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Annual variation in near-Earth solar wind speed: Evidence for persistent north-south asymmetry related to solar magnetic polarity

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Abstract. We study the annual variation in solar wind speed at Earth's orbit and in geomagnetic activity since mid-1960's. The two parameters depict a very similar annual variation during the whole period. Annual variation has maximum amplitude around sunspot minima. The phase of annual variation reverses soon after solar maxima, following the Sun's polarity reversal and indicating a new type of 22-year periodicity. Stronger solar wind is found at or close to the Earth's highest northern (southern, resp.) heliographic latitudes during solar minima with a negative (positive) magnetic polarity. This implies an asymmetric SW speed distribution across heliographic equator such that the minimum speed region during solar minimum times is displaced away from heliographic equator towards the northern magnetic hemisphere. This may result e.g. from a systematically larger extension of polar coronal holes from the Sun's magnetic south pole toward solar equator. We exclude the earlier explanations proposed for annual variation, such as accumulation of small comets within 1 AU, or internal solar variation.

Introduction

Annual variation in solar wind (SW) speed and ion density at Earth's orbit was recently reported by Bolton [1990]. Considering different possibilities, they concluded that annual variation results either from an accumulation of small comets within 1 AU, or from internal solar variation. More recently, *Paularena et al.* [1995] and *Szabo et al.* [1996], using 20 years of IMP-8 data, verified the existence of annual variation for SW speed, temperature and density. *Szabo et al.* [1996] also showed that annual variation is strongest around the two solar minima (1975 and 1986) included in IMP-8 data. However, no definite reason was given to the observed annual variation.

Annual variation in geomagnetic activity (GA) has been studied in several papers over decades, both using local observations at one station [*Courtillot and Le Mouel*, 1988], or indices of global GA [*Fraser-Smith*, 1972; *Delouis and Mayaud*, 1975; *Gonzalez et al.,* 1993]. Local magnetic observations show an annual variation which has been related to annual change in solar illumination, leading to changes in local ionosphere [*Patel*, 1977; *Courtillot and Le Mouel*, 1998] *Delouis and Mayaud* [1975] studied the 103-year long observations at two antipodal stations and showed that annual variation had an opposite phase at the two stations, with maximum during local summer. However, annual variation was found to exist even in the global aa index consisting of the average of the two stations. In a recent review, *Gonzalez et al.* [1993] verified the annual variation in global GA (as measured by the Ap index) but gave no definite explanation to this periodicity. Note that annual variation was also found in the long-term occurrence of auroras [*Silverman and Shapiro,* 1983].

In this paper we reanalyse the annual variation in SW speed at Earth's orbit, and in global GA since mid-1960's. We verify the observation by *Szabo et al.* [1996] that annual variation of SW speed has maximum amplitude close to sunspot minima. Moreover, we find that the phase of annual variation reverses from one solar minimum to another, depicting a new form of 22-year cyclicity. The same feature is observed in global GA also. Annual variation has its maximum around the highest northern heliographic latitude of the Earth's orbit (September 6) during a solar minimum with negative magnetic polarity, and around the highest southern heliographic latitude (March 5) during positive polarity. This implies a north-south asymmetry in SW speed around the heliographic equator which is related to solar magnetic polarity.

Annual variation in SW speed and geomagnetic activity

We have calculated the power spectra of solar wind (SW) speed, geomagnetic Kp index and interplanetry magnetic field (IMF) sector component for 1964–1996 (see Figure 1). SW and IMF data come from the hourly OMNI data set, and were averaged to daily values for Fig. 1. (IMF sector component is defined in the ecliptic plane, 44° off sunward direction, with positive values toward Sun). Occasional data gaps were filled with linear interpolation. All the three parameters depict a significant spectral power peak at 1 year, as found earlier [*Delouis and Mayaud,* 1975; *Gonzalez et al.,* 1993; *Bolton,* 1990; *Paularena et al.,* 1995; *Szabo et al.,* 1996]. The only other periodicities that are more pronounced at near-by frequencies are the 1.3-1.4-year peak that is particularly enhanced in SW speed [*Richardson et al.,* 1994] but is also found in GA [*Shapiro,* 1967; *Fraser-Smith,* 1972; *Delouis and Mayaud,* 1975; *Paularena et al.,* 1995], and the semi-annual peak in GA which is mainly due to the Russell-McPherron [1973] effect. Figure 2 depicts 27-day averages of SW speed for four 2-year periods close to the last four sunspot minima. In 1965-1966 (Fig. 2a) there were two broad maxima in SW speed each year close to the times of highest southern and northern heliographic lat-

