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Formation of Active Regions: Observations and Theory

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Abstract. Active regions can be used as a diagnostic of the sub-photospheric activity. In this review I will discuss how the physical conditions in the subsurface layers of the Sun form and modify the three dimensional complex of the active region. Many characteristics of active regions are related to the conditions under which magnetic flux tubes are generated and to their evolution as they rise in the surface. Statistical observations on active region size distribution, rotation and meridian flow, characteristics of growth and decay, reflect regularities of the behavior of the subsurface flux tubes through which the regions are formed. I will present several recent attempts to model the formation of active regions with diverse methods, such as single flux tube evolution inside the convection zone, statistical mechanics of a collection of magnetic flux tubes, and complex system theory (percolation theory and probabilistic competition models).

1. Introduction

Solar active regions are interpreted as the surface magnetic field of plages and sunspots and the various optical and radio features that they are responsible for. The most active phenomena above the solar surface are related with active regions. It is for these reasons that their study has attracted the attention of many observers and theorists in recent years.

The main focus of the current theoretical studies is on the question of how the subphotospheric activity is mapped into the formation and subsequent evolution of active regions. Two interrelated questions are usually posed: (1) where the magnetic fields are formed and (2) how they are manipulated by the convection zone.

The formation and evolution of magnetic flux tubes inside the convection zone is an important theoretical problem, which still remains open. We believe today that flux tubes are formed at the base of the convection zone and rise to the surface through buoyant forces. During their buoyant rise, flux tubes are influenced by several physical effects, such as the Coriolis force, magnetic tension, drag and large scale convection motion. The lack of understanding of the relative importance of these forces in the formation and evolution of active regions have forced many observers to develop large scale statistical studies for the characteristics of active regions. Several regularities are observed and will

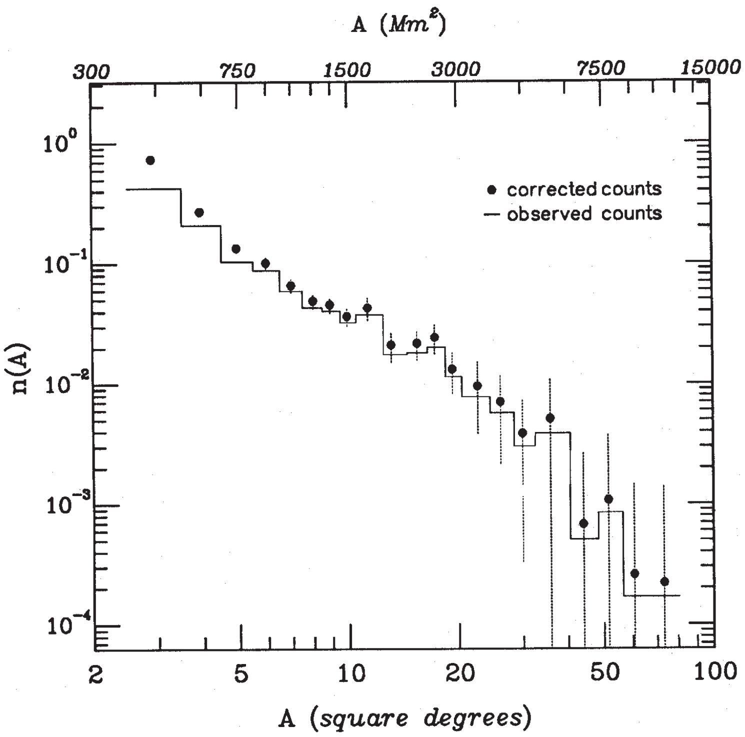

Figure 1. Size distribution of 978 active regions (from Harvey & Zwaan 1993).

be discussed in the following section (for a recent review of the statistical studies see Howard, 1996).

