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Long-term north-south asymmetry in solar wind speed inferred from geomagnetic activity: A new type of century-scale solar oscillation?

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Abstract. A significant and very similar annual variation in solar wind speed and in geomagnetic activity was recently found around all the four solar cycle minima covered by direct SW observations since mid-1960's. We have shown that the phase of this annual variation reverses with the Sun's polarity reversal, depicting a new form of 22-year periodicity. The annual variation results from a small north-south asymmetry in SW speed distribution where the minimum speed region is shifted toward the northern magnetic hemisphere. Here we study the very long-term evolution of the annual variation using early registrations of geomagnetic activity. We find a significant annual variation during the high-activity solar cycles in mid-19th century and since 1930's. Most interestingly, the SW speed asymmetry in mid-19th century was opposite to the present asymmetry, i.e., the minimum speed region was then shifted toward the southern magnetic hemisphere. This change of asymmetry suggests for a possible new form of century-scale oscillation in the north-south asymmetry of the Sun. We explain the asymmetry in terms of a relic magnetic field dislocated slightly in the north-south direction from the heliographic equator. The change in the asymmetry would result from the century-scale north-south oscillation of the location of the relic field across the ecliptic.

1. Introduction

Annual variation in geomagnetic activity (GA) and auroral occurrence was found in several studies over the last decades [see, e.g., *Fraser-Smith*, 1972; *Delouis and Mayaud*, 1975; *Silverman and Shapiro,* 1983; *Gonzalez et al.,* 1993]. The annual variation in GA is manifested as a difference between the two semiannual maxima close to the Spring and Fall equinoxes [*Meyer*, 1972; *Münch*, 1972; *Triskova*, 1989].

Annual variation is also known in solar wind (SW) speed, temperature and density [*Bolton*, 1990; *Paularena et al.*, 1995; *Szabo et al.*, 1996]. *Szabo et al.* [1996] showed that annual variation in SW speed is strongest around solar minima. In a recent study [*Zieger and Mursula*, 1998; to be called P1] we found that the phase of annual variation in SW speed (and in GA) reverses from one solar minimum to another such that a stronger solar wind is found when the Earth is at the highest northern heliographic latitudes (in September) during negative helicity minima and at the highest southern latitudes (in March) during positive minima. This implies a north-south asymmetric SW speed distribution across the heliographic equator such that the minimum speed region during solar minima is displaced towards the northern magnetic hemisphere. The alternating phase depicts a new form of 22-year cyclicity and excludes earlier explanations proposed for annual variation in SW speed such as internal solar variation. According to P1, the annual variation results from the Earth's annual passage through an asymmetric SW speed distribution. As discussed in P1 in more detail, several observations find evidence for a north-south asymmetry in SW speed distribution during three solar minima which are consistent with the alternating phase of the annual variation [*Hundhausen*, 1971; *Zhao and Hundhausen*, 1983; *Crooker et al.*, 1997].

In P1 we verified that SW speed and geomagnetic activity depict a very similar annual variation during the whole period of direct SW observations including the four last solar minima. Here we use this correlation to study the annual variation and the related north-south asymmetry in SW speed distribution before the time of direct SW measurements using the very early registrations of geomagnetic activity from mid-19th century onwards.

2. Long-term annual variation

We use two geomagnetic indices, the aa index [*Mayaud*, 1973] and the Ak(Hel) index [*Nevanlinna and Ketola*, 1993] which were adjusted to form the longest uniform index of global geomagnetic activity [*Nevanlinna and Kataja*, 1993], now extending over nearly 15 solar cycles. In Figure 1 we show the 27-day averages of these two indices for the overlapping time interval 1868-1880. There is an excellent correlation between the 27-day averages of the two indices with correlation coefficient r=0.95. We extended the aa index to the earlier time interval (1844-1867) covered by the Ak(Hel) index using the best fitting linear regression between the two indices aa=1.03*Ak(Hel)+1.27.

