ORIGIN OF SUNSPOTS

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Abstract. Sunspots, seen as cool regions on the surface of the Sun, are a thermal phenomenon. Sunspots are always associated with bipolar magnetic loops that break through the solar surface. Thus to explain the origin of sunspots we have to understand how the magnetic field originates inside the Sun and emerges at its surface. The field predicted by mean-field dynamo theories is too weak by itself to emerge at the surface of the Sun. However, because of the turbulent character of solar convection the fields generated by dynamo are intermittent – i.e., concentrated into ropes or sheets with large spaces in between. The intermittent fields are sufficiently strong to be able to emerge at the solar surface, in spite of the fact that their mean (average) value is weak. It is suggested here that magnetic fields emerge at the solar surface at those random times and places when the total magnetic field (mean field plus fluctuations) exceeds the threshold for buoyancy. The clustering of coherently emerged loops results in the formation of a sunspot. A non-axisymmetric enhancement of the underlying magnetic field causes in the clustering of sunspots forming sunspot groups, clusters of activity and active longitudes. The mean field, which is not directly observable, is also important, being responsible for the ensemble regularities of sunspots, such as Hale's law of sunspot polarities and the 11-year periodicity.

1. Introduction

Sunspots are the oldest and yet the most popular indicators of solar activity. Besides being confused by these impurities on the divine Sun, some old reports associated sunspots with natural hazards. For example, sunspots were believed to be the cause of great forest fares, see Figure 1. As a proxy for the solar activity sunspots are currently broadly used in Space Weather studies.

The origin of sunspots is still, however, a long-standing mystery. Why is it still an outstanding problem? We surely understand the nature of sunspots better than Sir Robert Hooke who believed that they were soot in the solar fire. It is now known by the public (see numerous web sites) that sunspots are relatively cool areas that appear as dark blemishes on the face of the Sun. Thus, a *sunspot is a thermal phenomenon by appearance.* We also know that a sunspot is an area of strong (3 kG) magnetic field that inhibits the convective transport of heat and consequently makes this area cooler than the surrounding surface. Therefore, *a sunspot is a magnetic phenomenon by origin.* Many early models that attempted to explain the origin of sunspots considered only magnetic features at the surface and close to the surface. [For a good review of early sunspot models see Wilson (1984).] Although 'local' models produced important insights, a more global approach seems to be the way

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Figure 1. An artistic view of the appearance of sunspots during forest fires, such as reported by Russian Church Chronicles in the 14th century (Vyssotsky, 1949). Smoke from fires makes sunspots visible to the naked eye. To what extent solar activity lead to droughts and fires is still unclear. The general level of solar activity at that time was rising strongly, as indicated by ^{14}C data (Eddy, 1976).

to the ultimate solution. What we need to understand is *how the magnetic field originates inside the Sun and emerges to its surface*. This approach was, in fact, well formulated in the classical concept of sunspot birth, according to which a magnetic flux rope rises through the convection zone and appears at the surface as a bipolar loop giving the birth to a pair of spots (Parker, 1955; Babcock, 1961). The flux rope was assumed to be generated in the convection zone by the differential rotation, its rise caused by the magnetic buoyancy (Parker, 1955) or due to the conversion of twist stored in the initial flux rope into a kink (Babcock, 1961).

This paper discusses modern developments of the classical concept. Because it is about the sunspot origin, magnetic fields are the central issue. Discussion of the sunspot thermal aspects, which are closely related to magnetic fields, can be found for example in (Spruit, 1977). For sunspot decay see (Petrovay and van Driel-Gesztelyi, 1997). Sunspots are interesting in the Earth's climate context because they, together with bright faculae cause solar irradiance variations (Hoyt and Schatten, 1998; Solanki and Fligger, 1998).

2. Observational Keys to the Nature of Sunspots

The understanding of sunspot origin is guided by a large number of observational facts. The major findings and those particularly related to the magnetic fields are:

– Spots occur in a latitudinal zone of width about 20 deg. The earliest spots in a given solar cycle appear at about 30 deg in both hemispheres. Each spot or sunspot group lives only days or month but the mean latitude of their appearance migrates toward the equator with the 11-year cycle (the butterfly diagram).
– Spots occur in bipolar pairs with preceding (p) and following (f) members showing opposite magnetic polarities. The p-f polarities are opposite in the northern and southern hemispheres and reverse with the 11-year cycle (Hale's law).
– The p spot is closer to the equator than the f spot. The angle between the line connecting these spots and the east-west direction increases with latitude.
– A sunspots is preceded by the appearance of bright and dark features (faculae and pores) and is formed by the merging of these features. Faculae are closely identified with small magnetic flux tubes, pores are middle-size flux tubes, see for example Zwaan (1979).
– Spots tend to recur in sites where there has been prior activity. This results in clustering of sunspots into groups and long-lived clusters of activity (Gaizauskas *et al.*, 1983).

