Solar Dynamo Mechanisms

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What is a dynamo in the context of the Sun and why must it be there?

The solar dynamo reveals itself through the magnetic activity cycle. The cycle displays an irregular pattern of magnetic activity with an underlying high degree of order. The pattern of magnetic activity on the solar surface obeys several well-established laws; Hale's polarity laws, Spörer's law of equatorial migration and the latitudinal dependence of bipolar region tilt angles among other things.

The magnetic activity cycle is the only aspect of the solar dynamo that we can observe directly. We have, however, a lot of indirect knowledge of the internal structure of the Sun that makes it easier to obtain an understanding of how the solar dynamo works.

We may consider the convection zone to consist of four energy reservoirs (see Brandenburg et al. 1996); the kinetic energy reservoir, the magnetic energy reservoir, the thermal energy reservoir, and the gravitational potential energy reservoir. These energy reservoirs are highly coupled by work and dissipation terms. The rate of change of the total magnetic energy $E_M = \int B^2/2\mu_0 dV$ is

$$\frac{dE_M}{dt} = -W_L - Q_J, \tag{0.1}$$

where W_L is the total work done by the Lorentz force $\mathbf{j} \times \mathbf{B}$ and Q_J is the total magnetic dissipation ηj^2. We have a (non-local) dynamo if $-W_L \geq Q_J \geq 0$. Generally speaking this happens when fluid motions performs work against the Lorentz force. Thus, to understand the solar dynamo we must understand what fluid motions that are available in the kinetic energy reservoir, the topology of the magnetic field in the magnetic energy reservoir, what fluid motions that make a dynamo possible by doing work W_L against the Lorentz force, and how the dissipation Q_J depends on the magnetic field. Finally we must also understand what the constraints from the observations are in this context.

What do we know about it?

The following few paragraphs are a summary in a compressed form of what we already know about the ingredients of the solar dynamo from observation and theory.

Observations: Surface magnetic fields

The magnetic field first appear on the solar surface as bipolar emerging flux regions (EFRs). These obey the well known laws observed by eg. Hale and Spörer. There are no characteristic scales of these EFRs since their distribution of areas obey a power law (see Schrijver & Harvey 1994 and Schrijver 1996) Similarly there are no characteristic scale of EFR flux since it is proportional to the EFR area.

On smaller scales concentrations of flux with an intrinsically strong field of 1-2 kG (flux tubes) are surrounded by weaker field of 50-500 G, barely resolved by the current resolution limit of 150 km. The strong flux tube concentrations are probably formed by convective collapse (cf. Parker 1978, Spruit 1978) of flux swept into the magnetic network by supergranular convection.

The combined rotational shear and supergranular convection acts to effectively diffuse the magnetic surface flux. The observed diffusion of the large scale photospheric magnetic field can be very nicely described by a diffusion model of the transport of magnetic flux. By invoking a continuum diffusion process based on the observed shear due to differential rotation, supergranular convection and meridional flow, the observed transport of surface magnetic flux can be more or less reproduced (see eg. Leighton 1964, Sheeley et al. 1987, Sheeley 1992, Sheeley et al. 1992). Even better results can be obtained by using a discrete random walk process (Wang & Sheeley 1994). This suggests that after emergence the surface flux is more or less decoupled from the subsurface field, possibly as a consequence of "dynamic disconnection" (cf. the conjecture of Fan et al. 1994).

Theory and helioseismology: The turbulent convection zone

The kinetic energy that is converted into magnetic energy in the dynamo process have two main sources; convection and differential rotation. It is the combined work of these two types of fluid motions against the Lorentz force that constitutes the dynamo. This is of course a very general statement in need of heavy refinement. Fortunately the dynamics of the convection zone is well understood, mainly from various kinds of numerical modeling (mixing length theory eg. Spruit 1974 and Skaley & Stix 1991 and direct simulations eg. Nordlund & Stein 1995) and from helioseismic measurements (eg. Christensen-Dalsgaard et al. 1995). The nature of the undershoot layer between the subadiabatic radiative envelope and the superadiabatic convection zone has also been the subject of both observational and numerical effort (eg. Christensen-Dalsgaard et al. 1995, and Brandenburg et al. 1991 and Skaley & Stix 1991, respectively). The undershoot layer constitutes a region in which a relatively strong field can be stored as a result of the stable stratification. Instability studies of a toroidal magnetic field in the undershoot layer suggests that a field of up to 10^5 G can be stored if the superadiabaticity is sufficiently negative $\delta \leq -10^{-5}$ (cf. Moreno-Insertis et al. 1992).

