INCREASE OF THE MAGNETIC FLUX FROM POLAR ZONES OF THE SUN IN THE LAST 120 YEARS

V. I. MAKAROV[1], A. G. TLATOV[1], D. K. CALLEBAUT[2] and V. N. OBRIDKO[3]
[1]*Pulkovo Astronomical Observatory, 196140, Saint Petersburg, Russia*
[2]*Physics Department UIA, University of Antwerp, B-2610, Antwerp, Belgium*
[3]*Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Russia*

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Abstract. Lockwood, Stamper, and Wild (1999) argued that the average strength of the magnetic field of the Sun has doubled in the last 100 years. They used an analysis of the geomagnetic index $\langle aa \rangle$. We calculated the area of polar zones of the Sun, A_{pz}, occupied by unipolar magnetic field on Hα synoptic magnetic charts, following Makarov (1994), from 1878 to 2000. We found a gradual decrease of the annual minimum latitude of the high-latitude zone boundaries, θ_{2m}, of the global magnetic field of the Sun at the minimum of activity from 53° in 1878 down to 38° in 1996, yielding an average decrease of 1.2° per cycle. Consequently the area of polar zones A_{pz} of the Sun, occupied by unipolar magnetic field at the minimum activity, has risen by a factor of 2 during 1878–1996. This means that the behavior of the index $\langle aa \rangle$ and consequently the magnetic flux from the Sun may be explained by an increase of the area of polar caps with roughly the same value of the magnetic field in this period. The area of the unipolar magnetic field at the poles (A_{pz}) may be used as a new index of magnetic activity of the Sun. We compared A_{pz} with the $\langle aa \rangle$, the Wolf number $\langle W \rangle$ and $\langle A^* \rangle$-index (Makarov and Tlatov, 2000). Correlations based on '11-year' averages are discussed. A temperature difference of about 1° between the Maunder Minimum and the present time was deduced. We have found that the highest latitude of the polar zone boundaries of the large-scale magnetic field during very low solar activity reaches about 60°, cf., the Maunder Minimum. It is supposed that the θ_{2m}-latitude coincides with the latitude where $\partial_r \omega = 0$, with $\omega(r, \theta)$ being the angular frequency of the solar rotation. The causes of the waxing and waning of the Sun's activity in conditions like Maunder Minimum are discussed.

1. Introduction

Recently it was argued that the average strength of the magnetic field of the Sun has doubled in the last 100 years from an analysis of the geomagnetic $\langle aa \rangle$ index (Lockwood, Stamper, and Wild, 1999). This index depends on the magnetic flux of the Sun and is defined as a result of measurements of the geomagnetic field every 3 hours (Mayaud, 1972). This result, obviously, is important to understand the evolution and generation of the solar magnetic fields. Particularly, it was suggested that this increase might be related to (chaotic) changes in the solar dynamo. A long-term growth of the solar magnetic flux concerns a change of the global warming and increase of the temperature of the oceans on the Earth that were registered both by meteorological and radionuclear measurements (Wilson, 1997; Cliver, Boriakoff, and Bounar, 1998; Cliver, Boriakoff, and Feynman, 1998; Kocharov *et al.*, 1995;

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Callebaut, Makarov, and Tlatov, 2000). Secular changes on a time scale of centuries were observed too. The Maunder Minimum in the second half of the 17th century is an excellent example. Naturally, a global warming at present is connected with industrial aspects, too.

It is well established that geomagnetic activity is driven by the solar wind. For example, there is the $\langle aa \rangle_{11} - \langle W \rangle_{11}$ correlation based on '11-year' averages of sunspot number ($\langle W \rangle_{11}$) and the geomagnetic $\langle aa \rangle_{11}$-index: $\langle aa \rangle_{11} = 0.22 \langle W \rangle_{11} + 7.6$ ($r = 0.96$) (Mayaud, 1972). Near sunspot minimum activity there are two distinct solar wind regimes: slow and medium-speed wind flowing from the coronal streamer belt that encircles the equator, and fast wind from the polar coronal holes. Legrand and Simon (1989) have found that the geomagnetic activity depends on solar wind streams from coronal holes during 90% of the time.

It is well known that the global solar activity is described by the polar faculae and the sunspot 'butterfly' diagrams in each hemisphere, divided at present by the latitude 38° (Makarov and Makarova, 1999). The third major component of the global solar cycle is connected with the unipolar regions of weak magnetic field (without active regions and sunspots). It was shown that the large-scale magnetic field cycle, $A^*(t) = (\mu_1^2 + \mu_3^2/3)^2$, where $A^*(t)$ is the square of the sum of the squares of the magnetic octupole and dipole moments of the unipolar large-scale regions, *precedes* the sunspot activity cycle $W(t)$ on the average by 5.5 years (Makarov and Tlatov, 1999; Makarov, Tlatov, and Callebaut, 2001). This means that the pattern of the large-scale magnetic field does not result from decay and diffusion of fields from active regions.

These fields emerge into the solar corona and interplanetary space. The contribution of these fields to the interplanetary field varies according to their origin. In fact, local magnetic fields (active regions and sunspots) yield a small contribution to the formation of the interplanetary field, although the equatorial coronal holes may contribute. According to Wang, Lean, and Sheeley (2000) and Wang, Sheeley, and Lean (2000) the large-scale magnetic fields determine the interplanetary magnetic field. We will assume here that the dominant contribution comes from the polar regions of unipolar magnetic field (including polar coronal holes). However, we will make calculations using two unipolar regions too (the polar cap and the neighboring zone), to confirm this viewpoint.

In the present paper we discuss long-time variations of the area of polar zones of the Sun A_{pz}, occupied by unipolar magnetic field, in connection with the evolution of the geomagnetic $\langle aa \rangle$ index during 1878–2000. The origin of the secular variation of the solar magnetic flux is the main goal. We shall touch upon the question how the Sun enters and leaves the Maunder Minimum.