In this review I will discuss briefly the statistical regularities and the current views on the formation of active regions. Studies on the evolution of strong magnetic field, confined in a single flux tube have shown that several characteristics of the active regions can be traced back to the formation of the flux tube (see Moreno-Insertis 1997). In the other extreme are the statistical studies which assume that flux tubes of all sizes are formed in the overshoot layer in the bottom of the convection zone and propagate through the turbulent convection zone. The statistical interaction of N flux-tubes is responsible for the formation of active regions (see Bogdan and Lerche 1985, Weiss 1997). Numerical simulations have also demonstrated the importance of global studies which will include all the important components in the evolution of the flux tubes inside the convection zone. Recently, theoretical models based on the assumption that active regions are complex systems, borrowed methods from complex system analysis and demonstrated that several of the regularities observed can easily be predicted by using very simple rules (see Wentzel and Seiden 1992, Seiden & Wentzel 1996, Mylonas et al. 1998).

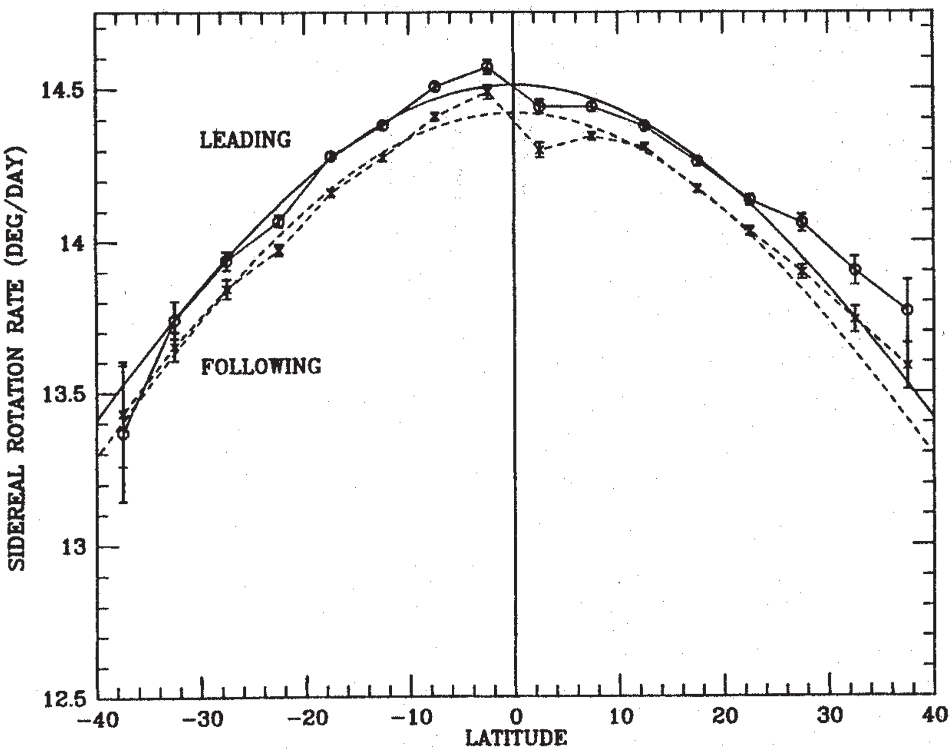

Figure 2. Siderial rotation as a function of latitude (Howard 1996).

2. Observations

2.1. Size Distribution

The distribution of active region sizes and total magnetic field is an important diagnostic for the nature of the subsurface source of magnetic flux. It is well known that sunspots and plages have different size evolutions. Sunspots decrease monotonically over a short time, plages evolve by expanding and weakening over a long interval.

In the recent years, several studies of the area-distribution of sunspots, plages, or surface magnetic fields have been published (see Tang et al. 1984, Bogdan et al. 1988, Howard 1989, Harvey & Zwaan 1993). In many occasions new active regions arise within previously existing regions. Harvey & Zwaan (1993) analysed these regions separately and found that the characteristics of the nested active regions are the same as those of the active regions formed where there is no pre-existing active region. The area distribution of plages from Harvey & Zwaan (1993) is shown in Figure 1.