We study the annual variation in GA using a similar procedure as in P1. We designed a finite impulse response band pass filter (see Figure 2) with a pass band of one year ± 5 % following the Parks-McClellan optimization procedure [see e.g. MATLAB, 1994] and filtered the 27-day averaged indices. The filter is flat in the pass band and attenuates the signal by 70 dB in the stop band. The upper color panel of Figure 3 displays the filtered annual variation of the extended aa index as a colour intensity map where one year is depicted along the vertical axis so as to demonstrate the phase of the annual variation. Red (blue) color represents a

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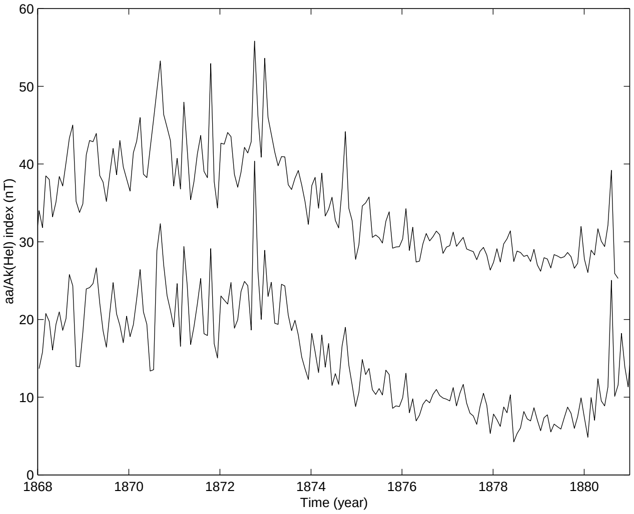

Figure 1. The Ak(Hel) index (upper curve) and the aa index (lower curve) forming the extended aa index, plotted over the common time interval from 1868 to 1881. The Ak(Hel) curve is shifted by 20 nT upward with respect to the aa index for better visibility.

large positive (negative) value of annual variation, while yellow and green color denote small amplitudes. In the lower color panel of Fig. 3 we reproduce the annual variation of the SW speed from P1, showing the alternation of the annual phase from Spring in positive helicity minima to Fall in negative minima. The same pattern is seen in the aa index during the overlapping time. Fig. 3 also includes the monthly sunspot numbers (top panel) with helicity signs denoted, and vertical lines marking the time two years after the sunspot maximum. This time is close to the average time of reversal of polar magnetic fields in the Sun.

Fig. 3 shows that since 1930's there was a significant annual variation in GA with phase in Spring during positive helicity minima and in Fall during negative minima. This extends the interval studied in P1 and shows that a significant north-south asymmetry persisted at least during the last 7 solar cycles. Accordingly, during the last 70 years the region of minimum SW speed was consistently shifted toward the northern magnetic hemisphere. Note also the phase change in 1999 which occurred very early in the cycle 23, in concert with the recent polarity reversal. (For solar observations see Wilcox Solar Observatory web site http://quake.stanford.edu/wso/wso.html).

It is interesting to note that the time interval of a sizable annual variation since 1930's coincides with the interval of recent high-activity solar cycles. On the other hand, around the turn of the century, during low-activity cycles, the annual variation was weaker. Even earlier, in mid-1800's, again during more active cycles, we find a strong annual variation with maxima alternating systematically between Spring and Fall from one solar minimum to another. However, most interestingly, the Fall maxima occurred during the two positive helicity minima included in this time interval and the Spring maxima during the negative helicity minimum. This is opposite to the Spring-Fall asymmetry observed during the last 7 solar cycles and implies an opposite shift of the SW speed distribution toward the southern magnetic hemisphere during these early cycles in mid-1800's.

3. Discussion

In Fig. 3 we have noted the approximate times of solar polarity reversal which occur typically two years after sunspot maxima. However, deviations exist to this rule and, thus, these times should only be considered indicative. E.g., during solar cycle 19, the two-year interval during which the reversal took place (see, e.g., *Makarov and Sivaraman*, [1986]) already ended two years after sunspot maximum, i.e., at the time noted in Fig. 3. On the other hand, during the two previous cycles, the reversal interval only started at the noted time and lasted 2-3 years. Accordingly, the annual variation with a Fall maximum which occurred exceptionally late in cycle 18 indeed corresponds to the helicity of the previous minimum, in accordance with the above explanation.

The pattern of an oscillating phase of annual variation breaks down during the low-activity cycles around the turn of the century. This happens first around 1880 with the start of low-activity cycles when the annual phase remained in Fall during two consecutive solar minima with opposite helicity. A similar break in the oscillating pattern took place between 1900's and 1910's, when the phase again remained in Fall after polarity reversal, and also later, with the start of high-activity cycles, when the Spring phase in 1920's did not reverse but prevailed during the next solar minimum with opposite helicity in 1930's. *Triskova* [1989] also found the alternating Spring-Fall asymmetry in GA during the last few solar cycles but claimed only one phase break in the oscillating pattern between 1910's and 1920's. On the contrary, we find a regular phase change from Fall to Spring between these two periods with opposite helicity. *Triskova* [1989] analysed the Spring-Fall asymmetry in the aa index using two equinox months and averaging over the roughly 10-year periods of definite magnetic helicity. Instead, our method gives the full annual variation with a better time resolution.

