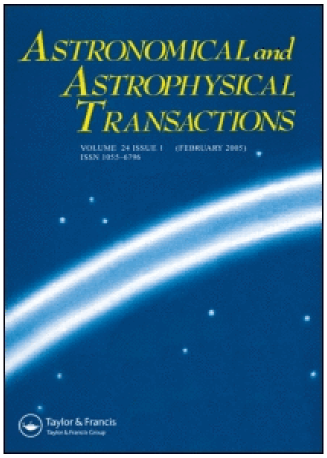

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P. Ambrož [a]; E. V. Kononovich [b]

[a] Astronomical Institute, Czech Academy of Sciences, Ondřejov, Czech Republic
[b] Sternberg Astronomical Institute, Moscow State University, Moscow, Russia

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SOLAR MAGNETIC FLUX TUBE EMERGENCE DIAGRAM

P. AMBROŽ

Astronomical Institute, Czech Academy of Sciences, 251 65 Ondřejov, Czech Republic

and

E. V. KONONOVICH

Sternberg Astronomical Institute, Moscow State University, 119899, Moscow, Russia

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It is emphasized that photospheric downdrafts represent the main feature common to both quit and active regions of the solar atmosphere. The results of the magnetic field transport velocity calculations are used to specify the convection zone magnetic structure. The concept of combined interface and convection dynamo is suggested. A time-spatial diagram is proposed to represent an active region evolution. The diagram is illustrated by a set of observations of an active region obtained from June 20 to July 1, 1981. A tentative scenario of an active region formation is outlined.

KEY WORDS Sun, convection zone, magnetic field, active regions.

1. MAGNETIC FLUX EMERGENCE

There are several types of observable motions on the Sun. Generally accepted are waves, turbulence and convection. We suggest to include also the process of magnetic field emergence, whose upward velocity is difficult to establish because, strictly speaking, it is not the velocity of matter, but the imprint of field emergence or more properly the appearance of a certain new structure. Emergent magnetic flux tubes incorporate a gas matter inside them and are necessary accompanied by outside matter downflows. Thus the velocity field is quite complicated in regions of magnetic flux emergence.

According to Parker (1975), an individual magnetic tube should emerge at the Alfvén velocity, while Unno and Ribes (1976), for the case of turbulent viscosity, introduce a factor equal to the Alfén to turbulent velocities ratio.

Krivodubskij (1984) has calculated the corresponding velocities using these and some other mechanisms of buoyancy and taking into account the diamagnetic plasma effects. The main result of his work is that all magnetic fields quickly rise up in the upper half of the solar convection zone at the speeds ranging from about $1\,\mathrm{m\,s^{-1}}$ to $0.1\,\mathrm{km\,s^{-1}}$. In the lower half of the convection zone, only strong fields (with intensity lower than 0.1 T) can go up against the turbulent convection viscosity. Weak fields have a tendency to sink down at the velocities up to $10\,\mathrm{m\,s^{-1}}$ to form a magnetic layer at the base of the convection zone.

These calculations permit to understand better how the dynamo can work. It seems very likely that it is operating smoothly, permanently supplying the magnetic layers at the upper and lower boundaries of the convection zone by a constant flow of magnetic field.

In the upper layers, it seems that a magnetic flux of moderate size is organized. Its structure is determined presumably by photospheric integranular down-draft motions. Observations (Beckers and Shröter, 1968) indicate that the flux tubes are located in the dark intergranular lanes, i.e. in the downdrafts rather than the updrafts (but see Ramsey *et al.*, 1977; Weiss, 1977). Assuming intergranular lanes to occuppy about 50% of the total photospheric area with the field strength of 0.1 T, we can suggest that an inactive region has in itself about 10% of magnetic flux required to form a typical sunspot with the 0.5 T field strength.

Strong magnetic field can go up floating from the convection zone base if the magnetic energy accumulated surpasses the threshold of buoyancy. That means it must occur occasionally which implies a stochastic character of the solar activity manifestations. This process of magnetic pumping was used by Spruit and Roberts (1983) in their suggestion of the "interace dynamo" to be added to numerous other dynamo models suggested up to date and outlined e.g. by Priest (1982).

The upper limit of magnetic field intensity detached by the diamagnetic effect against buoyancy depends upon accepted mechanism. Calculation results obtained by Krivodubskij range from 0.2 to 70 T. So it is difficult to speculate about the size and field strength of an upfloating region. Acccepting its magnetic flux equal to that of a large active region about 10^{-7} Wb and as maximum of the field value 10^{-3} T we obtain a flux tube having the diameter of about 1 Mn at the bottom of the convection zone.