2. Observational Data

In the absence of a long-term record of magnetograph measurements of the solar magnetic field the investigation of polar activity of the Sun in the last 120 years has been based on the latitude–time distribution of unipolar areas of the large-scale magnetic field of the Sun during 1878–2000. The unipolar regions are evident on magnetograms. At the boundaries of unipolar regions where the radial component of the magnetic field is zero, Hα prominences and dark filaments are observed. They form the pattern of the so-called magnetic neutral lines.

These charts, however, do not provide any information on magnetic field strengths. But when the features in the Ha spectroheliograms can be identified clearly, the neutral line pattern of these large-scale magnetic fields can be derived with greater confidence and accuracy than can be inferred from magnetograms especially in the regions of weak fields and polar zones (Duvall *et al.*, 1977). At present these Hα charts represent ready material for investigating global properties of large-scale magnetic fields for 12 solar cycles during which Hα observations were made while no magnetographs exist except in the last cycles. Using the distribution of the magnetic neutral lines (Makarov and Fatianov, 1982; Makarov, 1984; *Soln. Dann.*, 1978–2000) yielded a detailed analysis of polar magnetic field reversals of the Sun (Makarov and Sivaraman, 1983). E.g., three-fold changes of polarity of the magnetic field of the Sun (Makarov and Sivaraman, 1989) and a 55-year cycle of the torsional oscillations activity in the parameters of the solar rotation were found (Makarov and Tlatov, 1997; Makarov, Callebaut, and Tlatov, 1997; Obridko and Shelting, 2000a, b, 2001). The quasibiennial oscillations of the different multipoles were investigated (Shelting and Obridko, 2001). Moreover, it was shown that the large-scale magnetic field cycle *precedes* the sunspot activity cycle on the average by 5.5 years (Makarov and Tlatov, 1999; Makarov *et al.*, 2001). Recently Hα charts were compared with the solar and geophysical indices and they showed good correlations with the structure of the solar corona (Obridko and Shelting, 1999).

Polar activity of the Sun may be represented by the number of polar faculae (N_{pf}) according to observations at the Kislovodsk Solar Station during 1960–1999 (Makarov and Makarova, 1996). The correlation between the number of polar faculae and the intensity of the mean polar magnetic field of the Sun was investigated (Obridko and Shelting, 1999) and will be used here according to Makarov and Makarova (1998).

3. Treatment of Synoptic Charts

The synoptic charts show that the polarity of the large-scale magnetic field for any longitude alternates in sign at several latitudes between the equator and the poles, the line of demarcation being the filament bands that run approximately east to

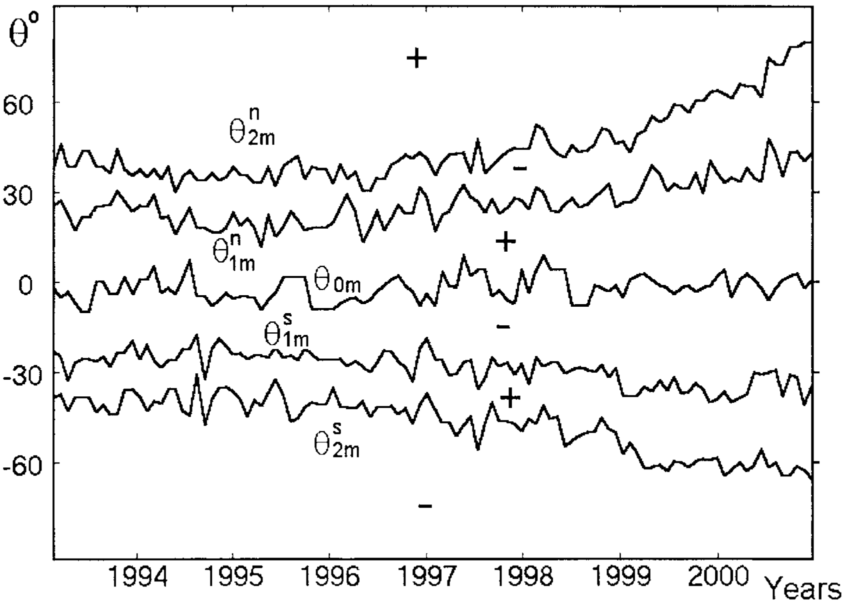

Figure 1. Solid lines represent migration trajectories of magnetic neutral lines (or the zone boundaries with the opposite polarities on either of its sides in the order +/− or −/+) of the large-scale magnetic field derived from Hα synoptic charts in the northern (θ_{1m}^{n}, θ_{2m}^{n}) and southern (θ_{1m}^{s}, θ_{2m}^{s}) hemispheres for the period 1993–2001. The latitude θ_{0m} is the equator boundary.

west. It is possible to assign the mean latitude to every filament band over each solar rotation. To make the value of the mean latitude quite representative we measure the latitudes of the filament band in every 20° longitude zone and average them over one rotation. This mean value forms one data point on the migration trajectory curve. By plotting all such points for the polemost filament as well as for other filament bands as a function of time, we obtain the trajectory of the boundaries of magnetic regions of one dominant polarity as they migrate to high latitude with the progress of solar activity. High (Θ_{2m}) and middle (Θ_{1m}) latitude are the boundaries of predominant polarity of the magnetic field, which were detected (Makarov and Sivaraman, 1989a, b; Callebaut and Makarov, 1992; Makarov and Tlatov, 1999). One may add Θ_{0m}, which is situated at the equator where new boundaries are generated.

