The Solar Dynamo and Emerging Flux

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Abstract. The largest concentrations of magnetic flux on the Sun occur in active regions. In this paper, the properties of active regions are investigated in terms of the dynamics of magnetic flux tubes which emerge from the base of the solar convection zone, where the solar cycle dynamo is believed to operate, to the photosphere. Flux tube dynamics are computed using the "thin flux tube" approximation, and by using MHD simulation. Simulations of active region emergence and evolution, when compared with the known observed properties of active regions, have yielded the following results:
(1) The magnetic field at the base of the convection zone is confined to an approximately toroidal geometry with a field strength in the range $3 - 10 \times 10^4$G. The latitude distribution of the toroidal field at the base of the convection zone is more or less mirrored by the observed active latitudes; there is not a large poleward drift of active regions as they emerge. The time scale for emergence of an active region from the base of the convection zone to the surface is typically 2-4 months. The equatorial gap in the distribution of active regions has two possible origins; if the toroidal field strength is close to 10^5G, it is due to the lack of equilibrium solutions at low latitude; if it is closer to 3×10^4G, it may be due to modest poleward drift during emergence.
(2) The tilt of active regions is due primarily to the Coriolis force acting to twist the diverging flows of the rising flux loops. The dispersion in tilts is caused primarily by the buffeting of flux tubes by convective motions as they rise through the interior.
(3) The Coriolis force also bends the active region flux tube shape toward the following (i.e. anti-rotational) direction, resulting in a steeper leg on the following side as compared to the leading side of an active region. When the active region emerges through the photosphere, this results in a more rapid separation of the leading spots away from the magnetic neutral line as compared to the following spots. This bending motion also results in the neutral line being closer to the following magnetic polarity.
(4) Active regions behave kinematically after they emerge because of "dynamic disconnection", which occurs because of the lack of a solution to the hydrostatic equilibrium equation once the flux loop has emerged. This could explain why active regions decay once they have emerged, and why the advection-diffusion description

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of active regions works well after emergence. Smaller flux tubes may undergo "flux tube explosion", a similar process, and provide a source for the constant emergence of small scale magnetic fields.
(5) The slight trend of most active regions to have a negative magnetic twist in the northern hemisphere and positive twist in the south can be accounted for by the action of Coriolis forces on convective eddies, which ultimately writhes active region flux tubes to produce a magnetic twist of the correct sign and amplitude to explain the observations.
(6) The properties of the strongly sheared, flare productive δ-spot active regions can be accounted for by the dynamics of highly twisted Ω loops that succumb to the helical kink instability as they emerge through the solar interior.

1. Introduction

Where do the Sun's magnetic fields come from? A great deal of effort is expended in trying to answer this question, with approaches ranging from detailed, high resolution observations of the Sun's magnetic flux evolution, to studies of how magnetic activity varies with different stellar parameters for solar-like stars, to sophisticated mathematical models of the solar cycle dynamo. Here, we attempt to answer this question from a narrow perspective, and review the evidence that magnetic fields in solar active regions originate from the base of the solar convection zone, with a roughly toroidal geometry, and with field strengths $\sim 3 \times 10^4 - 1 \times 10^5$G. The fields we see at the surface in the form of active regions appear to be loops of flux which for one reason or another have emerged from this layer. We will discuss how many of the known properties of active regions (though not all of them), can be explained by the dynamics of magnetic flux loops as they rise through the convection zone.

Solar active regions are bipolar, meaning that areas of strong magnetic field of one sign are paired with strong, adjacent fields of the opposite sign. This property suggests that active regions occur where the tops of magnetic flux loops pierce the solar photosphere (see Figure 1). Bright X-ray or EUV loops connect the two opposite polarities through the solar corona.

Hale's polarity law describes the observed orientation of active regions: On the average, active region bipoles are oriented nearly parallel to the E-W direction, with the same orientation in the northern hemisphere, but with the opposite orientation in the southern hemisphere. This simple relationship suggests an approximately toroidal pattern to

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the Sun's magnetic field geometry, with the toroidal field having opposite sign in the northern and southern hemispheres. The fact that active regions appear to be the tops of flux loops suggests that the toroidal field in the Sun is formed at a significant depth below the photosphere. The persistence of Hale's polarity law for periods of several years during a given solar cycle suggests that the toroidal fields must be residing in a relatively stable region in the solar interior. Several theoretical arguments suggest that the only place where such fields could be stored for long periods without being disrupted by either buoyancy instabilities or by turbulent convective motions is below the solar convection zone (van Ballegoooijen, 1982). Yet if the fields are stored at any significant depth below the convection zone (i.e. in the radiative zone), they will be so stably stratified that they could never erupt to the surface on the time scale of a solar cycle (van Ballegoooijen, 1982; Parker, 1979). Therefore, the only viable region for the storage of the magnetic flux appears to be an interface layer separating the solar convection zone from the radiative zone, known as the "convective overshoot layer". This region of the solar interior is now also known to coincide approximately with the transition from solid body rotation to the observed photospheric differential rotation pattern, the so-called "tachocline" deduced from inversions of the rotation profile in helioseismology (Corbard et al., 1999; Kosovichev, 1996). The presence of strong shearing motions, plus the right range of subadiabatic temperature gradients for flux storage suggests that this is not only where toroidal fields are stored, but probably where they also are generated by the solar cycle dynamo.

Further arguments which support the overshoot layer as the location for the solar cycle dynamo are given in the review article by Deluca & Gilman, 1991. Since that article was published, a number of new dynamo models have been proposed. Parker, 1993 introduced the idea of an "interface" dynamo, in which the convection zone and overshoot layer exhibit greatly different values of the magnetic diffusion coefficient, with turbulent motions in the convection zone leading to a much larger magnetic diffusion coefficient there. The "α-effect" takes place in the convection zone, while the reduced diffusion coefficient in the overshoot layer allows the field strength to grow to large values. The separation of the α and ω effects into different layers avoids the problem of "α quenching" (Vainshtein & Cattaneo, 1992) in which the increase in field strength stops the dynamo mechanism from operating. Interface dynamos using mean field electrodynamics are described by MacGregor & Charbonneau, 1997a,b with calculations carried out in both Cartesian and spherical geometry. More recent interface dynamo calculations have been undertaken by Markiel & Thomas, 1999 who find problems with the model if the solar rotation profile determined from helioseismology is used.

Other recent models (Durney, 1997, Dikpati & Charbonneau, 1999) assume that the α effect is due to the "tilt" of emerged active regions relative to the azimuthal direction – the original idea employed by the Babcock, 1961 and Leighton, 1969 solar cycle models – while using an internal rotation profile consistent with recent results from helioseismology. In §2.2, we will return to the subject of active region tilts, since emerging flux models have a great deal to say about the origins of these tilts. Dikpati & Charbonneau, 1999 and Choudhuri et al., 1995 also include the effects of an equatorward meridional circulation in the overshoot layer, required to balance the poleward flows observed in the surface layers of the Sun. The meridional flow could play a role in the equatorward migration of active latitudes over the solar cycle.

2. Flux Emergence: Studies Employing the Thin Flux Tube Model

The picture of bipolar active regions as emerging magnetic flux loops (Figure 1) suggests a simple theoretical approach as a first step: Derive an equation of motion for a flux loop moving in a field-free background model of the solar convection zone. The simplest such model is the thin flux tube approximation. As formulated by Spruit, 1981 the thin flux tube model is derived by simplifying the 3D ideal MHD momentum equation for a thin, untwisted magnetic flux tube surrounded by field-free plasma, subject to three constraints: (1) when the tube moves, it retains its identity as a "tube" (*i.e.* it does not fragment, disperse, or diffuse away); (2) the tube is thin, in that its diameter is small compared to all other physical length scales in the problem, and (3) quasi-static pressure balance across the diameter of the tube is maintained at all times. If these conditions are true, one can derive an equation of motion for the 1-D tube moving in a 3-D environment. There are many reasons to question the viability of the thin flux tube assumptions, but for now we will simply assume the model can be used. Certainly the observations suggest that active regions look and behave as though the magnetic field maintains a tube-like geometry, though there is the appearance that fragmentation of the tube has occurred by the time the active region reaches the photosphere (see Figure 1). Solutions of the thin flux tube equation of motion, along with the induction, continuity and energy equations, yield cross sectional averages of the magnetic field strength, thermodynamic variables, and velocity as a function of time and distance along the tube.

