

# On the Origin of Activity in Solar-Type Stars

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## ABSTRACT

The magnetic flux of solar coronal active regions is thought to originate in strong toroidal magnetic fields generated by a dynamo at the base of the convection zone. Once generated, this magnetic flux rises through the convection zone as discrete buoyant flux tubes, which may be formed into  $\Omega$ -shaped loops by their interaction with convective cells and strong downdrafts. The loops are prevented from fragmentation by twist and curvature of their axes, which are writhed by the Coriolis effect and helical convective turbulence. These  $\Omega$ -shaped loops emerge through the photosphere to form dipolar sunspot pairs and coronal active regions. These regions' free energy, relative magnetic helicity, and tendency to flare and erupt reflect the convection zone phenomena that dominate their journey to the surface, in which helical convective turbulence appears to play a primary role.

Recent research leads me to *suggest* a new paradigm for activity in solar-type stars with deep-seated (tachocline) dynamos. In the present paradigm, dynamo models are expected to explain the distribution of activity in the H-R diagram, as reflected in mean chromospheric emission in lower main-sequence stars. In the new paradigm, dynamo action simply generates the flux that is necessary, but not sufficient, for such activity, and the amplitude of activity depends most importantly on the kinetic helicity and turbulence of convection zone flows.

## THE DYNAMO AND THE CONVECTION ZONE

Since the development of helioseismology, the commonly accepted location of the dynamo that is thought to produce solar active region magnetic fields has shifted from within the convection zone to the tachocline. The velocity field at this location, at the interface between the convection zone and the radiative core, is distinctive. In the convection zone helioseismology has shown the solar angular rotation rate depends strongly on latitude (differential rotation), but in the core it does not. In the convection zone the radial gradient of the rotation rate is small. In the tachocline above  $\sim 30^\circ$  latitude, the radial gradient is significantly negative; below that latitude, it is positive. This radial shear makes the tachocline a plausible place at which to expect the induction of the strong toroidal fields that produce active regions at photospheric and coronal levels.

For the activity seen on the solar surface, an essential role of the dynamo is the production of magnetic flux. A considerable list of observational constraints on the solar dynamo has long been known. Those that most directly involve individual active regions include Hale's polarity rule and Joy's law of active region tilts (Hale et al. 1919). Only in the last decade or so has it become appreciated that there is an additional constraint on the sense of twist, or handedness, of active region fields in the photosphere and corona. The production of such twist is a common feature of interface and flux transport dynamos (Gilman and Charbonneau 1999). However, it is not clear that the hemispheric dependence of the handedness of the twist generated by these dynamos is meaningfully constrained by these observations, since the twist observed at photospheric and coronal levels seems to be dominated by other processes (Longcope et al. 1999).

Given that sufficient toroidal flux is formed by a suitable dynamo mechanism at the base of the convection zone, the formation of flux tubes from a neutrally buoyant layer of horizontal, unidirectional magnetic field in hydrostatic equilibrium is shown in the left panel of Figure 1. In this model (Fan 2001) the magnetic buoyancy

(Parker) instability creates the flux tubes shown, when the initial equilibrium is perturbed with an unstable undulatory mode. The scales of the buoyancy instability and external perturbations respectively determine the spatial scales of the tubes parallel and perpendicular to the magnetic field direction.