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itude, implying a semiannual variation in SW speed during these years. However, annual variation is also clearly visible in Fig. 2a as an asymmetry of the two semiannual peaks with a consistently higher SW speed maximum in Fall. A very different situation is found in 1975-1976 (Fig. 2b). The semiannual variation is hardly observed among the large annual variation. Moreover, annual variation has a clear maximum in Spring, in opposite phase with annual variation in Fig. 2a. The phase of annual variation is reversed back to Fall maximum around the next solar minimum in 1987-1988 (Fig. 2c). Moreover, the semiannual variation was exceptionally strong, especially in 1987. Finally, Fig. 2d shows the pattern close to the latest solar minimum which greatly resembles that found two solar cycles earlier (Fig. 2b) with a strong annual variation with Spring maximum. Accordingly, the two solar minima with positive polarity (SC 20-21, and 22-23) greatly resemble each other, and so do the two other minima with negative polarity. This implies a 22-year cyclicity in SW speed structure.

Fig. 2 suggests that annual variation in SW speed exists around sunspot minimum times and reverses its phase from one minimum to another. In order to study the annual variation over the whole era of in situ observations, we have used a filter with a pass band at 1 year ± 30 days to extract the annual signal from raw data (for this we used 10-day averages). An optimum filter was designed using the Parks-McClellan algorithm [see e.g. MATLAB, 1994]. The filter is very flat in the pass band and attenuates the signal by 85 dB within the transition band which extends 40 and 25 days above and below the pass band, respectively. Accordingly, the neighboring peaks at about 1.3y and 0.8y are in the stop band. The filtered SW speed, Kp index and IMF sector component were plotted in Figure 3 in color coding with vertical axis presenting the annual variation and horizontal axis ranging from 1964 to 1996.

Fig. 3a verifies that largest annual variation in SW speed is obtained around sunspot minima, as found earlier [*Szabo et al.,* 1996]. We have tested the significance of annual variation for three-year intervals around solar minimum times and solar maximum times by the Stellingwerf [1978] method. We found that while annual variation in minimum times is significant at least at 99.8in maximum times. (The weak annual variation in maximum times seen in Figs. 3 and 4 is only due to the effect of filter smoothing over about 2.5-3 years).

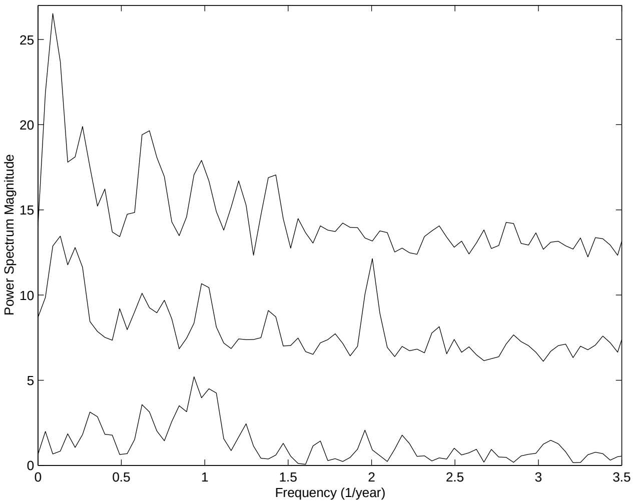

Figure 1. The power spectral densities calculated in 1964-1996 for (top) solar wind speed, (center) geomagnetic Kp index, and (bottom) the IMF sector component. The spectral densities are presented on a linear scale.

