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Letter to the Editor

Long-term variation of sunspot latitudes

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Abstract. We consider a continuous sunspot data set ranging from 1853 to 1996. The emphasis is given to long-term activity variations and north-south asymmetries. The difference of the distance between sunspot belts and equator between the northern and southern hemispheres is considered and a systematic variation is found. The period of this variation is about 8.4 sunspot cycles or about 90 years, and the amplitude is 1.3 degrees. This phenomenon could be explained by oscillation of a quadrupolar component of solar mixed parity mode magnetic field.

Key words: Sun: activity – Sun: magnetic fields – Sun: photosphere – Sun: sunspots

1. Introduction

The amplitude and length of sunspot cycles are known to vary within wide ranges. The quantitative data of sunspot numbers exist from around 1700, or the end of the Maunder minimum. Earlier records can be produced from ice cap drillings (e.g. Blunier et al., 1998) that indirectly reveal solar activity variations through their influence on Earth's climate. Only since the records by Carrington (1853-1861), have the heliographic coordinates of individual sunspot measurements been included. Sunspot cycles are variable with respect to magnitude, as measured by the numbers of spots, duration, as measured by the time between successive minima, and also in the latitudinal distribution of the spots. It is the latter which is the particular object of this study, with special attention being given to asymmetries between the north and south hemispheres.

Variations in all these three measures do not appear to be purely random, but rather to display long term patterns of behaviour. This has encouraged people to look for stable quantities or longer cycles than the 11-year one. Already Wolf (1861) proposed the constancy of the product of sunspot cycle length and amplitude which turned out to be, however, incorrect. Gleissberg (1967) introduced a long-time period, the Gleissberg cycle, having a period of about 80 years. This rather freely defined period is roughly estimated as the time lapse between groups of inactive cycles with active cycles in between. Later Yoshimura (1979) reported a modulation of the solar cycle length which repeated every 5 cycles. This cycle of approximately 55 years is difficult to reconcile with Gleissberg's result. Recently, growing interest has been shown to the possible solar impact on the observed global warming, in particular to evidence that long-term mean temperature variations are correlated strongly with variations in the length of the solar cycle (see Friis-Christensen & Lassen, 1991).

The north-south asymmetry of sunspots has been studied for the last five decades and its existence has proved to be real (Newton & Milson, 1955; Roy, 1977; Vizoso & Ballester, 1989). Waldmeier (1957 and 1971) pointed out a phase shift between hemispheres and suggested a period over 8 eleven-year cycles. Verma (1993) studied long-term north-south sunspot asymmetry and found a characteristic period of 110 years. Oliver & Ballester (1994) reported on a long-term trend in the asymmetry on a time-scale of $O(100)$ years, and also on a shift of the dominance of solar activity from the north to the south during sunspot cycle 22. In this letter we consider the activity variation and north-south asymmetry through sunspot latitudes and compare results with those in earlier studies.

The Sun's magnetic activity is generally believed to be supplied by a hydromagnetic dynamo operating either in or at the base of the solar convective zone. Dynamo models predict the possibility of mixed parity solutions where the field has both dipolar and quadrupolar components. Such fields would be asymmetric with respect to the equator. Indeed there is evidence that the Sun's field was highly asymmetric as it emerged from the Maunder Minimum (Ribes and Nesme-Ribes 1993, Sokoloff and Nesme-Ribes 1994). It is often stated that the solar field has been dipolar since then (e.g. Tobias 1996, 1998). The observed asymmetries would thus not be intrinsic to the dynamo and could be regarded as a noisy signal imposed on