The effect of differential rotation becomes important in a global simulation. The importance of the differential rotation to the dynamo process was recognized very early on in the quest for the solar dynamo (Parker 1955, Babcock 1961, Leighton 1964 and Leighton 1969). Global differential rotation has mostly been modeled to study the effects of the Coriolis force in the thin flux tube limit (eg. Spruit 1981, Moreno-Insertis 1986, Choudhuri 1989, Fan et al. 1993, Fan et al. 1994 and Caligari et al. 1995), whereas full MHD simulations incorporating differential rotation are non-global because of the enormous computer power needed to perform a global full MHD simulation.

The differential rotation at the solar surface may be approximated by a simple expression (cf. Snodgrass 1983 and Dziembowski et al. 1989) that is represents the rotation of the photospheric plasma (cf. the discussion in Wang & Sheeley 1994). This expression is a useful formula when the influence of the Coriolis force needs to be taken into account in a simplified model, but it should be remembered that an underlying theory that tells us the detailed physics behind this functional behavior is required. Helioseismic measurements (cf. Christensen-Dalsgaard et al. 1995) suggests that the principal radial gradient of differential rotation is located in the undershoot layer below which the Sun rotates as a solid body with a rotation corresponding to that of the surface at a latitude of $\theta \approx 30$ degrees. Both the radial and the polar shear due to differential rotation are thought to be crucial to the existence of the dynamo, but the matter is not at all clear.

Magnetic flux in the convection zone

A large number of authors have used the thin flux tube approximation (cf. Spruit 1981, Moreno-Insertis 1986, Choudhuri 1989 and many more) to study the buoyant rise of magnetic flux systems from the bottom of the convection zone (cf. Fan et al. 1993, Fan et al. 1994 and Caligari et al. 1995 for recent examples). This procedure gives the correct tilt angles and emergence latitudes for the emerging bipolar magnetic flux regions when the initial magnetic field has super-equipartition field strength of the order of 10^5 G. The scatter in the tilt angles can be interpreted as an effect of convection zone turbulence (cf. Longcope & Fisher 1996). These models are terminated at the point where the thin flux tube approximation breaks down ie. at the point where the ascending flux tube has expanded so much because of the stratification of the convection zone that it is no longer small compared to the pressure scale height. This point is around 10-20 Mm below the photosphere of the Sun where the pressure scale height starts to decrease very rapidly compared to its slow decrease through out the lower part of the convection zone. Thus, because numerical models like the ones mentioned above exhibit a behavior consistent with observed quantities like tilt angles and emergence latitude, they may be considered to be good examples of how a *reduced* scenario may contribute to the understanding of the solar dynamo.

Both observations (cf. Gaizauskas 1993) and numerical simulations points towards the idea, that the magnetic field just below the photosphere exists in the form of a lot of small scale structures, ie. the magnetic field does not emerge as a whole, but in a fragmented form. One expects the fragmentation to occur in the last 20 Mm of the ascent of the flux. As the flux rope expands and becomes comparable to the pressure scale height, various instabilities may be expected to try to pull the tube apart to prevent it from becoming any larger.