By emerging from the convection zone base, such a tube should increase its diameter as inverse square root of pressure, that is about 10^4 times. This is more then the solar diameter and suggests much smaller tubes to emerge presumably from some middle region of the convection zone. But in any case emergent field should correspond more and more with a large scale when deeper is the layer of its origin. On the other hand in the upper layers of the convection zone, where the turbulence is strong, emergent flux tube should be disrupted by strong subfotospheric downdrafts into a lot of small tubes. At the same time, a whole large scale emergence results in an inverse flow, producing and intensifying the downflows.

It is possible to suggest that the field emergence is a rather slow process so that the downdraft always balances the updraft. That means that both the upflows and downflows are enhanced during the emergence. According to Parker's (1979) model this possibly leads to sunspot formation.

Essentially the above processes should explain how does the dynamo work. Direct simulations resolve this problem more explicitly. Brandenburg *et al.*, (1991) simulated the convective overshoot to specify where the dynamo operates, the importance of magnetic buoyancy, the question whether the dynamo is fast or slow. Their results show large scale coherent magnetic structures. Magnetic flux tubes are seen to be pulled downwards and wounded up close to the interface between the convection zone and radiative interior. The dynamo is fast. The maximum of the magnetic energy occurs at the interface where both induction effects and Ohmic dissipation are the largest. There is no accumulation of magnetic flux in the upper layers. This means that magnetic buoyancy is not suppressed by the perfectly conducting upper boundary. The simulation pictures show the vorticity vectors to be organized into tubes with electric current sheets around this tubes. In some cases, the magnetic field tubes are aligned with the vorticity vectors and form "fox tails" above the interface.

2. TIME-SPATIAL DIAGRAM

We propose to illustrate the observed field evolution by a certain *Emergence Diagram* (ED) introduced by one us (Kononovich, 1984). The ED does not represent a real 3D magnetic flux rope structure. It only demonstrates a set of observed sunspot configurations, chronologically ordered.

Figure 1 represents such a diagram for the active region No. 270 according to

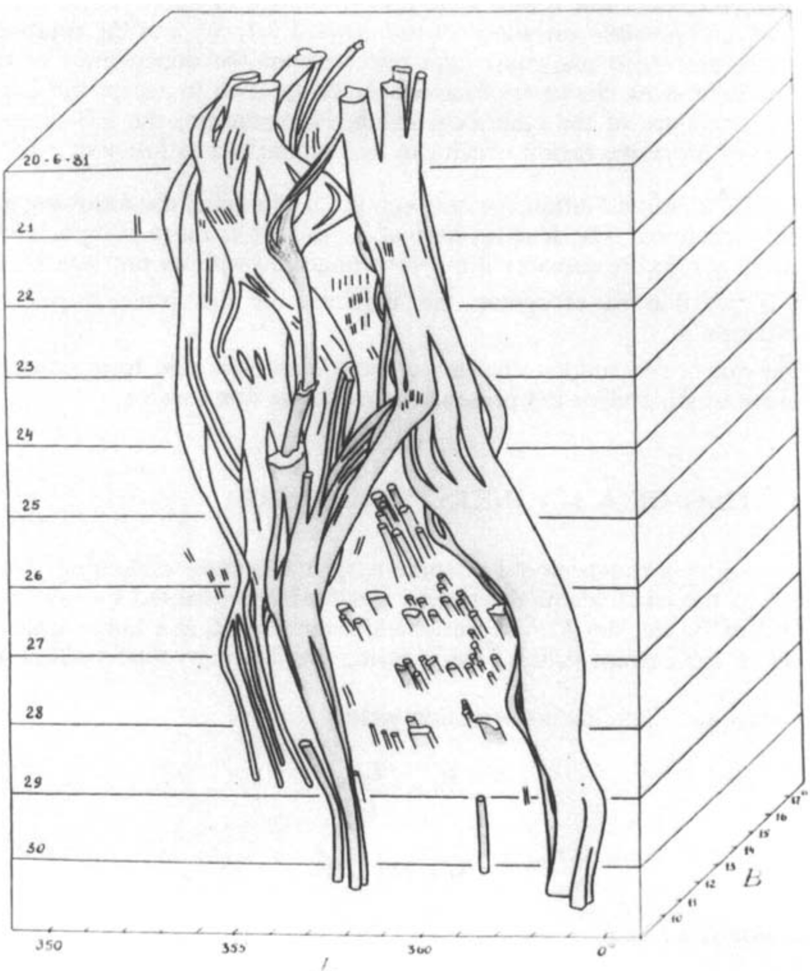

Figure 1 Time-spatial diagram (ED) for the active region observed from June 20 to July 1st, 1981.

