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LETTER

*Letter to the Editor*

# On the origin of sunspots

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**Abstract.** It is proposed that sunspots (and other flux emergence phenomena) originate due to the presence of fluctuating magnetic fields in addition to the regular, mean field in the convection zone. The mean field predicted by dynamo theories is too weak by itself to emerge at the surface of the Sun. However, the same dynamo processes that produce the mean field also produce fluctuating fields. 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. 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 fluctuations are responsible for emergence of the magnetic field of individual sunspots. A simple illustrative model calculation of a series of "sunspot cycles" is presented. The model spectrum compares well with the observed spectrum of sunspots.

**Key words:** Sun: sunspots – Sun: random magnetic fields

## 1. Introduction

The early concept of the origin of sunspots (Babcock 1961, Parker 1979) was based on the idea of a magnetic loop emerging from the convective zone to the solar surface due to buoyancy. The magnetic loops were assumed to be caused by instabilities of the largescale, mean magnetic field generated by the joint action of the differential rotation and mean helicity of the convection (dynamo). The mean field itself had the form of waves propagating from the poles to the equator in 11-years. This concept explained the solar sunspot cycle in its basic manifestations: the Maunder butterfly diagram and Hale's law of the field polarities. The idea of the mean field generation and its evolution has been justified and developed in numerous studies (c.f. Moffatt 1978, Parker 1979, Krause & Rädler 1981, Zeldovich et al. 1983). Theories of instabilities that could lead to the formation of emerging magnetic loops were less advanced however.

Recently a model of storage, instability and dynamical eruption of magnetic flux tubes in the convection zone has been developed (Schüssler et al. 1994, Caligari 1995). According to this model, a toroidal flux tube stored at the core/convective zone overshoot layer becomes unstable and erupts to the surface of the Sun when its field strength exceeds $10^5$ G. Weaker fields do not erupt. The model is in a good agreement with the basic observational facts related to sunspot magnetic fields in that the flux tubes emerge at low heliolatitudes and have the correct inclination and asymmetry with respect to the east-west direction. However, there is still a problem to resolve. Conventional dynamo theories do not predict such a strong magnetic field. The predicted field does not exceed the equipartition field which is only about $10^4$ G (Schüssler et al. 1994).

This paper suggests that the random, fluctuating magnetic fields in the solar convection zone play a central role in flux eruption. Although there are regularities in sunspot behavior, within these regularities each sunspot appears at a random time and at a random place. The number of sunspots observed in a given cycle varies from cycle to cycle. In addition, the simple question of why sunspots occupy so small an area on the solar surface (less than or about 1%) becomes a problem if we relate the sunspot origin to only the mean, largescale magnetic field produced by the dynamo.

The generation of fluctuating fields and their role in the generation of the mean field has been widely discussed: for early studies see for example Krause & Rädler (1981), Zeldovich et al. (1983), for numerical simulations see for example Meneguzzi et al. (1981), Brandenburg et al. (1990). Recently Ossendrijver et al. (1996) developed a solar dynamo model with a stochastic kinetic helicity. The fluctuations of the kinetic helicity excite overtones of the basic mode of the mean magnetic field. Schmitt et al. (1996) used magnetic fluctuations as a stochastic forcing control of the dynamo leading to grand minima in solar activity. The importance of fluctuating fields is indicated by sunspots observations. It has been noted that no single large flux tube emerges when sunspots are formed. Instead, the sunspot magnetic field is assembled over a period of hours and days through the progressive gathering of many flux tubes (Zwaan 1978). In accord with these observations the original concept of sunspot formation through flux tube emergence had been modified in such a way that the sunspot appears as a dynamical clustering of many separate flux tubes (Parker 1979). However, in this modification each flux tube was treated as regular and non-random.

In the model suggested here the randomness of the sunspots is considered to be a fundamental attribute. Also central for the model is the concept that noise plays a constructive role in the detection of weak periodic signals. This concept recently developed in the study of dynamical systems (see for example Wiesenfeld & Moss 1995) is often called "stochastic resonance" although it has been recognized that it is not a true resonance phenomenon. The present paper is restricted to the simplest model of the noise-periodic signal interaction.