Although the annual variation during low-activity cycles is quite weak we note that the phase of annual variation was mostly fairly close to Spring or Fall, supporting the view that the annual variation indeed reflects the evolution of the north-south asymmetry in SW speed even at this time. A

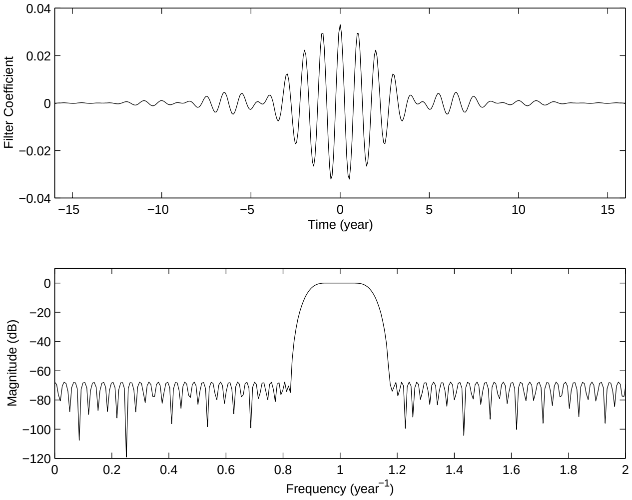

Figure 2. The time (upper panel) and frequency (lower panel) characteristics of the optimum filter used to extract the annual variation.

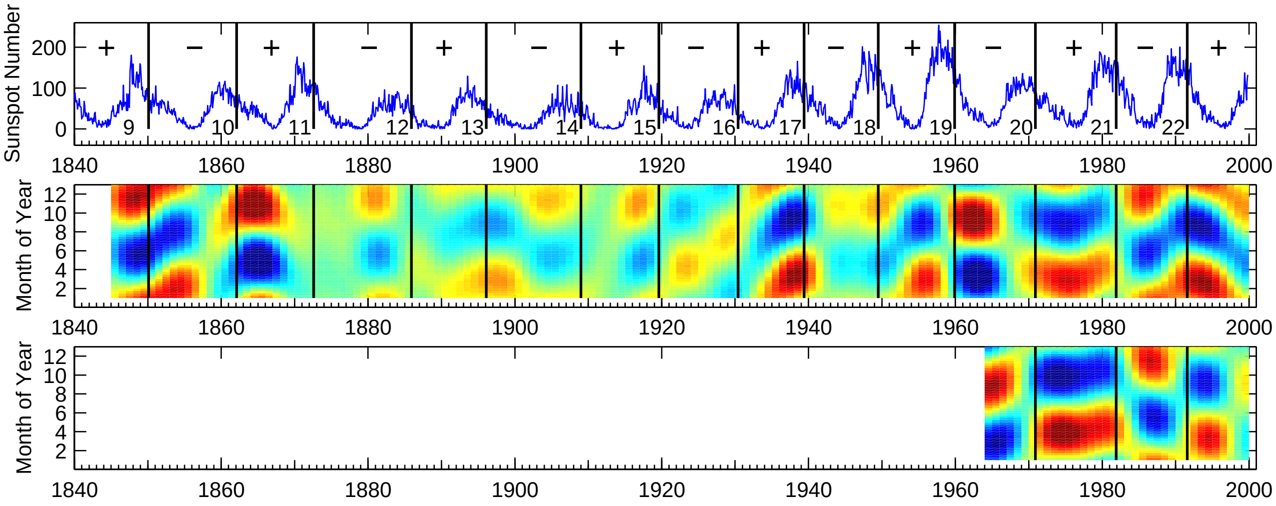

Figure 3. Monthly sunspot numbers with magnetic helicities noted by + and - signs (upper panel). Filtered annual variation of the extended aa index in 1845-1999 (upper color panel), and the solar wind speed in 1964-1999 (lower color panel) in the same color coding. The scale of the color code (the largest amplitude of annual variation) extends from -3.5nT to +3.5nT for the aa index and from -25 km/s to +25km/s for the solar wind speed. Vertical lines denote the approximate time of polarity reversal two years after official sunspot maximum.