Solnechnye Dannye, observed by one from as (P.A.) from June 20 to July 1st, 1981 on the Hvar Observatory in Croatia. The daily maps showing outlines of the sunspot umbrae were very precisely measured and rectified to the rectangular system of the Carrington reference frame. The charts obtained were used for construction of a 3D time sequence of the surface planes in axonometric projection. Then the most speculative part of the procedure begins: on all the planes, we try to identify the same features. In some cases we can connect them by cones. Otherwise we leave them open or identify them with the cone separations. The polarity of the field is of course controlled to remain constant.

The diagram proposed contains some information but the question is, how it can be treated? Unfortunately the diagram itself does not answer the main question: whether an active region is the result of magnetic field emergence or of some other in situ process. In the former case the ED somehow represents the spatial structure of emergent field, deformed by buoyancy, temporal evolution and other processes. But it also includes the change of atmospheric seeing from day to day and possible variations of the upward velocity and the rotation of the whole structure. Also one must take into account the dependence of the tube speeds on their sizes. So we try to avoid the temptation to accept this diagram as a real 3D structure of the emerging region. Nevertheless, the ED reveals some properties of an active region which can be summarized as follows:

- There is a marked difference between the leading and the following magnetic field structures. The leading part of a sunspot is more complicated as the following one. Presumably it may be connected with its previous character.
- It is possible to recognize the influence of disruptive forces on both polarities.
- One can notice sudden changes of tube diameters due to variations of the field strength and/or the presence of magnetic flux sources.

3. FLOATING OF A MAGNETIC STRUCTURE

Let us consider a rough model of some magnetic feature upfloating. The values referring to the level where the upflow starts will be denoted by subscript *zero*: the pressure P_0, density ρ_0, magnetic field induction H_0 and linear scale L_0. The P, ρ, H, L are current values. Those inside the floating volume will be denoted by *prime.*

The mass and field flux conservation yield:

$$\frac{\rho'}{\rho'_0} = \left(\frac{L_0}{L}\right)^3, \tag{1}$$

$$H = H_0\left(\frac{L_0}{L}\right)^2. \tag{2}$$

Eliminating L we have:

$$\frac{\rho'}{\rho'_0} = \left(\frac{H}{H_0}\right)^{3/2}. \tag{3}$$

Introducing $\beta = H^2/8\pi P$ we have

$$\rho' = \rho - \Delta\rho = \rho\left(1 - \frac{\Delta\rho}{\rho}\right) = \rho\left(1 - \frac{\Delta P}{P}\right) = \rho(1 - \beta), \tag{4}$$

since we assume the upflow to be small in comparison to the thermal relaxation time, i.e. $T = T'$ and $\Delta P/P = \Delta\rho/\rho$.

Setting $y = H_0/H$, $\eta = P_0/P$ and $\xi = \rho_0/\rho$, one can obtain

$$\frac{(1-\beta_0)y^{3/2}}{\xi} + \frac{\beta_0 y^2}{\eta} = 1. \tag{5}$$

If β is close to unity,

$$y_1 = \eta^{1/2}, \tag{6}$$

and for small β

$$y_2 = \xi^{2/3}. \tag{7}$$

The path through the whole convection zone corresponds to $\eta = 10^{-8}$ and $\xi = 10^{-6}$ and both y_1 and y_2 are of the order of 10^{-4}. A similar value we obtain also for $\beta_0 = 1/2$.

For example, if a bubble with a field 10^2 T reaches the upper layers it expands by a factor of about 100 and the field strength drops to 10^{-2} T. So one can admit its initial diameter as about 1000 km to cover a typical active region at the final stage of the emergence process.

It is evident that parameter β in our case is the fraction of the total volume emergent beyond the surface level at equilibrium state. The top β value for the above figures is about 10^{-2}. That means that the solar disc can be deformed by about 1 percent of the size of emergent active region. Such value can be observed by existing methods.

