A systematic 22-year pattern in solar wind

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Abstract.
It has been shown recently [1] that the average solar wind speed at 1 AU is faster (slower) in Spring than in Fall around positive (negative, respectively) helicity minima. This implies a related 22-year variation in the solar hemisphere from which a faster solar wind stream is received at 1 AU during each season. We have earlier studied [2] the effective latitudinal gradients of the solar wind speed in the two magnetic hemispheres around the heliographic equator by comparing observations at the Earth's orbit in Spring and Fall. We found that there is a large effective gradient of about 10 km/s/deg in the southern magnetic hemisphere around each solar minimum. However, no statistically significant effective gradient was found in the northern magnetic hemisphere. Here we discuss the related properties of the solar wind proton temperature and show that the temperature and speed behave very similarly in the two hemispheres. In particular, there is a large effective gradient of about 2700-5400 K/deg in the southern magnetic hemisphere while no significant gradient exists in the northern hemisphere. This supports the earlier result [2] that the streamer belt is systematically displaced toward the northern magnetic hemisphere. 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.

INTRODUCTION

Solar wind (SW) 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 [3,4]. 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 [5,6]. 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. Fig. 1 shows the annual averages of SW (proton) temperature and speed for 1965-2000 calculated from the OMNI data base, demonstrating the well known fact that SW speed and temperature at 1 AU are maximized during the late declining phase of the solar cycle [7,8,9].

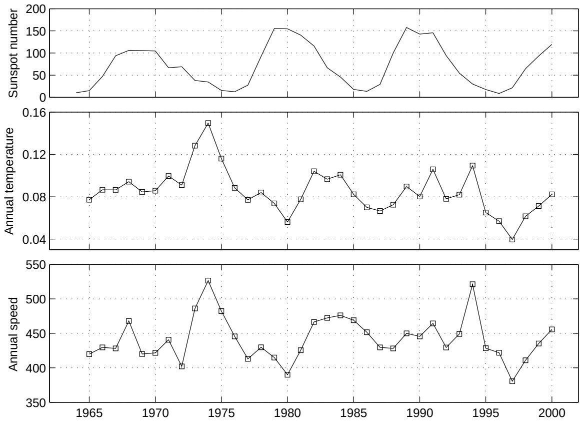

FIGURE 1. Top: annually averaged sunspot numbers; middle: annually averaged SW temperatures (in million K) for 1965-2000; bottom: annually averaged SW speeds (in km/s) for 1965-2000.

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 [1] that the two semiannual maxima in SW speed are systematically unequal, leading to a dominant annual (rather than semiannual) variation around solar minima. Moreover, it was found [1] that 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 (between cycles 20-21 and 22-23) and in Fall dur-

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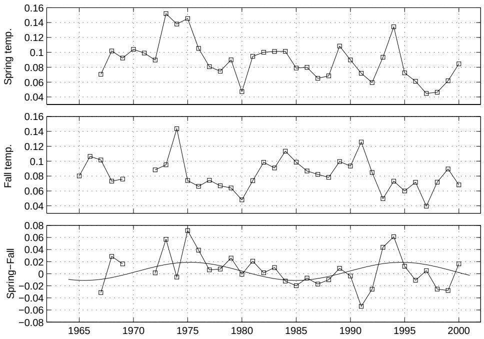

FIGURE 2. SW temperature (in million K); top: in Spring; middle: in Fall; bottom: Spring-Fall difference. The curve is the best fitting sinusoid.

ing negative minima (between cycles 19-20 and 21-22). We have studied if the same is true for SW temperature. Fig. 2 depicts the SW temperature for Spring and Fall separately, as well as their difference. (Here we use 3-month averages of February to April for Spring and August to October for Fall). It is seen (Fig. 2, bottom panel) that Spring clearly dominates during positive polarity times and Fall weakly during negative polarity times. The resulting effective 22-year variation is depicted by the best fitting sinusoid with a period of about 19.6 years and amplitude of about 15000 K. There is an overall offset of about 4000 K in the Spring-Fall difference.

