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The Increase in the Magnetic Flux from the Polar Regions of the Sun over the Last 120 Years

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Abstract—The latitudes of the zonal boundaries of the global magnetic field of the Sun are determined from the magnetic neutral lines on synoptic Hα maps obtained during 1878–1999. The area of the polar zone occupied by magnetic field of a single polarity at solar minima has doubled over the last 120 years. This provides an explanation for the secular increase in heliospheric characteristics, which differs from the two-fold increase of the magnetic field strength predicted for this period. The temporal variations of the magnetic flux from the polar regions and their role in global changes of the Earth's climate are discussed in connection with secular variations in the structure of the internal magnetic field of the Sun. © *2001 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

A number of indirect pieces of evidence for the growth in the solar magnetic field with time have recently been published [1]. This is related to both changes of the internal structure of the Sun and to the global warming and growth of the surface temperature of oceans on the Earth [2]. Recently, warming was detected in both meteorological observations and dendrology measurements. As a rule, global warming is associated with human activity. An analysis of measurements of the radial component of the interplanetary magnetic field detected at the Earth's orbit during 1964–1996 was performed in [1]. This analysis shows that the magnetic field in the solar corona has grown by 40 per cent over the last 32 years. The behavior of the ⟨aa⟩ geomagnetic-activity index over the last 100 years suggests that the solar magnetic field has grown by a factor of 2.3 [1].

This conclusion is very important from a theoretical point of view, since it presents fundamental new problems and restrictions for dynamo theory. In addition, it is obvious that this effect could be significant for geophysical phenomena and long-term climatic variations. On the one hand, the magnetic field is the source of every activity on the Sun. On the other hand, there is a correlation between the Wolf number (as an index of local activity) and the total flux of the solar radiation. Consequently, we expect that the flux of solar radiation should change with time. Indeed, the solar radiation changes with a period of about 11 years. However, we are interested here in the long-term trend, namely, the growth of the solar radiation by 0.036 per cent each decade [3].

Note, however, that a direct comparison of the results of [1] and [3] is rather complicated. One usually associates variations in the solar radiation with local fields (numbers of sunspots and flocculi). At the same time, the heliospheric magnetic field is determined by open configurations, which, in turn, are determined by global and large-scale magnetic fields. The contribution of local magnetic fields is rather small. These fields exhibit an 11-year periodicity, while variations in the global magnetic field of the Sun lead those of the local magnetic field by 5–6 yrs [4, 5]. In addition, it is shown in [6, 7] that the global magnetic field, together with the local field, is responsible for variations in the solar radiation to an appreciate extent. The results presented in [1] agree with the previous results of [8], which showed that computations of the magnetic field near the Earth and in the heliosphere based on observations of the photospheric magnetic field are in agreement with direct measurements made by instruments on spacecraft.

The results of [1] and [8] were recently criticized in [9, 10], where it was pointed out that solar observations over the last 32 years do not indicate any "secular" or long-term variations in the magnetic field. Kotov and Kotova [9, 10] attribute the agreement between the computations and measurements of the magnetic field to the application of an artificial correction that depends on the latitude of the measurement point. However, we do not accept all the arguments presented in [9, 10]. For example, the observations of the Sun as a star interpreted in [9, 10] as observations of the total magnetic field of the Sun are not unambiguously related to the interplanetary magnetic field. In fact, the "magnetic field of the Sun as a star" reflects the imbalance between the magnetic fluxes of opposite polarities detected in the visible solar hemisphere. The magnetic fields of various structures contribute to this quantity, with weights proportional to the radiation intensity. The peripheral portions of the visible solar hemisphere make a small contribution. It is particularly important that the polar magnetic field, which dominates in the formation of the heliospheric magnetic field, also makes a small contribution. These magnetic fields of various structures contribute to the "magnetic field of the Sun as a star" and the heliospheric magnetic field with different weights, which is of fundamental importance.