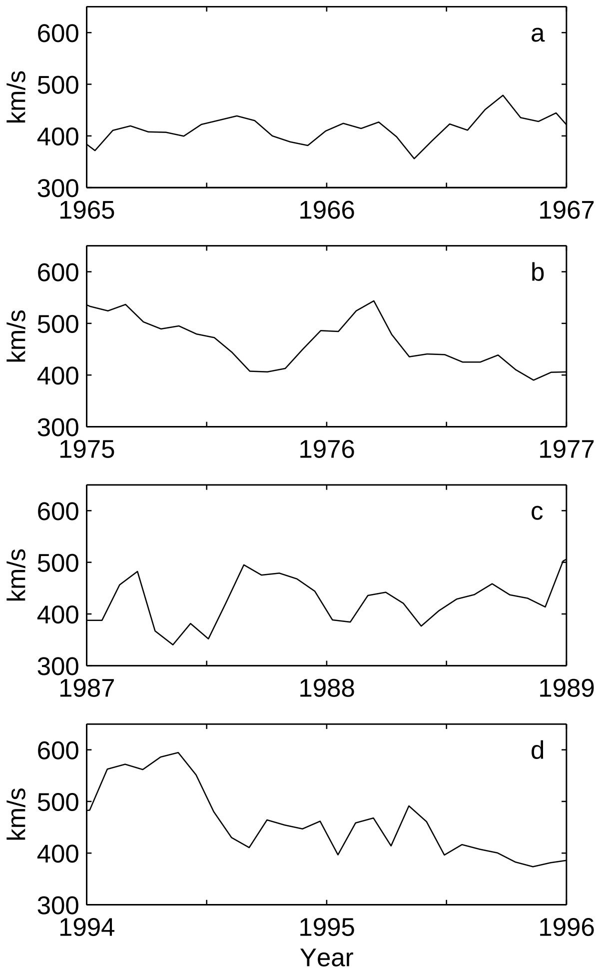

Figure 2. 27-day averages of SW speed for two years around the last four sunspot minima: (a) 1965-66, (b) 1975-76, (c) 1987-88, and (d) 1994-95.

Fig. 3a also shows the phase of annual variation. In agreement with Fig. 2, this phase is seen to reverse from one solar minimum to another so that the annual maximum is reached in Spring (Fall, resp.) during minima of positive (negative) solar polarity. During three solar minima (SC 19-20, 20-21 and 22-23) maxima and minima of annual variation are found close (within one standard deviation of about 20 days) to the dates of highest northern or southern heliographic latitude. During one minimum (SC 21-22), the phase is shifted slightly later in the year. Note that the time resolution of the filter is sufficient to reveal the long-term trend of the phase and its change from cycle to cycle. Our result on the phase of annual variation disagrees with that obtained by Bolton [1990] for SW density, where a winter maximum was dominating. Also, no systematic change of the phase from one cycle to another was found there.

Annual variation in GA (Fig. 3b; we use Kp index but similar results were found for other indices) follows fairly well the amplitude and phase pattern of SW speed. Largest amplitudes in annual variation are found close to solar minima, and the phase changes from one solar minimum to another in consort with SW speed. Since SW speed is well correlated with GA at time scales longer than about one month [*Gosling et al.,* 1976; *Crooker et al.,* 1977], this similarity is

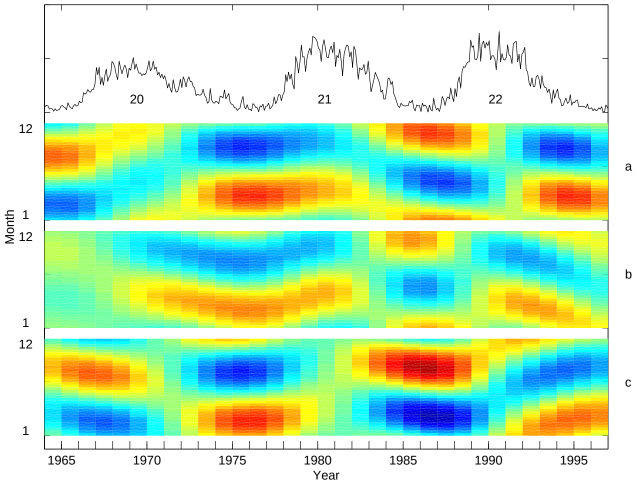

Figure 3. Filtered annual variation of (a) SW speed, (b) Kp index and (c) IMF sector component in color coding. Red presents higher SW speed, larger Kp index and a dominant IMF toward sector. Horizontal scale gives the time in years and vertical scale presents the variation in one year from January at bottom of each panel to December at top. (Monthly sunspot numbers are given at top of the figure for reference.)

expected. Moreover, since the Kp index forms a continuous and completely independent data set, this similarity gives strong support for the method and results obtained.