The thin flux tube equation of motion as commonly used is

$$\rho_i D\mathbf{v}/Dt = \mathbf{F_B} + \mathbf{F_T} + \mathbf{F_C} + \mathbf{F_D} \ , \qquad (1)$$

where

$$\boldsymbol{F_B} = g\ (\rho_e - \rho_i)\ \hat{\boldsymbol{r}}\ ;\ \boldsymbol{F_T} = B^2/8\pi\ \boldsymbol{\kappa}\ , \qquad (2)$$

$$\boldsymbol{F_D} = -\rho_e \frac{C_D}{(\pi\Phi/B)^{1/2}} |v_\perp| \boldsymbol{v}_\perp\ ;\ \boldsymbol{F_C} = -2\rho_i \boldsymbol{\Omega} \times \boldsymbol{v}\ . \qquad (3)$$

$\mathbf{F_B}$ is the magnetic buoyancy force, $\mathbf{F_T}$ is the force due to magnetic tension (field line bending), $\mathbf{F_C}$ represents the Coriolis Force (because D/Dt is the time derivative taken in the rotating reference frame), and $\mathbf{F_D}$ is an aerodynamic drag force resisting motion of the tube through the external, field-free plasma. The quantities ρ_i and ρ_e represent the mass density inside and outside the flux tube, respectively, and g is the local gravitational acceleration. The magnetic field $\mathbf{B}$ points in the direction of the tube's tangent vector $\hat{\mathbf{s}}$ ($\hat{\mathbf{s}} = \partial\mathbf{r}(s)/\partial s$), and the curvature vector $\boldsymbol{\kappa}$ which gives the direction of $\mathbf{F_T}$, is given by $\boldsymbol{\kappa} = \partial^2\boldsymbol{r}(s)/\partial s^2$. The vector $\boldsymbol{r}(s,t)$ denotes the tube position as a function of its own arc-length s and time t. In the expression for $\boldsymbol{F_D}$, $\boldsymbol{v}_\perp$ represents the normal component of velocity difference between the tube and the plasma outside the tube. The aerodynamic drag coefficient $C_D \sim 1$, as indicated from forces measured in fluid dynamics experiments around cylindrical objects at high Reynolds number (see e.g. Batchelor, 1967).

2.1. Latitudes of Active Region Emergence

Choudhuri & Gilman, 1987 were the first to use the thin flux tube model to study the emergence of magnetic flux from the base of the convection zone to the Sun's photosphere using a 3D, rotating model of the solar interior for the background plasma. For simplicity, they assumed the tubes were in the form of axisymmetric flux rings, oriented in the toroidal direction. They found that for flux rings with a field strength B_0 at the base of the convection zone of 10^4 G, the flux emerged parallel to the solar rotation axis and reached the photosphere at much higher latitudes than those corresponding to the observed latitudes of active regions. Only flux rings with $B_0 \sim 10^5$G had latitudes of emergence which could be consistent with observations. Choudhuri, 1989 extended this study to non-axisymmetric flux rings, and found similar results. At the time these simulations were done, dynamo theorists predicted that the field strength near the base of the convection could be no greater than 10^4G, based on arguments of equipartition between magnetic energy and the kinetic energy density associated with convective motions.

Studies of the latitude of active region emergence were also done by Fan et al., 1993, Fan et al., 1994, Schüssler et al., 1994, Caligari et al., 1995, Fan & Fisher, 1996, and Caligari et al., 1998. Fan et al., 1993 and Fan et al., 1994 basically confirmed the results of Choudhuri, 1989, namely that if the field strength B_0 is close to the equipartition value ($B_0 \sim 10^4$G), flux emergence occurs at very high latitudes. Caligari et al., 1995 criticized the thermal initial conditions used by Choudhuri, 1989, Fan et al., 1993, and Fan et al., 1994 as unrealistic, and instead emphasized that one must start with flux loops in force balance in the convective overshoot layer. In their case, they assume the equilibrium has toroidal symmetry, and then analyze the linear stability of the equilibrium. They find instability only if B_0 exceeds roughly 10^5G, with azimuthal wavenumbers of $m = 1$ or $m = 2$ being the most unstable, depending on the exact values of latitude and field strength. A more detailed analysis of the stability criteria for toroidal equilibria are presented in Ferriz-Mas & Schüssler, 1993, and Ferriz-Mas & Schüssler, 1995. For the flux rings which are unstable, and therefore result in erupting loops, the emergence is primarily radial, and there is no difficulty with flux emerging at latitudes which are too high. Fan & Fisher, 1996 take a different approach to the question of how magnetic flux is destabilized in the overshoot layer. They derive an energy equation for the transfer of heat into a flux ring in force balance, and find that over time, small entropy inhomogeneities in the flux ring will eventually evolve into flux loops which become buoyantly unstable under the influence of gradual heating. In this case a variety of different field strengths are possible, provided the subadiabatic gradient (usually denoted by the quantity $\delta = \nabla - \nabla_{ad}$) is not too small in absolute value (δ is negative when the gradient is sub-adiabatic). They find latitudes of emergence which could be consistent with observed active latitudes for values of B_0 down to 3×10^4G.

One cannot discuss the latitudes of active regions without also considering the nature of equilibria for toroidal flux rings in the convective overshoot layer. Moreno-Insertis et al., 1992 and van Ballegoooijen & Choudhuri, 1988 examined the conditions under which a toroidal flux ring can exist in equilibrium. In the overshoot layer, Moreno-Insertis et al., 1992 showed that the plasma in a toroidal flux ring which is in force balance must be rotating more rapidly than the adjacent external convection zone plasma, and that the degree of "super-rotation" becomes greater as the field strength is increased. If a flux ring were to originate at the equator in the overshoot layer, and have the local rotation rate, it therefore must move closer to the poles. This effect implies a minimum possible latitude for flux rings. The only way out of this situation is for the plasma in the magnetic ring to have originated with a greater angular momentum than that at the base of the convection zone. At these latitudes, this means the plasma would have to originate near the surface. Given the observed poleward meridional flow pattern in the upper convection zone, which transports mass away from the equator, this seems very unlikely.

Moreno-Insertis et al., 1992 (their Table 3) estimate the minimum latitude as a function of the magnetic field strength in a toroidal ring and show that if $B_0 \gtrsim 10^5$G, the minimum latitude of the toroidal ring at the base of the convection zone is $\gtrsim 17^\circ$. If the field strength is any greater than this, the initial latitude is too great to accomodate the low latitude active regions that emerge during the later part of the solar cycle, even assuming radial emergence trajectories. Thus just knowing the observed active latitudes provides a fairly stringent requirement on the field strength at the base of the convection zone: $10^4\mathrm{G} < B_0 < 10^5\mathrm{G}$. We are left with two possible explanations for the observed equatorial gap in the distribution of active regions: A field strength which is too high to accomodate the lowest latitude toroidal flux rings in equilibrium, or a field strength low enough to allow moderate poleward drift during the process of emergence.