In Figure 1 we show migration trajectories of magnetic neutral lines of the large-scale magnetic fields derived from Hα synoptic charts in the N and S hemispheres for the period 1993–2001. At the northern pole the magnetic field reversal was completed at the beginning of 2001, at the southern pole it is expected that polar reversal will be over later in 2001. At present (April 2001) both poles have the same polarity. One can see the formation of a new low latitude zone close to the equator at the beginning of each cycle. Thus an equatorial reversal takes place at the beginning of the cycle, while the polar reversal happens about 3–4 years later.

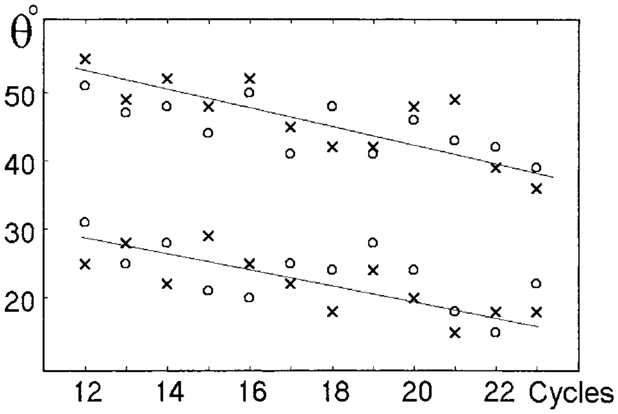

Figure 2. Annual mean latitude of the high-latitude (θ_{2m}) (*upper part*) and low-latitude (θ_{1m}) (*lower part*) zone boundaries of the large-scale magnetic field of the Sun (x are the northern and o the southern hemispheres) during the minimum of activity of 11-year cycles 12–23 according to Hα magnetic synoptic charts for 1878–1996.

In case there are several reversals this applies for the first one, while the second and third are somewhat shifted in time, see Figure 1 of Makarov and Sivaraman (1989a) and Figure 5(a) of Makarov (1994). Note as well that immediately after a polar reversal the next large-scale boundary suffers a drop in latitude to the level of about 40° at present.

4. Results

4.1. THE LATITUDE OF THE ZONE BOUNDARIES DURING 1878–1996

In the minimum of activity of the last cycle the zone boundaries were situated at latitudes of about 40° (Θ_{2m}), 20° (Θ_{1m}), and 0° (Θ_{0m}). To obtain an estimation of a centenary variation of the interplanetary magnetic field we determined the ratio of the areas occupied by the local (active regions) and polar magnetic fields during 11-year cycles. In Figure 2 and Table I we show annual mean latitude of zonal boundaries of the large-scale magnetic field in the minimum activity (θ_{2m} and θ_{1m} are, respectively, the annual minima of Θ_{2m} and Θ_{1m}) for N and S hemispheres for 1878–1996, i.e., solar cycle 12–23.

These boundaries separate the high- and middle-latitude unipolar magnetic fields of the Sun. From Table I one can see that the high-latitude zone boundary (θ_{2m}), average N and S, moved nearer to the equator by about 15° during 12 solar cycles. In the northern hemisphere the latitude (θ_{2m}) shifted from 55° in 1878 down to 36° (shift: 19°) in 1996. A similar process was observed in the S-hemisphere, where the latitude (θ_{2m}) shifted from 51° in 1878 to 39° in 1996 (shift: 12°). During the 12 cycles the dynamics of the θ_{2m}-latitude displays the 22-year magnetic cycle of

TABLE I

Annual minimum latitude of zone boundaries of the large-scale magnetic field during the minimum activity of the Sun.

Cycle	Epoch (min)	Northern hemisphere		Southern hemisphere	
		high-latitude	low-latitude	low-latitude	high-latitude
12	1878	55	25	31	51
13	1889	49	28	25	47
14	1901	52	22	28	48
15	1913	48	29	21	44
16	1923	52	25	20	50
17	1933	45	22	25	41
18	1944	42	18	24	48
19	1954	42	24	28	41
20	1964	48	20	24	46
21	1976	49	15	18	43
22	1986	39	18	15	42
23	1996	36	18	22	39

the Sun rather well as pairs of *even–odd* 11-year cycles: in an even 11-year cycle the latitude θ_{2m} is on the average 4° higher than for the subsequent odd one. This means that the area of a polar zone of the Sun occupied by a magnetic field of one polarity varies during a 22-year magnetic cycle (increasing from the even cycle to the subsequent odd one). The low-latitude zonal boundary (θ_{1m}) decreased similarly but less regularly. Nevertheless a correlation between the *odd–even* (opposite to θ_{2m}!) solar cycles is observed. From Figure 3 one can see the general increase of the area of the polar area of the Sun (A_{pz}), occupied by the magnetic field of one polarity during a minimum of activity.

We calculated the variation of the A_{pz} area during 1878–1996. A spherical segment with an angle of $\pi/2-\theta$, where θ is the latitude of high-latitude boundary, has relative area $S = (1 - \sin\theta)/2$ of the complete surface of the Sun. According to the Table I the polar caps of the Sun in a minimum of activity had a relative area 0.20 in 1878, and about 0.39 in 1996. This means that the areas, outlined by the latitude θ_{2m}, increased by a factor 1.95 during 118 years.

This doubling during the last 118 years of the area of the Sun's polar caps, occupied by unipolar magnetic field, corresponds rather well with the increase of the geomagnetic index $\langle aa \rangle$ in this period, Figure 3(a). This means that a doubling of the magnetic flux of the Sun during the past century may be connected, on the whole, with the increase of the magnetic flux from polar caps of the Sun. Indeed, according to Lockwood, Stamper, and Wild (1999) magnetic flux from the Sun (F_s)

was 2.308×10^{14} Wb in 1901 and it rose to a value of 5.325×10^{14} Wb in 1992. Thus there was a rise of the solar flux near the Earth by a factor of 2.3. According to Table I ($\theta_{2m} = 50°$ for 1901; $\theta_{2m} = 40.5°$ for 1986; averaged over N and S) the polar cap areas (A_{pz}) rose by a factor 1.5 during the period 1901–1992. (This is a rough estimation of the correction as the magnetic field lines are bent at distances like one AU.) The calculation goes as follows.

