GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 15, 1738, 10.1029/2002GL015318, 2002

Latitudinal gradients of solar wind speed around the ecliptic: Systematic displacement of the streamer belt

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Received 12 April 2002; revised 11 June 2002; accepted 11 June 2002; published 13 August 2002.

[1] We study the effective latitudinal gradients of the solar wind (SW) speed in the two magnetic hemispheres around the heliographic equator by comparing observations at the Earth's orbit in Spring and Fall since 1964. We find that there is a large, statistically significant effective gradient of about 10 km/s/deg in the southern magnetic hemisphere around each solar minimum. However, no statistically significant effective gradient is found in the northern magnetic hemisphere. This difference implies a systematic displacement of the minimum speed locus of the streamer belt toward the northern magnetic hemisphere. We note that at least during one minimum the streamer belt and the heliospheric current sheet seem to have been oppositely displaced. We also show that the average SW speeds from the two magnetic hemispheres are roughly equal. Therefore, the earlier reported annual variation in SW speed at 1 AU is due to the displacement of the streamer belt and not due to different speeds from coronal holes of opposite polarity. The displacement of the streamer belt implies a new, persistent north-south asymmetry related to the solar magnetic cycle which needs to be explained by realistic solar dynamo models. *INDEX TERMS:* 2164 Interplanetary Physics: Solar wind plasma; 2162 Interplanetary Physics: Solar cycle variations (7536); 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162)

1. Introduction

[2] Solar wind is the extension of solar corona into interplanetary space. It can be roughly divided into two main components: the slow, dense solar wind and the fast, sparse solar wind. The slow solar wind is related to closed solar magnetic field lines and the heliospheric current sheet, while the fast solar wind originates from the open magnetic field lines of solar coronal holes [*Krieger et al.*, 1973; *Sheeley et al.*, 1976]. During the 11-year solar cycle the solar magnetic field changes from a mainly dipolar form around solar minima to multi-polar around maxima. Correspondingly, the location and area of open and closed field line regions change dramatically during the solar cycle.

[3] 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; *Kojima and Kakinuma*, 1990; *Rickett and Coles*, 1991]. Simultaneously, large latitudinal gradients in SW speed arise close to the equator between the fast SW of coronal holes and the slow SW of the streamer belt extending around the minimum speed locus. So far, the minimum speed locus has mostly been associated with the heliospheric current sheet (HCS) [*Zhao and Hundhausen*, 1981; *Hakamada and Akasofu*, 1981]. Here we show that, although roughly following each other, the minimum speed locus and the HCS generally do not coincide and that there are times when they are systematically displaced with respect to each other. When HCS is sufficiently tilted, the high SW streams from coronal holes can be observed even at the Earth's orbit. This leads to the well known fact that SW speed at 1 AU is maximized during the late declining phase of the solar cycle [*Gosling and Bame*, 1972; *Bame et al.*, 1976; *Mursula and Zieger*, 1996]. This is seen also in Figure 1 where we have depicted the annual averages of SW speed for 1964–2000, calculated from the OMNI data base [*King*, 1977]. Clear peaks are observed in 1974 and 1994 and a broader maximum around 1984, all in the late declining phase of the corresponding solar cycle.

[4] The solar rotation axis is tilted by 7.2 deg with respect to the ecliptic so that the Earth achieves its highest northern (southern) heliographic latitudes in September (March, respectively). Accordingly, at times when large latitudinal SW gradients exist the SW speed attains two semiannual maxima. However, it was found in [*Zieger and Mursula*, 1998; to be called P1] that the two semiannual maxima are systematically unequal, leading to a dominant annual (rather than semiannual) variation in SW speed around solar minima. Moreover, it was found in P1 that the phase of this 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. This systematic phase change is shown in Figure 2 where the filtered annual variation of SW speed is depicted in intensity coding with one year plotted in a vertical strip (see also Figure 3a of P1). The annual variation has been filtered from raw data using an optimum band pass filter (see P1 for details). It was suggested in P1 that the annual variation in SW speed at the Earth's orbit is due to a north-south asymmetric SW distribution across the heliographic equator during times when fast SW streams exist close to the ecliptic. Another alternative is that the annual asymmetry results from an intrinsic

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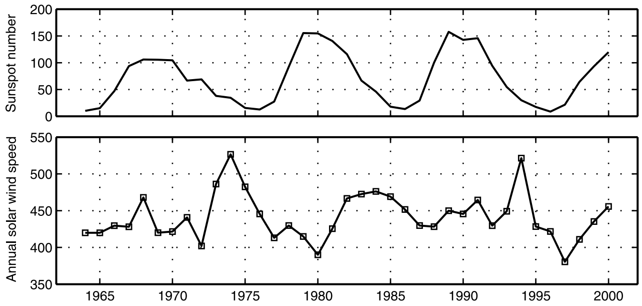

Figure 1. Top: annually averaged sunspot numbers for 1964–2000; bottom: annually averaged solar wind speeds (in km/s) for 1964–2000.

difference in SW speed between northern and southern coronal holes.