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Table 1. The relative number of sunspot measurements at different latitude bands (given in degrees) and cycles. The sum of each column is 100. In the last row the beginning year of each cycle is written

lat.	cycle												
range	10	11	12	13	14	15	16	17	18	19	20	21	22
> 40	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.1	0.2
35-40	0.2	0.5	0.1	0.0	0.0	0.1	0.2	0.2	0.1	0.8	0.4	0.9	0.5
30-35	1.4	1.5	0.1	0.2	0.3	0.3	1.2	1.1	0.8	2.7	1.4	1.5	2.4
25-30	3.2	3.7	2.0	2.2	0.9	1.9	2.6	3.6	2.9	6.2	3.5	3.9	5.0
20-25	6.4	7.8	6.7	6.3	5.1	5.9	8.5	6.8	8.1	10.8	8.9	7.4	7.7
15-20	9.6	10.0	9.5	11.5	8.9	11.2	11.3	10.0	11.0	11.1	12.7	13.5	10.4
10-15	14.9	11.0	14.6	13.7	15.6	15.6	13.0	15.5	14.8	12.7	15.1	11.7	9.9
5-10	10.7	10.5	8.3	8.4	15.0	14.1	13.3	9.4	8.8	9.9	9.9	7.5	7.7
0-5	3.3	2.8	3.2	3.6	3.4	4.3	3.5	2.6	2.6	2.8	3.3	2.8	2.5
-5-0	3.5	2.8	5.0	3.3	4.4	2.3	2.9	2.8	3.8	2.1	3.2	3.2	2.7
-10--5	11.0	10.9	13.4	11.1	11.4	10.0	11.2	11.1	10.0	6.7	10.0	9.7	9.8
-15--10	11.9	14.8	15.3	15.7	14.7	11.5	12.8	12.7	13.5	9.6	13.7	13.2	13.9
-20--15	10.0	9.9	13.5	13.1	13.3	13.3	11.5	11.0	12.0	10.4	9.4	10.8	12.2
-25--20	8.2	7.1	6.2	6.8	5.9	7.3	5.0	7.1	7.0	8.3	5.1	6.9	8.2
-30--25	4.1	4.1	1.9	3.0	0.9	1.7	2.4	4.2	2.7	3.6	2.3	4.8	4.0
-35--30	1.4	1.5	0.3	1.0	0.3	0.4	0.6	1.7	1.2	1.1	0.9	1.6	2.0
-40--35	0.2	0.7	0.1	0.1	0.0	0.1	0.0	0.2	0.5	0.4	0.1	0.2	0.7
< -40	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.1
beg. year	1855	1867	1878	1890	1902	1913	1923	1933	1944	1954	1964	1976	1986

the dipolar field. However, it has recently been proposed that the dipolar and quadrupolar components could both be oscillating coherently (although the quadrupolar component would be much weaker) and that therefore the observed asymmetry should have a periodic component to its signal (Brooke et al. 1998).

2. Data and results

We use the sunspot data over the whole range of modern observations, starting from Carrington's (1853-1861) and Spörer's (1861-1894) data. To extend this record to the present day (i.e. 1874-1996), the data from the Greenwich Photoheliographic Results and the Solar Optical Observing Network have been combined[1]. These data sets cover completely sunspot cycles 10 to 22 of which cycles 10 and 11 are taken from Carrington/Spörer data and cycles 12 to 22 from the Greenwich data. These long-term data have been used to analyse solar photospheric velocities by Pulkkinen & Tuominen (1998) where the data are also introduced in more detail.

An important feature connected with activity variations between cycles is the mean latitude $\langle\lambda\rangle_n$ of sunspots, taken as spatial averages over whole hemispheres or narrower latitude bands, and temporal averages over a cycle or shorter time range (n days). In practice, the shortest time range is about 10 days since sunspots are not always observed simultaneously at both hemispheres. The distribution over cycles 10 to 22 is given in Table 1. The latitude band with highest sunspot number is typically 10-15 degrees away from the equator, but the average latitude varies quite significantly as can be seen also in Fig. 1 where the cyclic averages have been computed from the whole hemispheric data. The rising activity during the first 60 years (cycles 14 to 19) of the 20th century is seen as higher latitudes of sunspots. Error bars (calculated as the mean error of the mean) being so small, the effect is rather strong and systematic, especially in the north. But the correlation between active cycles and high sunspot latitudes is not complete—the total cycle activity increased from cycle 12 to cycle 19 and then rapidly went down.