Annual variation in IMF sector component is depicted in Fig. 3c. Largest annual variation is found around solar minima. During all minima, annual maxima are located close to the dates of the Earth's highest northern or southern heliographic latitude, reflecting the *Rosenberg-Coleman* [1969] effect of dominant sector polarities. Annual variation in IMF sector component is thus quite similar to that in SW speed and GA. Note that a large annual variation in IMF sector component is observed if the heliosheet separating the two magnetic hemispheres is thin. Annual variation in IMF sector component reached its highest value at the minimum of 1985-87, in agreement with the result [*Richardson and Paularena,* 1997] that the heliosheet was exceptionally thin during this minimum. Note also that the phase of annual variation, i.e. sector polarity, reverses a couple of years after sunspot maximum, as found for earlier cycles by *Wilcox and Scherrer* [1972]. Corresponding phase reversal in SW speed occurs quite close to the IMF polarity reversal.

Discussion

Due to the 7.2° tilt of the solar rotation axis with respect to the normal of ecliptic, the Earth reaches the highest northern and southern heliographic latitude on September 6 and March 5, respectively, and crosses the heliographic equator twice a year between these dates. Since the average SW speed increases with heliographic latitude [see e.g. *Newkirk and Fisk,* 1985; *Kojima and Kakinuma,* 1990; *Rickett and Coles,* 1991], a semiannual variation in SW speed is expected at Earth's orbit with maxima around these dates. (Finite travelling time of solar wind will be ignored here).

However, this is the case only if SW speed distribution is symmetric with respect to heliographic equator. If not, i.e., if SW speed distribution is asymmetric or shifted with respect to equator, annual variation appears and the semiannual variation is correspondingly diminished. In fact, such an asymmetry was first noted by *Hundhausen* [1971]. When studying Vela spacecraft SW observations in 1965-68, he noted that the average SW speed was faster above the heliographic equator (in Fall) than below it (Spring) or at the equator. This corresponds well to the asymmetry depicted in Figs. 2 and 3 for the same time. *Hundhausen* [1971] suggested that a higher level of (transient) solar activity in the northern solar hemisphere causes the observed north-south asymmetry. However, our result shows that the asymmetry is a fairly persistent feature in the heliosphere, and is not directly related to solar activity.

Russell [1975] studied the annual asymmetry in GA using the aa index, calculating the Spring/Fall GA ratio. He concluded that a persistent asymmetry existed during several years around the minimum of 1965, i.e. during the period studied by *Hundhausen* [1971]. Higher GA was found in Fall, in agreement with *Hundhausen* [1971] and present results. *Zhao and Hundhausen* [1983] studied the latitude distribution of SW speed by IPS measurements in 1976, finding that SW speed distribution was asymmetric with respect to heliographic equator and that minimum speed locus was shifted 10° northward. (They only used 10° bins). This agrees again well with our results since the northward shift of minimum speed belt leads to a higher SW speed in Spring, as given in Figs. 2 and 3. Most recently, *Crooker et al.* [1997] studied Ulysses observations during its northbound ecliptic crossing in 1995. They noted that the locus of minimum SW speed was shifted 3°-4° northward from heliographic equator. This result is also in a good agreement with our result for the last solar minimum since the observed northward shift of minimum SW speed belt leads to annual variation with maximum in Spring, as observed in Figs. 2 and 3.

Fig. 1 suggests that the overall power of annual variation in SW speed greatly surpasses that of semiannual variation. We have studied semiannual variation in more detail by filtering the semiannual periodicity by an optimum filter with a pass band at T=183 ± 15 days, constructed in the same way as for annual variation. Figure 4 shows the filtered annual and semiannual variation. We find that annual variation (smoothed over 2-3 years) at solar minimum is typically about 50-60 km/s, and attains roughly equal amplitudes during the four solar minima. This further emphasizes the stability of annual variation. The amplitude of annual variation exceeds that of semiannual variation during three of the four solar minima studied. This implies that an asymmetric SW speed distribution is a more common situation than a symmetric one around solar minima. The only solar minimum where semiannual variation in SW speed was larger than annual variation was around 1986-87. This is due to the exceptionally thin heliosheet during this minimum, as discussed above and noted by *Richardson and Paularena* [1997].