SW IN 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 [10]. The situation is reversed one solar cycle later during a negative polarity minimum. Accordingly, the polarity dependent Spring-Fall difference in SW properties depicted in Fig. 2 could, in principle, result from an intrinsic difference between the northern and southern coronal holes so that the southern magnetic hemisphere (T sector) would always produce a faster and hotter solar wind than the northern magnetic hemisphere (A sector).

However, we have shown [2] that there is no systematic difference in SW speed between the two magnetic hemispheres. The same is found here to be true for the SW temperature, as demonstrated in Fig. 3. Here we have divided the SW data into two groups according to the direction of the simultaneously measured IMF. (We use the plane division of IMF so that, e.g., the T sector corresponds to Bx > By). Fig. 3 depicts the annual averages of SW temperature in the two magnetic hemispheres, as well as their difference. The T-A difference is also given for SW speed for comparison. The annual SW temperatures from the two magnetic hemispheres follow each other as well as the overall annual average (see Fig. 1) 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 its 22-year cycle depicted in Fig. 2 is not due to differences between the two magnetic hemispheres. On behalf of SW speed, this conclusion is in a good agreement with Ulysses results [11].

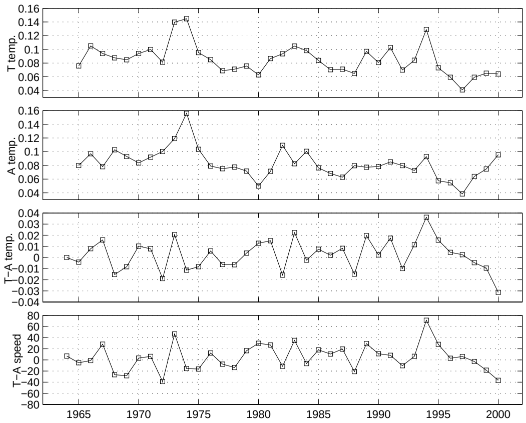

FIGURE 3. Annual SW temperatures (in million K); top: toward sector; second: away sector; third: toward-away difference. Bottom: toward-away difference for annual SW speed.

SPRING-FALL DIFFERENCE IN TWO IMF SECTORS

As another alternative explanation for the annual variation it was suggested in [1] that SW speed at the Earth's orbit is north-south asymmetric across the heliographic equator during times when fast SW streams exist close to the ecliptic. This was verified for SW speed in [2] by studying SW speed in Spring and Fall in the two IMF sectors separately. Fig. 4 presents the SW temperature in the T sector in Spring and Fall, as well as the Spring-Fall difference. Note first that, according to the expected latitudinal variation in the late declining phase, the highest SW temperatures in Spring and Fall are larger than the corresponding annual averages depicted in Fig. 1. This is particularly true for Spring in mid-1970's and mid-1990's. The Spring-Fall difference for SW temperature in the T sector depicts a clear variation related to the

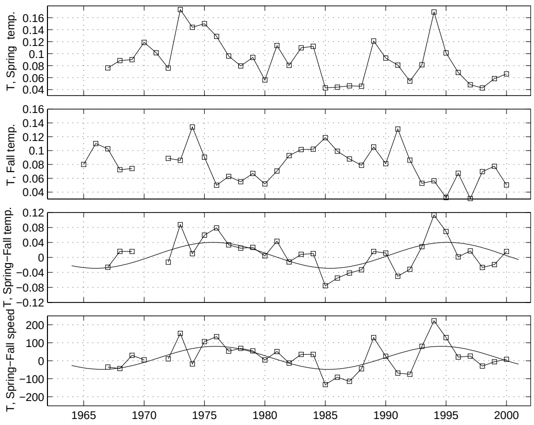

FIGURE 4. SW temperatures (in million K) in the toward sector; top: Spring; second: Fall; third: Spring-Fall difference. Bottom: Spring-Fall difference for SW speed in the toward sector. Curves give the best fitting sinusoids.

