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Solar excursion phases during the last 14 solar cycles

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Abstract. The strong half solar rotation (about 13-14 days) periodicity in solar wind, IMF and geomagnetic activity was recently shown to arise from intervals during which the heliospheric current sheet is flat and tilted. These intervals denote the excursion phases of the solar dipole. In this letter we locate the solar excursion phases for the last 14 solar cycles using long-term observations of geomagnetic activity. This allows us to study the evolution of the solar corona for more than 150 years, i.e. far longer than with any other continuous data set. In the last eight cycles, largest excursions were found in mid- to late declining phase of the solar cycle, in agreement with the present view on coronal development during the solar cycle. However, in most of the earlier cycles 9-14, excursions were less frequent and occurred close to sunspot maximum. This suggests that the solar corona was exceptionally stable during the early low-activity cycles, having open coronal holes until close to sunspot maximum. Furthermore, we find that there is a connection between new sunspot activity and the solar dipole tilt.

Introduction

Solar wind (SW) is an extension of the solar corona into interplanetary space, and the solar wind speed is the main driver of geomagnetic activity over long time scales [see e.g. *Gosling et al.*, 1976; *Crooker et al.*, 1977]. Recurrent geomagnetic activity driven by recurrent streams of high speed SW can be observed at times when the Sun's polar coronal holes extend towards the solar equator, forming a thin heliospheric current sheet with large speed gradients across it [see e.g. *Krieger et al.*, 1973; *Neupert and Pizzo*, 1974; *Sheeley et al.*, 1976; *Burlaga and Lepping*, 1977; *Newkirk and Fisk*, 1985; *Kojima and Kakinuma*, 1990; *Rickett and Coles*, 1991]. Then, if the current sheet (solar dipole) becomes sufficiently tilted, the Earth encounters two high speed streams per solar rotation [*Zhao and Hundhausen*, 1981; *Hakamada and Akasofu*, 1981].

In a recent paper [*Mursula and Zieger*, 1996; to be called P1] we studied the half solar rotation (13-14 days; to be called 13.5-day) periodicity in solar wind, IMF and geomagnetic activity. It was shown in P1 that the 13.5-day quasi-periodicity consists of separate specific intervals of two high speed streams. These intervals occurred when the interplanetary magnetic field had a two-sector structure and the solar dipole (heliosheet) was sizably tilted. Accordingly, these intervals could be identified with the excursion phases of the solar dipole in the solar two hemisphere model [*Saito*, 1989], and their occurrence and other properties can be used to study the Sun's magnetic cycle and its possible long-term change. The largest excursions during the last three solar cycles (SC 20-22) occurred in mid- to late declining phase of the cycle, in agreement with previous results on the occurrence of recurrent streams [see e.g. *Sargent*, 1986; *Rangarajan*, 1991; *Hapgood*, 1993].

In P1 we found an excellent correlation between the 13.5-day periodicity of SW speed and that of geomagnetic activity, and demonstrated the great similarity in the occurrence pattern and other properties of the two stream structures (excursion phases) observed in SW speed and geomagnetic activity. Now, using this correlation and the longest measures of geomagnetic activity we study the excursions of the solar dipole during the last 14 solar cycles. We find that the predominance of excursions in the declining phase exists during the last 8 cycles. However, excursions during the earlier cycles are less frequent and the largest excursions mostly occur in the ascending phase or close to sunspot maximum. Moreover, we note about a connection between the occurrence of new sunspots and recurrent activity which is most evident during weak solar activity, in particular during the early weak cycles and in the late declining phase of all cycles.

Long-term development of the 13.5-day periodicity

In this work we use three geomagnetic indices, the aa index [*Mayaud*, 1973], the Kp index [*Bartels*, 1939], and the newly presented Ak(Hel) index [*Nevanlinna and Ketola*, 1993] as measures of global geomagnetic activity. The aa and Ak(Hel) indices were recently adjusted [*Nevanlinna and Kataja*, 1993] to form the longest uniform index of global geomagnetic activity, extending over the last 14 solar cycles. When locating the two stream structures (excursions) contained in these indices we will adopt the same procedure as used and presented in P1. We filter the (daily averaged) indices using a finite impulse response band pass filter with a lower (higher) cutoff period of 13 (14) days. In P1 we designed an optimum filter for this purpose following the Parks-McClellan optimization procedure [see e.g. MATLAB, 1994]. (For further details of the method, see P1). After filtering, all the variables were normalized to the standard deviations of the respective raw data in order to allow intercomparison.