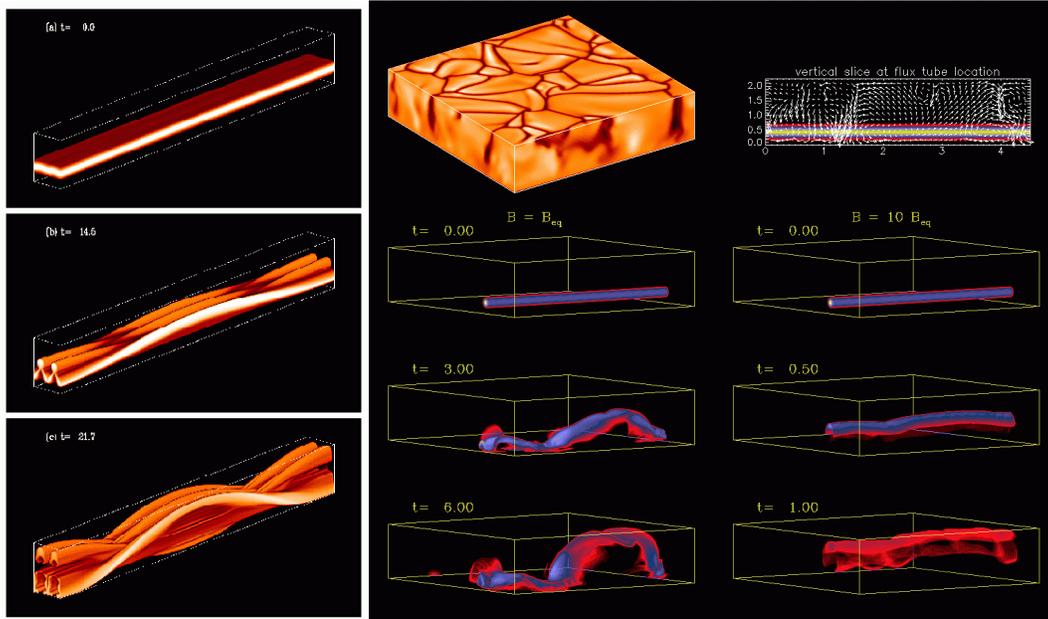


Fig. 1. Left: Three times during the formation of flux tubes from a flux sheet at the base of the convection zone. Right: Deformation of  $\Omega$  loops by convective flows. From Fan (2001) and Fan, Abbett and Fisher (2003), by permission.

The observed emergence of spots at low latitudes during the late phase of each sunspot cycle implies that fields at the base of the convection zone have strengths 30 - 100 times greater than the equipartition value that is required to balance the kinetic energy of surrounding field-free convection. Fan, Abbett, and Fisher (2003) have shown that for values of flux tube field strengths around the equipartition value  $B_{eq}$ , the downdrafts in the over-turning convection shown at the top row of the right panel of Figure 1 are able to pin down the uniformly buoyant flux tube, so that it rises only between the downdrafts (left column of the right panel). For values of flux tube field strength greater than about  $10 B_{eq}$  (right column of the right panel), little such distortion takes place, and axial variation of buoyancy may be required to explain the formation of  $\Omega$  loops.

Twist about the flux tube axis provides a restoring force that inhibits the fragmentation of flux tubes. In 2D simulations, Moreno-Inertis and Emonet (1996) and others showed that a minimum value of twist (larger than that observed in the solar photosphere) is required for flux tube cohesion. However, 3D simulations by Wissink et al. (2000), Fan, Abbett & Fisher (2003) and others have concluded that the amount of twist needed for cohesive rise to the surface is reduced dramatically by both the loop's  $\Omega$  shape and stochastic axial distortions due to turbulence.

Early studies of flux tube dynamics were made using the thin flux tube approximation (Spruit 1981), in which the flux tube is treated as a 1D curve moving through a model convection zone, influenced by magnetic buoyancy, magnetic tension, aerodynamic drag and the Coriolis effect. In general, the magnetic helicity  $H$  is given in terms of the vector potential  $\mathbf{A}$

$$H = \int_D \mathbf{A} \cdot \mathbf{B} dV,$$

by

where  $D$  is a domain bounded by a surface not crossed by magnetic field lines. For a thin flux tube,  $H$  reduces to

$$H = \int_{Tube} \mathbf{A}_a \cdot \mathbf{B}_a dV + 2 \int_{Tube} \mathbf{A}_a \cdot \mathbf{B}_m dV = Twist + Writhe.$$

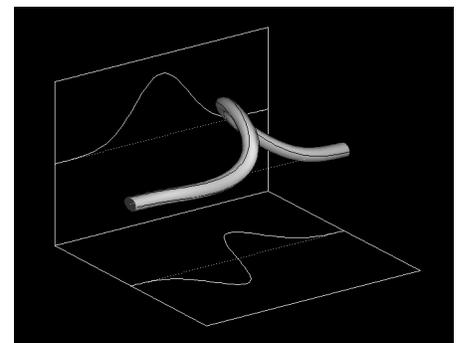


Fig. 2. A right-hand twisted and equally left-handed writhe magnetic flux tube. Courtesy Dana Longcope.

The subscripts indicate the axial (a) and meridional (m) fields of the flux tube, and *twist* and *writhe* describe distortion about the axis and of the axis respectively. As anyone who has coiled a garden hose knows,  $H$  is a conserved quantity as long as the ends are fixed and you don't take a blowtorch to the hose. If you add some twist, you subtract an equal amount of writhe. The analogy carries over to MHD, as shown by Longcope and Klapper (1997). Figure 2 illustrates how twist (the meridional winding of the magnetic field about the axis) is produced when the axis of an initially straight flux tube is wound in a helix. This picture obtains to a high degree of accuracy under solar conditions, even in the presence of magnetic reconnection, as long as the total magnetic helicity of the domain is well conserved. For observable solar phenomena, the domain is huge, which ensures that the relatively small region in which magnetic energy is liberated has a negligible effect on helicity conservation.