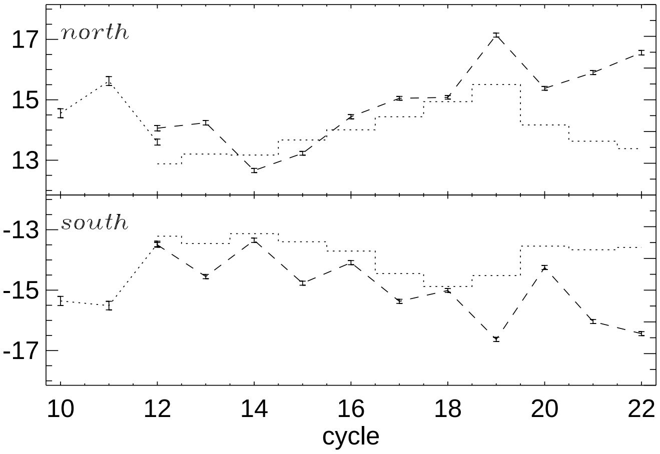

Fig. 1. The mean latitude of sunspots at both hemispheres at cycles 10 to 22. The dotted line denotes the Carrington/Spörer data and the dashed line the Greenwich/SOON data. The histograms denote the total area of sunspots over cycles 12 to 22 of which the area is obtainable. The area (right y-axis) unit is one hemisphere

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[1] The 1874-1996 data is obtainable at the internet site http://wwwssl.msfc.nasa.gov/ssl/pad/solar/greenwch.htm

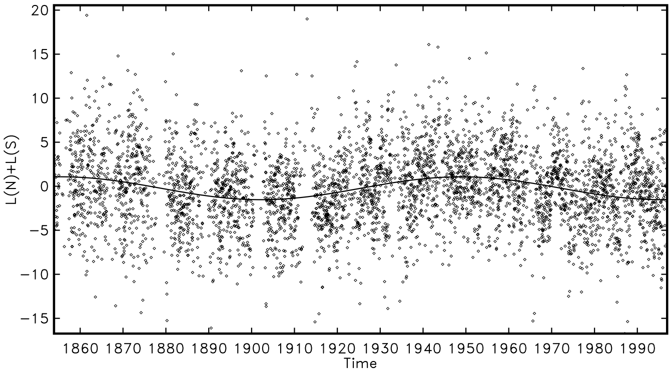

Fig. 2. Difference of the distance of sunspot belts from the equator. Each dot denotes a 10-day average

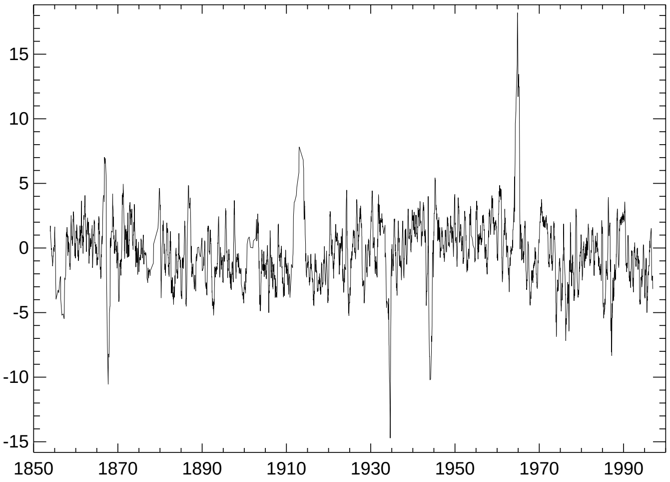

Fig. 3. Same as Fig. 2 except an 11 point weighted smoothing has been used with the number of measurements at each 10-day interval as weights

For sunspot latitudes, they went higher up between cycles 14 and 22, as if there were a phase shift.