Figure 1 displays the normalized 13.5-day periodicity as a colour intensity map where one Carrington rotation (27.2753 days) is depicted along the vertical axis so as to demonstrate the phase of the periodicity in heliographic longitude. The same color scale was used in all plots, red (blue) color representing a large positive (negative) value of 13.5-day periodicity, and yellow and green color small amplitudes. Figure 1 includes three panels, each containing two color strips of 13.5-day periodicity and the simultaneous sunspot numbers (averaged over one Carrington rotation) above the strips. The upper color strip in each panel represents the filtered aa index from 1868 until mid-1996. The lower strip in the top panel is the Helsinki Ak index spanning from 1844 to

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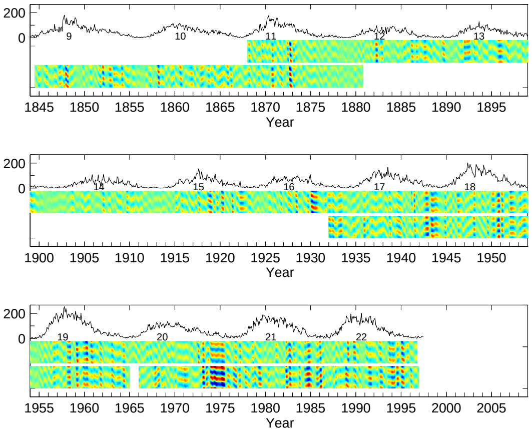

Figure 1. In each of the three panels of the figure, the 13.5-day periodicity for two variables is plotted as two color strips, and the sunspot numbers (averaged over one Carrington rotation) are added above them (solid line) with solar cycle numbers included. The upper strip in each panel is the geomagnetic aa index (1868-1996). The lower strip consists of the Ak(Hel) index (1844-1880), the Kp index (1932-1964), and the SW speed (1966-1996).

1880. The rest of the lower strip is formed by the Kp index for 1932-1964 and by the SW speed from 1966 onward. (SW speed was added here from P1 in order to depict the similarity of the pattern for SW and geomagnetic activity).

Excursions of the solar dipole are seen in Figure 1 as intervals of large 13.5-day periodicity which last a few (typically 3-4) solar rotations, as already observed in P1. The two colour strips in Figure 1 reveal a remarkably similar pattern of excursions over the whole overlapping period. All dominant and most smaller excursions are observed simultaneously and with the same duration and phase in the two panels. Most importantly, this excellent correlation (see the lower panel of Figure 1) is valid for the SW speed and the aa index which justifies the use of geomagnetic activity when locating the solar excursions before the start of direct SW measurements. (The same strong correlation was found in P1 for Kp and SW speed). Figure 1 also shows the nearly perfect correlation between the aa and Kp indices and between the aa and Ak(Hel) indices over the respective simultaneous time periods depicted.

The lower panel of Figure 1 verifies the observation of P1 that the largest excursions during cycles 20-22 occurred in the declining phase. During SC 20, several successive two stream structures took place in the late declining phase in 1973-1975. (This interval was also partly included in the analysis of *Bame et al.*, 1976, and *Gosling et al.*, 1976). The largest excursions of SC 21 and SC 22 were also found in the late declining phase in 1984 and 1995, respectively. (In addition, a few smaller excursions occurred during these cycles, most in the earlier declining phase, e.g. in 1972, 1982 and 1993-94, but a few even in the ascending phase, e.g. in 1979 and 1989). The two lower panels of Figure 1 show that a similar overall pattern continues during the five earlier solar cycles 15-19. For three of these cycles (16-18) the largest excursion was found fairly late in the declining phase, but for cycles 15 and 19 the largest excursion occurred only a couple of years after sunspot maximum. Moreover, the overall power of 13.5-day periodicity during the last eight solar cycles 15-22 remains rather similar. (One of the strongest excursions measured by the aa index occurred during SC 16 in 1930. As a historical curiousity, this excursion phase can also be seen e.g. as a persistent two-column pattern in the plots of daily geomagnetic activity prepared by *Bartels*, 1932, who, however, did not pay attention to this recurrency).

Interestingly, the above distribution of major excursions is not generally valid for the earliest cycles 9-14. First, SC 14 shows extremely little power in 13.5-day periodicity, far less than any other of the 14 cycles studied. In view of later discussion, we note that SC 14 was also the lowest sunspot cycle. Cycles 9-13 did experience a number of strong excursions, but the overall 13.5-day power remained somewhat lower than during the more recent cycles. However, most importantly, the distribution of the largest excursions of most of these early cycles is different from the pattern found above for the eight recent cycles. In particular, the largest excursions during cycles 9, 12 and 14 occurred close to sunspot maximum, and during SC 10 in the early ascending phase. Cycles 11 and 13 contained one strong excursion in the early declining phase and another, slightly weaker activation close to maximum or in the ascending phase, respectively.