It is clear that the number of sunspots falls off very rapidly with increasing area. It is important to notice that the size distribution follows a well defined power law $n(A) \sim A^{-1.5}$. The eruption of new flux in pre-existing flux poses a number of questions for the origin of the flux tubes.

2.2. Rotation

It is well known that the Sun rotates differentially and that sunspots and other magnetic features rotate faster than the surface plasma (Howard & Harvey 1970). A possible explanation was given by D' Silva & Howard (1994); they suggested that the effect of buoyancy and drag, coupled with the Coriolis force, can lead to a faster rotation for the emerged flux tubes.

The siderial rotation of plages is shown in Figure 2. There are 11.909 plages shown in this Figure (see Howard et al. 1984, Howard 1990). Leading and following spots show significantly different rotation rates.

2.3. Growth and Decay

Howard (1992) has shown many interesting characteristics in the growth and decay of plages and sunspots in recent years. Regions with rotational rates that deviate from the average rate grow and decay faster than regions near the average rotational rate. Smaller groups grow faster than they decay, and larger groups decay faster than they grow. It is suggested that some of the differences in growth and decay rates between fields of opposite polarities are due to the fact that leading fields are inclined at a greater angle to the local vertical than the following fields.

It is well known to the observers that plages grow faster than they decay (Kiepenheuer 1953). The same is true with sunspots. In addition, leading polarity fields grow and decay faster than normal polarity regions.

2.4. Magnetic Field Orientation

The orientation of magnetic field lines is one of the most interesting parameters for the study of the formation and evolution of active regions. The angle between the line joining the centroids of the two polarities in the region with the local parallel of latitude is called *tilt-angle*.

The average tilt-angle of regions is roughly $+5^o$. In Figure 3 we show the distribution for plages and sunspots separately.

2.5. Fractal Dimension

Magnetic flux in the solar photosphere is intermittently structured down to the smallest scales. This manifests itself in a scale similarity of the distribution of magnetic areas on the solar surface and corresponds to a fractal dimension $D \simeq 1.6$ (Tarbell et al. 1990). The application of fractal and multifractal methods to solar problems is becoming increasingly common (Brandt et al. 1991, Lawrence 1991, Ruzmaikin, Sokoloff & Tarbell 1991, Schrijver et al. 1992, Lawrence & Schrijver 1993, Milovanov & Zelenyi 1993, Lawrence et al. 1995, Tao et al. 1995). It was shown by many authors that the fractal dimension for active regions is $D \simeq 1.5 - 1.7$ (see Lawrence et al. 1996). Lawrence, Ruzmaikin & Cadavid (1993) found that the solar flux is multifractal. The appearance of multifractal structures in the magnetic field poses a number of problems for several theoretical models for the formation of active regions (e.g. the single flux-tube scenario cannot explain such complex structures for the active regions) which will be discussed in the next section.