Note that some of these remarks are also applicable to the Stanford measurements of the magnetic field used in [8]. It is well known that the solar polar magnetic fields indicated by magnetograph measurements are strongly underestimated. A correction taking into account the latitude dependence of the polar field is not unquestionable and, in part, was introduced precisely to provide agreement with measurements performed near the Earth. Therefore, we cannot consider an agreement between the computations and spacecraft measurements as an independent verification of the relation between them. Note also that the "coronal" magnetic field used in [1], in fact, is the magnetic field at the base of the heliosphere; i.e., at distances of $(2.5–3.5)R_0$ from the center of the Sun. As a rule, the coronal magnetic field is defined as the field at distances considerably smaller than $2.5R_0$.

2. OBSERVATIONAL DATA

We consider here data on the latitude-temporal distribution of unipolar regions of large-scale solar magnetic field accumulated over 120 years (1878–1999). These data were derived from synoptic Hα maps of the distribution of magnetic neutral lines constructed using the technique presented in [11, 12]. Although these data are based only on the polarity of the magnetic field, they provide reliable statistic information on long-term variations of the global field. Studies of magnetic Hα maps have led to detailed analyses of changes in the polarity of the solar magnetic field [13], the discovery of three-fold changes in the polarity of the polar magnetic field [14], the detection of the 55-year cycle of solar activity in torsional vibrations [15], and the conclusion that the large-scale magnetic field of the Sun is primary with regard to the local fields of active regions [5, 16]. The magnetic Hα maps were tested via comparisons with various solar and geophysical data: the number of polar faculae and the divergence of polar magnetic field lines indicated by eclipse data [17], and variations of Galactic cosmic rays [18, 19]. We can estimate the polar activity of the Sun at the photospheric level from the number of polar faculae observed at the Kislovodsk Mountain Station of the Main Astronomical Observatory in 1960–1999 [20]. There is a correlation between the number of polar faculae and the strength of the polar magnetic field [21].

3. VARIATIONS OF THE AREA OF POLAR REGIONS

The axially symmetric component of the solar magnetic field exhibits a zonal structure with a characteristic scale that is determined by either the mean latitude of the magnetic neutral lines or the boundaries of the zonal structure [13, 14]. As a rule, at solar minima, $l = 3$ for $m = 0$, where l and m are numbers of harmonics of the magnetic field expanded in spherical functions. During an activity minimum, the boundaries of the zonal structure are located near latitudes of 40° and 0°, but vary from cycle to cycle. At solar maxima, the magnetic-field structure is described by $l \sim 5–7$ for $m = 0$. During these periods, in addition to two high-latitude boundaries that drift toward the poles, there are two zonal boundaries at latitudes of about 20° in both hemispheres.

As is noted in [1], solar magnetic-field data for the last 100 years were derived from analyses of the geomagnetic index $\langle aa \rangle$. This planetary magnetospheric index has been determined since 1868 from three-hour measurements of the geomagnetic field at two antipodal stations [22]. The high correlation between $\langle aa \rangle$ and the velocity of the solar wind near the Earth reflects the fundamental relationship between solar and geomagnetic activities. It is known that the cycle of the geomagnetic index $\langle aa \rangle$ includes several components [23]. The component related to the poloidal magnetic field (polar coronal holes) is shifted with respect to the sunspot cycle by 5–6 yrs [23]. The heliospheric magnetic field is determined by collections of open magnetic lines associated with the solar polar regions.

We can estimate the secular variations of the heliospheric field by estimating long-term variations in the ratio of the areas occupied by local and global fields. The concept of a boundary separating regions of global (polar) and local magnetic fields was introduced in [24]. This boundary characterizes secular variations in the ratio of the areas occupied by local and global fields in the clearest manner at the minima of 11-year cycles. Table 1 and Fig. 5b of [24] present the locations of high-latitude boundaries of the zonal structure of the magnetic field at solar minima. These boundaries separate the high-latitude unipolar magnetic field of the Sun from the local magnetic fields of active regions of sunspots and faculae. Table 1 and Fig. 5b of [24] show that the high-latitude zonal boundary separating polar and sunspot activities moved toward the equator by on average 15° over the 12 solar cycles from 1878 to 1999 (Fig. 1). The northern zonal boundary shifted from 55° in 1878 to 36° in 1996. A similar phenomenon takes place in the southern hemisphere, where the zonal boundary shifted from 51° in 1878 to 39° in 1996. During this whole time, the behavior of the high-latitude boundary clearly exhibits the magnetic 22-year cycle as a pair of even and odd 11-year cycles. On average, the latitude of this high-latitude boundary is 4° higher in even cycles than in odd cycles. This means that the area of the solar polar zone occupied by magnetic field of a single polarity and, probably, the flux of the dipolar magnetic field change during the 22-year cycle. This behavior is less clearly visible for the low-latitude boundary. Nevertheless, a reversed law can be observed; i.e., a pair of odd and even cycles. Note that the northern hemisphere was more active than the