The conditions for excursions to occur require that the heliosheet is sufficiently thin at the time of an excursion. This also applies to those excursions found to occur close to the sunspot maxima. It is known that the structure of the heliosheet is controlled by the strength of the solar dipole moment, and that the solar dipole moment varies over the solar cycle, attaining its maximum (minimum) close to sunspot minimum (maximum) (for a review see, e.g., *Legrand and Simon*, 1991). During sunspot maximum times, i.e. when the dipole moment is weak, the heliosheet has typically a very complex, non-dipolar structure. Therefore, the occurrence of excursions close to sunspot maxima is against the present view of coronal development.

Connection with sunspot number increases

Let us first note that many of the strong excursions in Figure 1 seem to coincide with sudden large increases of sunspot numbers. This connection is more clear for the early, low-activity cycles, in particular for the largest excursions of cycles 9, 12 and 14 in 1847, 1882 and 1907, respectively. Other examples of coinciding activations in low-activity cycles that are visible even in the highly compressed format of Figure 1 occur e.g. in 1889, 1918, 1922, and 1930. This connection is less clear for the later, high-activity cycles, partly because the individual sunspot activations stand out less clearly from the higher average sunspot level, partly because the heliosheet is more perturbed during high activity. However, a number of such coinciding cases can be seen even for the later cycles, such as those in 1959, 1973, 1975 and 1989.

In order to further clarify the possible connection between excursions and sunspot number increases, we plotted in Figure 2 the mean amplitude of the 13.5-day periodicity in two years prior to the sunspot minimum of each cycle, as a function of the simultaneous average sunspot number activity. During low average sunspot number level, in particular close to sunspot minima, the new sunspot activations stand out more clearly and form a larger share of the total sunspot number than during high sunspot activity. Thus we can regard, at least approximately, the sunspot numbers as sunspot number increases during this time. Furthermore, as

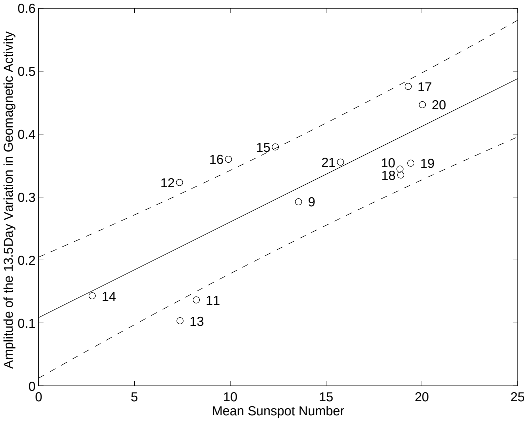

Figure 2. Correlation between the average sunspot numbers and the mean 13. 5-day amplitude of the combined aa and Ak(Hel) index. Each point represents an average value over two years in the late declining phase before sunspot minimum. The corresponding 13 solar cycles 9-21 of the aa/Ak(Hel) series are indicated by numbers. The solid line is the best fitting line and the dashed lines represent the 50% error curves.

already mentioned above, the solar dipole moment attains its maximum value close to sunspot minimum, forming a thin heliosheet and fulfilling thereby the primary condition for excursions to occur.

Figure 2 depicts a good correlation between the 13.5-day amplitude and sunspot number with a correlation coefficient of 0.76. We also used Student's test to check the statistical significance of the correlation. The test showed that we can reject the null hypothesis of no correlation at 99% confidence level. This is consistent with the idea that the changes in the magnetic field responsible for creating new sunspots or sunspot groups are also responsible for the increase of the tilt angle of the heliosheet (solar dipole). Figure 2 shows that, during the times when the heliosheet is thin, the mean amplitude of excursions is dependent on and proportional to the level of new solar activity. The correlation of Figure 2 is, of course, only valid in the late declining phase when the solar dipole moment attains its maximum value in each cycle. It also depends on the assumption that sunspot number increases can be replaced by absolute values. Clearly, this assumption can not be made during high activity. In order to test the possible correlation between sunspot number increases and excursion phase amplitude irrespective of the phase of the solar cycle, other methods have to be used. We have used a superposed epoch method to test this correlation and found a significant increase of sunpot numbers before excursion phases of certain minimum amplitude. However, the results of this analysis have to be postponed to another publication. Finally, we would like to note that no overall correlation between 13.5-day periodicity and sunspot numbers was found in P1 for the last 3 cycles. This also emphasizes that the correlation of Figure 2 is only valid at certain times when the well-defined conditions required for excursions are fulfilled.