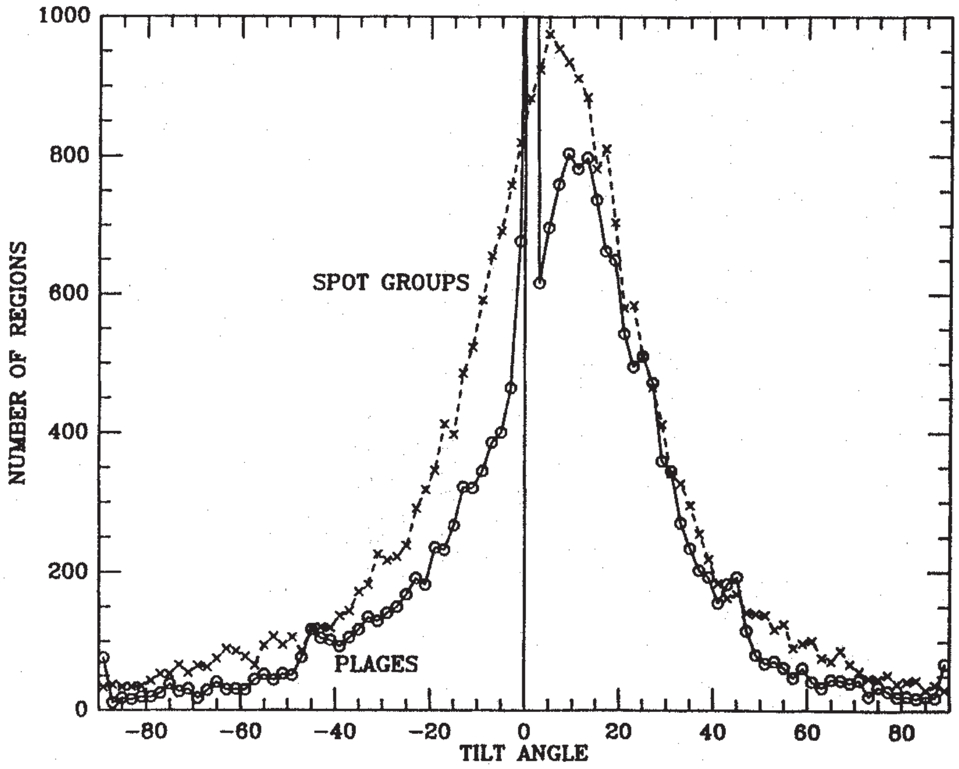

Figure 3. Distribution of tilt-angles of plages (o) and sunspot groups (x) (Howard 1996).

3. Theoretical Models

Numerical simulations of the magnetoconvection were reviewed recently by Weiss (1997) and we will not discuss them here. This field of research is growing fast, and in a few years, with the development of massive parallel computers, we will be able to study the turbulent convection zone and understand more on the structures of velocity and magnetic fields.

3.1. Single Flux Tube Dynamics

The evolution of a single flux tube from the overshoot layer, where it is generated till it reaches the photosphere, is a very difficult and challenging problem. Studies of the dynamics of a 1-D (slender) flux tube are useful since they permit calculation of the evolution as the flux-tube propagates through the convection zone. The 2-D and 3-D characteristics of the rise of magnetic flux tubes allow us to understand the role of the twist in the properties of a rising flux-tube. Untwisted flux tubes cannot rise easily through the convection zone. Magnetic flux will be transported from the bottom of the convection zone to the photosphere only through twisted flux tubes. A recent review of the main results on the evolution of 1-D, 2-D and 3-D flux tubes was given by Moreno-Insertis

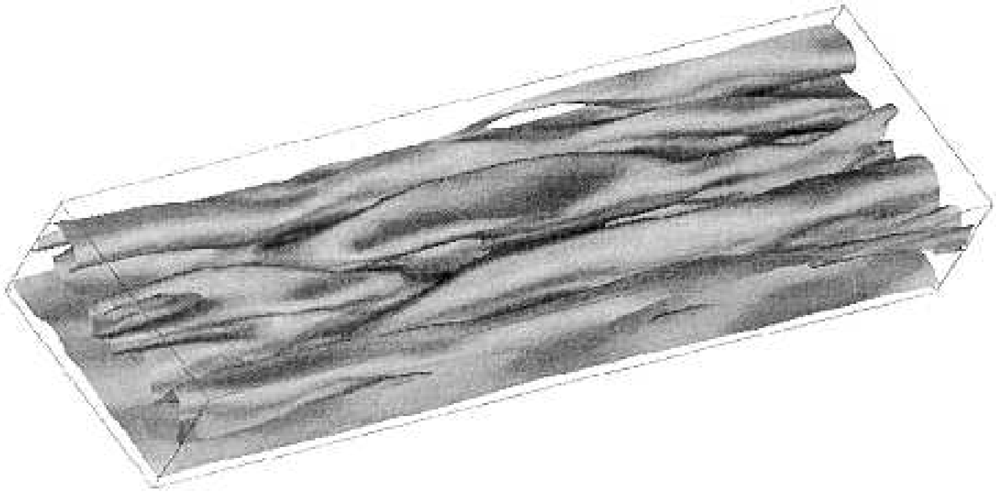

Figure 4. Formation of magnetic flux tubes (Hughes et al. 1997).