## 2. The formation of sunspots as a threshold-crossing phenomenon

Assume that sunspots originate according to the scenario described in the model (Schüssler et al. 1994, Caligari 1995) but with the relatively weak (subthreshold) mean field generated by dynamo. The crossings of the $10^5$ G threshold, required for the fields to emerge to the solar surface, will be provided with the help of fluctuating magnetic fields (noise) superimposed on the mean field. Note that in the stability analysis cited above this threshold was obtained for the fields with the longitudinal wavenumbers $m = 1, 2$. For the perturbations localized at higher wavenumbers the instability threshold is higher and the demands on the amplitude of fluctuations would be much stronger. In addition, the tilt angle of small-scale rising loops would be too small. However the dynamo generated intermittent magnetic fluctuations are not localized in the Fourier space. Typically they have a self-similar power-law spectrum with the power growing towards the largest scale. Thus one can expect that the fluctuations with larger scales (smaller $m$) play the basic role in order to satisfy the requirements of the instability analysis. The same remark refers to the time scale of the fluctuations because the life-times of the perturbations with the larger wavenumbers are shorter. Although in the qualitative study presented below the daily variations are used, a timescale of one month seems to be more adequate for the effects demonstrated (see Fig. 1).

The presence of the mean field explains the basic observational regularities and relates sunspots to the solar cycle. Thus, the basics of the original concept are preserved. However, an important new element appears: from time to time the fluctuations are strong enough to permit the magnetic flux emergence.

To produce the mean field, regular motions such as differential rotation, and correlations such as kinetic helicity, are needed (Moffatt 1978, Parker 1979, Krause & Rädler 1981). The fluctuating magnetic fields are produced by the same convection which drives the dynamo. The generation of the fluctuating magnetic field is less demanding then that of the main field: any three-dimensional random motions are sufficient (Zeldovich et al. 1983, Molchanov et al. 1984). An important feature of fluctuations is the absence of an upper limit on their magnitude. Although the variance of fluctuations is limited, say by the equipartion between the kinetic and magnetic energies, the occurrence of large random deviations is restricted only by the form of the distribution function of the fluctuating field.

Consider a simple one-dimensional system which consists of a threshold, a subthreshold periodic signal and noise (see the upper panel of Fig. 1). The periodic signal represents the mean magnetic field $B$ generated by the dynamo. The noise is a random, fluctuating magnetic field $b$. Both the amplitude of the periodic field and the variance of fluctuating fields are assumed to be subthreshold. The threshold is crossed at the times when the total field $H = B + b$ is large enough, i.e. $H \geq H_{th}$. The threshold crossings is a random signal modulated by the periodic mean field. Each crossing can be interpreted as a flux tube emergence. The number of crossings per a certain time interval simulates the sunspot number. It is clear that the number of crossings depends on both the magnitude of B and the high intensity tail of the distribution of b. In principle there will be some crossings for any distribution that has no upper limit.

To make a numerical example consider the mean field as a sine function. The distribution of the fluctuations could be assumed to be Gaussian, however there is no physical reason to make that assumption. In fact, general considerations show that this distribution function is not expected to be Gaussian. The expected form of the distribution has been discussed for an MHD dynamo in which the turbulent velocities were assumed to follow a Gaussian distribution (Molchanov et al. 1984). These velocities fold the magnetic fields in baker type transformations (Finn & Ott 1988). The baker transformation process is multiplicative and leads to a lognormal type distribution for the resultant turbulent magnetic fields. The probability for high intensity fields in a such distribution is much higher than in the Gaussian distribution. In the numerical example below the high intensity (non-Gaussian) tail of the distribution is approximated by an exponential.

