMF so that, e.g., the T sector corresponds to Bx > By). Fig. 1 depicts the annual averages of SW temperature in the two magnetic hemispheres, as well as their difference. The T-A sector difference is also given for SW speed. The annual SW temperatures from the two magnetic hemispheres follow each other quite reliably. Despite some evidence for an overall slightly faster and hotter solar wind from the T sector, the difference between T and A sector is neither statistically significant over the whole interval nor follows any specific pattern with respect to the solar magnetic cycle. Therefore the Spring-Fall difference and the implied 22-year cycle at 1 AU is not due to different SW speeds and temperatures in the two magnetic hemispheres. On behalf of SW speed, this conclusion is in a good agreement with Ulysses results (*McComas et al.*, 2000).

3. SPRING-FALL DIFFERENCE IN TWO IMF SECTORS

The explanation for the annual variation is that solar wind distribution at 1 AU is north-south asymmetric across the heliographic equator during times when fast SW streams exist close to the ecliptic. This was first verified for SW speed in (*Mursula et al.*, 2002a) by studying SW speed in Spring and Fall in the two IMF sectors separately. Fig. 2 presents the SW temperature in the T sector in Spring and Fall, as well as the Spring-Fall difference (in the T sector)

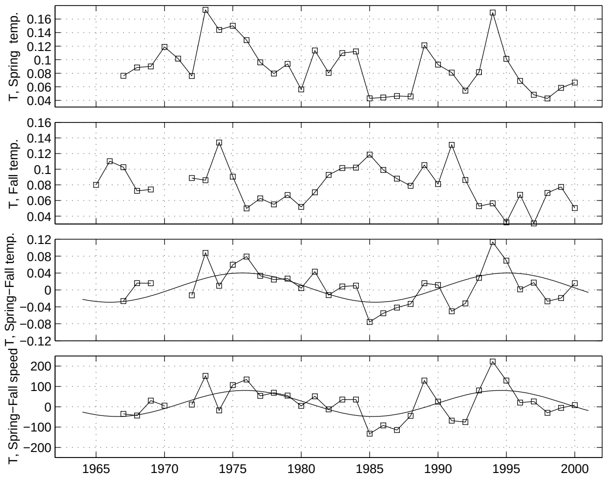

Figure 2. SW temperatures (in million K) in the toward sector; top: Spring; second: Fall; third: Spring-Fall difference. Bottom: Spring-Fall difference for SW speed (in km/s) in the toward sector. Curves give the best fitting sinusoids.

for both SW temperature and speed. The Spring-Fall differences for SW speed and temperature in the T sector depict a clear variation related to the magnetic cycle. The best fitting sinusoids are well in phase and have roughly similar periods (18.7 and 19.4 years), close to the average length of the modern magnetic cycles of about 20 years. The amplitudes are about 64 km/s and 35000 K but the largest values are twice larger. Note also that the relative amplitude of this 22-year variation is larger, about 40 % (roughly 35000K/90000K) for SW temperature than for SW speed, about 15 % (roughly 60/400 in km/s).

Fig. 3 depicts the SW temperature in Spring and Fall for the A sector, as well as the Spring-Fall difference (in the A sector) for both SW temperature and speed. As noted in (*Mursula et al.*, 2002a), the magnetic cycle in the Spring-Fall difference in the A sector is far less evident than for the T sector. The phase of the best fitting sinusoid (not shown) is, as expected, roughly opposite to the phase of the corresponding sinusoid in the T sector but the amplitude is not statistically significant. Note also that despite the small amplitudes, the Spring-Fall differences for SW temperature and speed are greatly similar.