break in the oscillating phase of annual variation between two subsequent solar minima with opposite helicities would imply that the SW speed distribution changed its asymmetry between the two solar minima. The asymmetry is found to change three times during the 155-year interval studied in this paper. Note that one of these changes occurred at the end of high-activity cycles in 1870's, one at the start of current high-activity cycles in 1930's and one during the low-activity cycles. However, because of the rather weak overall level of annual variation during low-activity solar cycles, it is difficult to prove that the observed short-term fluctuation in asymmetry is significant. Nevertheless, a definite proof of the change in the SW speed asymmetry during the studied interval is obtained by the oppositely oscillating annual phase between mid-1800's and the latest high-activity cycles. At these times the annual variation was large and the phase changed consistently with the polarity reversals of the Sun. Accordingly, we find that the SW speed distribution was, from the start of the extended aa index until 1870's, clearly asymmetric and shifted toward the southern magnetic hemisphere. During the low-activity cycles from 1880's to 1920's, the asymmetry was rather small and was fluctuating between magnetic north and south. Finally, with the start of high-activity cycles, a fixed asymmetry with a shift towards the northern magnetic hemisphere was established.

Since the north-south asymmetry in SW speed is related to the heliomagnetic (not heliographic) hemispheres and oscillates in concert with the 22-year magnetic (Hale) cycle, it must be related to dynamo mechanism and the generation of magnetic field deep in the convection layer. Moreover, it implies an asymmetry in magnetic flux generation between the two halves of the magnetic cycle. Such an asymmetry in flux generation can occur, e.g., if there is a relic magnetic field in the Sun [*Cowling*, 1945; *Sonett*, 1982; 1983]. Recently, *Mursula and Usoskin* [2000] have found a persistent 22-year cyclicity in sunspot activity, giving strong support for the existence of a relic field directed toward southern heliographic hemisphere. Also, in order to explain the present dominance of the southern magnetic hemisphere, the relic field must be located asymmetrically across the heliographic equator. If the relic is shifted northward of the heliographic equator, it would imply a larger flux in the southern solar hemisphere than in the northern hemisphere during positive helicity cycles, and vice versa during negative helicity cycles, leading to the observed dominance of the southern heliomagnetic hemisphere.

The observed change from the magnetically southward directed asymmetry in mid-1800's to the magnetically northward asymmetry since 1930's suggests that the location of the solar relic field is oscillating between the northern and southern (heliographic) hemispheres. Although we can not exactly determine the period of this oscillation with present observations, it must be at least some 200 years because the maximum southward asymmetry is not later than 1860 and the maximum northward asymmetry not earlier than 1960. Accordingly, the period is longer than, e.g., the 80-100-year Gleissberg cycle [*Gleissberg*, 1944] in sunspot activity, and probably also longer than the 178.8-year periodicity in solar motion [*Jose*, 1965; *Landscheidt*, 1999]. On the other hand, the rather short length of the interval with weak, oscillating asymmetry (or no asymmetry at all) at the turn of the century suggests that the period is not considerably longer than, say, 250-350 years. We know of no other long-term solar changes in the same period range and, therefore, suggest that the present results give the first evidence for a new oscillating phenomenon in solar activity.

4. Conclusions

We use very long-term observations of geomagnetic activity to study the north-south asymmetry in the location of the minimum solar wind speed region. This asymmetry is found to be related to the solar magnetic field and causes the annual variation in geomagnetic activity and solar wind speed, as well as the oscillation of annual phase. We find a strong annual variation, and thus a significant north-south asymmetry, during the high-activity cycles in mid-19th century and since 1930's. Interestingly, while the solar wind distribution is shifted toward the northern magnetic hemisphere since 1930's, it was opposite in mid-1800's, i.e., directed toward the southern magnetic hemisphere. The observed change in this asymmetry between mid-1800's and presently implies a new form of century-scale oscillation in the north-south asymmetry of solar magnetic activity. We suggest that the observed solar wind asymmetry related to solar magnetic cycle is produced by a relic magnetic field in the solar convection layer which is located slightly asymmetrically across the heliographic equator. The century-scale oscillation in the asymmetry could be due to the north-south oscillation of the location of the relic field.

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