Figure 1 shows the result of a numerical simulation. The upper panel shows the threshold, the mean field and the fluctuating field used in the simulation. The threshold ($H_{th} = 10^5$ G) is taken as a unit for the field amplitude. The magnitude of the sinusoidal mean field dynamo is chosen as 0.5 threshold. The fluctuating field is exponentially distributed. Although the exponential distribution is unrealistic for small amplitude fields, this will not effect the results of the simulation because only the high intensity random fields will cause threshold crossings and those are well approximated. A 40 thousand point realization of the fluctuating field is generated and normalized so that the mean of the fluctuations is set to zero and the variance is set to 0.3 threshold. This realization simulates one value for the random field per day for 110 years. This whole period corresponds to 10 cycles of the mean field variation. Although the simulation was carried out for the 110 "year" sample, for the sake of graphical clarity the figure shows only half of the 110 "year" interval and only every 30-th point of the random fluctuations. The lower panel shows the number of "days per year" for which

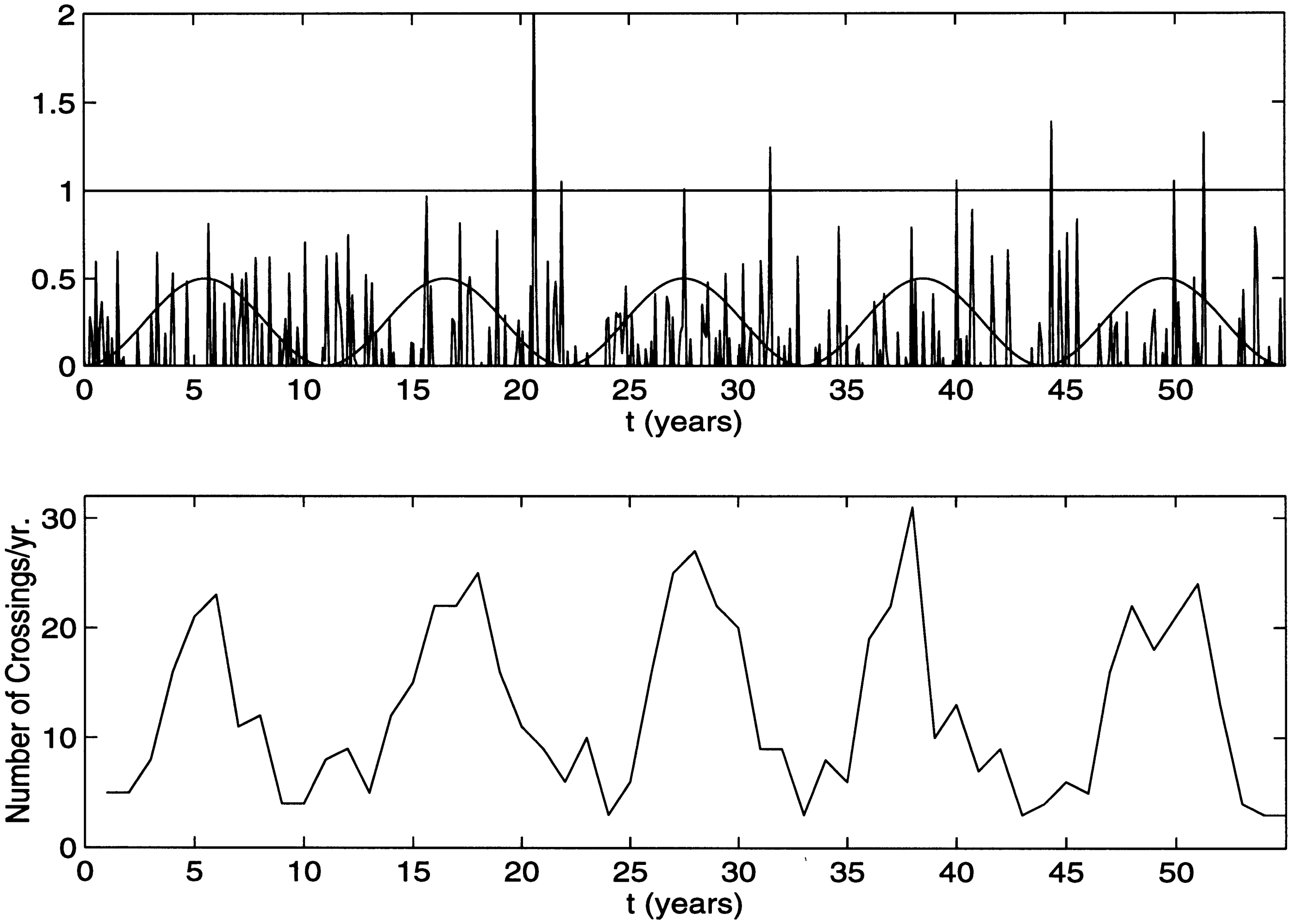


**Fig. 1.** A threshold (the straight line of the unit height), a subthreshold 11-year periodic signal of 0.5 amplitude and the exponentially distributed fluctuations of a variance 0.3. When the sum of the fluctuating and mean fields exceed the threshold a crossing occurs, simulating a magnetic loop emerging at the surface of the Sun. The number of crossings per year is shown on the low panel