4. THE DOWNDRAFTS

It seems that the downdraft is the main feature of the photospheric fine structure. For the granulation, it is proved by impressive coincidence between observations and numerical simulations (Spruit *et al.*, 1990). Recently, direct confirmation of model calculations by spectral line parameter variations was obtained by Hanslmeier *et al.*, (1991). As for the sunspots, observations made by Grigoryev and Selivanov (1986) showed that there is a good agreement between the observed dynamics of the convection in the active region and a model for magnetic flux emergence from beneath the photosphere developed by Parker (1979). Here occurs a dynamic interaction between the convection around a spot and convective downward motion within sunspot flux tube. But note that this model is based on asymmetrical convection cell opposite to that calculated by Simon and Weiss (1968).

Grigoryev and Seliavanov emphasize that the downward motion at the site of a sunspot formation is noticeable at the earliest stage of magnetic field enhancement. Downflow is increasing together with magnetic flux. So does the whole active region network of cell downflows and spot themselves originating in their nodes. A ring of descending material is forming around the spot soon after penumbra and Evershed flow formation. It agrees with the Parker model of a sunspot formation by the magnetic field configuration in which the field divides into individual flux tubes some distance below the visible photosphere. We would like to emphasize once again that this downdraft enhancement is due to the general large scale upflow connected with magnetic field emergence.

5. WHAT AN ACTIVE REGION IS?

Now we try to summarize the considerations outlined above:

1. Even the quit photosphere is strongly magnetic because of a permanent magnetic field flux generated by dynamo process and exerted by the magnetic buoyancy and diamagnetic effect. Dynamo calculations treat only averaged fields. Thus we have no information about their structure and scale. But we may suggest that they are strongly affected by convection and turbulence and should be very chaotic and having a very wide spatial spectrum. And only in large scale they have predominant orientation in the case of a proper action of the dynamo process.

2. The photospheric layers including overshoot regions produce an organizing role of prime importance upon the magnetic structure. The existence of upward (in granules) and downward (in dark intergranular lanes) flows is a direct result of the mass conservation. But numerical simulations of the convection show that upflow motions push magnetic tubes to the convective cells borders. Thus upflows incorporate two kinds of motion: floating up magnetic tubes pushed by diamagnetic effect of turbulent velocity gradient together with magnetic buoyancy and presumably non-magnetic convection streams connected with the regions near around the center of convective cells. This is a problem concerning the magnetism of the downdraft. If the plasma inside the tubes begins to sink, then the tube immediately shrinks because of Bernoulli's law and the magnetic field intensifies to stabilize the outer pressure. So the gas motion inside an ascending tube depends upon the dynamics of the tube environment. In any case corresponding velocities should be small in the case of the tube stability. The gas sinks outside the tubes in the regions on the borders of the convective cells. These downflows force to change chaotic fields into presumably vertical magnetic tubes. On this level a stationary process takes the form of a normal granulation pattern.

3. Occasionally larger magnetic fields must begin their rise presumably from the convection zone base as suggested by Spruit and Roberts (1983). The upper limit of magnetic field intensity detached by diamagnetic effect against buoyancy depends upon the adopted mechanism. Calculation results obtained by Krivodubskij range from 0.2 to 70 T as was mentioned above, depending on the mechanism of buoyancy.

4. The above calculations show that the emergence of a field tube of several thousands kilometers size and less than 10 T of intensity is quite sufficient to product an active region in the solar atmosphere. According to Krivodubskij (1984), the upflow time is of the order of 1 year or even less. The whole picture of the tube emergence is very well described by Zwaan (1985) from the observational point of view. In that case it seems likely that our spatial-time

diagram may represent the structure of an emerging region. But the complexity of the tube structure illustrated by Figure 1 is against such a simple model. There are two possibilities to solve this puzzle:

(a) The emerging tube is deeply deformed and distorted during its up-flow. Twisting of the tube is a very likely process leading to the tube stability. A corresponding time, however short it can be, is greater than the time scale of convection cells (especially in the upper layers). So the tube will be strongly affected by convection and turbulent motions. But at the supergranular level where the field is strong enough to control motions the process must go more smoothly. This is in contradiction to the abrupt magnetic flux change showed by the diagram.

(b) Another possibility very likely to be significant is the controlling role of the photosphere structured by downflows and interfering with emergent field. The emergent field provides a vast opportunity for downflows in much greater scale then in quit photoshere namely in the scale of a whole supergranule.