2. SW Speed in Magnetic Hemispheres

[5] The latitudinal variation of the dominant IMF sector around solar minima is known since long [*Rosenberg and Coleman*, 1969]. Accordingly, during a positive polarity 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. The oscillation of the annual maximum of SW speed depicted in Figure 2 shows that the solar wind coming from the regions dominated by the southern magnetic hemisphere is, on an average at 1 AU, faster than that coming from the regions dominated by the northern magnetic hemisphere. Therefore, one might conclude that the southern magnetic hemisphere (T sector) would always produce a faster solar wind than the northern magnetic hemisphere (A sector).

[6] In order to test this possibility we have divided the SW speed data into two groups according to the direction of the simultaneously measured IMF. The requirement of having both SW and IMF data simultaneously available reduced the data coverage slightly from 60% to 52%. (We used the plane division of IMF so that, e.g., the T sector corresponds to Bx > By). Figure 3 depicts the annual averages of SW speed in the two magnetic hemispheres, as well as their differences. It is seen that the annual SW speeds from the two magnetic hemispheres follow each other as well as the overall annual average (see Figure 1) quite reliably. Despite some evidence for an overall slightly faster solar wind from the T sector, the difference between T and A sector is neither statistically significant nor follows any specific pattern with respect to the solar magnetic cycle. Therefore the annual variation in SW speed observed at 1 AU is not due to different speeds in the two magnetic hemispheres. This conclusion is in a good agreement with the rough equality of the average SW speed originating from the northern and southern coronal holes [*McComas et al.*, 2000].

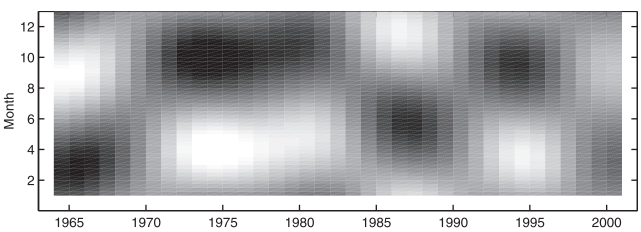

Figure 2. Filtered annual variation of SW speed in intensity coding, white (black) representing high (low) speeds. Vertical scale presents the variation in one year from January to December.

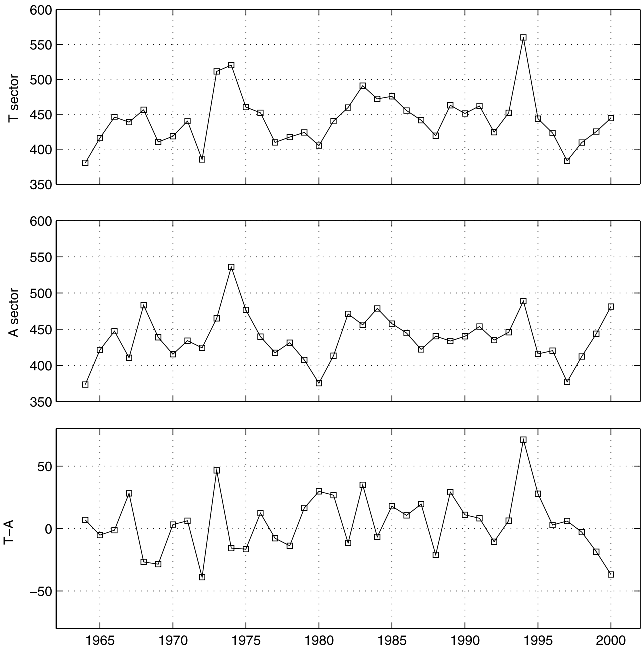

Figure 3. Annual SW speeds (in km/s); top: in the toward sector; middle: in the away sector; bottom: toward-away sector difference.