4. DISCUSSION

During positive polarity minima, the T (A) sector is the favoured IMF sector at high southern (northern) heliographic latitudes, i.e., in Spring (Fall). Accordingly, in Spring the solar wind of the T sector comes preferably from the relatively higher southern heliomagnetic latitudes. On the other hand, in Fall the T sector is disfavoured and the corresponding SW comes preferably from the low heliomagnetic latitudes. Therefore, taking the Spring-Fall difference in the T sector gives, in addition to the SW variation in the southern magnetic hemisphere across the

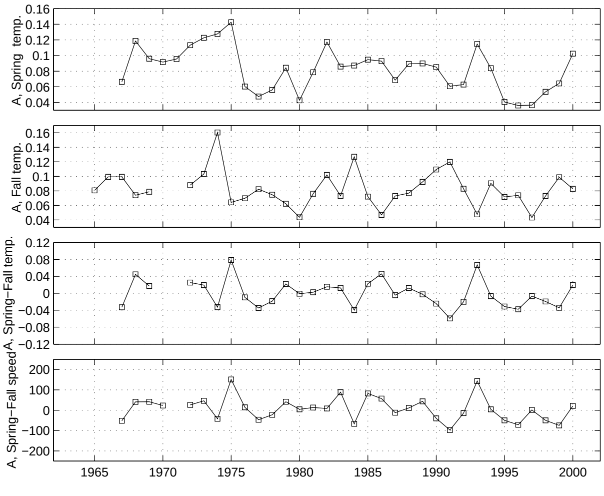

Figure 3. SW temperatures (in million K) in the away sector; top: Spring; second: Fall; third: Spring-Fall difference. Bottom: Spring-Fall difference for SW speed (in km/s) in the away sector.

heliographic equator, a rough estimate for the effective SW gradient with heliomagnetic latitude in the southern magnetic hemisphere during positive polarity times (and the gradient with negative sign during negative polarity times). Similarly, the Spring-Fall difference in the A sector also gives, in addition to the heliographic variation in the northern magnetic hemisphere, the heliomagnetic gradient with negative sign (gradient with positive sign) in that hemisphere during positive (negative, resp.) polarity times.

Accordingly, the strong quasi-22-year cycle in the Spring-Fall difference in the T sector (see Fig. 2) proves that there is a large effective latitudinal (heliographic and heliomagnetic) gradient in SW speed and temperature in the southern magnetic hemisphere around the ecliptic. Using the amplitude of the sinusoid and the Spring-Fall latitude difference of the Earth's orbit (now effectively about 13 deg) we get a rough estimate for the average effective speed (temperature) gradient of about 5 km/s/deg (2700 K/deg) in the southern magnetic hemisphere. During some solar minima the gradient can even be twice as large. On the other hand, the Spring-Fall difference of SW temperature in the A sector (see Fig. 3) does not depict a significant quasi-22-year cycle. This means that, contrary to expectations based on a symmetric streamer belt, the effective heliomagnetic (and heliographic) latitudinal gradient is insignificantly small in the northern magnetic hemisphere. Accordingly, the latitudinal gradients around the ecliptic are systematically different in the two magnetic hemispheres.

A symmetric case where the minimum speed locus of the streamer belt coincides with HCS and the heliographic equator, and where the latitudinal gradients in the two hemispheres are the same is excluded. The same is true for the solar wind temperature. It was shown recently that HCS was displaced southward by about 10 degrees in 1994-95 (*Simpson et al.*, 1996; *Smith et al.*, 2000). Supposing that the SW distribution would strictly follow the HCS and was similarly displaced southward would, however, lead to small (large) SW gradients in the T (A, resp.) sector, contrary to observations at this time and to the general pattern during positive polarity times. Accordingly, the HCS and the streamer belt were separated at least at this time, as also observed by *Crooker et al.* (2000) using Ulysses data. On the other hand, if the streamer belt is displaced toward the northern magnetic hemisphere by a few degrees, we would find a significant effective gradient in the southern magnetic hemisphere and a small or negligible effective gradient in the northern magnetic hemisphere. This is in agreement with the present observations.