5. Thus we come to the conclusion that the sunspot model suggested by Parker (1975) and supported by observations (Grigoryev and Selivanov, 1986) is essentially based on the same downdraft pattern as outlined by Srpuit *et al.*, (1990) for intergranular lanes. The sunspot is turning to be a conglomerate of intergranular nodes (so called poruls) "*held in a loose cluster by the buoyancy of the Wilson depression at the visible surface and probably also by a downdraft beneath the sunspot*" (Parker, 1975). As a result we have to admit that the emergent magnetic flux only intensifies the downdraft in the future active region, supplying it by the magnetic flux to compensate intergranular field collapsed into the spot. There is no evidence to identify the emerging field structure with the future sunspot group pattern. The emergent field presumably is of larger scale, intensifying photospheric magnetism together with downdraft and this process provokes the transition of a certain photospheric area into the other state—"*cluster of many separate fluxtubes*".

6. ACTIVE REGION FORMATION

Now we would like to revise the general steps of an active region formation proposed earlier (Kononovich, 1984) and illustrated in Figure 2:

- The magnetic layer at the bottom of the convection zone is supplied by the sinking of mostly weak magnetic fields mainly from the lower part of the convection zone pushed away by diamagnetic effect.
- According to different upflow models, the magnetic layer continues to be stable up to field strength in the range from 0.2 to 70 T at most. The flux tubes with the field which is greater than this threshold should upflow. The beginning of this process is stimulated by the condition of convective instability. As a result a giant convective cell incorporating imbedded magnetic flux tube appears. The existence of the large-scale or giant convective cells was documented only recently by Ambrož (1993). Studying the time evolution of the large-scale magnetic flux distribution in the solar photosphere, the

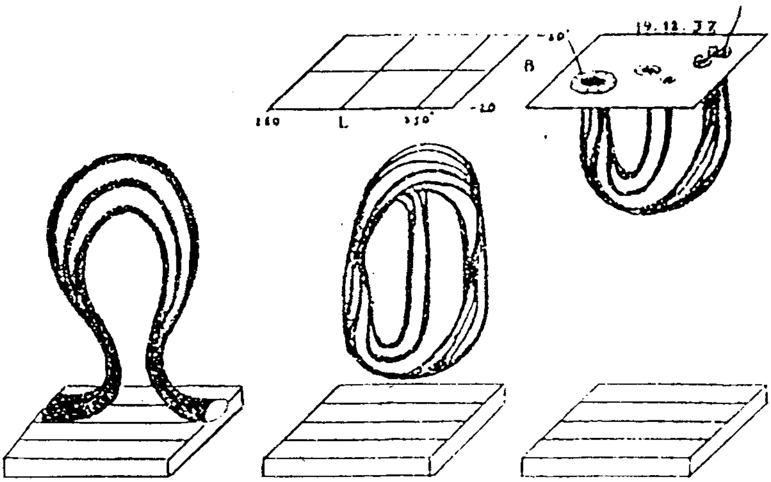

Figure 2 A preliminary sketch of the magnetic structure emergence process (After Kononovich, 1984).

horizontal large-scale velocity field was inferred (Ambrož, 1992). Solving the 2D streamline equation for the free test particles we are able to characterize the large-scale horizontal flow. As presented in Figure 3, the initially uniformly distributed free particles are scattered very inhomogeneously after three solar rotations. The particles are grouped on the borders of the regular giant convective elements. We are speaking about the areas with zero horizontal velocity and with dominating large-scale downflow. On the contrary, the

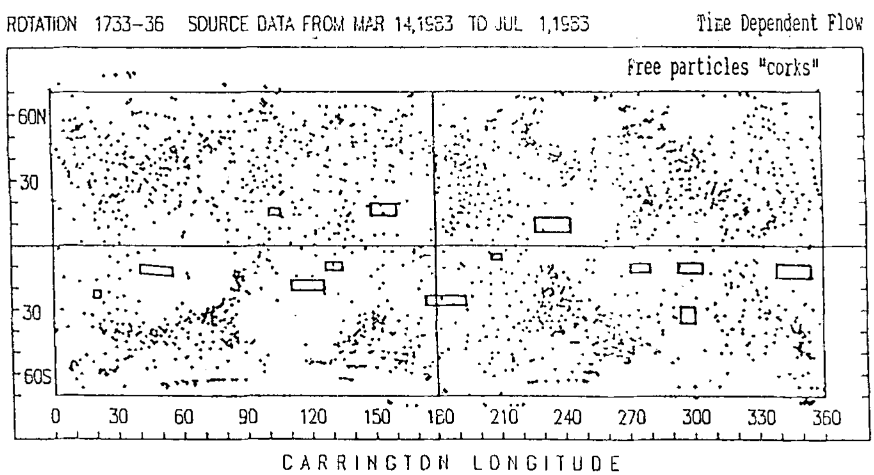

Figure 3 A demonstration of the giant convection cell distribution on the solar synoptic chart. The originally uniformly distributed free particles are carried out by the large-scale horizontal flow to the apparent cell boundaries which are characterized by downflows. The presented cellular structures are well developed. Active regions are displayed as the boxes inside the empty parts of the synoptic chart with characteristic large-sacale plasma upflow.