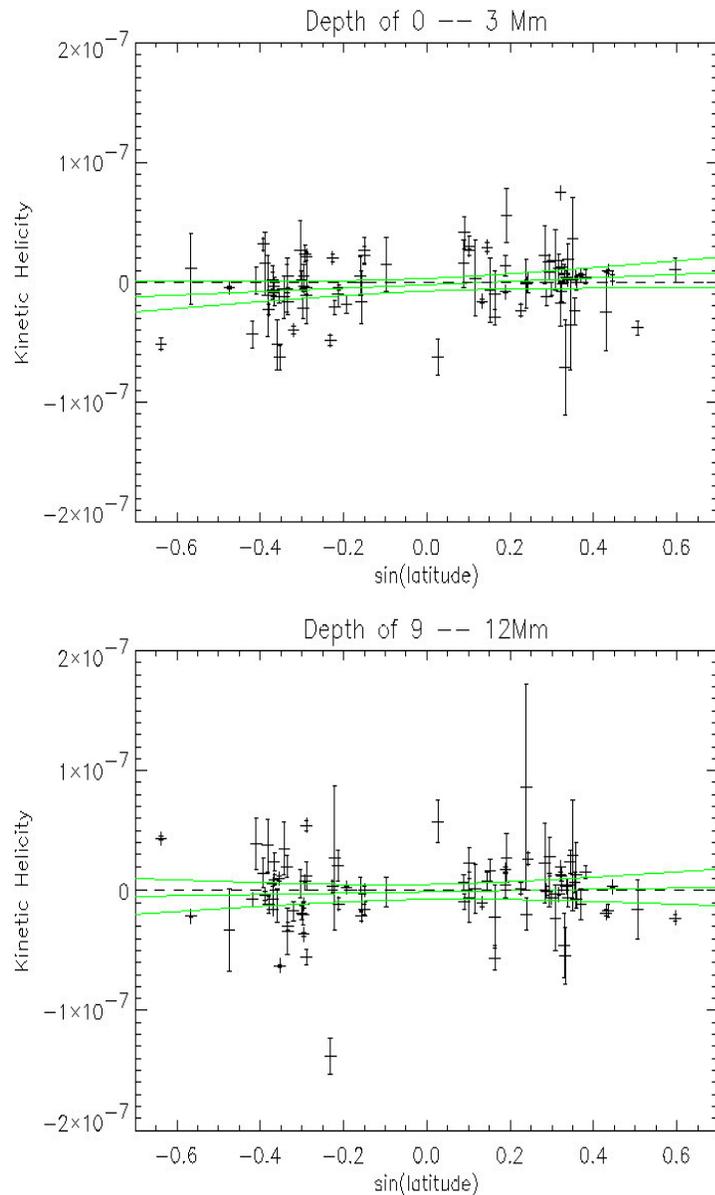


Fig. 3. Latitudinal dependence of kinetic helicity at two depths beneath the photosphere, from SOHO/MDI data. Courtesy Junwei Zhao.

Local helioseismology has developed sufficiently to determine the value of the spatially averaged kinetic helicity  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$  of *velocity* fields in the uppermost layer of the convection zone beneath active regions. Zhao et al. (2002) have determined  $\langle v_z (\partial v_y / \partial x - \partial v_x / \partial y) / \sqrt{(v_x^2 + v_y^2 + v_z^2)} \rangle$  at two depths beneath 87 active regions observed by MDI during sunspot cycle 23 (Figure 3). The error bars are the difference between the values for the first and second halves of the data acquisition periods for each region, which range from hours to days. The lines show the best linear fit and its uncertainty. Their results show two features of immediate interest. First, a weak hemispheric dependence appears. On average, the flows beneath northern hemisphere active regions show positive values of  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$  (right handed), and those beneath southern hemisphere active regions have negative values. However, this contradicts basic expectations, which hold that the effects of solar rotation on convection yield negative  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$  in the northern hemisphere (Moffatt, 1978; Longcope & Pevtsov, 2003) in the upper part of the convection zone. Since the hemispheric trends in Figure 3 are very small compared to their error, it is premature to conclude that there really is a problem. More importantly for this paper, the scatter of values considerably exceeds the error bars for each individual region, and overwhelms the hemispheric trend. The interpretation is apparent; the stochastic nature of turbulence has a more powerful effect on  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$  than does the Coriolis effect.