The surface of polar cap with the latitude θ is $S = 1/2(1 - \sin\theta)$, in units $4\pi R^2$ (πR^2 is more suitable as only half the solar surface is visible from the Earth and as only the flux from one cap at a time is relevant for the Earth; however this is irrelevant as we use ratios). Hence $\mathrm{d}S = -1/2 \cos\theta\, \mathrm{d}\theta$. With the induction B we obtain for the change in flux parallel to the equator $\mathrm{d}F = B \cos\theta\, \mathrm{d}S$, where a factor due to the azimuth is omitted as it will just lead to the same factor of proportionality. Integrating from $\theta = \pi/2$ to θ_{2m} under assumption $B =$ constant and omitting the factor of proportionality yields

$$F = 1/2(\pi - \sin 2\theta_{2m} - 2\theta_{2m}). \tag{1}$$

For the ratio between 1901 and 1992 we now obtain 1.8.

We repeat the same calculation using the polar cap corresponding to θ_{1m} (25° for 1901, 16.5° for 1986; average N and S). Now the ratio of the areas is 1.24 and the ratio of the fluxes 1.34. These values seem a little low, which confirms our hypothesis that it is essentially the polar cap corresponding to θ_{2m} that is relevant. In reality the fluxes from the cap to θ_{2m} and the region between θ_{2m} and θ_{1m} are opposite and part of them neutralize each other. So in reality we may have to use a polar cap, which does not extend up to θ_{2m} and this will increase the ratio of the fluxes somewhat, but probably not up to 2.31. Another small increase in the ratios of the surfaces and fluxes may be obtained by using the averages of Θ_{2m}, instead of its minimum θ_{2m}: then some 3° have to be added to the values of θ_{2m}, decreasing the areas a bit, but increasing the ratios. The remaining part may be attributed to an increase of the magnetic field strength (during last 2 or 3 cycles, see below). However, we may agree that there was an increase, on the whole, of the value of the polar cap areas and a minor increase of the field. We shall return to this question in Section 4.4 when discussing the solar magnetic flux during 1964–1992.

4.2. CORRELATIONS BETWEEN $\langle aa \rangle_{11}$, $\langle A_{pz} \rangle_{11}$, $\langle A^* \rangle_{11}$, AND $\langle W \rangle_{11}$-INDEX

It is known that the cycle of a geomagnetic index $\langle aa \rangle$ is displaced with respect to the sunspot cycle (W) by 5–6 years (Simon and Legrand, 1989). However, $\langle aa \rangle$ corresponds rather well with the large-scale cycle $A^*(t)$ that represents the square of the sum of the squares of the magnetic octupole and dipole moments of the unipolar areas. The $\langle aa \rangle$ index is connected with the high-latitude component of the magnetic field and with polar coronal holes. The interplanetary magnetic field is determined by the set of open magnetic fields that depends on unipolar regions.

In Figures 3(a,b,c) we show changes of $\langle aa \rangle_{11}$ index and polar cap areas of the Sun, occupied by unipolar magnetic field $\langle A_{pz} \rangle_{11}$ during 1878–2000. In Fig-