2.2. Joy's Law and Active Region Tilts

The topic that has received the most attention with the thin flux tube model is the "tilt angle" of active regions and its variation with latitude, known as "Joy's Law". Joy's Law (the name for this relationship can be attributed to Zirin, 1988) is a slight deviation from Hale's law. The observed average orientation of bipolar active regions is actually not quite toroidal, but instead is tilted slightly away from the azimuthal direction, with the polarity in the leading direction (the direction toward solar rotation) slightly closer to the equator than the following polarity. Further, the tilts are a function of latitude, with the size of the tilt angle roughly proportional to the latitude. The tilts are not large; at latitudes of 30°, the average tilt angle for spot groups is roughly 7° (Fisher, Fan & Howard, 1995). Even though Joy's Law might seem like a subtle and inconsequential effect, it plays a very important role in several classical solar cycle dynamo models. In the Babcock, 1961, Leighton, 1969, Wang, Sheeley & Nash, 1991, and Durney, 1997 dynamo models, the tilt from active regions is included as an empirical effect, and is the agent by which the poloidal flux from the previous cycle is reversed by the poloidal flux from the current cycle. While Joy's law is incorporated into these models, the models do not address its physical origin.

D'Silva & Choudhuri, 1993 studied non-axisymmetric perturbations of initially toroidal flux loops lying at the base of the solar convection zone. They found from their thin flux tube simulations that active region tilts could be explained by Coriolis forces acting on rising, expanding magnetic flux loops, and that if the field strength at the base of the solar convection zone was $\sim 10^5$G, that Joy's law could be reproduced. Similar tilt angle results were also reported by Fan et al., 1994, Schüssler et al., 1994, Caligari et al., 1995 and Fan & Fisher, 1996. These studies employed a wide variety of different initial conditions for the rising loop calculations, but they were all able to reproduce Joy's law for physically reasonable values of the field strength at the base of the convection zone. Caligari et al., 1998 note that active region tilt angles are one of the most robust predictions of thin flux tube models, with tilts depending primarily on latitude and the field strength at the base of the convection zone and not on the details of the initial conditions used in the simulations. Schüssler et al., 1994 find best agreement with observed tilts for flux loops originating in the lower part of the convective overshoot region, corresponding to field strengths of $1.2 - 1.4 \times 10^5$G, if the flux loops originate from unstable equilibria. Fan & Fisher, 1996 find good agreement for tubes which are destabilized by gradual radiative heating if the field strength lies in the range $4 - 10 \times 10^4$G (see Figure 2). They find the reverse of Joy's law (i.e. the tilts go the wrong direction, in some cases) if $B_0 \lesssim 3 \times 10^4$G (Figure 2).

If the Coriolis force can account for Joy's Law, it should be possible to explain the phenomenon in a simple fashion without resorting to detailed flux tube simulations. Fan et al., 1994 present a simple cartoon model in which the buoyancy-driven rise of a flux tube is balanced by an aerodynamic drag force, leading to a rising, diverging loop geometry. The Coriolis force then acts on the diverging velocity field to twist this loop into a backward "S" shaped geometry (in the northern hemisphere) when viewed from above (see Figure 3). If this Coriolis force is then balanced with a magnetic tension force opposing the twisting motion, one can show that $\alpha \propto \Phi^{1/4} sin\theta$, where α is the tilt angle, Φ is the magnetic flux in the rising tube, and θ is latitude. This simple analysis not only yields Joy's law, but also predicts a new relationship between tilt and magnetic flux that can be tested with observation.

Fisher, Fan & Howard, 1995 tested this prediction by examining the tilt angles of a large number (24,701) of spot groups observed at Mt. Wilson over many decades during the 20th century (see Howard, Gilman & Gilman, 1984). An illustration of how the tilt angle of a spot group is determined is shown in Figure 4. While white light spot group measurements contain no magnetic information, there are proxy relationships that can be used. Howard, 1992 has shown that the separation distance d between the poles of spot groups is a reasonable proxy for the magnetic flux Φ. Fisher, Fan & Howard, 1995 found that tilt angles were indeed an increasing function of both latitude and d, with the data consistent with $\alpha \propto d^{1/4} sin\theta$. These results can also explain the d variation in the "residual tilt" found by D'Silva & Howard, 1993. Fisher, Fan & Howard, 1995 argued that the best fit to the data from flux tube simulations is obtained for $B \sim 2 - 3 \times 10^4$G, based on the simulations of Fan et al., 1994. On the other hand, those simulations had initial conditions which were not consistent with flux tubes initially in force balance, as Caligari et al., 1995 and Caligari et al., 1998 have noted. The Fan & Fisher, 1996 simulations assume a more physically self-consistent de-stabilization of the flux tubes. In this case, a best fit of the data are obtained with field strengths in the range $4 - 10 \times 10^4$G, i.e. at significantly higher values than those quoted in Fisher, Fan & Howard, 1995. (see Figure 2)

The observed d dependence of active region tilts also argues against the explanation of Joy's law proposed by Babcock, 1961 that the tilt angle simply reflects the underlying orientation of the magnetic field at depth. Babcock, 1961 suggested that such an orientation would occur because of differential rotation with latitude. If this were the only origin of active region tilts, tilt angles would have no dependence on the amount of magnetic flux in an active region. While an underlying orientation that is not purely toroidal cannot be ruled out, the observed d dependence of tilt suggests that the dominant tilting occurs from Coriolis forces.

2.3. Tilt Angle Dispersion

A further result regarding active region tilts was shown in Fisher, Fan & Howard, 1995: The behavior of the tilt angle "noise" as a function of d and θ. Figure 5 shows that there is actually a huge scatter of individual active region tilts around the average Joy's law behavior. What is the origin of this? Is it measurement error, or does this tell us something about flux tube dynamics in the Sun? In an effort to understand the scatter, Fisher, Fan & Howard, 1995 first measured the level of scatter as a function of both latitude and polarity separation distance d. They found that the degree of tilt scatter $\delta\alpha$ was *independent* of latitude (in contrast to the latitude dependence of the mean tilts), but *did* depend on d, roughly as $d^{-3/4}$. Next, they investigated the measurement error in the tilt angle, by analyzing the algorithm used to define the tilt angle of a spot group in terms of the positions of the constituent spots. They found measurement errors which were significantly smaller than the levels of scatter shown by the spot group dataset, and concluded that the tilt scatter has a physical origin. Fisher, Fan & Howard, 1995 propose that the scatter is due to the buffeting of flux loops by turbulent motions as they rise through the convection zone.

Longcope & Fisher, 1996 performed a detailed analysis of the convective buffeting hypothesis, by considering an initially horizontal flux tube rising through a turbulent medium. The velocity amplitude and the eddy size are assumed to be determined by a mixing length model of the convection zone. They found that the d dependence of the tilt fluctuations from the theoretical models could be closely matched to the observed tilt scatter found by Fisher, Fan & Howard, 1995, for physically reasonable values of the magnetic field strength and for mixing length parameters close to the accepted solar values. The theoretical d dependence derived from two effects: tubes with larger magnetic flux (and hence larger d) rise faster and are perturbed less by turbulence, and the larger footpoint separation averages over more distortions in the tube's axis. Values of B which seemed consistent with the observed behavior were in the range $2 - 4 \times 10^4$G. The flux tubes in this study were not initially in force balance, and thus the criticisms of Caligari et al., 1995 and Caligari et al., 1998 apply. It is not clear at this time how this might change the field strength that results from a best fit to the observations.

2.4. Asymmetries - Field Strength

The Coriolis force accounts for several other effects which appear as asymmetries in the physical properties between the leading and following polarities of an active region. Fan et al., 1993 found an asymmetry in the magnetic field strength between the leading and following legs of an active region flux loop. The field strength asymmetry occurs because of the combined action of several different flow patterns within the rising flux loop. On the one hand, a rising flux loop will induce a Coriolis force which drives counter-rotating flows along the rising portion of the loop. Counter-rotation occurs because the plasma in the loop would like to preserve its initial angular momentum; as the loop rises, the rotational motion slows down to preserve angular momentum - and in the rotating reference frame, this appears as counter-rotation. On the other hand, the rising flux loop also induces draining motions down both legs of the loop. The combination of counter-rotation and draining results in a significantly greater divergence of the velocity in the leading leg of the flux loop relative to the following leg. This leads via the continuity equation to a lower density, and hence gas pressure, in the leading leg relative to the following leg. But because of the balance of total pressure across each leg of the flux loop, this means the magnetic pressure, and hence magnetic field strength, must be higher in the leading leg of the loop. Fan et al., 1993 speculate that the field strength asymmetry is the explanation for the more compact appearance of the leading polarity of active regions relative to the following polarity, which usually appears more fragmented upon emergence. According to Fan et al., 1993 the stronger fields along the leading leg are more capable of resisting the turbulent hydrodynamic forces in the convection zone acting to rip the magnetic flux tube apart.