As the mean latitude of sunspots, or the whole sunspot belt, is varying between cycles and hemispheres, their relative distance from the equator is changing too. This can be seen, when we calculate the latitude of the "magnetic equator" defined by sunspot latitudes. This is the sum ($\langle\lambda(S)\rangle_n$ is negative) of mean latitudes $\langle\lambda(N)\rangle_n + \langle\lambda(S)\rangle_n$. An interesting pattern is seen in Fig. 2 where this sum is plotted as 10-day averages. In symmetric case this sum should be zero, but this band, although wide, is clearly moving up and down rather systematically. If this is fitted to a sinusoidal profile (solid line in Fig. 2), we get

$$\langle\lambda(N)\rangle_{10} + \langle\lambda(S)\rangle_{10} \equiv A\cos(\Omega t) + B\sin(\Omega t) = 1.29(\pm 0.10)\cos\left(\frac{2\pi t}{P}\right) + 0.20(\pm 0.21)\sin\left(\frac{2\pi t}{P}\right), \quad (1)$$

where time t is measured in days, $t = 0$ being Nov 8, 1853, the first measurement by Carrington. The period of this variation $P = 33900 \pm 950$ days, and the amplitude 1.31 ± 0.13 degrees. Fig. 3 shows the same as Fig. 2 but with 11 point smoothed average. The alternating pattern is even clearer, only with few outlying measurements denoting gaps between two sunspot cycles.

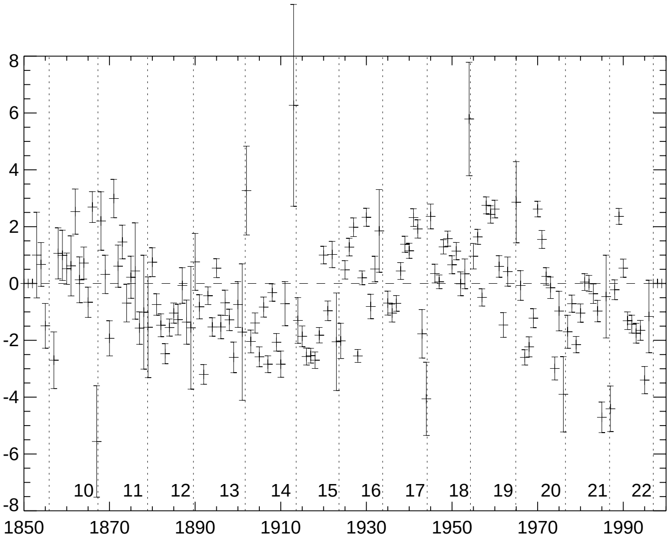

Fig. 4. Yearly averages of the difference $\langle\lambda_{\mathrm{N}}\rangle_{365} + \langle\lambda_{\mathrm{S}}\rangle_{365}$. The vertical dotted lines denote beginnings of sunspot cycles which are numbered in the lower part

If we repeat the above procedure with yearly averages, the sinusoidal variation of Fig. 2 still appears to be present (Fig. 4). Here the error bars are simply sums of errors of $\langle\lambda(N)\rangle_{365}$ and $\langle\lambda(S)\rangle_{365}$ separately, so they may be exaggerated. Of course, we may compute the trigonometric fit, and then $A = 1.08 \pm 0.21$ and $B = 0.24 \pm 0.40$. Here, $P = 32200 \pm 2100$ days and the amplitude is 1.1 ± 0.3 degrees.

If we consider the error ranges for the coefficients over 10-day or yearly averages, we see that the two curves are compatible. Thus the sinusoidal form of the curve appears to be robust to the form of averaging employed.