## THE PHOTOSPHERE AND THE CORONA

Useful measures of the twist of the magnetic fields that thread vertically through the photosphere are the current helicity  $H_c = \mathbf{B} \cdot \nabla \times \mathbf{B}$  and the related parameter  $\alpha$ , defined by the force-free field relationship  $\nabla \times \mathbf{B} = \alpha \mathbf{B}$ . No general analytical relationship exists between  $H_c$  and  $\alpha$ , but the fact that there is a physical relationship can be seen analytically for a force free field, for which  $\mathbf{B} = \alpha \mathbf{A}$ , so  $H_c = \alpha \mathbf{B}^2$ . Figure 4 shows the latitudinal dependence of  $\alpha_{\text{best}}$ , the value of  $\alpha$  for a linear force-free field based on the observed photospheric vertical magnetic field that best fits the horizontal magnetic field of a given active-region magnetogram. Noteworthy features are hemispheric dependence (a preference for left-handed twist in the northern hemisphere, and the opposite in the southern) and large scatter. Longcope, Fisher and Pevtsov (1998) explain both the hemispheric dependence and the amplitude of the observed scatter in terms of what they call the  $\Sigma$  effect, in which helical turbulent convection imparts twist to flux tubes by helically writhing their axes, while conserving magnetic helicity (Figure 2). Their spatially averaged source term for twist due to the writhing of the axes of flux tubes by turbulence is  $\langle \Sigma \rangle = -(\tau_c/5) \int k^2 F(k) dk$ , where  $\tau_c$  is the correlation time of the turbulence and  $F(k)$  is the spectral density distribution of its kinetic helicity as a function of wave number. The spatially averaged kinetic helicity is related to  $F(k)$  by  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle = -\int F(k) dk$ .

The key point for the discussion below, is the demonstration by Longcope, Fisher and Pevtsov (1998) that helical turbulent convection alone, acting on untwisted flux tubes generated by the dynamo, can explain the amplitude of the active region twists shown in Figure 4. Charbonneau and Gilman (1998) estimate that the helical pitch  $q_0$  of the field generated by the dynamo may range from  $3 \times 10^{-6}$  rad/Mm to  $3 \times 10^{-2}$  rad/Mm, depending on parameters such as the dynamo  $\alpha$  and the dynamo number, and a reasonable choice of those parameters gives  $q_0 \approx 3 \times 10^{-6}$  rad/Mm. Since the  $\Sigma$  effect produces a typical twist  $q \sim 2 \times 10^{-2}$  rad/Mm (Longcope et al. 1999), and that value matches well the scatter in the observations shown in Figure 4 ( $q \sim \alpha/2$ , shown by Longcope & Welsch, 2000), it is reasonable to believe that the dynamo contributes negligibly to the twist observed at the photosphere.