Caligari et al., 1995 argue that the situation described by Fan et al., 1993 occurs only for some ranges of the initial magnetic field strength and initial conditions for the rising flux loop. Because a toroidal flux ring in equilibrium must already have a super-rotational velocity (Moreno-Insertis et al., 1992) if the field strength of the initial toroidal ring is sufficiently great, the initial super-rotational velocity could exceed the counter-rotational effect driven by the emerging flux loop. In that case, the field strength in both legs might be nearly equal (e.g. Figure 17, Caligari et al., 1995).

Fan & Fisher, 1996 re-examined the field strength asymmetry for flux loops initially in force balance, and self-consistently destabilized by radiative heating. They find significant field strength asymmetries over the bottom portion of the convection zone for all initial field strengths, but nearly equal field strengths in the upper convection zone for $B_0 \gtrsim 6 \times 10^4$G. For $B_0 \simeq 4 \times 10^4$G, a value which seems to be in agreement with the latitude and tilt angle results described earlier, the field strength asymmetry hypothesis for the asymmetric fragmentation of active regions still seems viable.

On the other hand, the counter-rotating flow field predicted by Fan et al., 1993 prompted an observational search for velocity asymmetries between the leading and following polarities of newly emerging active regions (Cauzzi et al., 1996a). Interestingly, Cauzzi et al., 1996a found just the reverse of the velocity field predicted by Fan et al., 1993. Greater downflows were found in the leading polarity as compared to the following polarity. They speculated this was caused either by the pressure gradient between the following and leading legs, which after the cessation of the rising motion might lead to a backflow, or to the residual signature of the super-rotational velocity due to a large field strength ($B \gtrsim 10^5$G) toroidal flux ring at the base of the convection zone.

Clearly, more work on the origins of asymmetries in active region morphology is needed, from both the observational and theoretical perspectives.

2.5. Asymmetries - Inclinations, Spot Group Motions

In contrast to the inconclusive observational results regarding the asymmetric fragmentation of active regions, thin flux tube models have had great success in explaining the differences in magnetic field inclination and spot motions between the leading and following sides of active regions.

The same phenomenon described above, namely the tendency of plasma to try and preserve its angular momentum, will not only tend to drive a counter-rotational flow, but will also change the shape of an emerging flux loop (see Figure 6). Moreno-Insertis et al., 1994 and Caligari et al., 1995 point out that the conservation of angular momentum will result in a counter rotational distortion of a rising loop of flux, yielding a leading leg which has a shallow angle of inclination, and a following leg which has a steep angle of inclination relative to the radial direction. If one imagines what happens to such a distorted loop as it rises through the photosphere, two observationally testable phenomena become immediately apparent: There will be a more rapid motion of the leading polarity sunspots away from the emerging flux region as compared to the motion of the following polarity spots, and the field inclination near the following polarity will be steeper than the leading polarity. This property of spot motions is well known (e.g. van Driel-Gesztelyi & Petrovay, 1990, Chou & Wang, 1987). The field inclination predictions have been confirmed indirectly through the observation that the magnetic neutral line appears closer to the following polarity spots (van Driel-Gesztelyi & Petrovay, 1990, Cauzzi et al., 1996b).

2.6. Dynamic Disconnection and Flux Tube Explosion

Once active regions have formed, the large-scale, long term evolution of the magnetic field at photospheric levels is described very well through a simple kinematic approach, using only the processes of advection and diffusion. In particular, the classic papers by DeVore & Sheeley, 1987, Sheeley, Nash & Wang, 1987, and Wang, Nash & Sheeley, 1989 demonstrate that the large scale magnetic field evolution can be modeled very well by viewing the emergence of active regions as a source term, and that thereafter the magnetic flux evolves according to advection at the observed photospheric rotation rate (which varies with latitude), an additional advection due to a poleward meridional flow field, and with an effective diffusion coefficient of roughly 600 $\mathrm{km}^2\ \mathrm{s}^{-1}$, attributed to turbulent diffusion.

This picture is completely different than what we have described thus far in this paper, namely that the observed properties of active regions can be explained mainly in terms of dynamic effects within the solar interior. How do we reconcile these two completely different pictures?

Fan et al., 1994 and Moreno-Insertis et al., 1995 have found a peculiar property of flux tube equilibrium solutions, or rather the lack of equilibrium solutions, which might explain how an active region can initially behave as a rising tube, and then later behave passively through advection and diffusion. If one calculates the depth dependence of the magnetic pressure in a flux tube in hydrostatic equilibrium, and assumes that the tube has emerged adiabatically through the superadiabatically stratified convection zone, there are many cases for which no equilibrium is possible - a negative magnetic pressure results somewhere in the middle of the convection zone. The reason for this is that the slight temperature excess between the adiabatically stratified tube and the superadiabatically stratified convection zone can result in an external gas pressure that drops more rapidly with height outside the flux tube than inside, making external gas pressure support impossible.

Many of the initial flux tube configurations in the simulations performed by Fan et al., 1994 have no hydrostatic equilibrium solutions, but those flux tubes were so far from hydrostatic equilibrium during emergence that no peculiar behavior was seen. Fan et al., 1994 proposed that after the loops have risen to the surface, the plasma then attempts to establish hydrostatic equilibrium, since the overall rising motion has ceased. The plasma in the tube near the surface will cool and undergo convective collapse (Spruit, 1979), but most of the plasma in the tube is too far from the photosphere to do anything except settle into adiabatic hydrostatic equilibrium. But if hydrostatic equilibrium is impossible, what happens? Fan et al., 1994 argue that at those depths where hydrostatic equilibrium cannot be established, the magnetic field becomes very weak and the tube is ripped apart by convective motions. At this point, there is a "dynamic disconnection" between the toroidal flux ring at the base of the convection zone and portions of the flux ring that have emerged to the surface. Fan et al., 1994 argue that this is the reason why active regions decay once they have emerged, why the photospheric fields (at least on the largest scales) behave kinematically, and evolve mainly via turbulent diffusion and advection by large scale differential rotation and meridional flows.

Flux tube explosion (Moreno-Insertis et al., 1995) occurs for essentially the same reason, namely the lack of a hydrostatic equilbrium solution for a rising flux tube. Moreno-Insertis et al., 1995 considered the rise of flux tubes with initial field strength $B_0 \sim$ few $\times\ 10^4$G and with small values of the magnetic flux Φ, which evolve much closer to hydrostatic equilibrium than the large active region scale tubes modeled by Fan et al., 1994. In this case, once the flux tube apex reaches the height at which hydrostatic equilibrium ceases to exist, the apex of the loop "explodes" into a a very broad flux system which, since the field strength is very small, becomes mangled by convective motions. Moreno-Insertis et al., 1995 also suggest that flux tube explosion will suck a large amount of mass from the toroidal flux system at the base of the convection zone, which will in turn strengthen the magnetic field strength there, in order re-establish pressure balance. Flux tube explosion provides an appealing possibility for the source of the constantly emerging small scale magnetic field making up the so-called "magnetic carpet" (Title & Schrijver, 1998) detected by the MDI instrument on SOHO.

