RELATION BETWEEN ‘SOLAR MAGNETIC DIPOLE’ AND FILAMENT BANDS

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ABSTRACT

The “solar magnet” consists of several components: (a) the large-scale unipolar magnetic field regions and their boundaries, the filament bands; (b) a variable dipole yielding polar plumes; (c) other effects. The filament bands have a poleward motion (speeds up to 50 m/s) except for a “recoil” after polar reversal (when the upper unipolar zone disappears at a pole) and the subsequent “rest” during the minimum of solar activity. The filament bands carry huge currents, which repulse/attract each other. Numerical estimates yield large accelerations which are roughly compensated by the friction of the “skin layer” constituting the unipolar regions slipping over the solar surface as a connected sheet as it is pervaded by a magnetic field and does not mix with the solar surface. When new large-scale unipolar zones originate near the equator the additional repulsion of the filament bands causes the poleward motion of the previous filaments; moreover the upper one interacts with the dipole of the polar plumes. The surprising “recoil” of the remaining filament bands may be partially explained by the variation of this dipole and by a recoil of the “skin layer”.

Key words: filaments, unipolar regions, polar reversal, solar cycle.

1. INTRODUCTION

The need to connect the variety of magnetic phenomena on the Sun becomes more and more apparent as the observations show more and more that they are all causally related. During more than a solar cycle we have been stressing the relations between the various magnetic phenomena on the Sun: (a) Relation between sunspots and polar faculae: the butterfly diagram for polar faculae precedes (and allows predictions) of the butterfly diagram for the sunspots, Makarov (1983), Makarov and Sivaraman (1989), Makarov and Makarova (1996); moreover Makarov and Makarova (1999); see Martin and Harvey (1979) too. (b) Relation between the Wolf number and the large-scale unipolar magnetic fields, Makarov and Sivaraman (1986), Makarov and Sivaraman (1989), Callebaut and Makarov (1992), Makarov (1994), Makarov and Tlatov (1999), Makarov et al. (2001a). (c) Relation between Maunder Minimum and absence of polar magnetic field reversals, Makarov and Sivaraman (1983), Makarov and Callebaut (1999). (d) Relation between solar cycle, radius and luminosity, Callebaut et al. (2000). (e) Maunder Minimum, magnetic flux and climate, Makarov et al. (2001b). (f) Relation between polar field reversals, filament bands and solar activity, Makarov and Sivaraman (1983), Makarov et al. (2001). (g) In fact all phenomena are related, including the so-called torsional oscillations, the strength and variation of the so-called solar dipole, etc.

Globally one may state that 3 phenomena dominate (at least in appearance) the solar magnetic activity: the sunspots, the polar faculae and the large-scale unipolar field regions. The relevance of these three major aspects of the global solar cycle was stressed by Callebaut and Makarov (1992). Here we are essentially concerned with the large-scale unipolar field regions, or rather with the filament bands (= filaments joined together by filament channels) which encircle the whole Sun and form the borders of the large-scale unipolar regions. They divide the whole surface of the Sun in 5 to 7 or 9 irregular zones encircling the Sun. It may be noted that McIntosh (2003) investigates these large-scale unipolar regions in a somewhat different way which make his interesting results rather complementary to ours. The generation of new unipolar regions and filament bands near the equator, their pole-ward motion, their oscillations around a stationary position between the equator and pole, their disappearance at the poles entailing a polar reversal of the magnetic field and a recoil of the subsequent filament band are the object of the present study. This, however, entails considerations on the rather vague concept of the solar dipole or rather the solar magnet as a whole.

This paper corrects and extends our previous work (Callebaut et al., 2002).
2. OBSERVATIONAL DATA

2.1. Observational basis

Observational data on the polar migration of magnetic fields were obtained from the H-alpha synoptic charts for 1880 - 1992. They reflect the distribution of polarity of the magnetic field in this period, Makarov and Sivaraman (1969). Cf. Makarov and Callebaut (1999). The value of the field doesn’t follow from these observations (it is a few gauss), only the sign. It turns out that there are many regions of unipolar fields with predominantly the same polarity - opposite to the existing field- which are generated near the solar equator, when a new cycle starts. They increase in surface and after a few solar rotations they merge into very irregular large-scale unipolar regions which after a few years have typically a size like a quarter of the solar surface. Their pole-ward motion is equally well observed through the motion of the filament bands which form the separation between the neighboring regions.