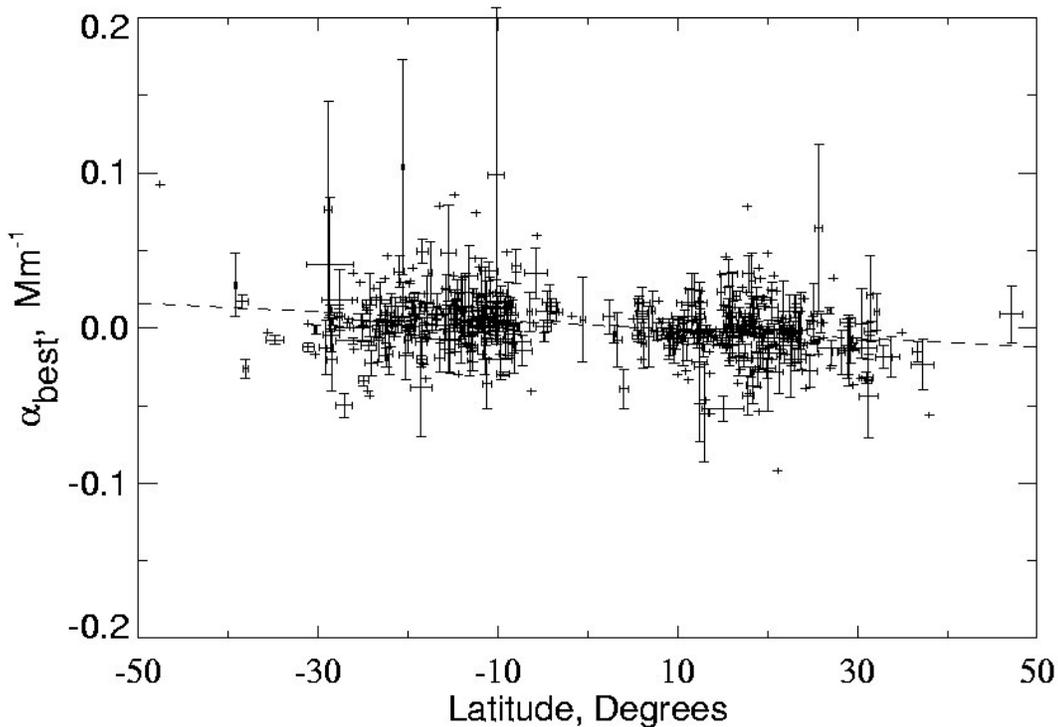


Fig 4. Haleakala Stokes Polarimeter observations of the overall twist of the magnetic fields of 466 solar active regions from cycles 22 and 23. Each data point represents one active region. The error bars show the range derived from multiple magnetograms. Courtesy Alexei Pevtsov.

Pevtsov, Canfield & McClymont (1997) used sigmoids in the Yohkoh SXT images to determine values of  $\alpha$  in the corona, denoted by  $\alpha_c$  in Figure 5, in active regions for which  $\alpha$  had been measured in the photosphere, denoted by  $\alpha_p$  in the figure. From the clear statistical relationship between the photospheric and coronal  $\alpha$  values they inferred that the observed coronal twists, and their attendant currents, are of sub-photospheric origin.

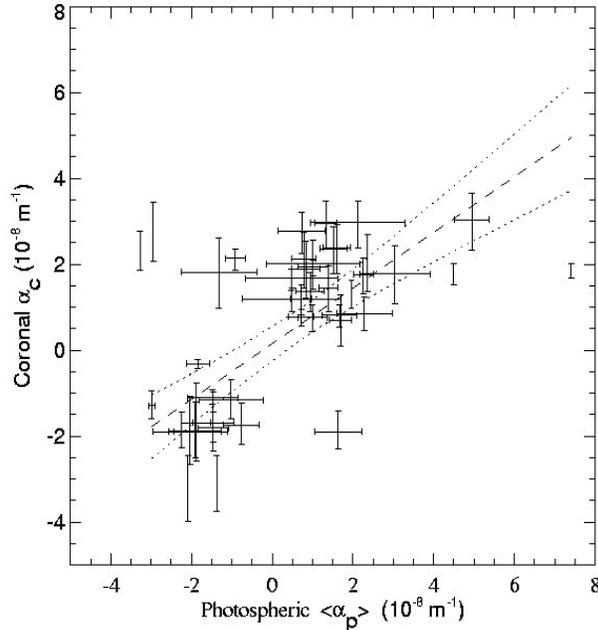


Fig. 5. Comparison of coronal and photospheric twist from Pevtsov, Canfield & McClymont (1997), by permission.

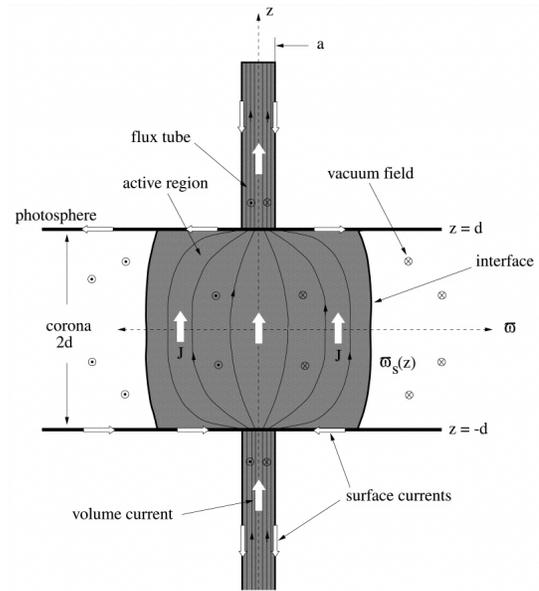


Fig. 6. Magnetic flux and current systems in the emerging flux model of Longcope and Welsch (2000), by permission.

Longcope and Welsch (2000) studied the relationship between  $\alpha_c$  and  $\alpha_p$  using a dynamical model of flux emergence whose currents and fields are shown in Figure 6. The model takes into account the very different nature of the magnetic fields and electric currents in these two regimes, above and below the photosphere (which Metcalf et al. (1995) found to be the approximate depth in the solar atmosphere above which the magnetic field is force free). Below the photosphere a return current on the surface of the tube balances the total current  $I$  inside it, which is  $\alpha_p \Phi$ , where  $\Phi$  is its magnetic flux, whereas in the corona there are initially no currents. The model recognizes that there must be torque balance at the interface between the photosphere and the corona. Upon flux emergence, the force-free field in the corona causes a torsional Alfvén wave (twist rarefaction) to be launched into the flux tube in the convection zone. As this wave goes to greater depths, the coronal twist asymptotically approaches  $\alpha_p$ , as the observations suggest.