Observations of individual sunspots are fully consistent with the classic concept of an emerging magnetic loop, whose feet then form the opposite-polarity part of the newly born sunspot pair. At the same time, the observations show that a sunspot is not formed in a single flux emergence but through the assembling of many emerged features (loops) and that sunspots have a tendency to group.

Observations of sunspots as an evolutionary ensemble indicate the existence of a regular azimuthally directed subphotospheric magnetic field which changes its direction each 11-year cycle.

3. Theoretical Keys

3.1. The Cause of Cyclic Behavior

Theoretical studies were first aimed mainly on explaining the solar cycle behavior of sunspots. Magnetic loops were assumed to be caused by instabilities of a largescale, mean magnetic field **B** generated by the dynamo action of the differential rotation $\nabla\Omega$ and mean helicity α of the convection jointly:

$$\frac{\partial B}{\partial t} = \nabla\Omega \cdot \nabla \times \mathbf{A} + \eta \Delta B, \tag{1}$$

$$\frac{\partial A}{\partial t} = \alpha B + \eta \Delta A, \tag{2}$$

where B is the azimuthal (toroidal) component of the mean field and A is an azimuthal component of the vector potential of the poloidal (radial and latitudinal) part of the field ($\mathbf{B_p} = \nabla \times \mathbf{A}$) and η is the magnetic diffusivity (Parker, 1955; Moffatt, 1978; Krause and Rädler, 1981; Zeldovich *et al.*, 1983). Meridional circulation, omitted from Equations (1) and (2) for the sake of simplicity, also affects the mean field (Durney, 2000). These mean motions (differential rotation, helicity and circulation) arise due to interaction of solar rotation and turbulent convection. The solution of Equations (1) and (2) has the form of equatorward propagating waves:

$$B = B(k\theta - \omega t), \qquad B_p = B_p(k\theta - \omega t + \varphi). \tag{3}$$

The frequency and wavelength of these waves are determined by the distribution of the differential rotation and the mean helicity. These distributions can be adjusted to yield the 11-year period, and the ratio and phase shift φ between the toroidal and poloidal components observed on the photosphere. These conditions are at best satisfied if the differential rotation is concentrated in a thin layer at the convection zone-radiative core boundary and the helicity is located higher up in the convection zone (Ivanova and Ruzmaikin, 1976). Modern mean-field dynamo models, which include the differential rotation found from helioseismic data (Tomczyk *et al.*, 1995), support this type of distribution (Charbonneau and MacGregor, 1997). The field amplitude is mainly constrained by the back action of the field on the mean helicity[1].

Thus, it looks like the mean-field dynamo explained the basics of the sunspot cycle: the butterfly diagram and Hale's law of spot polarities.

3.2. Why and How the Magnetic Loops Emerge

More recently, theories of instabilities leading to the formation of emerging magnetic loops have been advanced (Fan *et al.*, 1993; Caligari *et al.*, 1995, 1998; Matthews *et al.*, 1995; Weiss, 1997; Dikpati and Gilman, 1999). The emergence of loops is treated in the thin flux tube approximation which describes a flux tube as a string of Lagrangian fluid elements subjected to the action of magnetic, pressure, gravitational and rotational forces. It has been shown that a simple untwisted horizontal flux tube, rising through the convection zone, rapidly develops a mushroom shape and splits into a vortex pair that move horizontally instead of rising (Schüssler, 1979; Longcope *et al.*, 1996). If however the magnetic field inside the flux tube is twisted, i.e., has both longitudinal and transverse components, the flux tube can be stable against the splitting. Because the longitudinal field decreases

[1] The criticism of the dynamo, based on the idea that the dynamo action is quenched if the mean field exceeds some very small critical value (Vainshtein and Rosner, 1991), has been shown to be invalid (Field *et al.*, 1999).

more rapidly than the transversal component, a rising flux tube becomes more twisted and could be kink unstable converting the twist into coil – the effect we experience when twisting a telephone cord. This effect, in fact, was proposed by Babcock (1961) as a crucial element in sunspot formation.