Even before the ascending flux reaches the top portion of the convection zone other instabilities occur: Numerical simulations of ascending flux tubes (cf. Schussler 1979, Tsinganos 1980, Cattaneo & Hughes 1988, Cattaneo et al. 1990, Matthews et al. 1995 and Emonet & Moreno-Insertis 1996a) show that Rayleigh-Taylor like instabilities occur that tends to destroy the buoyant flux tubes very early on in their journey up through the convection zone. This apparent disruption is the result of the assumption of a simple field line topology. In models where buoyantly ascending flux tubes experience this kind of disruption it is assumed that the magnetic field lines are parallel to the flux tube axis. The disruption is prevented if the field lines have a more complex topology ie. if they are entangled as a result of chaotic mapping by turbulent dynamo action (cf. Dorch & Nordlund 1996) or if a twist is imposed on the flux tubes (cf. Emonet & Moreno-Insertis 1996b – it is not clear what kind of physical mechanism that could produce such a twist though). Furthermore, an 'explosion' of the flux tubes may occur before emergence as a consequence of the establishing of hydrostatic equilibrium along field lines (cf. Moreno-Insertis et al. 1995). For field strengths below equipartition, the explosion height is approximately half the extension of the convection zone and only flux ropes which initially had a field strength of the order of 10^5 G emerge on the surface.

Dynamo Mechanisms

The solar dynamo may not be one mechanism, but several physical processes acting together. In fact, by recognizing that it is the work done by fluid motions against the Lorentz force that drives the dynamo and by remembering that the Lorentz force can be decomposed into two terms (a pressure gradient and a tension force), it is possible (at least conceptually) to divide dynamo effects into two categories; *barometric effects* that have to do with effects caused by the magnetic pressure and *topological effects* that have to do with the magnetic field line tension (which may then again be subdivided).

Parker 1993 proposes that there are a natural barometric effect associated with the rise of omega-loops that automatically ensures a minimum value of 10^5 G of the field strength of the loop at the point where it is anchored ie. in the undershoot layer. This "Omega-pumping" comes about through the tendency to establish hydrostatic equilibrium along the loop field lines. It is basically the same effect that renders dynamo action possible in the course of establishment of hydrostatic equilibrium after explosion of buoyant weak flux tubes (cf. Moreno-Insertis et al. 1995).

Topological dynamo effects are easily modeled using toy models of simple mappings of field lines. A famous and realistic simple model is the *stretch-twist-fold* (STF) dynamo (cf. Vainshtein & Zel'dovich 1972). Many kind of dynamo can probably be viewed as special cases of a STF dynamo (cf. Childress & Gilbert 1995). One may eg. consider the classical ω-effect to be a *stretch* dynamo. In the turbulent convection zone a lot of STF (not necessarily in that order) of field lines are going on. There has been much ado about the possible suppression of turbulent diffusion of super-equipartition fields and there are also claims (cf. Cattaneo & Vainshtein 1991, Vainshtein & Rosner 1991 and Vainshtein & Cattaneo 1992) that turbulent diffusion is strongly suppressed even for equipartition fields. On the other hand careful numerical experiments show that small scale dynamo action is not significantly suppressed in an intermittent 3D MHD plasma (cf. Nordlund et al. 1992). Local small scale turbulent dynamo action was studied in the context of turbulent convection. In this case spontaneous dynamo action occur resulting in a dynamo generated magnetic field in the vicinity of strong convective downdrafts. The small scale dynamo action in a (local) geometry such as that of Nordlund et al. 1992 is qualitatively similar to the STF-dynamo.

What don't we know and what can we do about it?

Our aim is not to construct a global, "correct" theory of the solar dynamo and the solar magnetic activity cycle. Such a theory is perhaps desirable from some views on the philosophy of science, but it is an ideal concept that we can only hope to approach – at best asymptotically. Rather we aim at developing an *understanding* of the basic ingredients of the solar dynamo in the hope that this will yield an understanding of the global solar dynamo. Indeed, *to understand* is here the keyword; Without qualitative experience it is less plausible that the introduction of new concepts, approximations and models will lead the quest for the solar dynamo anywhere but into a blind alley. It is the goal to understand the different *pieces* of the solar dynamo puzzle and their couplings.

The current knowledge leaves us with some information about the necessary ingredients in a potential global dynamo model. Let us try to summarize the current paradigm in the following and pose questions that suggests in what direction we should put our effort.