3. Beyond the Thin Untwisted Flux Tube Approximation

3.1. Testing the Thin Flux Tube Assumptions with MHD Simulations

Given the large number of published results that use the thin flux tube approximation, there is an increasing interest in understanding its range of validity. Schüssler, 1979 and Longcope, Fisher, & Arendt, 1996 showed with 2D MHD simulations that an initially buoyant, untwisted magnetic flux tube with axial symmetry will break apart into two counter-rotating elements which then repel one another. Moreno-Insertis & Emonet, 1996, Emonet & Moreno-Insertis, 1998 and Fan, Zweibel, & Lantz, 1998a showed that if the magnetic field is twisted, the tendency to break apart is lessened; if the tube has a degree of twist which exceeds a certain critical value, the tube no longer fragments. The critical degree of twist can be determined in an approximate fashion by equating the Alfvén speed of the azimuthal component of the field with the flux tube's rise speed through the solar interior. At face value, these results suggest that a flux tube must have some minimum degree of twist to maintain its tube-like nature. Emonet & Moreno-Insertis, 1998 and Fan, Zweibel, & Lantz, 1998a have also shown via MHD simulation that the aerodynamic drag formulation for the force of the background plasma on a thin flux tube, which is commonly used in the thin flux tube models, is approximately correct. On the other hand, Hughes & Falle, 1998 argue that if the effective Reynolds number of the plasma in the simulations is increased to much greater (and more realistic) values, asymmetric vortex shedding results in forces on the tube which can't be included as a simple aerodynamic drag term. Clearly a deeper understanding of when the thin flux tube approximation can and can't be used is necessary. Fully 3D MHD simulations are essential. We expect this to be an active research area for quite some time.

3.2. Twist in Ordinary Active Regions

Understanding the origins and role of twist in active region flux tubes is very important. Recent observations (Pevtsov, Canfield, & Metcalf, 1995; Longcope, Fisher, & Pevtsov, 1998, Zhang & Bao, 1999) show that most active regions have a modest level of twist which shows considerable scatter when plotted as a function of solar latitude. There is, however, a slight but clearly discernable trend in the data, with active regions in the northern hemisphere tending to have a negative twist, while those in the southern hemisphere are positively twisted. Longcope, Fisher, & Pevtsov, 1998 have proposed that the origin of the latitudinal twist variation is ultimately from a non-zero average kinetic helicity contained within the turbulent motions of the solar convection zone. This kinetic helicity results from the action of the Coriolis force on convective eddies. The kinetic helicity "writhes" the axis of the flux tube, which then induces a magnetic twist within the tube with the opposite sign of the writhe (Moffatt & Ricca, 1992). Longcope, Fisher, & Pevtsov, 1998 find that the sign, latitudinal variation, and even the degree of scatter in the observational data can be explained quantitatively by this effect, which they call the "Σ-effect". The equations that are used to evolve the twist were originally derived by Longcope & Klapper, 1997. If the flux tubes are not too strongly twisted, the twist evolution equations can be decoupled from the untwisted thin flux tube equations, an approximation that Longcope, Fisher, & Pevtsov, 1998 exploited. The same equations have also been used by Fan & Gong, 1999 to solve for the twist evolution in an Ω loop rising from an initially toroidal configuration, and containing a modest, initially uniform degree of twist.

3.3. δ-Spot Active Regions

While most active regions seem to exhibit modest amounts of magnetic twist, there are a few active regions with unusual morphology and orientation (δ-spot active regions), which seem to be very highly twisted. δ-spot active regions are also responsible for the largest solar flares; similarly, active regions with coronal loop structures that are "sigmoidal", also an indication of strong active region magnetic twist (Canfield, Hudson & McKenzie, 1999), are associated with large coronal mass ejections. From the "space weather" perspective, δ-spot active regions are clearly of great importance.

δ-spot active regions emerge with opposite magnetic polarities jammed together – sunspot umbrae of opposite magnetic polarity are frequently contained within a single penumbra. δ spot regions often emerge highly tilted away from the E-W direction, and frequently appear to rotate as they emerge. Observations with a vector magnetograph show that the magnetic field in δ-spots is strongly twisted; the transverse field along the magnetic neutral line is strongly sheared away from the direction that a potential field extrapolation would indicate. These properties can be seen in Figure 7 showing a vector magnetogram of a δ-spot region taken with the HSP instrument (Mickey, 1985) at the University of Hawaii's Mees Solar Observatory. Analysis of the observed development of δ-spot regions over time have convinced many observers that the magnetic field has a kinked or knotted geometry below the photosphere (Tanaka, 1991, Kurokawa, 1991, Leka et al., 1996).

These results have motivated a great deal of theoretical work on the possible relationship between δ-spot active regions and magnetic flux tubes which are sufficiently twisted to become kink unstable. Linton et al., 1996 did a comprehensive linear stability analysis of the kink mode for an infinitely long, pressure confined twisted flux tube with cylindrical geometry, in a high β plasma. Given the axial field component $B_z(r) = B_0(1 - \alpha r^2 + \cdots)$, the azimuthal component $B_\theta(r)$ of the tube is given in terms of a twist parameter q as $B_\theta(r) = qrB_z(r)$. Linton et al., 1996 showed that if the twist q exceeds a critical twist q_{cr}, the tube is kink unstable. q_{cr} depends only on the 2nd order term of the Taylor expansion of $B_z(r)$: $q_{cr} = \sqrt{\alpha}$. Linton et al., 1996 give a complete prescription for computing all the growth rates, range of unstable wavenumbers, and eigenfunctions of the unstable modes. They also showed that as a twisted flux tube rises through the solar interior, a tube that is initially stable to the kink mode may become unstable as it emerges, due to the fact that flux tube expansion will decrease the axial field more rapidly than the azimuthal component of the field, and will therefore decrease the kink stability threshold q_{cr} while q remains roughly constant.

Fully compressible 3D MHD simulations of the kink instability in a high β plasma (Linton et al., 1998) confirmed the growth rates predicted by Linton et al., 1996, and also showed that the kink mode saturates in roughly 10 linear growth times scales, at amplitudes of roughly 30% of the tube radius for the fastest growing modes. Linton et al., 1999 then showed that if several unstable modes are excited simultaneously, as seems likely in the highly turbulent convection zone, that the modes can interfere constructively and produce complex, large amplitude knot-like geometries, with a strong resemblance to the inferred shape of δ-spot active regions. "Magnetograms" reconstructed from the simulations show that many of the observed δ-spot properties are reproduced.

Simulations of kink unstable flux tubes in a gravitationally stratified model of the solar interior by Fan et al., 1998b and Fan et al., 1999, using a 3D anelastic MHD code confirm the overall picture of Linton et al., 1999. They further show that the apparent spot-group rotation of the kink instability is enhanced as a result of the greater expansion of the kink at the apex as compared to the legs, and that the kink instability greatly enhances the buoyancy of the tube. By including gravity, Fan et al., 1998b and Fan et al., 1999 were able to show directly from the simulations that the morphology of the kink unstable Ω loop strongly resembles the behavior and appearance of δ-spot active regions.

4. Summary

Over the past decade, the use of flux tube dynamics to study and interpret the observed properties of solar active regions has been extremely productive, and has resulted in a much more holistic and physical picture of solar activity and solar magnetic fields.

Thin flux tube models of emerging active regions have been quite successful in reproducing many observed properties of active regions, and in deriving constraints on the magnetic field generated by the solar cycle dynamo. The interplay between theory and observation has been particularly rich and rewarding, as illustrated with the thin flux tube model of active tilts: Once the Coriolis force acting on rising flux loops was proposed as the source of tilts, theory predicted that tilts should also depend on the amount of magnetic flux, which was then confirmed observationally. Observations then showed that tilt dispersion was a function of active region size, but not latitude, suggesting a connection with convective motions. A theoretical model was developed with was then found to be consistent with the observed behavior of tilt dispersion.