A flux tube rising with speed v is influenced by solar rotation. The Coriolis force $2v \times \Omega$ suppresses the motion perpendicular to the axis of rotation thus forcing the rising flux tubes to move along this axis and emerge at higher latitude (Choudhuri and Gilman, 1987). To satisfy the observed latitudinal distribution of sunspots, indicated by the butterfly diagram, the Coriolis action has to be compensated by the magnetic buoyancy that pushes the flux tubes to emerge radially. This compensation occurs only if a field at the bottom of the convection zone is sufficiently strong, about 10^5 G. A field of this strength is also required to obtain the observed inclination of the line connecting the p and f spots with respect to the east-west direction (Howard, 1992; D'Silva and Choudhuri, 1993).

The results of numerical simulation of the flux tube dynamics depend on the initial conditions adopted at the bottom of the convection zone. A flux ring (located in a plane parallel to the equator) in mechanical equilibrium is a proper initial state to which other states, such as a flux tube in a thermal equilibrium with the environment, tend to attract (Caligari *et al.*, 1995, 1998). Mechanical equilibrium means that the flux tube is non-buoyant and the inward-directed magnetic curvature force is compensated by the outward-directed centrifugal force due to the faster rotation of plasma inside the tube. The non-buoyant nature of the mechanical equilibrium permits the storage of flux tubes at the bottom of the convection zone (in particular in the overshoot layer) for a period of time during which the field strength can be amplified by the dynamo to a critical value about 10^5 G. At this value the flux tube looses its stability, becomes buoyant, and, within a month or so, rises to the solar surface.

3.3. DYNAMO AND FLUX TUBES

Now it is natural to combine the dynamo, which generate the initial magnetic field, and the models of storage-instability-eruption of flux tubes. However, there is a problem to resolve. The mean-field dynamo described above does not produce magnetic fields as large as 10^5 G. The maximum field produced by the mean-field dynamo can not exceed the value of about 10^4 G. This estimate follows from the balance of magnetic and Coriolis stresses: $B_p B_\phi \approx 4\pi \rho v \Omega l$, where Ω, l are the angular velocity and the characteristic scale of the field at the bottom of the convection zone. It is known from surface observations that the mean azimuthal field exceeds the mean poloidal field by a factor of 100. This ratio of the azimuthal and poloidal fields also follows from the comparison of poloidal and toroidal terms in Equations (1) and (2). Using $\Omega \approx 3 \times 10^{-6}$ s^{-1}, and $l \approx 0.05\times$ depth of convection zone $\approx 2 \times 10^9$ cm, $\rho \approx 0.1$ g cm^3, $v \approx 2 \times 10^3$ cm s^{-1}, the mean field value is estimated to be 8.7×10^3. Although the estimation includes somewhat uncertain parameters, using different values or different arguments, such as equipartition, results in an even lower value for the field. A field that weak will not erupt at all.

To resolve the problem we reexamine the nature of the solar dynamo. The motions in the convection zone are highly turbulent. Only on average can these motions be approximated by the differential rotation, mean helicity and meridional circulation. The magnetic fields must also be highly turbulent. Equations (1) and (2) obscure this point. However, remember that although the production of the toroidal field from the poloidal field (due to the differential rotation) does not require any turbulent (fluctuating) fields, the fluctuating field, **b**, is needed to produce the poloidal field. The explicit form of the source for the poloidal field is $\overline{\mathbf{v} \times \mathbf{b}}$, which is approximated by $\alpha B + \eta \Delta A$ in Equations (2) assuming that $B \gg b$. This condition is valid because the magnetic Reynolds number R_m in the convection zone is very large ($> 10^8$) (Krause and Rädler, 1981; Zeldovich *et al.*, 1983). Without the reproduction of poloidal field the toroidal field dissipates within the turbulent diffusion time of a few years. Hence, the solar dynamo mainly produces strong random, fluctuating fields which, after averaging, give a weak mean field.

These random fields are not everywhere but are distributed intermittently in space and time. What causes the intermittency? The magnetic field in the solar convection zone is highly frozen-in, i.e., controlled by plasma motions because the magnetic Reynolds number is extremely large. The shear motions at the bottom of the convection zone (Kosovichev *et al.*, 1997) tend to stretch any initial field distribution into ropes or sheets with large spaces in between. Even under a pure random distribution of stretching-squeezing directions, the stretching effect will predominate. The probability density of the field amplitudes generated by random motions has a large, non-Gaussian tail and progressively growing statistical moments indicating a very non-uniform, concentrated spatial and time distribution (Molchanov *et al.*, 1984). In the fully frozen-in situation the stretching would produce infinitely thin flux tubes. In reality, the Ohmic resistivity defines the flux tube thickness. The mean field is evidently much less than the field in a flux tube. This picture has been supported by numerical simulations (Meneguzzi *et al.*, 1981; Brandenburg *et al.*, 1990). Although the magnetic Reynolds number used in these simulations is much smaller than that in the Sun, the simulations show a very clear tendency toward increasing intermittency with the increase of R_m.