2.2. Filament bands

Filaments and filament channels may constitute together a filament band, i.e. a magnetic flux tube encircling the whole Sun. As they represent the border between regions of opposite polarity they have no magnetic field in the line of sight; however, a field of a few gauss parallel to the tube exists and huge currents flow in the tubes. Taking a radius of 5 000 km for the flux tube and a current density of 1 mA/m² yields $10^{11}$ A. Even a value of $3 \times 10^{11}$ A is mentioned by Priest (1985).

The very irregular shape of the flux tube becomes more and more circular as it reaches higher latitudes. One may introduce for each filament band a kind of average latitude $\theta$ at a given moment for each of them. Thus we may consider $\theta$ as evolving with time from the equator to a pole. For simplicity we consider one hemisphere only. Usually we have three filament bands in an hemisphere, which we label by $\theta_0$ for the one situated near the equator, $\theta_1$ for the previous one, which has moved already at a somewhat higher latitude, and $\theta_2$ for the one who has a still higher latitude. However, their motion to the poles is by no means uniform: during the minimum of the solar cycle they all remain more or less at the same latitude: say $\theta_0 = 0$, $\theta_1 = \theta_{1m}$ and $\theta_2 = \theta_{2m}$. Numerical values of $\theta_{1m}$ and $\theta_{2m}$ are given in Makarov (1994), where it is shown that these latitudes decrease on the average over about $13^\circ$ after each cycle. For the cycle 23 we have in the northern hemisphere $\theta_{1m} = 18^\circ$ and $\theta_{2m} = 36^\circ$, while in the southern hemisphere we have $\theta_{1m} = 22^\circ$ and $\theta_{2m} = 38^\circ$. Clearly these values represent a time average during the phase of minimum solar activity: in reality oscillations around these values occur: a few degrees up or down, with a quasi-period of 1.3 to 1.6 years, Makarov (2002b). When a new cycle starts all three filament bands move to the pole until $\theta_2$ reaches the pole and disappears, changing the polarity of the pole as the next unipolar region now takes over. After this polar reversal the other filament bands experience a recoil, i.e. they move away from the pole toward the equator by about $10^\circ$ in the course of say 2 years. These recoils are nearly absent or much less pronounced in the case that 3 polar reversals occur during one maximum.

3. DRIVING MECHANISMS OF THE POLE-WARD MOTION OF FILAMENT BANDS

How to explain the pole-ward motion of the large-scale unipolar magnetic regions and their accompanying filament bands? Pole-ward speeds of 10 to 50 m/s, even 70 m/s, occur, while after polar reversal first an equator-ward motion (recoil) happens, followed, during the period of low solar activity, by a more or less stationary situation with small back and forth oscillations.

3.1. Magnetic surface layer

At the beginning of a new solar cycle, new magnetic unipolar regions are generated around the equator: they increase in size and spread and merge with each other after a few rotations to form a large-scale region. One can imagine that a lot of matter pervaded by a weak magnetic field is pumped up to the surface in the vicinity of the equatorial plane and spreads to form ultimately a magnetic layer of say 100 to 1000 km thick, which covers the solar surface corresponding to a large-scale unipolar region like a sheet. This sheet is not perfectly unipolar: some small “islands” of opposite polarity are present too. The larger the separating power of the instruments, the more small islands of opposite polarity may be visible, but still the dominance of one polarity in a large-scale zone is overwhelming. However, this magnetic sheet does not merge with the underlying solar surface as its magnetism prevents it, according to the theorem for perfectly conducting plasma attributed to Alfvén. Hence it may slip over the solar surface with not too great frictional resistance.