Magara and Longcope (2002) have modeled the emergence into the corona of an initially straight twisted flux tube through a 3D MHD numerical simulation. When they perturb the initial equilibrium at its center, it forms an  $\Omega$  shape and the top begins to emerge through the photosphere. The field lines near the original axis of the flux tube form a sigmoidal shape in the corona. This topology is known to be associated with enhanced probability of coronal eruption (Canfield, Hudson & McKenzie 1999). One can draw the following parallel between the rates of emergence of energy (Poynting flux, left column) and magnetic helicity (right column) through the photospheric surface  $S$  into the corona (Berger & Field, 1984):

$$\dot{E}_S = \frac{1}{\mu_0} \int_S \mathbf{B} \times (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{n} dS$$

$$\dot{E}_S = \dot{E}_t + \dot{E}_n$$

$$\dot{E}_t = -\frac{1}{\mu_0} \int_S (\mathbf{v}_t \cdot \mathbf{B}_t) \mathbf{B}_n \cdot \mathbf{n} dS$$

$$\dot{E}_n = \frac{1}{\mu_0} \int_S B_t^2 \mathbf{v}_n \cdot \mathbf{n} dS$$

$$\dot{H}_S = 2 \int_S \mathbf{A}_p \times (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{n} dS$$

$$\dot{H}_S = \dot{H}_t + \dot{H}_n$$

$$\dot{H}_t = -2 \int_S (\mathbf{v}_t \cdot \mathbf{A}_p) \mathbf{B}_n \cdot \mathbf{n} dS$$

$$H_n = 2 \int_S (\mathbf{A}_p \cdot \mathbf{B}_t) \mathbf{v}_n \cdot \mathbf{n} dS$$

The terms in the third row are due to shearing motions (transverse velocities,  $v_t$ ), and the terms in the fourth row, flux emergence (normal velocities,  $v_n$ ). Magara and Longcope (2002) show that in their model the time dependence of the variation of the emergence term and the shear term are quite different. In panels a) and b) of Figure 7 we see that as the magnetic energy of the corona increases above that of the potential field, the emergence term dominates earlier, and the shear term dominates later. Similarly, in Panels c) and d) we see the same relationship, though the dominance of the helicity emergence rate by shearing motions later in the process is much more dramatic.

One of the more promising developments of the last few years has been the application of these expressions to the observational estimation of the rate of helicity emergence. D emoulin et al. (2002) developed techniques for studying shearing motions by applying the transverse velocities of differential rotation to MDI line-of-sight magnetograms of an active region over many months, tracking the shear contribution to helicity and the number of CMEs from this region. They confirmed Devore's (2000) predicted rate of helicity generation by differential rotation, and compared it to the rate of helicity loss by interplanetary flux ropes (magnetic clouds). They concluded that the shear term was far too small to account for the observed helicity loss in flux ropes, and therefore that the flux emergence term must dominate the shear term. Chae (2001) developed techniques for studying shearing motions by applying local correlation tracking techniques to MDI line-of-sight magnetograms of an active region over several days to determine the  $v_t$  distribution. Their work showed complex patterns of the shearing term, consistent with what would be expected from dominance by turbulent convection over differential rotation as a source of twist.

Another important advance was made by Kusano et al. (2002), who use the induction equation to infer both  $v_n$  and  $v_t$  from observations. Their technique allows them to determine both the flux emergence term and the shearing term when they have vector magnetogram data, since the helicity emergence term includes  $B_t$ . Like Chae et al. (2001) found for the shearing term, they find a complex spatial pattern of helicity injection into the corona, as shown in Figure 8, but for *both* the flux emergence term (middle row) and the shear term (bottom row). They also find that the two terms have quite different temporal dependence; helicity emergence is dominated by the flux emergence term early (as in region A of Figure 8, for example), and the shearing term later. It remains to be seen that this early dominance by the flux emergence term is a general tendency, though that is suggested by Magara & Longcope's (2002) simulation. Factors such as the current profile within the flux tube may play a sufficiently important role to change things. Furthermore, it remains to be seen whether the use of local correlation tracking, in combination with the inversion of the induction equation to get  $v_t$ , correctly captures the relevant physics.