On these grounds, the present author proposed invoking fluctuating magnetic fields (in addition to the regular, mean field) in the flux emergence problem (Ruzmaikin, 1997). Because there is no limit on the possible strength of a fluctuation (except a diminishing probability of having a stronger one) the problem of insufficient field strength immediately disappears. The magnetic fields emerge at the solar surface at random times and places when the total magnetic field (mean field plus a fluctuation) exceeds the threshold for buoyancy (Figure 2). In this way the mean field is responsible for observed regularities of the sunspot magnetic fields, such as the Hale's law and the 11-year periodicity, and the fluctuating fields are responsible for emergence of individual flux tubes then merging into sunspots.

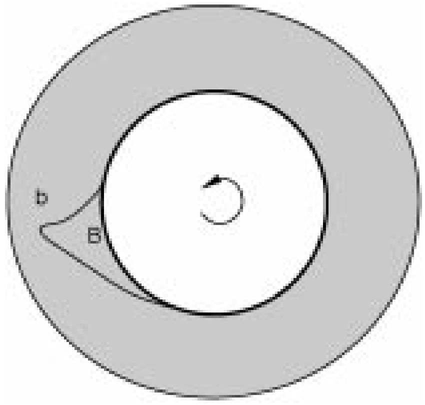

Figure 2. A schematic illustration of cooperative emergence of the mean, B, and fluctuating, b, magnetic fields. Shown is a latitudinal cut of the Sun viewed from the North Pole.

4. Sunspot Formation as a Clustering Phenomenon

Faculae and pores that coalesce into sunspots are also due to emergence of magnetic fields, suggesting that sunspot formation is a result of clustering of many magnetic loops (Zwaan, 1978; Parker, 1979b). This leads to a picture, first introduced by Piddington (Wilson, 1984), in which the subsurface magnetic field of sunspots has a treelike structure with tiny flux fibers branching from flux strands that are in turn branching from a base flux rope (Schruver and Title, 2000). This picture, however, precariously assumes that for each sunspot there is a strong subphotospheric flux rope located below the photosphere at a shallow depth of a few sunspot sizes.

An alternative view advocated here is a clustering of intermittent magnetic fields generated by dynamo in the deep convection zone. The principle difference to the above approach is that it does not assume the existence of a single flux tube (a trunk of the ‘Piddington tree’) which then splits into a bunch of smaller flux tubes. Magnetic fields emerge naturally whenever and wherever their strength exceeds the 10^5 G threshold. The only requirement is that the sum of the mean field determined by the mean-field dynamo and a coherent fluctuating field must exceed the threshold. Those emerged magnetic loops that were spatially correlated at the base of the convection zone form patterns (clusters) on the surface of the Sun. The cause of this coherency is the mean field, the size of the coherent region is probably determined by a turbulent cell disturbing the mean field. Near the surface, the loops of the same polarities are attracted to each other. The mechanisms of the flux tubes attraction near the solar surface are discussed by Parker (1979). The merging feet of these loops, which have same polarities, form a sunspot. The magnetic loops which are not involved in clusters show up as numerous faculae spread over the solar surface.

In principle, the same random clustering can lead to the formation of sunspot groups. However the number of observed large-scale patterns of solar activity is noticeably deviates from clustering expected from purely random emergence (Harvey and Zwaan, 1993). There are too many clusters of activity which often group at some 'active longitudes' (Gaizauskas *et al.*, 1983). Thus emergence of a fluctuating field on the back of the uniform (toroidal) mean field is not sufficient. To explain the persistency of flux emergence we need some enhancements (' humps') of the mean field. The magnitude of humps can still be smaller than the threshold (Ruzmaikin, 1998). Then, whenever a coherent (i.e., having the same direction) fluctuating field of sufficient amplitude appears in the vicinity of the hump, the resulting field emerges to the surface of the Sun. The threshold for these fluctuating fields is thus effectively lower in the vicinity of the hump.