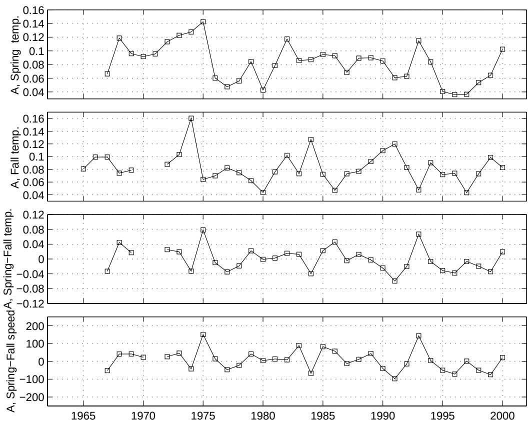

FIGURE 5. SW temperatures (in million K) in the away sector; top: Spring; second: Fall; third: Spring-Fall difference. Bottom: Spring-Fall difference for SW speed in the away sector.

magnetic cycle. The best fitting sinusoid has a period of about 19.4 years, close to the average length of the modern magnetic cycles of about 20 years. The amplitude of the best fitting sinusoid is about 35000 K but the largest values are much larger, more than 100000 K. Note that the period and phase of the best fitting sinusoid for SW temperature are very similar to those of the SW speed depicted in Fig. 4 (bottom panel) [2]. Note also that the relative amplitude of the 22-year variation is clearly larger, about 35 % (roughly 35000K/100000K) for SW temperature than for SW speed, about 15 % (roughly 60/400 in km/s).

Fig. 5 depicts the SW temperature in Spring and Fall for the A sector. As observed earlier for SW speed [2], 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 that despite the small amplitudes, the Spring-Fall differences for SW temperature and speed are greatly similar.

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, as noted in [2], taking the Spring-Fall difference in the T sector gives, in addition to the SW variation in the southern magnetic hemisphere across the 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. 4) proves that there is a large effective latitudinal (heliographic and heliomagnetic) gradient in SW temperature in the southern magnetic hemisphere around the ecliptic. Using the amplitude of the sinusoid (about 35000 K) 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 2700 K/deg in the southern magnetic hemisphere. During some solar minima the gradient can even be twice as large. Note also that the latitudinal gradient and its evolution over the solar magnetic cycle is very similar for the SW temperature and speed (see the two lowest panels of Fig. 4).

On the other hand, the Spring-Fall difference of SW temperature in the A sector (see Fig. 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 insignificantly small in the northern magnetic hemisphere. Accordingly, the latitudinal gradients around the ecliptic are systematically different in the two magnetic hemispheres.

As noted in [2], 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 present results demonstrate that 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 [12,13]. 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 (see Figs. 4 and 5) and to the general pattern during positive polarity times. Accordingly, the HCS and the streamer belt were separated 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 agreement with the present observations. The different effective latitudinal gradients in the SW parameters 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.

CONCLUSIONS

We have shown here that the effective latitudinal gradients of SW temperature across the heliographic equator are different in the northern and southern magnetic hemisphere, as earlier observed for SW speed [2]. As expected, there is a large, statistically significant effective gradient of about 2700-5400 K/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 temperature locus of the streamer belt toward the northern magnetic hemisphere in the same way as for the minimum SW speed locus. At least during one minimum in 1994-95, the streamer belt and the heliospheric current sheet have been oppositely displaced.

We have also demonstrated that the average SW temperatures from the two magnetic hemispheres are roughly equal, as they are for the SW speeds at the Earth's orbit [2] and at Ulysses [11]. 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. The displacement of the streamer belt and the different effective SW 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. The solar wind is probably the first solar 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.

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