On the downside, there are some predictions of the thin flux tube model which are inconclusive: the flow asymmetry between following and leading polarities in active regions was the opposite of what was originally predicted, and the interpretation of these observations is not clear. Further, from the theoretical perspective, the range of validity of the thin flux tube model is unknown. Much more research with 3D MHD simulation will be necessary before we understand when the thin flux tube approximation applies and when it does not.

The linkage between kink unstable flux tubes and δ-spot active regions is very promising, but there is much that remains to be done. For example, the kink hypothesis for δ-spot active regions predicts that the twist and writhe in δ-spot active regions should have the same sign. Does it? We will only find the answer to this question once a large number of observations of δ-spot active regions are carefully examined.

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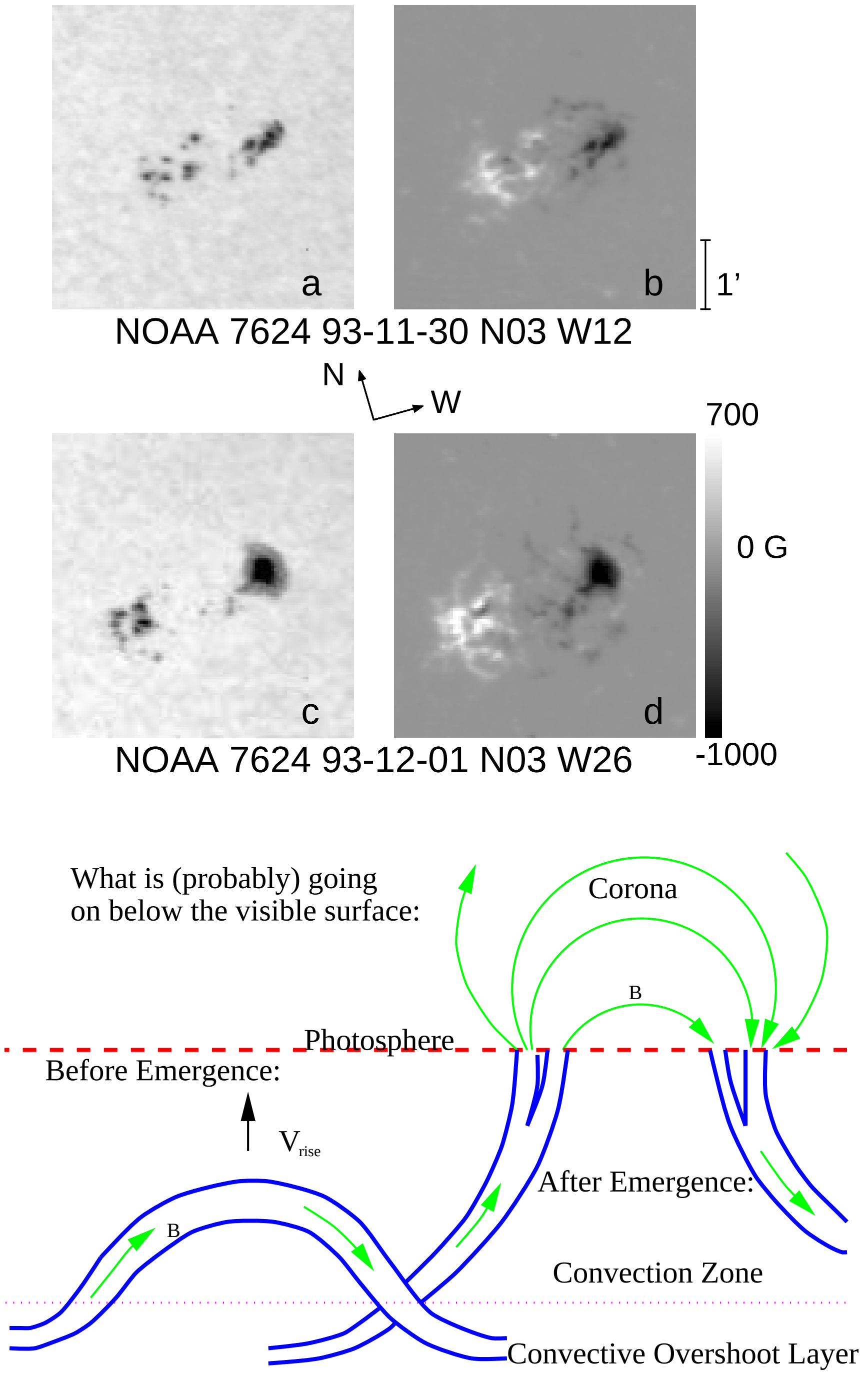

Figure 1. Top 4 panels (taken from Cauzzi et al. [1996]) show an emerging active region developing over a 1 day period on Nov. 30 (upper 2 panels) and Dec. 1 (bottom 2 panels) of 1993. The active region is viewed both as a white light image (left panels) and as a magnetogram showing vertical field strength (right panels). Diagram at bottom shows the likely sub-photospheric magnetic structure of an emerging active region.

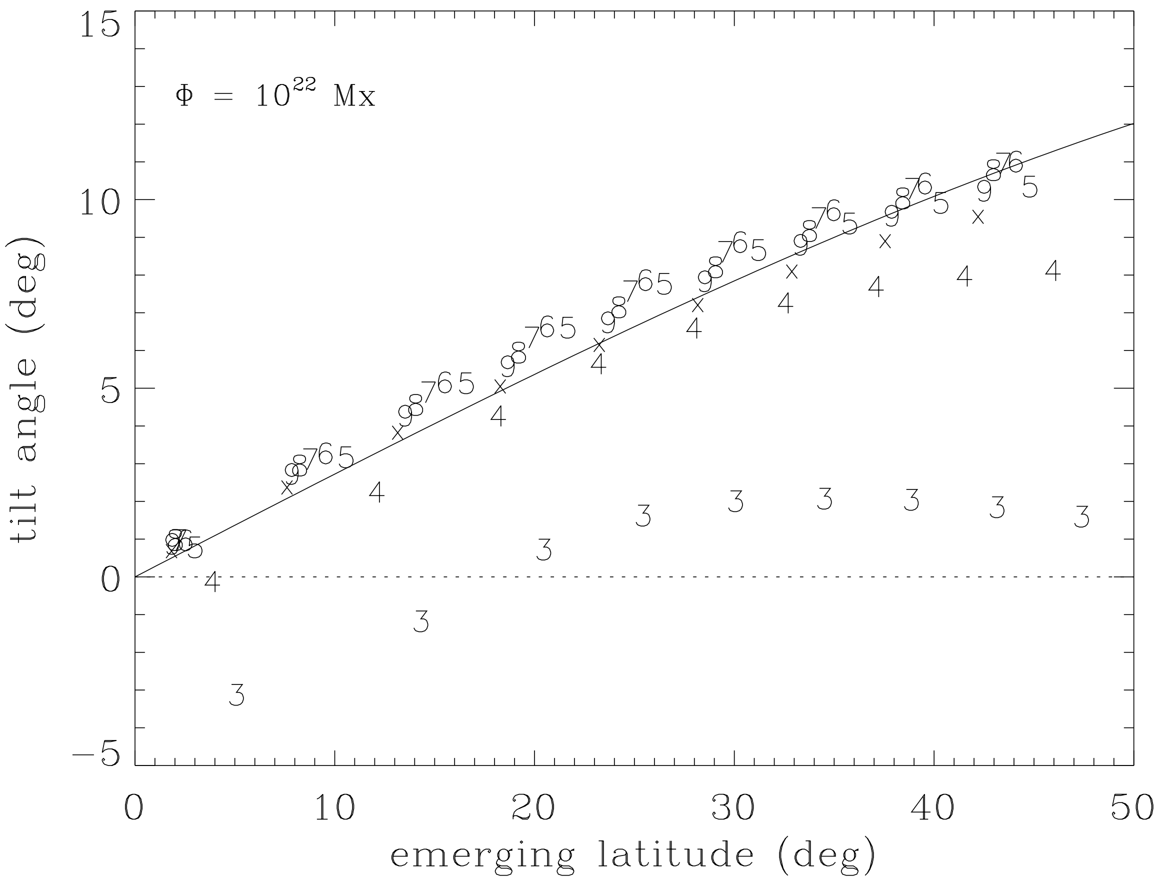

Figure 2. Plot of the tilt angle versus emergent latitude computed from thin flux tube simulations of Fan & Fisher (1996). The numbers on the plot represent the tilts from different values of the field strength ($B_0/10^4$G). Also plotted (solid line) is the least squares fit ($\alpha = 15.7 sin\ \theta$) from tilted spot groups of all sizes found by Fisher, Fan & Howard (1995). The simulations assumed $\Phi = 10^{22}$Mx (a fairly typical active region value) for the tube.