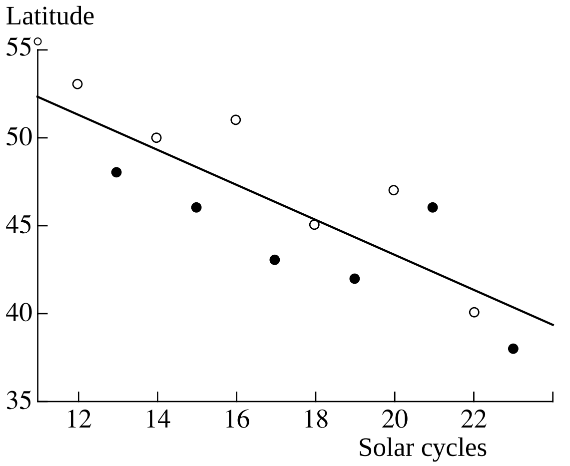

Fig. 1. The latitude of the zonal boundary of the large-scale magnetic field of the Sun at minima of 11-year cycles 12–23 from 1878 to 1996 from magnetic synoptic Hα maps (the filled and empty circles correspond to odd and even cycles).

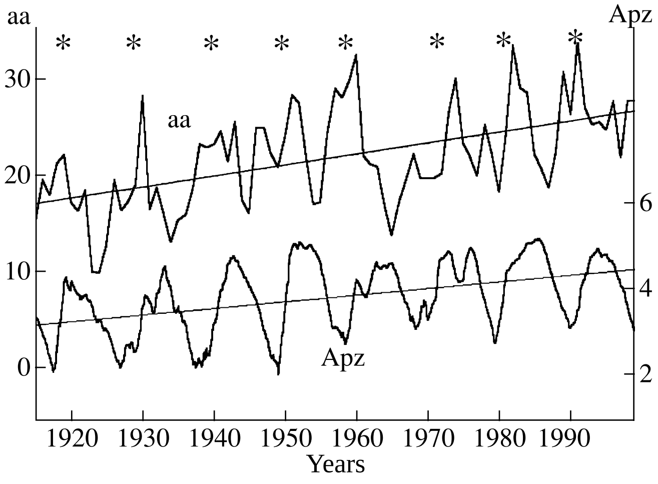

Fig. 2. The annual average geomagnetic index ⟨aa⟩ and area Apz of unipolar magnetic regions of the solar polar caps for latitudes above 40° and corresponding linear approximations. The asterisks mark epochs of polarity reversals of the polar magnetic field derived from Hα maps.

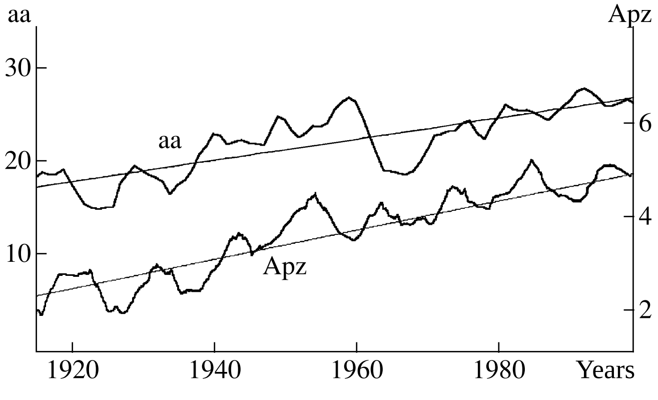

Fig. 3. The index ⟨aa⟩ and area Apz of polar caps smoothed with a window of six years during the period 1915–1999.

southern hemisphere over the last 120 years, since it displayed a shift of the zonal boundary toward the equator of 19°, while the southern shift was only 12°. Nevertheless, the total increase in the area of the solar polar zone occupied by magnetic field of a single polarity at solar minima is clearly observed.