3. Spring-Fall Difference in SW Speed in Two IMF Sectors

[7] Let us now study the SW speed in Spring (February–April) and Fall (August–October), i.e., at the highest heliographic latitudes of the Earth, in the two IMF sectors separately. Figure 4 presents the results for the T sector. It is seen that, according to the expected latitudinal variation in the late declining phase, the highest SW speeds in Spring and Fall are clearly larger than the corresponding annual averages depicted in Figure 1. This is particularly true for Spring in mid-1970's and mid-1990's (during positive solar polarity) and for Fall in mid-1980's (during negative polarity). Note also that neither Spring nor Fall systematically differs from the annual average in the T sector at other times. The Spring-Fall difference in the T sector (bottom panel of Figure 4) depicts a clear variation related to the magnetic cycle. The best fitting sinusoid has a period of about 18.7 years which is close to the average length of the modern magnetic cycles of about 20 years. This periodicity is significant at a 96% confidence level. The amplitude of the best fitting sinusoid is about 64 km/s but the largest values are much larger, about 150–200 km/s.

[8] Figure 5 depicts the SW speed in Spring and Fall for the A sector. Interestingly, the magnetic cycle in the Spring-Fall difference in the A sector (bottom panel of Figure 5) is

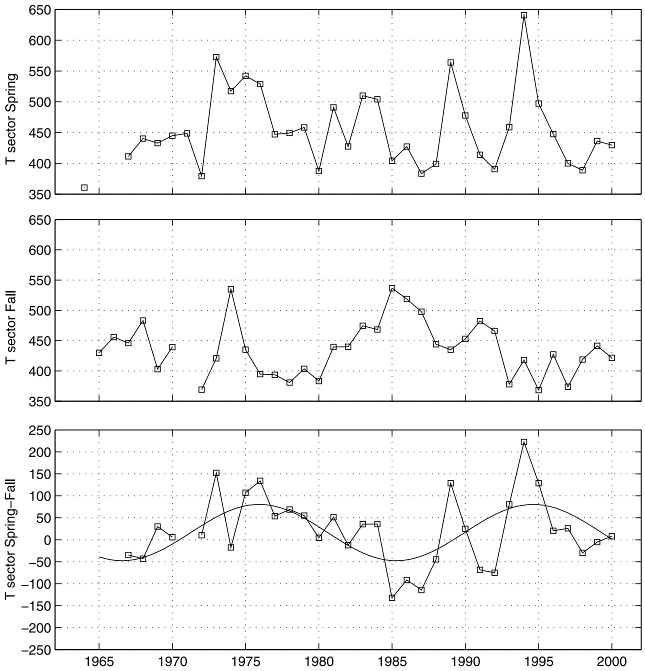

Figure 4. SW speeds (in km/s) in the toward sector; top: 3-month averages in Spring; middle: 3-month averages in Fall; bottom: Spring-Fall difference. The curve is the best fitting sinusoid.

far less evident than in Figure 4 for the T sector. The best fitting sinusoid has a period of 17.9 years and its phase is, as expected, roughly opposite to the phase of the corresponding sinusoid in the T sector. However, the amplitude of the sinusoid, about 8 km/s, is much smaller than in the T sector and is not statistically significant.

4. Discussion

[9] During positive polarity minima, the T (A) sector is, as discussed above, the favoured IMF sector at high southern (northern) heliographic latitudes, i.e., in Spring (Fall). Accordingly, in Spring the SW speed 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 solar wind comes preferably from the low heliomagnetic latitudes. Therefore, taking the Spring-Fall difference in the T sector gives, in addition to the variation of SW speed in the southern magnetic hemisphere across the heliographic equator, a rough estimate for the effective gradient of SW speed 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.

[10] Accordingly, the strong quasi-22-year cycle in the Spring-Fall difference of SW speed in the T sector (see bottom panel of Figure 4) proves that there is a large effective latitudinal (heliographic and heliomagnetic) gradient in SW speed in the southern magnetic hemisphere around the ecliptic. This latitudinal gradient is roughly equal around positive and negative polarity minima. Using the amplitude of the sinusoid (about 64 km/s) 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 gradient of about 5 km/s/deg in the southern magnetic hemisphere. However, during solar minima the gradient can be twice as large (see bottom panel of Figure 4).

[11] On the other hand, the Spring-Fall difference of SW speed in the A sector (see bottom panel of Figure 5) 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 zero or insignificantly small in the northern magnetic hemisphere. Accordingly, the latitudinal gradients around the ecliptic are systematically different in the two magnetic hemispheres.