(1997). It is well documented from numerical simulations that untwisted flux tubes will never reach the photosphere and twisted flux tubes can rise almost without change through the convection zone, if the azimuthal magnetic field is strong.

Two very important questions should be addressed: (1) How are flux-tubes formed from a large scale magnetic field and, (2) which is the origin of the twist in the flux tubes. Hughes et al. (1997) address this problem; their main conclusion is that the non-linear evolution of the magnetic Rayleigh-Taylor instability is responsible for the formation of magnetic flux tubes (see Figure 4).

The origin of the twist is a much more complex problem. There are several possibilities: (1) the flux-tubes are formed with a large twist in the overshoot layer, (2) the twist is built during the propagation inside the convection zone. It is still an open question if the required twist can be there from "birth" or is added later. The details of the formation of Ω-loops out of a 3-D instability have been studied recently (see Matthews et al. 1995). We are far from understanding the details both of the formation and the origin of the twist. Large scale 3-D simulations of the formation and evolution of magnetic flux tubes will solve many of the open problems that still exist.

It is also true that only a few of the statistical properties reported in the previous section can be explained from the study of the dynamics of a single flux tube.

3.2. Statistical Properties of N Flux-Tubes

We move from the single flux-tube scenario to the idea that magnetic flux-tubes of all sizes and twists are generated in the overshoot layer and propagate towards the photosphere.

The idea to study the formation of active regions as the outcome of the statistical evolution of N randomly moving flux-tubes was proposed by Bogdan (1984) and developed subsequently in many articles (Bogdan 1985, Bogdan &

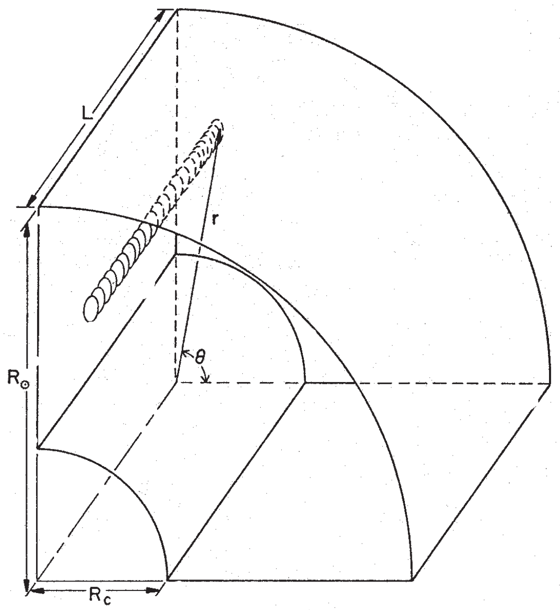

Figure 5. Idealization of the solar convection zone. A twisted magnetic fibril is located at $\vec{r}$.

Lerche 1985). Similar studies on the statistical mechanics of a gas of vortices, embedded in a two-dimensional inviscid fluid, were performed by Fröhlich and Ruelle (1982). The statistical evolution of a collection of N flux-tubes can probably address the statistical properties of the observed data.

Assuming a gas of flux-tubes moving inside the convection zone (Figure 5), Bogdan & Lerche (1985) developed a two-dimensional ($\partial/\partial z = 0$) theory of their evolution. The properties of the magnetic flux-tubes are described by the distribution function $f(t, r, \theta, v_r, v_\theta; \Gamma)$, where Γ characterises the internal structure of the flux tubes. The evolution of f is described by a collisional Boltzmann equation,