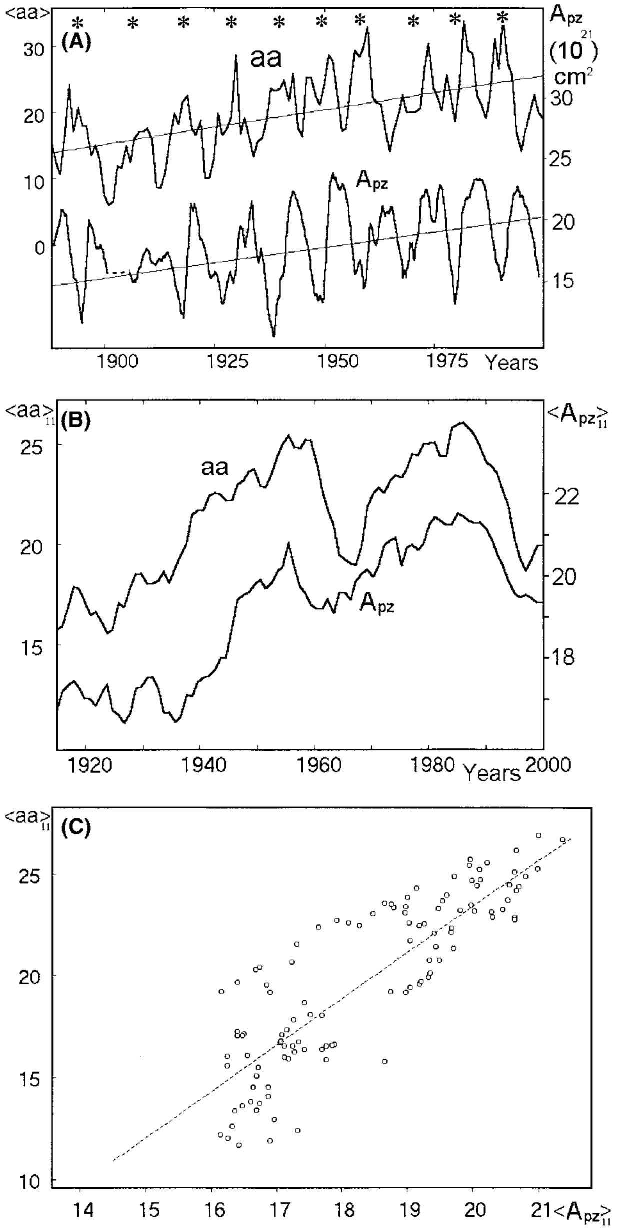

Figure 3. (a) Annual mean value of a geomagnetic index $\langle aa \rangle$ and the area of unipolar magnetic regions of polar caps of the Sun, A_{pz}, at latitudes higher than 40° and their linear approximations. The symbol $*$ marks the epoch of polar magnetic field reversals of the Sun according to Hα synoptic charts. There is no constant phase shift between $\langle aa \rangle$ and $\langle A_{pz} \rangle$ as there is no constant time between two polar reversals. In case there is a three-fold reversal we plotted only the last one. (b) The *continuous curve* A_{pz} represents the run of mean annual area of unipolar magnetic regions of polar caps of the Sun, averaged with 11-year smoothing, during 1915–1999. The *upper curve* represents the value of the geomagnetic index $\langle aa \rangle$ averaged with 11-year smoothing. (c) Correlation between the geophysical index $\langle aa \rangle_{11}$ and the polar cap area $\langle A_{pz} \rangle_{11}$ during 1878–2000. The *points* are obtained from Figure 4 using a one-year unit.

ure 3(a) it is seen that both indexes change practically simultaneously during the last 120 years. The symbol $*$ in Figure 3a marks the epoch polar magnetic field reversals (Makarov and Makarova, 1996). It is remarkable that immediately after a polar magnetic field reversal of the Sun a sharp increase of the $\langle aa \rangle$ index occurs. This is connected with the formation of new polar coronal holes that are responsible for strengthening the solar wind and correspondingly the geomagnetic index $\langle aa \rangle$. Below are shown the correlations based on '11-year' averages of the Sun and the geomagnetic activity over a 118-year period (1878–1996). The regression lines for Figure 4 are

$$\langle aa \rangle_{11} = 0.19 \langle W \rangle_{11} + 8.1 \qquad (r = 0.93), \tag{2}$$

$$\langle A_{pz} \rangle_{11} = 0.16 \langle W \rangle_{11} + 9.3 \qquad (r = 0.82), \tag{3}$$

$$\langle A_{pz} \rangle_{11} = 0.84 \langle aa \rangle_{11} + 22.5 \qquad (r = 0.82), \tag{4}$$

$$\langle A^* \rangle_{11} = 0.15 \langle W \rangle_{11} - 1.6 \qquad (r = 0.87), \tag{5}$$

$$\langle A_{pz} \rangle_{11} = 60.8(1 - \sin \theta_{2m}). \tag{6}$$

(The error flags are usually much larger than what one might expect from the last digit of the coefficients.)

It is noted that the Mount Wilson observations of polar faculae for the time span of about 80 years do not show a long-term variation of the cycle-averaged number of polar faculae. This number may be considered as an index of the polar magnetic field (Sheeley, 1991; Makarov and Makarova, 1998). This may be interpreted that the intensity of polar magnetic field did not change in this period. This suggests the conclusion that the long-term increase of the magnetic flux from the Sun and of the $\langle aa \rangle$ index is caused essentially by growth of the area of polar caps of the Sun.

4.3. POLAR ACTIVITY OF THE SUN DURING 1970–1996

According to the measurements of the near-Earth interplanetary magnetic field the total magnetic flux leaving the Sun has risen by a factor of 1.4 since 1964. At present we have data on the polar cap areas (A_{pz}) and some data on the magnetic field during 1964–1996. According to Table I the value of A_{pz} rose by a factor of 1.4 since 1964, which agrees with the variation of the flux (F). However, we have found an increase of polar magnetic field strength (B_p) from the Kislovodsk observations of the annual mean number polar faculae (N_{pf}) in this period. Indeed, there is a correlation between N_{pf} and the value of polar magnetic field (B_p in gauss) according to Kitt Peak magnetographic observations (Makarov and Makarova, 1998),

$$B_p(\mathrm{G}) \approx 3/40 N_{pf} + 1.0. \tag{7}$$

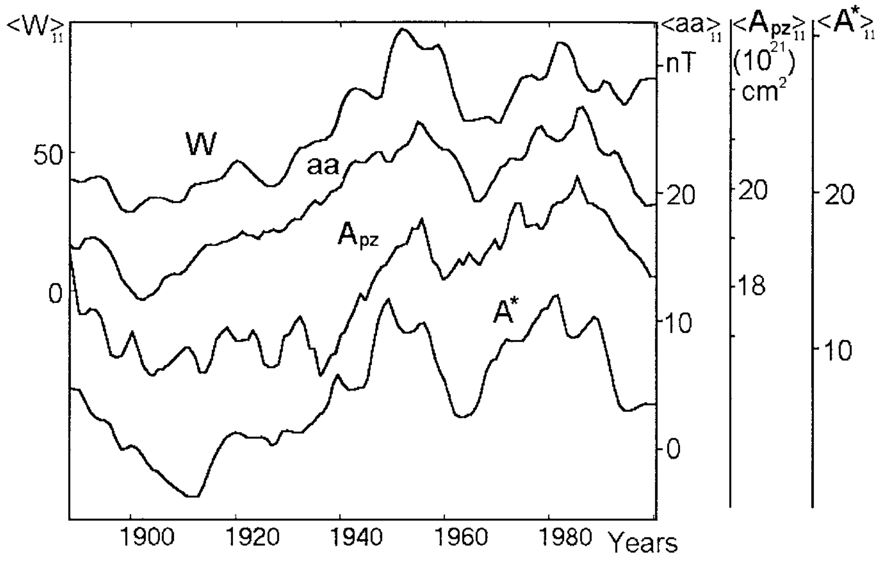

Figure 4. The continuous curves represent different types of solar activity: W is the Wolf number, aa is the index of geomagnetic activity connected with the solar wind, A_{pz} is the area of unipolar magnetic regions of polar caps of the Sun, $A^*(t)$ is the sum of the squares of the magnetic octupole and dipole moments of the unipolar regions. All values are averaged with 11-year smoothing.