This layer may not be too thick: as it moves over the photosphere or forms part of it, it has to be fairly transparent and 1000 km seems an upper limit taking a reasonable density. On the other hand it may not be too thin either since the decay time for its magnetic field then becomes too short. The characteristic decay time (i.e. to drop by a factor e) for a field with wavelength $\lambda$ is

$$\tau = \frac{\lambda^2}{4\pi^2 \eta}$$

with $\eta = (\mu \sigma)^{-1}$ the resistivity; SI units. We estimate $\eta$ to be 1 to 100 m²s⁻¹. Taking $\eta = 10$ m²s⁻¹
and identifying \( \lambda \) with its upper limit, i.e. the thickness \( D \) of the layer, we obtain \( \tau = 2.5 \cdot 10^7 \) s or about a year for \( D = 100 \) km. This is too short as the sheet lives about 2 solar cycles (meaning that at least three characteristic times have elapsed). On the other hand, taking \( D = 1000 \) km yields a characteristic time of 100 years, which is definitely too long. Hence a fair estimate for \( D \) is 200 - 300 km (about the thickness of the photosphere), however depending on the estimate for \( \eta \).

Clearly this sheet, in popping up and spreading, pushes the preceding filament bands and the previous unipolar regions away toward the poles. However, the inertia and the viscous resistance of the existing layer opposes this and it seems hard to believe that the mechanism of emerging and spreading is powerful enough.

3.2. Sunspots?

It was shown by us, Makarov et al. (2000), that the pole-ward migration rate of the large-scale fields is practically linearly related to the power of the solar cycle, i.e. the accumulated number of sunspots (similarly their accumulated surface) as represented by a new index "the strength of the solar cycle". This suggests the following idea. Sunspots pop up and spread their surface as well as the large regions of weak fields do. However, a sunspot has a surface which is about \( 10^{-4} \) of the solar surface. Hence 100 sunspots only cover a per cent of the solar surface. Even taking this 5 times larger does not seem relevant to push the large-scale regions away. Moreover the sunspots, even if they are only a 1000 km deep, may be anchored deeper into the solar material by a magnetic tail, which rather will prevent motion. In fact it is known that sunspots have a small pole-ward motion, of the order of one m/s; in fact they are dragged by the pole-ward motion of the surface magnetic sheet which is driven by another, much stronger force. However, the spots can not be the immediate cause of the pole-ward motion in spite that the correlation found in Makarov et al. (2000), is very convincing. (We refer essentially to the cases where only one polar reversal occurs in the hemisphere; when the number of sunspots is very large 3 polar reversals may occur in one or both hemispheres during one cycle. The relation is then similar but more complicated.) The real cause must be narrowly connected and about simultaneous with the accumulated Wolf number, i.e. the generation of sunspots and the generation of new unipolar magnetic field zones around the equator are two manifestations of the same basic mechanism.

3.3. Repulsion between filament bands

It was stated above that huge currents flow in the filament bands. Neighboring filament bands have anti-parallel currents, which repel each other. For the force per running meter we have: 
\[
F = \mu I_1 I_2 / d^2 \quad \text{N/m, where } I_1 \text{ and } I_2 \text{ are the (anti)parallel currents, } d \text{ is the distance between them and } \mu = 4\pi \cdot 10^{-7} \text{ henry/m. If } L \text{ is the length of the filaments and taking the currents both equal to } I \text{ we have:}
\]
\[
F(L) = \frac{\mu I^2 L^2 g^2}{d^2}.
\]