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} + \dot{\vec{v}} \cdot \frac{\partial f}{\partial \vec{v}} = S \tag{1}$$

where S is the collision integral. The collision integral contains two terms: (a) the evolution of the internal structure, and (b) changes in the velocities without alteration of the internal structure. It is more interesting to work with the density of flux tubes $N(t, r, \theta; \Gamma) = \int d^3\vec{v} f$. A new evolution equation can be written

$$\frac{\partial N}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}[r u(r, \theta, t) N] - \vec{\nabla} \cdot [\vec{\vec{k}}(r, \theta, t) \cdot \vec{\nabla} N] = S \tag{2}$$

where $u(r, \theta, t)$ is the average velocity with which flux tubes move towards the surface. The complicated chaotic motion of a single flux tube is superposed on this mean velocity, and $\vec{\vec{k}}$ is the spatial diffusion tensor. The diffusion coefficient is difficult to estimate, since it includes all the information of the turbulent velocity-field. The velocity u and the parameter k are free parameters, so the transport equation is never going to be an "accurate" procedure for the estimation of the evolution of N. In order to work further with Equation (2), we should discuss the collision integral S. We can describe a flux tube with its flux, Φ. The magnetic flux Φ remains constant throughout the motion and serves to distinguish one flux-tube from another.

Assuming that the collision integral does not produce large changes in velocity space, the collision integral expresses mostly the annihilation and coalescence of flux tubes

$$\begin{aligned} S &= -N \int d\Phi' \sigma(\Phi, \Phi'; r, \theta, t) N(t, r, \theta; \Phi') \\ &+ \frac{1}{2} \int d\Phi' \sigma(\Phi - \Phi'; r, \theta, t) N(t, r, \theta; \Phi - \Phi') N(t, r, \theta; \Phi') \end{aligned} \tag{3}$$

where σ is the annihilation/coalescence reaction cross-section. The diffusion equation (2) will now evolve to the equation

$$\frac{\partial N}{\partial t} + \frac{N}{T} + \frac{1}{r}\frac{\partial}{\partial r}[ruN] - \vec{\nabla} \cdot [\vec{\vec{k}} \cdot (\vec{\nabla} N) = S \tag{4}$$

where T is the rate at which flux tubes will spontaneously decouple and precipitate rapidly to the surface. Unfortunately, the diffusion equation (4) has so many unknown parameters $(u, \vec{\vec{k}}, \sigma)$, that it can hardly predict any of the measured quantities discussed in Section 2.

3.3. Active Regions as "Complex Systems"

A new and exciting development in the study of dynamical systems is the appearance of new tools for the analysis of complex systems, like the convection zone. I have already presented observational evidence which suggests that active regions are not formed randomly at the surface of the sun. The formation of structures which follow a power law distribution, the presence of fractal patterns with concrete dimension, suggest that the turbulent convection zone is playing a key role in the formation and evolution of active regions.

Wentzel & Seiden (1992) were the first to propose a simple percolation model for the formation of active regions. They assumed that flux-tubes released from the overshoot-layer rise buoyantly and finally become observable at the surface as emergent flux. They have defined a probability, P, for the rise of a flux-tube in the neighbouring of an existing flux tube. The motivation for the stimulation of the rise of magnetic flux next to an existing magnetic loop is related with the tendency of rising flux tubes to stimulate neighbouring flux-rise in a convection zone full of N randomly moving flux-tubes.

Wentzel & Seiden (1992) constructed a grid and initiated their simulation by randomly selecting a few points to carry the first magnetic flux tubes (this was defined as initial loading). Magnetised grid points will stimulate neighbouring flux tubes in every time step. Flux tubes can also disappear by diffusion, D, which is the reverse process of the stimulation mentioned above. The evolution