These enhancements could be perturbations with strong but sub-threshold amplitudes. The enhancements also arise as non-axisymmetric modes of the mean field (Ruzmaikin, 1998). These modes give preferred longitudes. The main mode in the mean-field dynamo (Equations (1) and (2)) is axisymmetric (has azimuthal number m=0). The m=1 and m=2 and higher m modes ($B \propto \sin m\phi$) are also excited, see for example (Krause and Rädler, 1981) and observed on the solar surface (DeToma *et al.*, 2000). The m=1 mode of the toroidal magnetic field superimposed on the axisymmetric mode will produce a 'hump' near the maximum of $\sin\phi$. When the turbulent motions are strong enough the amplitudes of these modes can be comparable to the amplitude of the axisymmetric mode (Krause and Rädler, 1981). The humps are unstable when their field strength reach 4×10^4 G (Caligari *et al.*, 1995, 1995). Because the growth of these 'weak' perturbations is affected by the continuous stretching by differential rotation, they will be destroyed before leaving the bottom of the convection zone. The stretching time scale of several months is in agreement with the observed life-time of the clusters of about 6 months (Gaizauskas *et al.*, 1983).

5. Sunspot Cycle as a Threshold-Crossing Phenomenon

From observations we know that individual sunspots appear in days and disappear in weeks, but as an ensemble they come and go with the 11-year solar cycle. The concept of strong random fields with a weak regular mean value allows a natural explanation of this ensemble behavior (Ruzmaikin, 1997). The principle is similar to the threshold-crossing effect used in the studies of weak periodic signals detected in the presence of noise (Wiesenfeld and Moss, 1995). Figure 3 illustrates this idea. The 11-year periodic signal represents the mean magnetic field near the bottom of the convection zone. The amplitude of this signal is small so that the field can not exceed the buoyancy threshold shown by a line at unity. Thus the mean field is invisible to the surface observer. Random fields, in contrast, can from time to time exceed the threshold but if there is no regular mean field they would appear on the

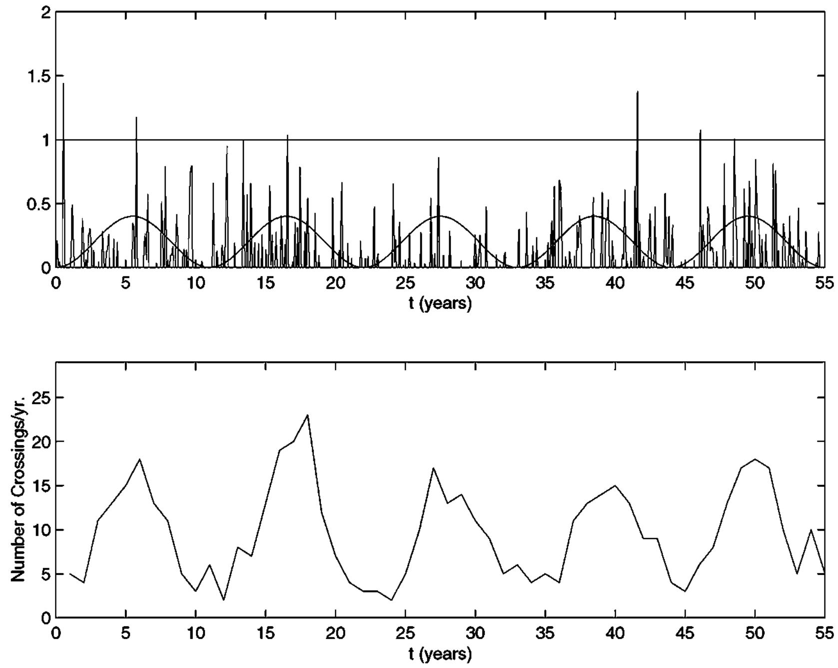

Figure 3. Upper panel: Plotted is the sum of a sub-threshold 11-year periodic signal of 0.5 amplitude and exponentially distributed fluctuations (with variance 0.3) crosses the threshold, simulating the appearance of a magnetic loop at the surface of the Sun. Lower panel: The calculated number of crossings per year, simulating the sunspot number.

solar surface as uncorrelated events. The weak mean field modulates (groups) the emergence of the random field so that the time series of emerged events produced by the sum of the mean and fluctuations carries the periodic informat ion – clearly seen from the time series of the number of crossing events (the lower panel in Figure 3).

6. A Final Remark

Sunspots appear at the surface of the Sun as local features. However, the explanation of their origin requires the understanding of global dynamical properties of the Sun, in particular the process of generation of strong random magnetic fields (intermittent flux ropes or sheets) with a weak regular mean value. This process is global because it involves all solar motions, from the general rotation to turbulent convection cells.

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