Let us consider variations of the area of the polar zone of single polarity of the solar magnetic field during 1878–1999. A spherical segment with angle $\pi/2 - \varphi$, where φ is the latitude of the high-latitude boundary, occupies a relative area $S = (1 - \sin\varphi)/2$ in units of the total solar surface. Table 1 from [24] shows that, at solar minima, the polar region of magnetic field of a single polarity occupied a relative area of 0.202 in 1878 and 0.392 in 1996; i.e., this area increased by a factor of 1.9. This almost twofold increase in the area of the high-latitude zone of unipolar magnetic field over the last 120 years is in agreement with the increase in the geomagnetic index ⟨aa⟩ during the same period (Fig. 2). Therefore, we attribute the doubling of the solar magnetic field obtained in [1] to an increase in the magnetic flux from the polar regions of the Sun, associated with an increase in the area occupied by field of a single polarity. Obviously, this polar magnetic flux is determined by polar coronal holes and is directly related to the geomagnetic activity expressed by ⟨aa⟩. This result is connected with the problem of long-term changes in the internal structure of the Sun, which, in turn, is related to global variations of solar activity and the Earth's climate. The Maunder minimum of solar activity and corresponding "little ice age" on the Earth is a clear example of climatic changes due to the global changes in solar activity.

Let us introduce as an index of variations of the global magnetic field the area of the solar polar cap (with latitudes higher than 40°) occupied by magnetic field of a single polarity. We denote this area Apz. Figure 2 compares the temporal variations of ⟨aa⟩ and Apz in 1915–1999; it is clear that variations in ⟨aa⟩ and Apz are virtually identical. The asterisks in Fig. 2 mark epochs of polarity reversals for the polar magnetic field during this period (according to [20]). We can see an abrupt increase in ⟨aa⟩ immediately after polarity reversals. This is clearly associated with the formation of polar coronal holes, which enhance the solar wind and, accordingly, the geomagnetic index ⟨aa⟩. Figure 3 shows ⟨aa⟩ and Apz smoothed over six years. We can see that the behavior of the two indices is virtually the same over these 85 years.

We can obtain another estimate of this effect by calculating the sum of the magnetic moments of the solar dipole and octupole fields [5] using the coefficients of the expansion of the magnetic field into spherical functions for Hα maps for 1915–1999 [17]:

$$h_{10} = \mu\sin\varphi, \quad g_{11} = \mu\cos\varphi\cos\lambda,$$
$$h_{11} = \mu\cos\varphi\sin\lambda,$$

where μ is the dipole magnetic moment, φ and λ are the latitude and longitude of the north pole of the dipole in

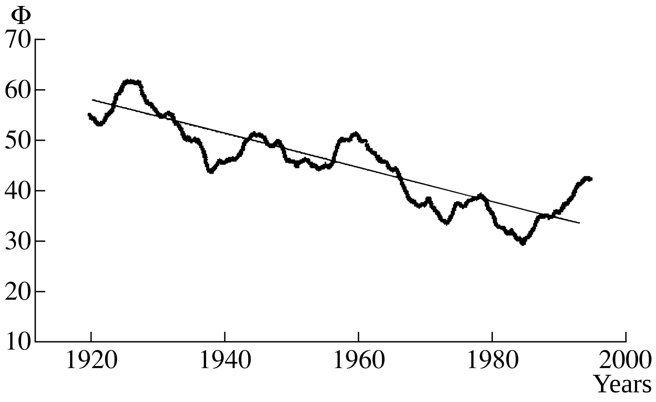

Fig. 4. The latitude of the solar magnetic dipole "equator."