Discussion

Note that all those four early cycles 9, 10, 12, and 14 that have an exceptional pattern of excursions also had a very slow rise of sunspot activity after the previous minimum. This observation is of interest when trying to better understand the exceptional occurrence of the excursion phases during these cycles. According to the solar dynamo model [see e.g. *Babcock*, 1961; *Leighton*, 1964; *Yoshimura*, 1975; *Krause and Radler*, 1980], a strong (weak, resp.) dipole moment leads, by the effect of differential rotation, to a strong (weak) toroidal field and to large (small) sunspot numbers during the following sunspot cycle. Thus the slow rise of solar activity implies that the dipole strength during the previous minimum was rather weak, and that the toroidal field develops slowly, allowing the dipolar structure to sustain for a longer time after the minimum. Accordingly, during slowly increasing solar cycles, the polar coronal holes were retreating exceptionally slowly polewards after the previous minimum. This forms a good possibility for large excursion phases to arise during the ascending phase or even close to sunspot maximum once a strong new magnetic activity causes a sufficiently large tilt. Note however that a weaker dipole moment implies a thicker heliosheet, low heliomagnetic gradients around the ecliptic and, thereby, weaker excursions. Therefore, a sufficiently large new activity is needed for an excursion of observable magnitude. This is extremely well depicted in case of cycles 9 and 12 where only a very large and abrupt sunspot increase (after a slow initial increase) leads to a sizable excursion.

On the other hand, in the more active solar cycles a faster increase of solar activity after the preceding sunspot minimum soon destroys the dipolar structure and polar coronal holes. Instead, the toroidal field is evolving faster, leading to larger instabilities and to a more disturbed heliosheet. Since the excursion phase requires a flat heliosheet, their occurrence is expected to be weaker during the ascending phase of the high-activity cycles. (This is also the reason why we used in Figure 2 an asymmetric time interval of two years before, not around minima).

According to Figure 2 the average excursion activity before sunspot minima is roughly proportional to the simultaneous sunspot activity. This correlation is surprisingly strong, taking into account e.g. the fact that the dipole strengths may vary from cycle to cycle. As already mentioned above, a strong (weak, respectively) solar dipole moment implies a thin (thick) heliosheet, suggesting that excursion activity is stronger around the minima of cycles with a stronger dipole strength. However, the strong correlation in Figure 2 implies that the observed differences in dipole strengths are, at least effectively, not very large. This may, on one hand, be due to the divergence of interplanetary field lines which alleviates the difference in excursion activity observed at 1 AU for different dipole strengths. On the other hand, the occurrence of excursion phases depends, in addition to the thickness of the heliosheet, also on the dipole tilt. If the size of the tilt angle produced by sunspot activity of certain magnitude is larger in case of a weaker dipole strength, the excursion activity would be correspondingly enhanced. Thus, during a solar minimum of a stronger (weaker) dipole strength the heliosheet would be thinner (thicker) but have a smaller (larger) tilt for the same magnetic activity, leading to roughly equal excursion activity.

As already noted, the weakest overall 13.5-day periodicity was observed during cycle 14 which also has the lowest sunspot activity. Even the largest excursion of SC 14 that occurred close to sunspot maximum, in connection with the largest sunspot number increase of the cycle, remained very weak. Also, there was no significant excursion activity during the ascending phase despite reasonably large sunspot activations. These facts, together with the slow increase of sunspot activity during this cycle, suggest that the dipole moment during the previous sunspot minimum was abnormally weak. It is also supported by the fact that the minimum prior to SC 14 (point 13 in Figure 2) is weaker in 13.5-day periodicity than predicted by the average correlation. Accordingly, our results give independent support for the suggestion for a weak solar dipole moment at the turn of the century [*Legrand and Simon*, 1991], leading to a weak average solar wind speed at the ecliptic at that time [*Feynman and Crooker*, 1978]. By the same argument, the two previous sunspot minima had somewhat different dipole moments, one (between SC 12-13; point 12 in Figure 2) stronger, the other (between SC 11-12; point 11) weaker than average. This suggests that the dipole strength was fluctuating before reaching its minimum value between SC 13-14. Note also that the longest intervals of extremely weak 13.5-day periodicity (see Figure 1) occurred during the two weakest dipole moments between cycles 11-12 and 13-14. These minima are also the only cycles below the 50% error curves of the correlation depicted in Figure 2.

Conclusions

Concluding, we have studied the excursions of the solar dipole during the 14 solar cycles 9-22 using long-term registrations of geomagnetic activity. During the 8 most recent cycles (SC 15-22) the main excursions occurred in the mid- to late declining phase of the cycle. However, during most of the earlier cycles, they were found in the ascending phase or close to maximum. This is against the present view of coronal 11-year change which holds that coronal holes vanish soon after sunspot minima and that the solar corona has a complex, non-dipolar magnetic structure at sunspot maxima. Instead, we have found that coronal evolution during the slowly increasing, low sunspot number cycles is very stable, with a flat heliosheet and open coronal holes until close to sunspot maximum. The overall occurrence of excursions remained very weak during some early cycles, in particular during SC 14, supporting the previous result that the solar dipole moment was weaker at the turn of the century than during the more recent cycles. Furthermore, the strong correlation in the late declining phase between excursion phase and sunspot activity suggests that new sunspot groups and solar dipole tilt are generally related, being probably due to common magnetic processes.

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