We used this correlation to estimate $\langle B_p \rangle_{11}$ for cycles 21 and 23 (1971–1978; 1991–1999). According to Makarov and Makarova (1996, 1999), the mean number of polar faculae per cycle, $\langle N_{pf} \rangle_{11}$, has been 20 for cycle 21 and 40 for cycle 23. Correspondingly the value of $\langle B_p \rangle_{11}$ may be estimated as 2.5 G in cycle 21 and 4.0 G in cycle 23, i.e., an increase by a factor of 1.6.

The observations of polar faculae at the Mount Wilson during about 80 years do not show long-term increase of the number of polar faculae (Sheeley, 1991). According to the formula above the value of polar magnetic field of the Sun did not change during about 80 years. Thus the growth of the field during the last two or three cycles is rather a short time fluctuation. We stay with our conclusion of the last section: the long-term increase of magnetic flux from the Sun and $\langle aa \rangle$ index was caused mainly by growth of the area of polar cap of the Sun occupied by the unipolar magnetic field.

4.4. A DECREASE OF THE TILT OF HELIOSPHERIC CURRENT SHEET DURING THE LAST 80 YEARS

Another estimation of the effect connected with the increase of polar cap areas results from considering the sum of the magnetic moments of the dipole and octupole of the Sun related to the areas of unipolar fields. In reality, the magnetic field of the Sun differs from a dipole and an octupole. The radial component of the heliospheric magnetic field measured by *Ulysses* in both hemispheres showed no variation with

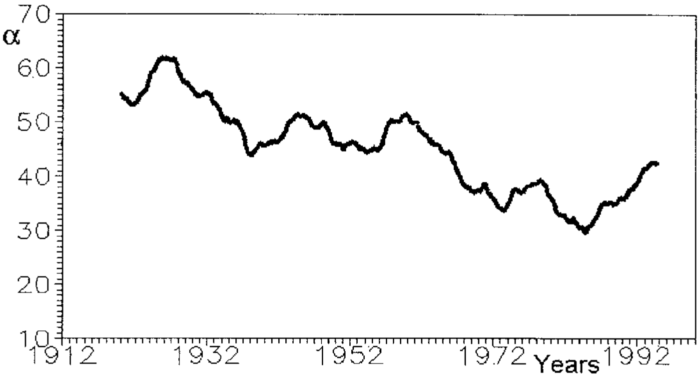

Figure 5. The latitude of the 'equator' plane of the dipole corresponding to the large-scale unipolar magnetic field zones of the Sun during 1915–1999.

latitude, in contrast to what would be expected if the Sun had a dipole for which the radial component is greatest over the poles. Nevertheless we used coefficients of the spherical functions for decomposition of the magnetic fields on Hα charts (Obridko and Shelting, 1999):

$$g_{10} = \mu \sin\theta, \qquad g_{11} = \mu \cos\theta \cos\lambda, \qquad h_{11} = \mu \cos\theta \sin\lambda. \tag{8}$$

Here μ is the magnetic moment, θ is the latitude and λ the longitude of the northern pole of the dipole. These coefficients were used without polar correction. It is possible to determine the magnetic moment of the dipole and the latitude of its 'equator' $\alpha = 90° - \theta$ for every Carrington rotation. The values of α were smoothed out by the '10-year' averages, $\langle\alpha\rangle_{10}$. Figure 5 shows the dynamics of the latitude of the dipole's equator of the Sun during the past 60 years. It decreased approximately from 60° in 1920 to 40° in 1990. This means that '10-year' averages of the latitude of heliospheric current sheet decreased too. Figure 6 shows the value of magnetic dipole of the Sun, μ. One can see a gradual increase in the value of μ, which one might possibly interpret as a growth of the dipole component of the magnetic field. However, it must be kept in mind that we used the neutral lines of the magnetic field on Hα charts and not a real dipole. In fact the increase of the value of μ essentially reflects the growth of the areas occupied by unipolar magnetic field.

4.5. THE LATITUDE ZONE BOUNDARIES DURING THE MAUNDER MINIMUM

The nature of the solar wind during very low sunspot activity like the Maunder Minimum remains uncertain. High correlation between the solar activity (Wolf numbers) and the geomagnetic $\langle aa\rangle$ index allows an extrapolation of the observed solar wind variations to the Maunder Minimum condition. Here we use the correlation between the geomagnetic $\langle aa\rangle_{11}$ index and polar cap areas $\langle A\rangle_{11}$ to obtain an estimate of the latitude of the high-latitude zone boundary (θ_{2m}) in the Maunder Minimum. Using an '11-year' average of the index we obtained

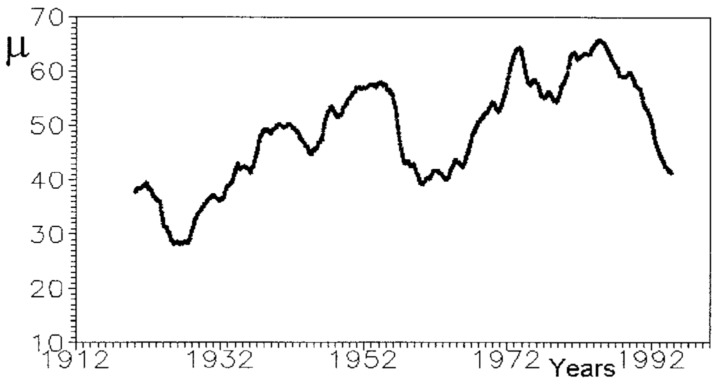

Figure 6. The dipole moment of the large-scale magnetic field of the Sun during 1915–1999.