Here \( g \) is a geometrical factor: indeed half of the “interaction space” between the currents is taken by the Sun and its high conductivity screens the interaction (even a bit more than half in view of the curved surface; on the other hand the highly conducting solar surface may “mirror” somewhat the field lines causing some compensation); moreover the current in a unit length may interact only with about 1/4 of \( L \) as the rest is too far away and disappears behind the solar horizon. Hence we estimate that \( g = 1/2 \times 1/4 = 1/8 \). The minimum distance for \( d \) seems to correspond to about 20º: this is the distance between the rest latitudes of the filament bands; it is as well roughly the distance between the newly born filament band and its predecessor. The maximum distance for \( d \) corresponds roughly to 40º at most: say the difference in latitude when the upper filament reaches the pole and the next filament band has exceeded the upper rest latitude (about 40º) by about 10º. That means that the value for \( d \) lies between 250 000 and 500 000 km. The currents may vary between \( 10^9 \) to \( 3 \cdot 10^{13} \) A. Taking moderate values: 
\[
d = 4 \cdot 10^8 \text{ m, } L = 3 \cdot 10^9 \text{ m and } I = 3 \cdot 10^{10} \text{A}
\]
yields 
\[
F(L) = 10^{15} \text{ N. According to Newton's law we equalize this force to the inertial force:}
\]
\[
Ma = F(L),
\]

where \( a \) is the acceleration and \( M \) the mass of a filament band. Taking a cylinder of length \( L \), radius \( r_o \) and mass density \( \rho \), with \( n \) the number density and \( m \) the amu (1.67 \cdot 10^{-27} \text{ kg})), \( n \) may vary from \( 10^{13} \) to \( 10^{18} \text{ m}^{-3} \). Taking \( n = 6 \cdot 10^8 \text{ m}^{-3} \), thus \( \rho = 10^{-10} \text{ kg/m}^3 \) and \( r_o = 5 \cdot 10^5 \text{ m} \). Thus 
\[
M = \frac{\pi r_o^2 L \rho \text{ kg, yielding } M = 2 \cdot 10^{13} \text{ kg. Substituting in Newton's law yields for the acceleration}}
\]
\[
a = \frac{\mu I^2 L^2 g^2}{\pi r_o^2 \rho d^2}.
\]

With the chosen values we obtain 50 ms^{-2}. This value is exceedingly high, in spite of the fact that we took moderate values. Such an acceleration means that in about 1 s the maximum speed of the poleward motion is reached! The current has the strongest influence: taking it 10 times smaller still yields an acceleration of 0.5 ms^{-2}, still very large. Varying the other values may alter the result somewhat but not the conclusion: clearly some slowing down mechanism(s) must be taken into account and there is no doubt that the repulsion between the filament bands is the major driving force of the poleward motion.
3.4. Correction for the mass of the magnetic surface sheet

In fact the filament band is linked magnetically to the surface sheet and when the filament band moves the surface sheet has to move too; indeed, the filament band constitutes the boundary of the large-scale unipolar regions and they move together. Hence in the previous calculation we have to add the mass of the surface sheets over nearly half a hemisphere. Taking a thickness of 306 km and the same mass density as the one in the filament band yields a mass \( M' = 2 \pi R^2 D \) which is 5 times the one which we calculated for the filament itself. That means that the acceleration will be 5 times smaller. Still there is a strong need for slowing down mechanisms.

4. SLOWING DOWN MECHANISMS

4.1. Friction force

Although the magnetized sheet does not mix or merge with the underlying solar surface and thus "easily" slips over it, a certain friction force should be taken into account. This force will be proportional to the surface area, which for all large-scale regions of one hemisphere is close to half the total surface of the Sun. We may estimate the friction coefficient to be very low in the equatorial region, but it will be stronger in the polar region, as the surface sheet is not an ideal conductor and thus some re-connection and merging with the underlying material will occur after a few years and as the fields weaken due to the resistive losses (see section 3.1). Yet, it seems very difficult to estimate such a friction force. We do not know of experiments in laboratories where such measurements were done.

However, it is possible to calculate it indirectly from the "near to stationary situation" at the rest latitudes. Indeed, during the minimum of solar activity the two filament bands remain at their rest latitudes, about 39° and 18° for this cycle which means that their current repulsion is compensated by the friction force. (Note that their difference in latitude remained practically constant during 12 cycles, which indicates that the friction force remained constant too during some 130 years, as it should.) The fact that the filament bands still make small oscillations around their rest latitudes indicates that the two forces are rather well in balance. Thus we obtain:

\[
F_{\text{fric}} = \frac{\mu I' I'' L' L'' y^2}{a^2},
\]

where \( d' \) is the corresponding distance (250 000 km, see section 3.3) and \( L' \) and \( L'' \) are the lengths of the filament bands at their rest latitudes. Similarly for the currents \( I' \) and \( I'' \). The latitude circles are a bit shorter than the equator; on the other hand the filament bands are still very irregular in that position, making them much longer. However, only the parallel components are relevant so we take \( L' = 4 \times 10^4 \) m and \( L'' = 2 \times 10^9 \) m. The currents are not yet much weakened thus we take again \( I = 3 \times 10^{10} \) A for both. There results: \( F_{\text{fric}} = 2 \times 10^{16} \) N.