3. Discussion

Our main result is that the "magnetic equator" of the Sun displays a long term variation between north and south latitudes. The magnetic equator is defined by the average of the signed value of the latitude of each sunspot (positive for north, negative for south). From the data since 1853, the form of this variation appears to be well approximated by a sinusoidal curve with a period of about 90 years and an amplitude of 1.3 degrees. Since the average latitudinal distance from the equator of the main activity belts is around 15–17 degrees, this is a striking variation. Onto this long-term variation, is superimposed a highly irregular signal with an amplitude that can be over 10 times greater. Carbonell, Oliver & Ballester (1993) considered the signal of the asymmetry to have a dominant noisy component, a periodic (12.1 years) signal and a long-term trend. Our 90 year signal would correspond to this long-term trend. It is important to note that our measure of north-south asymmetry via latitudinal variation differs from the measure usually adopted, where the activity measures are totalled in each hemisphere separately and then compared. The usual index is $AS = (N-S)/(N+S)$ where N

and S are the total activity counts in the northern and southern hemispheres. Such a measure loses all information about the latitudinal variation of the sunspots and, as far as we can tell, our result is novel in this aspect.

This result appears to confirm other evidence pointing to a 90 year cycle, such as variation in cycle length (Lassen & Friis-Christensen 1995). The variation in latitude can be explained as a mixed parity mode in which a quadrupolar component is oscillating with this period. The well-defined sinusoidal form of the time series curve would seem to indicate that the quadrupolar component is frequency-locked to the dominant dipolar mode in the manner described in Brooke et al. (1998). We can see this by examining the formulas used in the aforementioned work, for example a modified version of their formula (8)

$$\begin{array}{ccc} t & t+\tau/2 & t+\tau \\ \begin{pmatrix} +b+\delta b \\ +b-\delta b \end{pmatrix} & \begin{pmatrix} -b+\delta b \\ -b-\delta b \end{pmatrix} & \begin{pmatrix} +b+\delta b \\ +b-\delta b \end{pmatrix} \end{array} \tag{2}$$

Here b represents the toroidal component of the quadrupolar field and δb represents the toroidal component of the dipolar field, the δ notation indicating that this is considerably weaker. We use a matrix notation where the upper row represents the field in the northern hemisphere and the lower the field in the southern hemisphere at a given latitude. The period at which the components are locked is represented as τ, this would be several times longer than an individual solar cycle. If we postulate that the level of activity in the magnetic activity belts is a measure of the absolute value of the total toroidal field $|b_{total}| = |b_{sg}+\delta b_{sg}|$ (where b_{sg} and δb_{sg} indicate the signed values of the quadrupolar and dipolar components of the toroidal field), then we see that $|b_{total}|$ is larger in the northern hemisphere at time t and larger in the southern hemisphere at time $t+\tau/2$. If we multiplied $|b_{total}|$ by the (signed) latitude representing the activity belt then this weighted average latitude would oscillate about zero. The above argument is of course schematic, for instance we have to add that the latitude at which the field values are given by (2) will be migrating with time. However it does indicate a possible mechanism to account for the variation in the "magnetic equator" as defined as the weighted average of the two activity belts. We are preparing a more extended version of this argument for subsequent publication.

A possible alternative explanation of the oscillations in the "magnetic equator" would be systematic errors in coordinate measuring, perhaps due to a precession of the Sun's magnetic field or rotational axis. Precession of the rotation axis can immediately be ruled out since such an effect would be immediately seen over one rotational period, by tracking a long-lived spot group. In addition, the Earth's precession period is 26,000 years and it is hardly conceivable that the Sun would precess in 90 years. A precession of the Sun's magnetic axis about the rotational axis would be observed as a thickening of the activity belts due to rotation. Essentially the activity belts where the majority of spots are observed would be inclined to the equator, thus the spots would appear to be distributed over a wider range of latitude. The effects of precession would be, in effect, hidden by the Sun's rotation. Thus we consider the measurements correct and the effect genuine.

The latitudinal distribution of sunspots separately is also interesting. The mean latitude wanders higher up as the century proceeds. It is puzzling that the apparent correlation between high sunspot latitudes and active cycles is no longer valid at the less active cycles 20 to 22. It will be seen in the next decades whether the mean sunspot latitude will come lower following the descending solar activity, or another new "period" will be discovered. We note here that if the latitudinal distribution of the spots is different in each hemisphere, this provides an alternative mechanism for the effect in Fig. 2 to the arguments about weighted averages presented above, thus this is another important avenue of investigation.

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