$$\langle aa\rangle_{11} = 1.2\langle A_{pz}\rangle_{11} - 3.0, \tag{9}$$

$$\sin\theta_{2m} = -0.014\langle aa\rangle_{11} + 0.96. \tag{10}$$

According to Cliver, Boriakoff, and Bounar (1998), the mean level of geomagnetic activity during the Maunder Minimum (1645–1715) was approximately a third of that observed for recent solar cycles ($\langle aa\rangle_{11} = 6.9$–$7.5$ nT vs ≈ 24 nT). Using these estimates one can find that the polar cap areas of the Sun $\langle A_{pz}\rangle_{11}$ correspond to the value of $\theta_{2m} \sim 60°$ in the Maunder Minimum. Putting $\langle aa\rangle$ drastically equal zero yields $\theta_{2m} \sim 75°$, which may be considered as an absolute upper limit latitude of the polar zone boundaries of the large-scale magnetic field during very low solar activity. This absolute upper limit is confirmed by a linear extrapolation in Figure 2, which yields $\theta_{2m} = 83°$ in 1640 when the Maunder Minimum started. The possibility that θ_{2m} starts at 90° at the transition of a new era (like a Maunder Minimum) seems to be excluded by the aa relationship which yields only about 60° as upper limit.

Thus we expect that θ_{2m} oscillates between some upper limit, say 60°, and some lower limit, $< 38°$ (its present value). A deep minimum like the Maunder Minimum may correspond to an extremum of θ_{2m}.

4.6. TEMPERATURE VARIATIONS OF THE EARTH FROM THE MAUNDER MINIMUM TO THE PRESENT TIME

It is known that Earth's surface temperature is correlated with the geomagnetic $\langle aa\rangle$ index (Cliver, Boriakoff, and Bounar, 1998; Cliver, Boriakoff, and Feynman, 1998). For the period 1880–2000 we found that the regression lines for Figures 7(a) and 7(b) are

$$\langle T\rangle_{11} = 0.039\langle aa\rangle_{11} - 0.88 \qquad (r = 0.82), \tag{11}$$

$$\langle T\rangle_{11} = 1.8° - 2.9° \sin\theta_{2m} \qquad (r = 0.75). \tag{12}$$

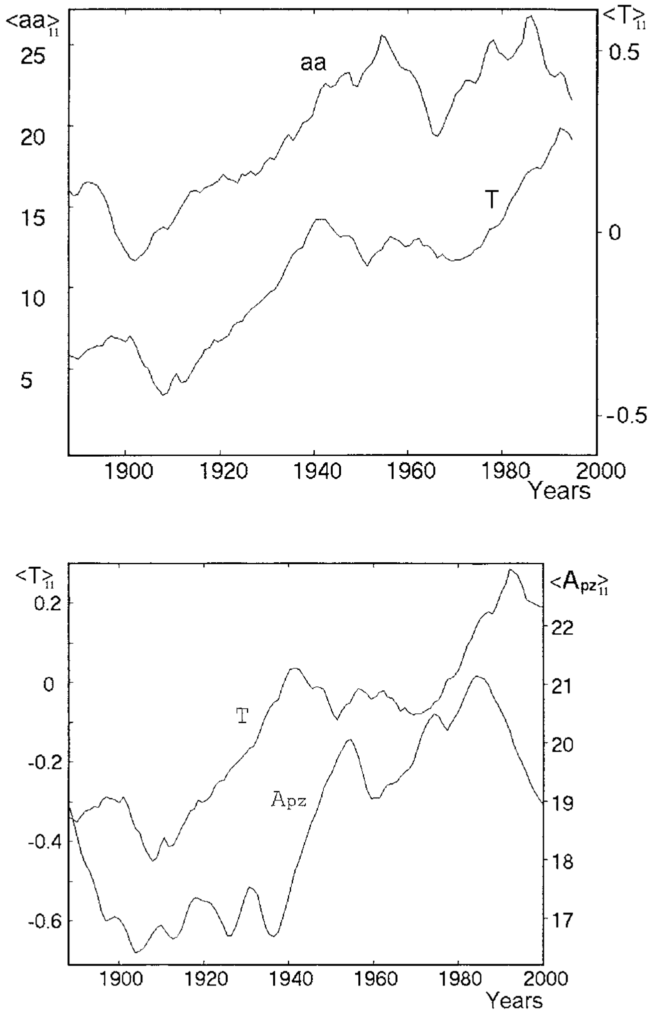

Figure 7. (a) Comparison of the geomagnetic activity $\langle aa\rangle_{11}$ and the variation of the global surface temperature of the Earth, $\langle T\rangle_{11}$, over the last 120 years for 1880–2000. (b) Comparison of the Sun's polar cap area occupied by unipolar magnetic field, $\langle A_{pz}\rangle_{11}$, and the variation of the global surface temperature of the Earth, $\langle T\rangle_{11}$, over the last 120 years for 1880–2000.

We can extrapolate (12) to the Maunder Minimum to infer the solar-induced temperature change. We obtained estimates for the temperature deficit during the Maunder Minimum (−1.0°) relative to the present (~ 0°), yielding an increase of 1.0°. Cliver, Boriakoff, and Bounar (1998) estimated an increase of ~ 0.7°–1.5° in global surface temperature since the second half of the 17th century. Thus, an increase of the Sun's polar cap area occupied by unipolar magnetic field (solar forcing) is correlated to the global warming over the past 350 years besides greenhouse warming, ocean–atmosphere coupling, etc.