It is most likely that the 10^5 G toroidal flux system is generated in the undershoot layer as a result of the combined action of differential rotation, radial and polar shear and turbulent convection. Differential rotation stretches the field lines in the toroidal direction while the relative importance of the two kinds of shear are not clear: There is virtually no radial shear on the part of the flux system located in the undershoot layer at around 30 degrees latitude, because the rotation through out the convection zone at this latitude matches the solid body rotation of the interior. However at around that latitude the polar shear has its maximum. It may be more than a coincidence that a new magnetic activity cycle begins with EFRs appearing at or near this latitude.

If the main magnetic field generation takes place in the lower part of the undershoot layer and results in a strong magnetic field in thermal equilibrium, the flux system, being buoyant, ascends up through the undershoot layer until a state of mechanical equilibrium obtains. This mechanical equilibrium may also be a result of the fact that the flux system is supplied by entropy deficient material from within the convection zone by undershooting plasma plumes. To be in mechanical equilibrium and thus stored in the undershoot layer the flux system must be a few degrees colder than the ambient medium, with peak field strengts less than or of the order of 10^5 G. It appears likely, both from theoretical consideration, and from the stochastic nature of active region emergence, that the total flux is distributed over a number of entangled fragments (perhaps with a fractal distribution in a cross section). The parts of the flux system that are not cold enough, and thus are not neutrally buoyant, enter the convection zone directly.

Small perturbations from undershooting convective plumes may also destabilize the upper part of the toroidal flux system and push fragments into the convection zone. Note that, if the overall strength of the flux system is growing with time (because of differential rotation), then as fragments are coming close to becoming bouyant, they are easily disturbed by, for example, undershooting convective motions, even though the field strengths are formally far above equipartition relative to the kinetic energy in those motions.

In the convection zone the flux ropes start ascending and expand as they move towards the surface. Only flux systems that stay buoyant will reach the sub-surface layers. Strong fields may reach the sub-surface layers, while weak fields explode inside the convection zone or are caught in convective up and downdrafts.

Because of the exponential stratification the ascending flux systems will expand vastly in the upper parts of the convection zone. To keep the flux tubes from becoming any larger than of the order of the local pressure scale height, they are likely to split into smaller pieces with sizes comparable to the local scale height. Thus when they emerge they will typically be small scale flux tubes.

The emergence typically takes place in convective upwelling regions – that is – inside the granular cells. After emergence the small scale flux tubes/ropes are swept into the inter-granular lanes where they are concentrated, both by flux addition and by convective collapse. The active regions in which the flux emerges diffuses across the surface eventually resulting in the reversal of the polar field.

We are now left with several questions:

1. What are the effect of the two types of shear on the magnetic field in the undershoot layer? What are the combined effect of the differential rotation shear and the convection?

2. What part does the undershooting convective downdrafts play in the dynamo? Does it supply cold plasma (enough) to the stored magnetic field that keeps it stored? Does it inject an enhanced magnetic field into the undershoot layer? Does it perturb the stored field and move it into the convection zone?

3. What is the behavior of the buoyant flux in the last 10-20 Mm of the convection zone?

4. Why and how can the surface flux be advected like a passive scalar after it has emerged?

We propose to study the above problems using the code described in eg. Nordlund & Galsgaard 1996 to extract the generic truths hidden in the full MHD equations, including the observed structure of the solar differential rotation (cf. Snodgrass 1983, Dziembowski et al. 1989 and Christensen-Dalsgaard et al. 1995), in a cartesian geometry resembling various parts of the solar convection zone. The following numerical experiments are underway:

- A study of the explosion of resolved buoyantly ascending flux tubes in the convection zone, in order to understand how the explosion depends on field strength, topology and differential rotation. This will also give clues on barometric dynamo effects.

- A study of the effect of shear (radial and polar) on the magnetic field located in the undershoot layer. This should give hints on the structure of the magnetic field stored in the undershoot layer and on the effectiveness of the omega effect(s).

- A study of the behavior of buoyant non-thin flux tubes in a strong stratification to examine the instabilities that are a precursor of EFRs.

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