We have also studied the long-term evolution of the streamer belt asymmetry (*Mursula and Zieger*, 2001) using the good correlation between SW speed and geomagnetic activity. Fig. 4 depicts the filtered annual variation for SW speed and the extended aa index (*Nevanlinna and Kataja*, 1993) which covers nearly 160 years. Note first the similar annual pattern during the overlapping time interval. Fig. 4 shows that there was a strong annual variation in mid-1800's and more recently since 1930's. These two time intervals coincide with intervals of high solar activity. On the other hand, around the turn of the century, during low-activity cycles, the annual variation was weaker. This implies that the Sun is more north-south asymmetric during high solar activity times (*Mursula and Zieger*, 2001).

Note also that during the last 70 years of large asymmetry the SW distribution was shifted toward the northern magnetic hemisphere. However, most interestingly, the asymmetry was opposite in mid-1800's, as depicted by the annual maxima in Fall (Spring) during positive (negative) polarity minima. Accordingly, the streamer belt was shifted towards the southern magnetic hemisphere in mid-1800's. This implies that the solar north-south asymmetry is oscillating in time with a period which is on the order of 200 years long.

5. CONCLUSIONS

The effective latitudinal gradients of SW speed and temperature across the heliographic equator are different in the northern and southern magnetic hemisphere (*Mursula et al.*, 2002a; 2002b). There is a large, statistically significant effective gradient of about 5-10 km/s/deg in SW speed (2700-5400 K/deg in SW temperature) in the southern magnetic hemisphere around each solar minimum. However, no systematic and statistically significant effective gradient is found in the northern magnetic hemisphere. This difference implies a persistent displacement of the minimum SW speed and temperature locus of the streamer belt toward the northern magnetic hemisphere during the whole time interval of direct SW measurements. Note that at least during one min-

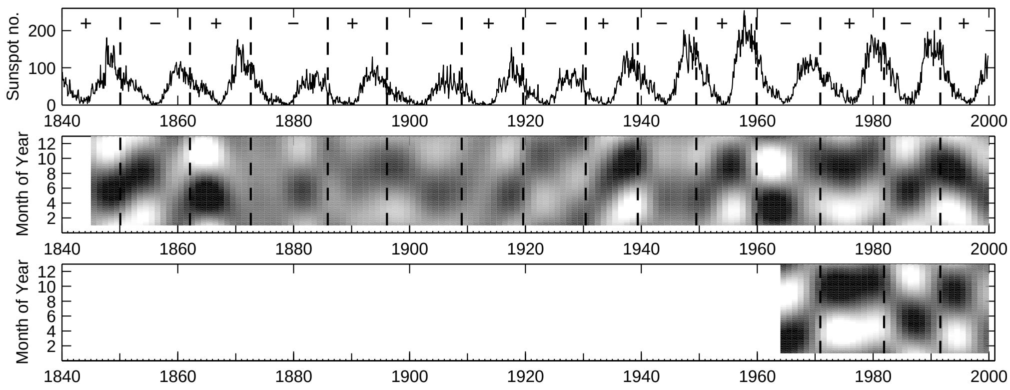

Figure 4. top: Monthly sunspot numbers with magnetic polarities noted by + and - signs; center: Filtered annual variation of the extended aa index, bottom: the same for SW speed in 1964-1999. Annual maxima (minima) are denoted by white (black) color. Dashed vertical lines denote the approximate times of polarity reversal.

imum in 1994-95, the streamer belt and the heliospheric current sheet have been oppositely displaced.

The systematic displacement of the streamer belt towards the northern magnetic hemisphere implies a persistent north-south asymmetry in the Sun. The solar wind is probably the first solar parameter which depicts such a persistent long-term north-south asymmetry clearly related to the magnetic cycle. This asymmetry also suggests for a similar persistent north-south asymmetry in large-scale solar magnetic fields which needs to be explained by realistic solar dynamo models.

Moreover, we have shown (*Mursula and Zieger*, 2001) that the Sun is clearly more north-south asymmetric during high solar activity times. Accordingly, the dynamo is the more asymmetric the stronger it is. The asymmetry also depicts an interesting century-scale long-term oscillation.

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