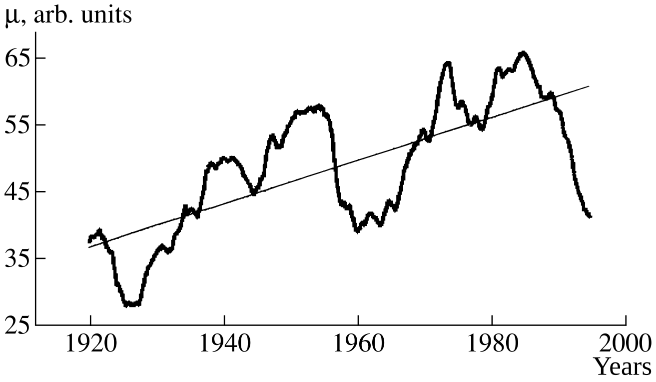

Fig. 5. The magnetic dipole moment of the Sun.

a Carrington coordinate frame, and g_{10}, g_{11}, and h_{11} are the expansion coefficients presented in [17]. Note that these coefficients do not include a polar correction. We can determine the dipole magnetic moment and the latitude of its "equator" $\Phi = 90° - \varphi$ using these relations for each Carrington rotation. We then smoothed these quantities with a ten-year window. Figure 4 presents the position of the solar dipole equator Φ. We can see a gradual trend of Φ to move toward lower latitudes. This means that the average (over 10 years) position of the solar dipole equator and the similar tilt of the heliospheric current sheet decrease with time. Figure 5 shows the magnetic dipole moment μ of the Sun. We can see that there is a clear trend, which can be interpreted as a growth in the magnetic dipole field. However, we should remember that our calculations use only neutral lines of the magnetic field derived from Hα maps. This means that the increase in μ actually describes the growth of the polar-cap area discussed above.

Therefore, this suggests that the area of the polar region occupied by magnetic field of a single polarity at solar minima has nearly doubled over the period 1878–1996. This is directly related to the conclusion drawn in [1] based on an analysis of the geomagnetic index ⟨aa⟩ that the magnetic field increased by a factor of two over the past 100 years [1]. Here, we show that the increase in ⟨aa⟩ is more likely due to an increase in the area of the solar polar cap and the corresponding increase in the magnetic flux from the Sun, which had been interpreted as an increase in the magnetic field strength. However, our result does not resolve the problem of global secular variations of the solar magnetic field, but only turns it in another direction. The nature of secular variations of the zonal structure of the solar magnetic field remains unclear.

4. POLAR MAGNETIC FIELD OF THE SUN

High-latitude and polar activity of the Sun is not displayed only by coronal holes. Polar faculae in white light accompanied by kilogauss magnetic fields, bright X-ray points, and transient active regions represent a special class of solar activity at latitudes above 40°. We have a uniform series of measurements of the number of polar faculae performed in Kislovodsk since 1964 and the dependence of the polar magnetic field on the number of polar faculae [21]. We can use these data to estimate changes in the polar magnetic field of the Sun from 1964 to the present and compare these with observations.

We will consider the 20th to 23rd cycles of solar polar activity (1965–1999) separately. According to [1], the total magnetic flux from the Sun has increased by a factor of 1.4 since 1964. Since a substantial fraction of the flux is associated with the solar polar region, we can use the available data on the area of the polar cap and the mean number of polar faculae per cycle [21]. Using these data, we can easily show that the area of the polar cap occupied by magnetic field of a single polarity (at solar minima) has increased by a factor of 1.5 over this period. This provides evidence that changes in the magnetic flux from the Sun are mainly associated with changes in the high-latitude region occupied by field of a single polarity.

According to [1], the annual average amplitude of the radial component of the interplanetary magnetic field near the Earth has increased by a factor 1.4 since 1964. It is well known that the mean number of polar faculae per cycle increased by a factor of three from 1965 to 1996. There is a relation between the number of polar faculae (NPF) observed at Kislovodsk and the polar magnetic field (in Gauss) measured at Kitt Peak. According to [21], we obtain

$$B\,(\mathrm{G}) \sim 3/40\ \mathrm{NPF} + 1.0.$$

Using the published data, we can easily see that the mean magnetic field of the Sun has increased by a factor of 1.5: from 2 G in 1965 to 3 G in 1996. Taking into account our estimates and the correlations presented in [1], we find that the solar polar magnetic field did, indeed, increase, but over a shorter time interval of about two–three 11-year cycles. Since the Mount Wilson polar-faculae observations do not indicate any long-term increase in the number of polar faculae over 80 years [25], this suggests that the polar magnetic field did not change. Thus, we conclude that the long-term increase in the magnetic flux from the Sun and in the index ⟨aa⟩ is associated with a growth in the area of the solar polar cap during this period.

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