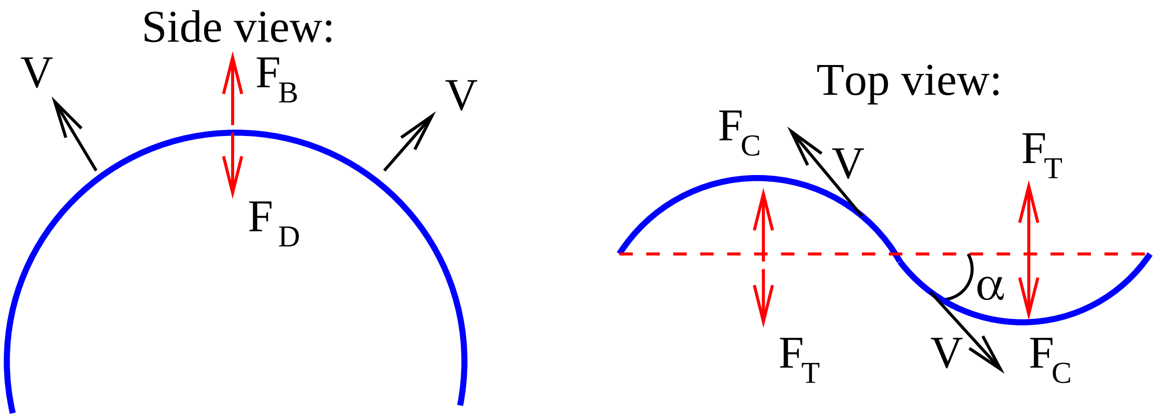

Figure 3. This diagram illustrates how the Coriolis Force introduces a clockwise tilt on an emerging flux loop rising in the northern hemisphere. The side view shows the upward motion being determined by a balance between magnetic buoyancy and aerodynamic drag. The top view shows how the Coriolis force twists the rising, expanding tube into a backward "S" shape; the Coriolis force is opposed by a magnetic tension force acting to straighten the tube. Balancing these forces results in the prediction that $\alpha \sim sin\theta\ \Phi^{1/4}$.

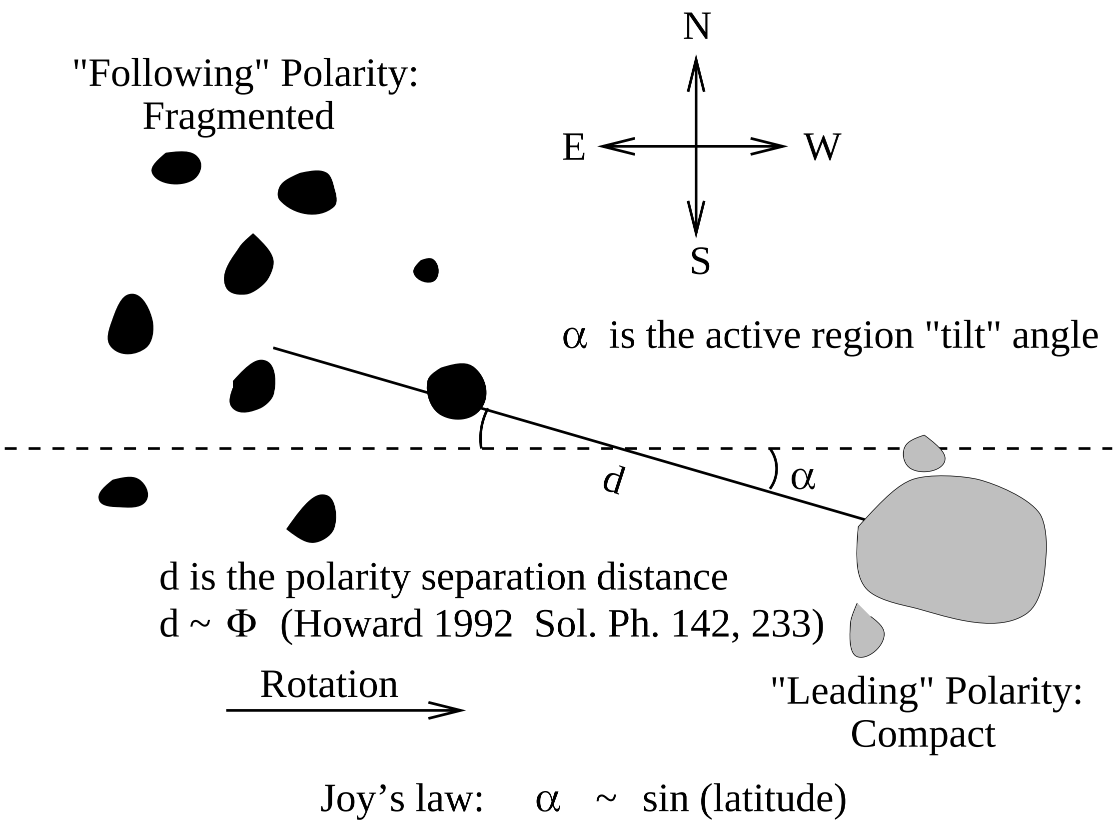

Figure 4. Illustration of how the polarity separation d and tilt angle α are defined for a sunspot group. Note the use of the "solar" definitions of East and West.