[12] Clearly, 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. It has recently been shown 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 speed gradients in the T (A, resp.) sector, contrary to observations at this time (see Figures 4 and 5) and to the general pattern during positive polarity times. This implies a separation of the HCS and the streamer belt, at least at this time. On the other hand, if the streamer belt is displaced toward the northern magnetic hemisphere by a few (e.g., 4–6) 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

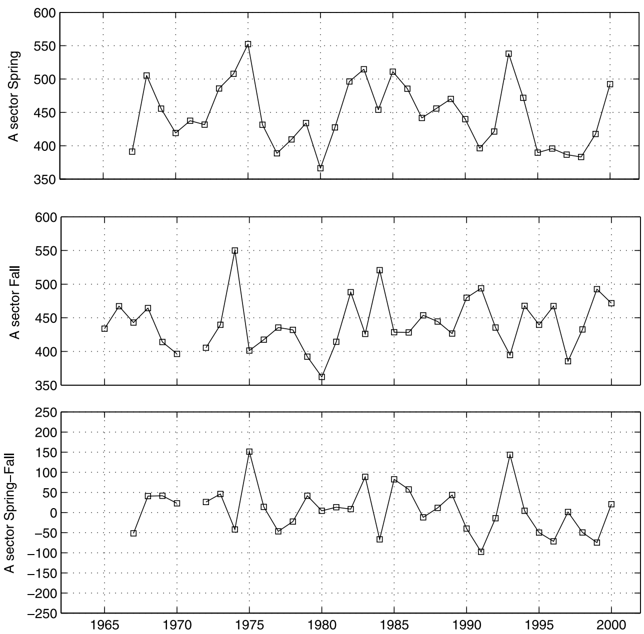

Figure 5. SW speeds (in km/s) in the away sector; top: 3-month averages in Spring; middle: 3-month averages in Fall; bottom: Spring-Fall difference.

agreement with the present observations. Note that such a small northward displacement of the streamer belt and a separation of the streamer belt and HCS was reported by *Crooker et al.* [1997] in 1994–95 Ulysses observations. This observation fits in with the general cyclic pattern of the displaced streamer belt presented in this paper. Note that although the effective gradients around the ecliptic have been found to be different, the SW speed distribution may still be symmetric around its minimum speed locus.

[13] The different effective latitudinal gradients in SW speed across the heliographic equator in the northern and southern magnetic hemispheres imply a new, persistent north-south asymmetry which is related to the solar magnetic cycle. The larger effective gradient in the southern magnetic hemisphere could be due to a systematically larger extension of polar coronal holes from the southern magnetic hemisphere toward the heliographic equator. (Note that the total coronal hole area may not be larger in the southern magnetic hemisphere.) However, the separation (and the opposite displacements) of the streamer belt and the HCS remain so far unexplained.

5. Conclusions

[14] We have shown that the effective latitudinal gradients of SW speed across the heliographic equator are different in the northern and southern magnetic hemisphere. As expected, there is a large, statistically significant effective gradient of about 5–10 km/s/deg 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 in the effective gradients implies a persistent displacement of the minimum SW speed locus toward the northern magnetic hemisphere. At least during one minimum in 1994–95, the streamer belt and the heliospheric current sheet have been oppositely displaced. It remains to be verified if this is a general pattern.

[15] We have also demonstrated that the average SW speeds from the two magnetic hemispheres are roughly equal. Therefore, the earlier reported annual variation in SW speed at 1 AU [*Zieger and Mursula*, 1998] is due to the displaced streamer belt and not due to intrinsically different speeds from coronal holes of opposite polarity, in agreement with Ulysses observations [*McComas et al.*, 2000]. We suggest that the polar coronal holes extend closer toward the heliographic equator in the southern magnetic hemisphere, shifting the streamer belt toward the northern magnetic hemisphere and leading to larger effective latitudinal gradients in the southern magnetic hemisphere at 1 AU.

[16] The displacement of the streamer belt and the different effective SW speed gradients in the northern and southern magnetic hemispheres imply a persistent north-south asymmetry in the Sun which lasts at least for the whole 40-year interval of directly measured solar wind. Moreover, indirect evidence suggests that the asymmetry existed even longer and experienced interesting long-term oscillations and phase changes [*Mursula and Zieger*, 2001]. The SW distribution is probably the first parameter which depicts a long-term north-south asymmetry clearly related to the magnetic cycle. This asymmetry also suggests for a persistent north-south asymmetry in large-scale solar magnetic fields which needs to be explained by realistic solar dynamo models.

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

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