$H = B + b$ exceeds $H_{th}$ and thus simulates sunspot cycles. A comparison of the simulated cycles with the real observed cycles shows many interesting similarities. For example, although there is a strong 11 year cycle, the shapes and amplitudes differ from cycle to cycle.

## 3. The model and observed spectra

The spectrum of the number of crossings per year (Fig. 2) is compared with the spectrum of the real yearly sunspot number in (Fig. 3). One can see a qualitative similarity between the two in that in both the simulated and observed spectra the 11-year periodicity arises on top of a noise spectrum. In that sense the basic approach adopted in this paper is supported by observations. This type of spectrum is typical of "stochastic resonance" phenomena observed in different physical and biological experiments (Wiesenfeld & Moss 1995). Note that Gaussian noise with the same variance as the exponential noise results in a noisy spectrum without the 11-year line due to the lack of fluctuation crossing the threshold. However by increasing the variance, say twice in the above numerical experiment, one can obtain the same spectrum, i.e. 11-year line plus the noise part. Thus, the spectrum itself does not distinguish between different distributions of the fluctuations. However the requirement on the amplitude of fluctuations in the Gaussian case is more stronger.

In summary, although the dynamo produces a magnetic field too weak to be able to emerge at the surface of the Sun, the presence of magnetic fluctuations, also having a subthreshold variance, will allow the flux to emerge. The mean field plays a vital role in producing the observed features of the sunspots magnetic field and the solar cycle itself. The fluctuating field is responsible for allowing the mean field to be observed and for producing the cycle to cycle variations. The simple model presented in this paper serves as a qualitative demonstration of how sunspots (or active regions in general) could result from stochastic fluctuations superposed on a weaker mean field. More sophisticated 2-D models which will include the spatial distribution of the magnetic field (dynamo waves for the mean field) and a more realistic presentation for the fluctuating fields are required and are under development.

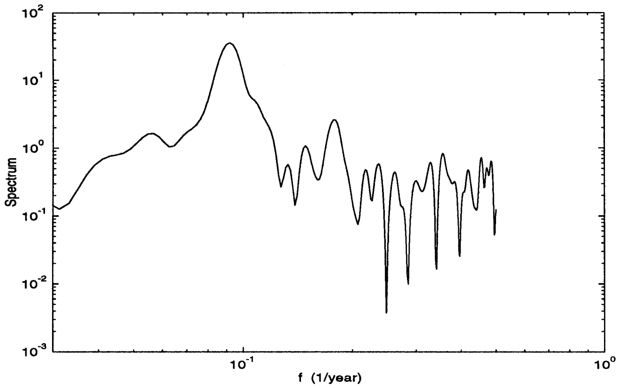


**Fig. 2.** The spectrum of the number of crossings per year, i.e. of the signal shown on the second panel of figure 1

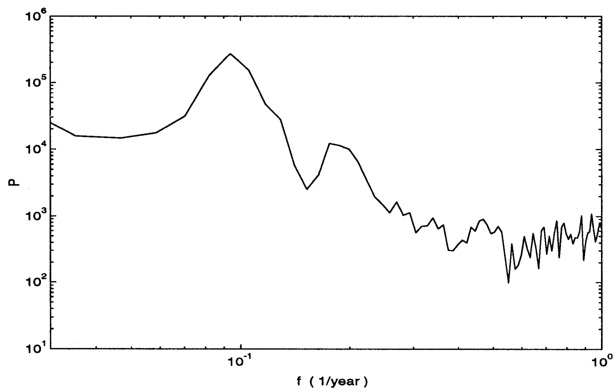


**Fig. 3.** The spectrum of monthly averaged sunspots number for the period 1745-1990

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