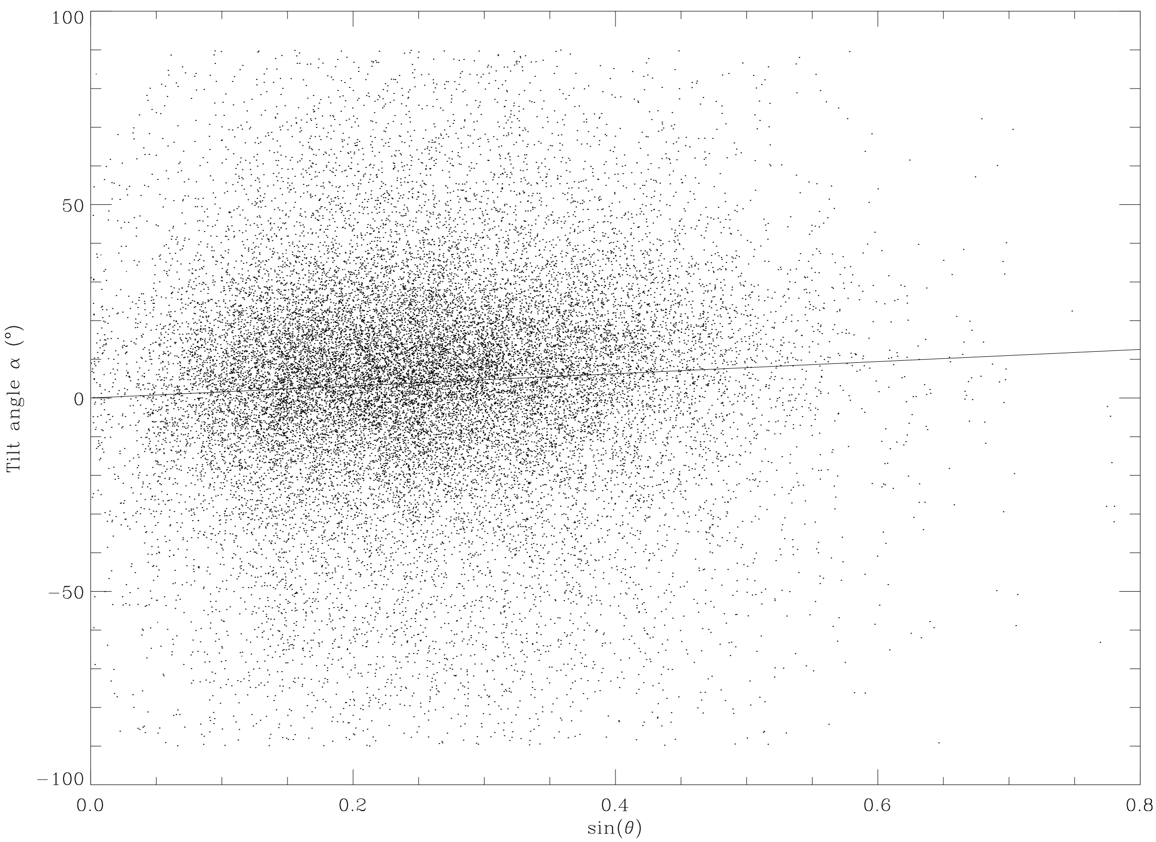

Figure 5. The tilt angles of 24,701 spot groups observed at Mt. Wilson since WWI as a function of latitude. The straight line ($\alpha = 15.7 \pm 0.7 sin\theta$) is a least squares fit to the data (plot taken from Fisher, Fan & Howard 1995).

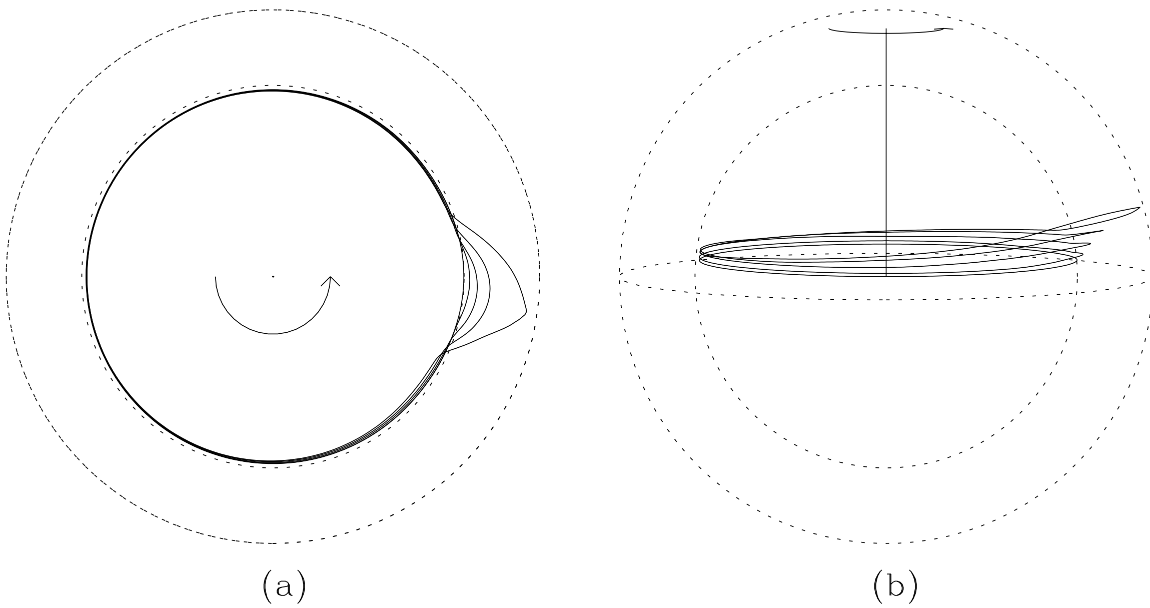

Figure 6. Emergence of a flux loop computed with the thin flux tube approximation. Panel (a) shows a view from the north pole; panel (b) shows a view from 10° above the equator. Outer and inner dotted circles correspond to the photosphere and base of the convection zone, respectively. The separate curves denote several snapshots in time of the flux tube position during its emergence. Note the difference in loop leg shapes between the leading and following side (§2.5) and the modest poleward drift of the flux loop.

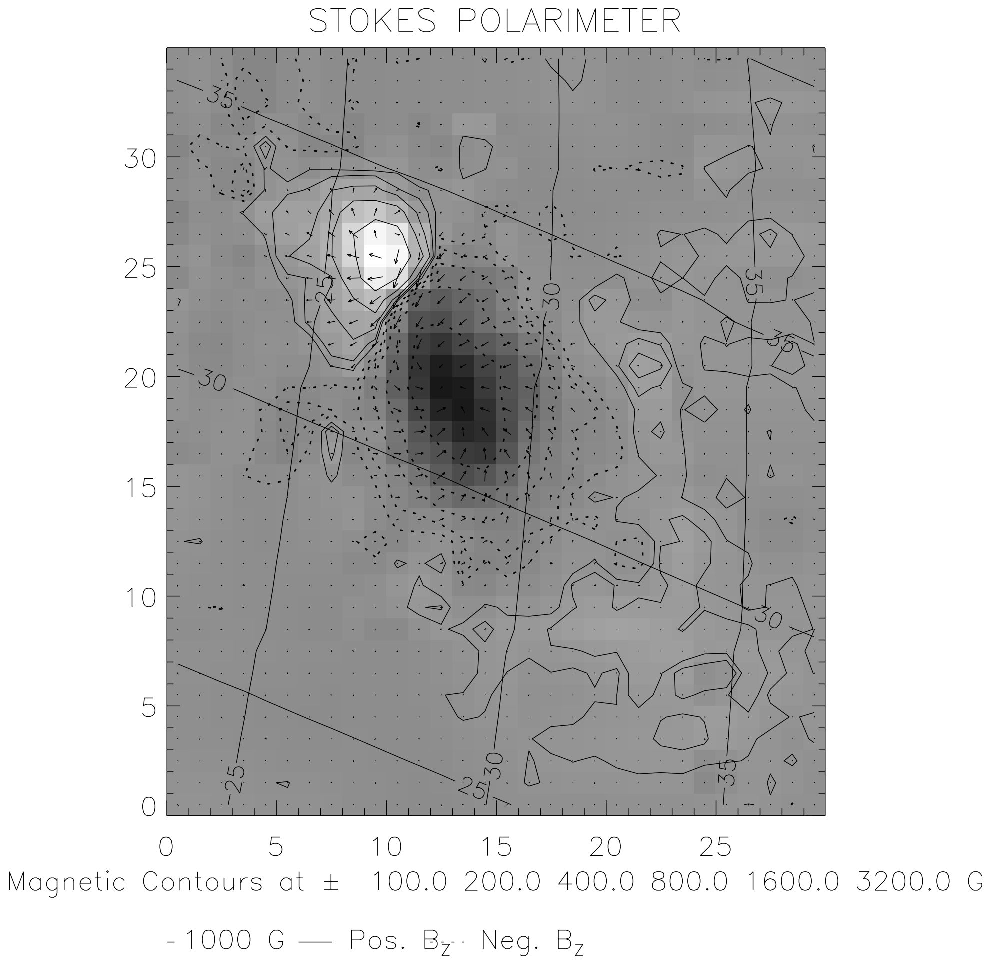

Figure 7. Vector magnetogram of a δ spot active region taken on May 13, 1991 with the University of Hawaii's Haleakala Stokes Polarimeter (Mickey 1985). The greyscale and the contours show the vertical component of the magnetic field, while the vectors show the horizontal component of the field. The cross-hatched lines show heliographic latitude and longitude. Note the twisted horizontal fields, the opposite polarities that are jammed together, and the large shear along the neutral line.