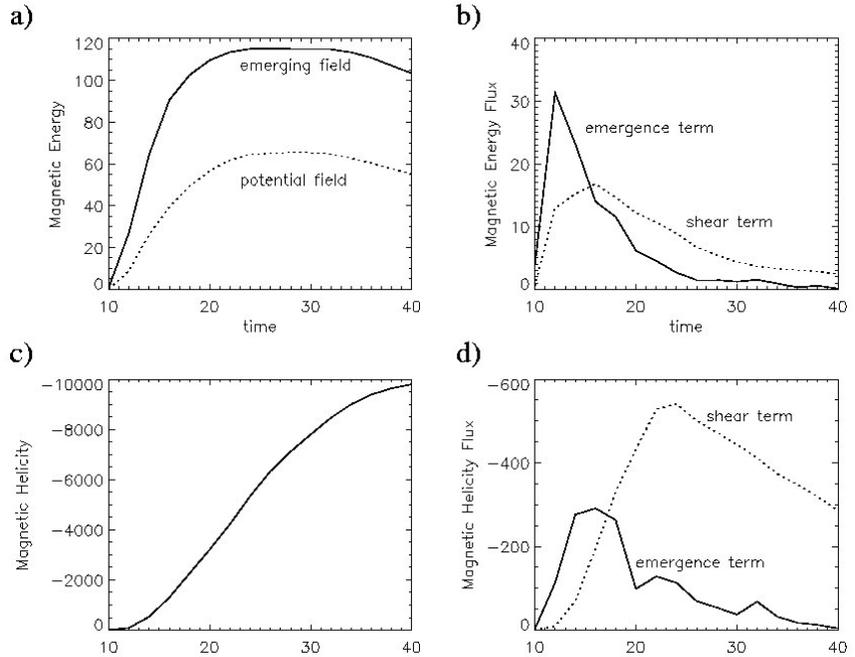


Fig. 7. The temporal dependence of magnetic energy and helicity as a single flux tube with a Gold-Hoyle magnetic field and current profile emerges through the photosphere into the corona. Courtesy T. Magara