Conclusions

Our results show that annual variation in near-Earth SW speed is a persistent periodicity which exists around all solar minima at roughly the same overall level and vanishes around solar maxima. It is related to Earth's orbital motion in a latitudinally asymmetric solar wind. Accordingly, we disagree with the view of Gazis [1996] which relates the annual variation and the 1.3-year periodicity so that the period of long-term enhancements changed from 1 year prior to 1986 to 1.3 years thereafter. Rather, annual variation exists (around minima) even if large scale intrinsic solar variations

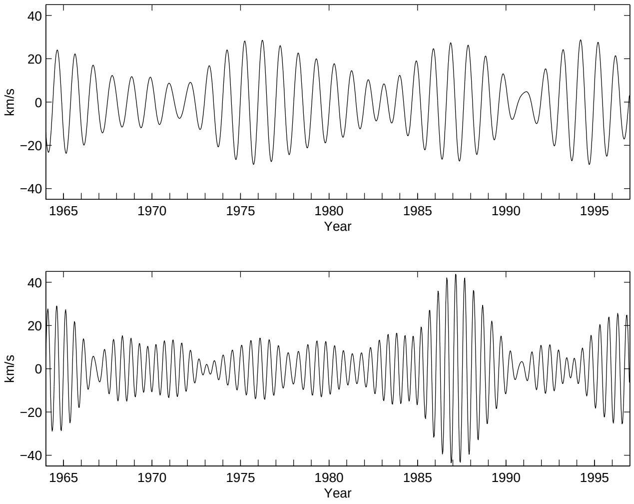

Figure 4. Filtered annual variation of (a) SW speed, (b) Kp index and (c) IMF sector component in color coding. Red presents higher SW speed, larger Kp index and a dominant IMF toward sector. Horizontal scale gives the time in years and vertical scale presents the variation in one year from January at bottom of each panel to December at top. (Monthly sunspot numbers are given at top of the figure for reference.)

(such as the 1.3-year variation) may temporarily dominate and mask it in SW speed time series. Our view is further supported by early observations [*Fraser-Smith,* 1972; *Delouis and Mayaud,* 1975; *Silverman and Shapiro,* 1983; *Gonzalez et al.,* 1993] where the annual and 1.3-1.4-year variations were found to coexist in several data sets long before 1987. The present results also explain the long-existing dilemma about the nature of annual variation in global geomagnetic activity.

The phase of annual variation changes from one solar minimum to another, depicting a new form of 22-year periodicity and reflecting its relation to solar magnetic cycle. The phase change of annual variation in SW speed excludes the other mechanisms proposed earlier to explain the annual variation, such as a belt of small comets crossing the ecliptic plane within 1 AU, or intrinsic solar modulation [Bolton, 1990]. The phase change implies that the north-south asymmetry in SW speed changes its sign with solar polarity so that the minimum speed region during solar minima is displaced away from heliographic equator towards the northern magnetic hemisphere. We discussed several independent observations which support the existence of a fairly persistent north-south asymmetry, and the change of its phase from cycle to cycle. These include observations from three of the last four solar minima [Hundhausen, 1971; Russell, 1975; Zhao and Hundhausen, 1983; Crooker et al., 1997]. Such a north-south asymmetry related to solar magnetic cycle may result e.g. from a systematically larger extension of polar coronal holes from the Sun's magnetic south pole toward equator, or from a different latitudinal distribution of magnetic fields in the two solar magnetic hemispheres.

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Correction to "Annual variation in near-Earth solar wind speed: Evidence for persistent north-south asymmetry related to solar magnetic polarity" by B. Zieger and K. Mursula

In the paper, "Annual Variation in near-Earth solar wind speed: Evidence for persistent north-south asymmetry related to solar magnetic polarity," by B. Zieger and K. Mursula, *Geophysical Research Letters, 25* [6], 841-844, an error appeared in the third paragraph of page 842. An incorrect caption was also included for Figure 4. Both corrections appear below:

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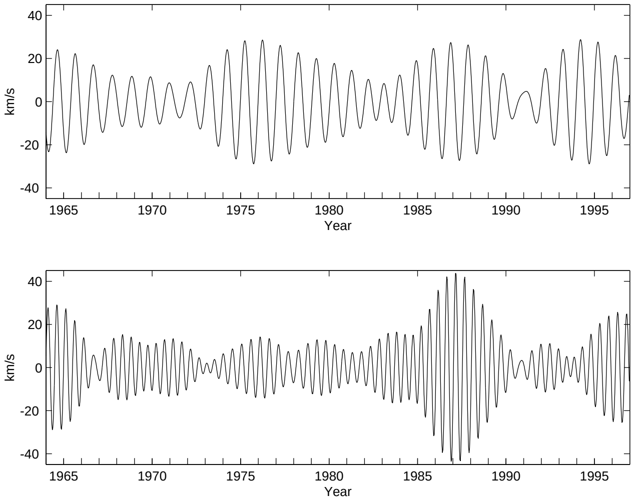

Figure 4. The filtered (top) annual and (bottom) semiannual variation in S W speed in 1964-96.

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