5. Discussion

In the last cycle 23 the value of $\langle A_{pz}\rangle_{11}$ corresponds to the latitude $\theta_{2m} = 38°$. This value is not far from the latitude $\sim 37°$, where $\partial_r\omega = 0$ with $\omega(r,\theta)$ the angular frequency of the solar rotation (Kosovichev *et al.* (1997). The Sun has a central uniformly rotating sphere ($\partial_r\omega = 0$ and $\partial_\theta\omega = 0$) to which two 'conical blades' ($\theta \sim 37°$) are attached where $\omega(r,\theta)$ has the same value. These conical blades, one in each hemisphere, extend from the uniformly rotating sphere to the solar radius. They separate the polar sectors, where $\partial_r\omega < 0$, from the equatorial sectors, where $\partial_r\omega > 0$. These sectors correspond respectively with the polar faculae and sunspot regions. The separation between those sectors, $\partial_r\omega = 0$, corresponds with θ_{2m}, (the minimum of the annual averages of Θ_{2m}) or with the average of Θ_{2m}, the more or less stable position of the boundary of the polar region of unipolar field from polar reversal till the beginning of the next cycle. Hence this yields an additional link between the large-scale unipolar field, sunspot cycle and polar faculae cycles, besides the previous links (i.e., all three have the same period and the large-scale field regions and the polar faculae cycles precede the sunspot one). The large-scale regions pass from the sunspot region to the polar faculae region and take their 'rest' at Θ_{2m} during minimum activity at the separation between both, where $\partial_r\omega \sim 0$. (We do not bother here that there may be a few degrees difference between $\partial_r\omega = 0$, θ_{2m} and the average Θ_{2m}.)

Table I and Figure 2 clearly show that θ_{2m} has been steadily decreasing during the last 120 years. We advance the hypothesis that the conical blades, where $\partial_r\omega = 0$, have the same evolution as they are presumably the cause of Θ_{2m} and θ_{2m}. Clearly this must bear consequences for the sunspot and polar faculae phenomena, including the deep minima.

Thus the layer in the convection zone where $\partial_r\omega = 0$ decreases too from some upper limit in latitude (60°). For the lower limit of θ_{2m} we have no hard arguments. However, the difference $\theta_{2m} - \theta_{1m}$ is about 21° and remained roughly the same during the last 120 years. For θ_{1m} we do not have a clear link with $\omega(r,\theta)$. Supposing that $\theta_{1m} - \theta_{0m}$, where $\theta_{0m} = 0°$ (new boundaries are generated at the equator), should not drop below 21° (i.e., the same difference as $\theta_{2m} - \theta_{1m}$) then θ_{1m} is at present at its low minimum. The coming cycles may be rather particular, maybe on the verge of a new deep minimum. However, as now θ_{2m} reaches its minimum value instead of its maximum, the coming deep minimum may have a different character (may be similar to the Spörer Minimum instead of the Maunder one?). Anyway, we suggest that the causes of the waxing and waning of the Sun's activity like in the Maunder Minimum are connected with poleward and equatorward migration of the conical blade, where $\partial_r\omega = 0$.

The relation between the concentration of ^{14}C and solar activity is well known. Stuiver and Quay (1980) have detected a few periods of very low activity of the Sun: the Maunder Minimum (1645–1715), the Spörer Minimum (1416–1435, 1470–1534), the Wolf Minimum (1282–1342) and, probably, the Oort Minimum

(1010–1050). The mean duration of low activity is about 60 years and the mean length of time between the minima is about 220 years, or about 20 solar cycles. This corresponds to a latitude drift of the zone boundary of 24°. Again this is an indication that the Sun may be turning soon (in 1 or 2 cycles?) into a period of low activity with a duration of about 60 years. Some other papers also predicted the period of very low solar activity at the beginning of the XXI century (Chistyakov, 1983; Badalyan, Obridko, and Sýkora, 2001).

One may wonder whether there is a contradiction between A_{pz} increasing (and contributing to global warming) and a grand minimum. However, a grand minimum may constitute a phase of reorganization so that θ_{2m} and θ_{1m} occur again at higher latitudes. Anyway in a grand minimum the activity becomes so low that the corresponding flux practically vanishes.

6. Conclusion

Our analysis indicates that the area of polar zones of the Sun, occupied by unipolar magnetic field at the minimum activity, has risen by a factor of 2 during 1878–1996. Using only the component parallel to the equator yields roughly 2.4. Thus the behavior of the index $\langle aa \rangle$ in this period and consequently the magnetic flux from the Sun may be explained by an increase of the area of polar caps with roughly the same value of the magnetic field, although the field shows fluctuations, as, e.g., an increase during the last 3 cycles. Indeed our analysis shows that the magnetic flux from the Sun increases by a factor of 1.4 since 1964 and this agrees with the observations. But we have found an increase of polar magnetic field strength (B_p) from the observations of the annual mean number of polar faculae (N_{pf}) in this period. Consequently the mean polar magnetic field $\langle B_p \rangle$ has been estimated of 2.5 G in cycle 21 and 4.0 G in cycle 23, i.e., an increase by a factor of 1.6. Hence there was an increase of the value of the polar field of the Sun, but on an interval of time of about two to three 11-year cycles. Long-term increase of magnetic flux from the Sun was mainly caused by growth of the area of polar cap of the Sun occupied by the unipolar magnetic field.

A new index of polar activity of the Sun $\langle A_{pz} \rangle$ (area of polar cap occupied by a unipolar fields) has been compared with the aa, W and A^*-index. We used the correlations between $\langle aa \rangle$ and $\langle A_{pz} \rangle$ to estimate the limit latitude of the high-latitude zone boundary θ_{2m} to be about 60°. Its minimum is $< 38°$, the present value.

We suggest that θ_{2m} practically coincides with the conical blades where $\partial_r \omega = 0$ and thus that these conical blades have a similar oscillatory motion between say 60° and $< 38°$. It is supposed that deep minima of solar activity may occur when these conical blades reach extreme latitudes. This may be an indication that we are approaching a new deep minimum.

We estimated an increase of 1° in the temperature of the Earth from the Maunder Minimum to the present time.

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