empty, i.e. particle-free regions, which coincide very well with positions of the active regions (displayed as rectangles) are characterized by the upward large-scale flow. The typical diameter of the giant cells is about 700 Mm, the life time is from 80 to 330 days and the mean horizontal flow velocity is about $25\,\mathrm{m\,s^{-1}}$.

- But it is not obvious that such a magnetic structure is going to evolve into a future active region. More likely it provokes some other structure to be detached from its roots at a certain level to start upfloating and exercise a complicated process of active region formation. Thus in principle we have to admit the possibility of existing of a certain region with possibly a varying depth and size which we can identify with the level of activity formation. Here the most important process should occur resulting in formation of a free structure, rather small in size but incorporating a large magnetic flux. The corresponding time of a "future active region seed" origination and its upfloating should be greater than the travelling time of several month for large fields up to 2 or 3 years for fields weaker then 0.05 T.
- The upfloating free magnetic structure embedded into the convection eventually should take the form of a loop deformed by downflows (the omega shape loop) and seriously affected by surrounding motions.
- At the supergranular level, the upper part of the loop must be seriously influenced by network downdrafts, the loop is deformed into a large horizontal part and two vertical arms with corners driven to the supergranular borders. Here the granular and supergranular downdrafts seriously affect the emerging field dividing it into numerous thin tubes. Topologically only such a structure can found its way to the surface using the tree branch vertical structure of the downdraft.
- As a result we can see that the ED proposed in this paper possibly represents time evolution process of interlocking between emergent field structure and that of convection mainly at supergranular level.

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References

Ambrož, P. (1992). In *Solar Cycle*, ed. K. L. Harvey, *ASP Conference Series* **27**, 35.

Ambrož, P. (1993). Submitted to *The Magnetic and Velocity Fields of Solar Active Regions*, ed. H. Zirin, *ASP Conference Series*.

Brandenburg, A., Jennings, R. L., Nordlung, A., Stein, R. F. and Tuominen, I. (1991). In *The Sun and Cool Stars: activity, magnetism, dynamos*, eds. I. Tuominen, D. Moss and G. Rüdiger, *Lecture Notes in Physics* **380**, Springer-Verlag, 86.

Grigoryev, V. M. and Selivanov, V. L. (1986). *Contributions of the Astronomical Observatory Skalnate Pleso* **15/1**, 87.

Hanslmeier, A., Mattig, W. and Nesis, A. (1991). *Astron. Astrophys.* **251**, 669.

Kononovich, E. V. (1984). *Astron. Circ.* No. 1335, 1.

Krivodubskij, V. N. (1984). *Astron. Zh.* **61,** 354.
Parker, E. N. (1975). *Astrophys. J.* **198,** 205.
Parker, E. N. (1979). *Astrophys. J.* **230,** 905.
Priest, E. (1982). *Solar magnetohydrodynamics,* Reidel Publ. Comp., Dordrecht.
Ramsey, H. E., Schoolman, S. A. and Title, A. M. (1977). *Astrophys. J.* (*Letters*) **215,** L41.
Simon, F. W. and Weiss, N. O. (1968). *Z. Astrophys.* **69,** 435.
Spruit, H. C. and Roberts, B. (1983). *Nature* **304,** No. 5925, 401.
Spruit, H. C., Nordlund, A. and Title, A. M. (1990). *Ann. Rew. Astr. and Astrophys.* **28,** 263.
Unno, W. and Ribes, E. (1976). *Astrophys. J.* **208,** 222.
Weiss, N. O. (1977). *Monthly Not. R.A.S.* **183,** 63P.
Zahn, J.-P. (1987). In *Solar and Stellar Physics,* eds. E.-H. Shröter and M. Schlüssler, *Lecture Notes in Physics* **292,** Springer-Verlag, 55.
Zwaan, C. (1985). *Solar Phys.* **100,** 397.