Now the mechanism becomes clear: during the minimum of the solar activity the currents in the filament bands keep each other at a (roughly constant) distance, being halted by the friction force. As soon as new unipolar magnetic field zones start to be born around the equator, the supplementary force of the new filament band gives a hand and the friction force is overcome and the pole-ward motion of the former filament bands sets in. As soon as the upper filament band has reached the pole (and thus disappears) the repulsive force is reduced and the friction force may balance again the repulsion between both remaining filament bands.

4.2. Attraction between not-neighboring filament bands

The second next neighboring filament bands have parallel currents and thus exert an attractive force. As the distance may be taken twice as large as for neighboring ones, the attractive force is one quarter of the repulsive one. This would introduce a factor 3/4 in our previous calculation, but not drastically reduce the acceleration. Moreover, second next filament bands are too large extend hidden for each other by the curved solar surface, even if they are some 30 000 km above the solar surface. However, near the equator, where the unipolar regions are generated the second next filaments may play a serious role, as the filament bands are rather near to each other; moreover they have a very irregular shape there. These aspects may be relevant in connection with the stationary phase which they experience during minimum activity and for the more precise calculation of the friction force.

4.3. Influence from currents in the corona

There are currents flowing in the corona, especially in the equatorial region. These may affect somewhat our previous calculations, in particular the one concerning the friction force.

4.4. Own repulsion from a filament band

A circular current experiences some repulsion on its own current. However, this may play only a role when the filament band has shrunk already very much, so that the curvature of the solar surface does not prevent the repulsion from the other parts of the circle on an element. Moreover, when a filament band is near the pole, its current has decreased a lot, due to eruptions and to resistivity.
5. RECOIL MECHANISM AFTER POLAR REVERSAL

When a filament band reaches a pole the enclosed unipolar region disappears and a polar reversal occurs as the next unipolar region takes over: it looks like as the Sun has changed the polarity of this pole (the other pole changes its polarity too, at a time interval of usually a few months). Then a surprising equator-ward motion of the subsequent filament bands starts. This stops gradually and the filament bands reach their rest latitudes after one or two years. This “recoil” is surprising, in view of the previously explained balance between the repulsive forces and the friction. However, the material of the magnetic sheet has been accumulated within a ring growing smaller and smaller, hence the thickness of the layer increases considerably at the pole. Once the filament band decays by eruptions and by resistive losses, this accumulated matter flows back and pushes the subsequent unipolar sheet and filament band back, causing the recoil. However this may be only part of the story: presumably the solar magnetic dipole (see below) plays a role too.

That the pole changes its polarity although the former surface layer is still present may be due to two reasons. In fact the magnetic field in the former sheet layer has decreased very much due to ohmic losses. Secondly, the interaction with the solar magnetic dipole (see below) plays a role as well.

6. THE SOLAR MAGNET

The concept of solar magnet is usually rather vague. In fact there are several components:

(a) Clearly the large-scale unipolar magnetic field regions and their associated filament bands constitute largely the global solar magnetism. Moreover, the upper unipolar region, covering the pole has a dominant importance, certainly when looking at the Sun from a distance. The magnetic field lines of filament bands below latitude 45° close in themselves so that the contribution from that region to the global solar magnetism is negligible. It may be noted that we showed (Makarov et al., 2002) that the large-scale unipolar region covering the polar region has doubled its surface during the last 120 years; this may be relevant in various ways: as a possible explanation of the supposed doubling of the magnetic flux at the Earth (Lockwood et al., 1999, but contested by Svalgaard, 2003) and as an explanation for the decrease in the temperature of the corona in polar regions (Makarov et al., 2003).