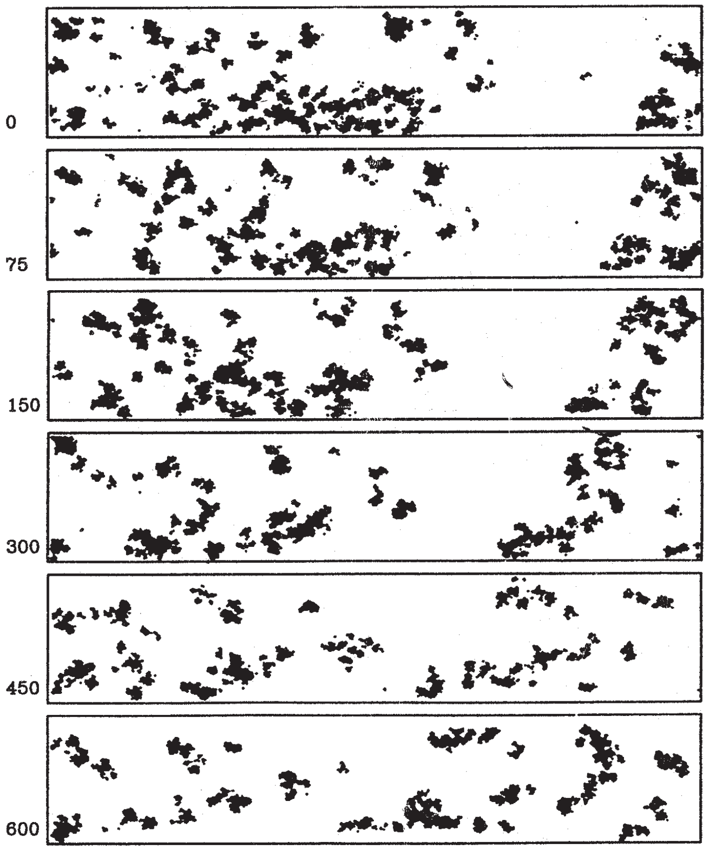

Figure 6. Maps of simulated active regions for $P_{st} = 0.1818$ and $D = 0.05$ between latitudes 30^o north and south at intervals of about 2 weeks (see Wentzel & Seiden 1992).

of active regions is driven by these two tendencies, stimulation and magnetic loss.

In Figure 6 I present the results from a simulation with probabilities $P = 0.1818$, and $D = 0.05$. The most interesting conclusion from this simulation is that it is able to reproduce the observed size distribution of active regions. I should emphasize here that no previous model was able to reproduce these observations. Seiden & Wentzel (1996) continue their initial work with the inclusion of bipolar regions. The model became reacher, but it produces similar results with their initial work.

Mylonas et al. (1998) have attempted to model the formation of active regions using a probabilistic competition-model. They assumed that the appearance of new flux at the surface competes with the diffusion and loss of magnetic energy. This model, too, was able to reproduce the observed size distribution and fractal dimension.

The main problem these models face is their lack of correlation to the physical characteristics of the convection zone. The probability of stimulation for the appearance of new flux and diffusion for the existing magnetic flux are just the free parameters of the model, showing the main tendencies which are under work.

These models tackle the statistical features of the observational data and allow MHD models to focus on the main aspects of the interaction of magnetic flux tubes with the turbulent convection zone. I hope that soon all the diverse models will combine to solve the extremely complex phenomenon of active regions.

4. Conclusions

Recent observations on the evolution of active regions suggest that magnetic flux tubes generated in the overshoot layer evolve rapidly according to their internal characteristics. Twisted flux tubes with strong magnetic field will easily reach the surface without many changes, contrary to flux tubes with weak magnetic field which will never reach the surface. I believe that the convection zone greatly influences the statistical behaviour of the flux tubes. Collision and annihilation will change the characteristics of the "gas of flux tubes", and some of them will escape and participate in the surface.

Finally, I have shown that simpler percolation models and probabilistic competition models can capture many of the characteristics of the evolution of flux tubes by using probabilistic rules. The highly twisted flux tubes play a major role in stimulating the emergence of weak field flux-tubes trapped inside the convection zone. The weak magnetic field flux-tubes then can reach the surface through substantial evolution inside the convection zone.

I feel that the modeling of the formation of active regions will soon reach the level to predict the observed characteristics.

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