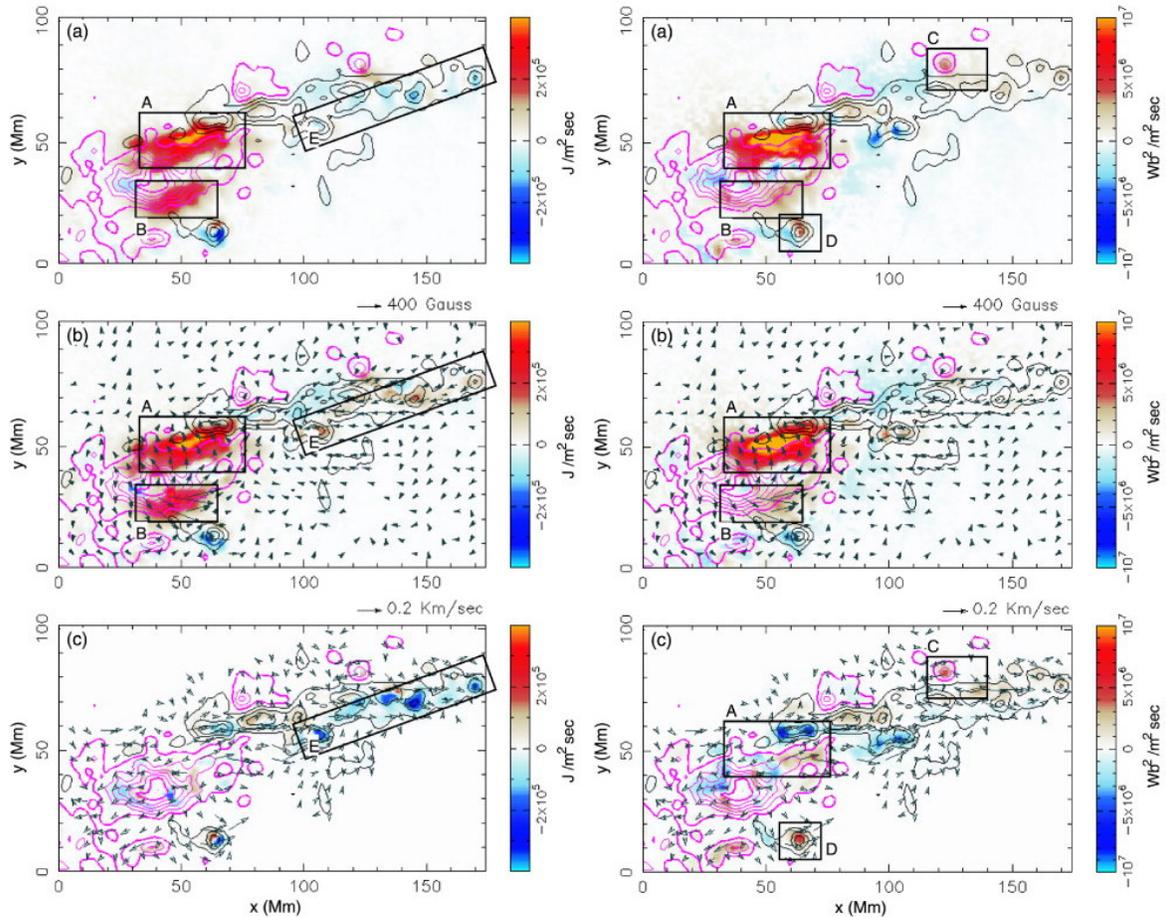


Fig. 8. Left: The rate of emergence of magnetic energy (left column) and relative magnetic helicity (right column) at one time active region (NOAA 8100). Top row: total values; middle row: values due to flux emergence; bottom row: values due to shearing motions. From Kusano et al. (2002), by permission

## A NEW PARADIGM FOR STELLAR PHYSICS

The scenario developed above can be summarized quite succinctly. In the Sun, large-scale dynamo action is thought to take place near the tachocline, creating a sheet of magnetic flux from which distinct tubes form. Initially slightly twisted, apparently enough to ensure their cohesion, these flux tubes rise buoyantly through the convection zone. During this rise they encounter helical turbulent convection, which writhes them and, through helicity conservation, twists them much more than does the dynamo itself. The twist imparted by convection adequately accounts for the observed hemispheric dependence and scatter of active region twists. In the new way of thinking, this is more than just an accounting for observed active region twist. The broader implication is that the twist imparted to these flux tubes by convective turbulence is the dominant driver for coronal heating and solar activity.

The obvious implication of this scenario for dynamo theory is that the mantle of generation of the non-potential fields that are responsible for the solar corona and its activity falls upon helical turbulent convection, not the dynamo itself. The large-scale dynamo need only account for more basic production of magnetic flux, solar cycle, etc. Recent solar observational and theoretical research compels one to believe that only helical turbulent convection can explain the hemispheric amplitude and variance of twist observed in the photosphere and corona. In this new paradigm the kinetic helicity of the turbulence, not the dynamo itself, determines the level of solar coronal activity.

Longcope and colleagues have worked out the functional relationship of twist to the average kinetic helicity of turbulent convection in a series of papers. Longcope, Fisher & Pevtsov (1998) adopt a simple model that assumes that turbulent convection is homogeneous, isotropic, and incompressible, and is adequately characterized by the length  $l_{ml}$  and velocity  $v_{conv}$  from mixing length theory (Bohm-Vitense 1958). The spatially averaged source term for

twist due to the writhing of the axes of flux tubes by helical turbulent convection (the  $\Sigma$  effect) combined with helicity conservation is  $\langle \Sigma \rangle = -(\tau_c/5) \int k^2 F(k) dk$ , where  $\tau_c$  is the correlation time of the turbulence and  $F(k)$  is the spectral density distribution of its kinetic helicity (Longcope & Pevtsov 2003). The spatially averaged kinetic helicity is related to  $F(k)$  by  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle = -\int F(k) dk$ . Taking  $F(k)$  from Zeldovich, Ruzmaikin, & Sokoloff (1983), Longcope, Fisher & Pevtsov (1998) show that the average kinetic helicity of the turbulence is  $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle = 6\pi v_{conv}^2 / l_{ml} R_0$ , where  $R_0$  is the Rossby number, the ratio of the star's rotation period to the convective turnover time. The key point is that the amplitude of twist generated by the  $\Sigma$  effect is inversely proportional to  $R_0$ .

I propose a new paradigm for solar and stellar physics, in which the implications of this point are recognized for the relationship between rotation, convection, and magnetic activity in the Sun and other lower main-sequence stars. In current work on dynamo action in such stars (e.g., Montesinos et al., 2001), the demonstration by Noyes et al (1985) that Ca II H and K emission is inversely correlated with  $R_0$  is taken to be a constraint on dynamo theory. The  $\Sigma$  effect frees dynamo theory from this constraint. The  $\Sigma$  effect alone fully explains this  $R_0$  correlation, freeing dynamo theory for the more basic task of explaining the generation of magnetic flux.

Is this new paradigm correct, or just a misguided personal bias? Time will tell.

## ACKNOWLEDGMENTS

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