(b) Yet, at the poles there is a kind of polar cap (some 20° around the pole) with polar plumes, as observed during eclipses and then daily by SOHO. By drawing tangents to the polar plumes one may define a “solar magnetic dipole”. In fact the tangents converge rather well, of course each hemisphere has its part of this “solar magnetic dipole”. However, this dipole is variable. Moreover, during the polar reversal, when the large-scale unipolar region overtakes it, it is barely observable. Hence it may be supposed that it is weaker than the large-scale unipolar region, and, yet, not too much, as it pops up again afterward. However, this “solar magnetic dipole” maybe changes polarity around the time that the large-scale unipolar region overtakes the pole. It seems excluded that a kind of permanent magnetic dipole (or multipole) exists in the convective zone. However, a small oscillation of the bottom layer of the convective zone may create such a kind of variable dipole, or at least a field which manifests itself as such by being transported from the bottom of the convective zone to the solar surface by the convection.

(c) Other effects: all other magnetic phenomena on the Sun may contribute, but seem less important as they vary in shorter time spans than the causes considered above.

7. RELATED PHENOMENA

7.1. The 1.3 - 1.6 year oscillations of the magnetic neutral lines

Using \( H_g \) charts we analyzed the latitude drift of the zonal magnetic boundaries during 1915 - 2000, Makarov et al. (2002b). A new type of long-term latitude oscillations of these boundaries with quasi-period of about 1.3 to 1.6 years was found. Their properties (horizontal velocity and amplitude) were studied during 8 solar cycles. On the other hand the rotation rate at the base of the convection zone in the equatorial plane shows an oscillatory behavior with a period of about 1.3 year during 1995 - 2000. It is supposed that there may be a possible link between the latitude fluctuations of the magnetic boundaries of the large-scale regions and this kind of deep equatorial torsional oscillations. See next section too.

7.2. Relation between \( \theta_{2\nu} \) and the conical blades where the angular rotation velocity is stationary

The angular rotation velocity \( \omega (r, \theta) \), with \( r \) the radial co-ordinate and \( \theta \) the latitude, has inside the Sun a locus where it remains constant with respect to \( r \), while \( \theta \) practically remains constant. Thus a conical blade in each hemisphere of constant \( \omega \) is present. For the latitudes closer to the equator \( \omega / \partial r > 0 \), while for the latitudes on the polar side of these blades \( \omega / \partial r < 0 \). Inside the Sun they start at the sphere where \( \omega \) is practically constant. They cut the solar surface at about 37°, which practically coincides with the stationary localization of the filament bands during the time of minimum magnetic activity. This is roughly the separation between the sunspot region and the polar faculae region. The latitude oscillations mentioned in the section above may thus...
be connected with the deeper regions, in particular the bottom of the convection zone and thus with the torsional oscillations which appear there.

8. CONCLUSION

The huge currents flowing in the filament bands bordering the large-scale unipolar field regions exert a strong repulsive action on their neighboring filament bands. This, enforced by the generation of new unipolar regions and filament bands near the equator, causes the pole-ward motion of those structures. The unipolar regions are presumably constituted by a surface sheet, pervaded by a small magnetic field, which may slip over the underlying solar material. The repulsive forces are much too strong for the observed speeds of the pole-ward motions, even when the mass of the surface sheet is taken into account to increase the inertia of the filament bands. Several possible mechanisms that may slow down the motion are considered. The stationary phase, in which the filament bands and the large-scale unipolar regions take a rest and make only small oscillations around a kind of equilibrium, allows to estimate the friction force. It is our aim to determine the values of various quantities involved, in particular the currents flowing in the filaments and in the equatorial region of the corona, from observations, in order to be able to give more precise results. A possible (partial) explanation for the surprising recoil of the subsequent filament bands after polar reversal is given. The solar magnetic dipole causing the polar plumes in a region of about 20° around each pole may play a role too in this.

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