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DEPTH OF ORIGIN OF SOLAR ACTIVE REGIONS[1]

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ABSTRACT

Observations show that the individual bipolar magnetic regions on the Sun remain confined during their decay phase, with much of the magnetic field pulling back under the surface, in reverse of the earlier emergence. This suggests that the magnetic field is held on a short rein by subsurface forces, for otherwise the region would decay entirely by dispersing across the face of the Sun. With the simple assumption that the fields at the surface are controlled from well-defined anchor points at a depth h, it is possible to relate the length l of the bipolar region at the surface to the depth h, with $h \approx l$. The observed dimensions $l \approx 10^5$ km for normal active regions, and $l \approx 10^4$ km for the ephemeral active regions, indicate comparable depths of origin. More detailed observational studies of the active regions may be expected to shed further light on the problem.

Subject headings: hydromagnetics — Sun: activity — Sun: magnetic fields

I. BEHAVIOR OF BIPOLAR ACTIVE REGIONS

The individual ephemeral active regions on the Sun have net fluxes $\Phi \lesssim 1 \times 10^{20}$ maxwells, while the normal active regions are larger, with $\Phi \gtrsim 3 \times 10^{20}$ maxwells (Golub *et al.* 1977). The number of ephemeral active regions varies relatively little, and more or less inversely, with the number of normal active regions (see description in Martin and Harvey 1979; Golub and Vaiana 1980). At sunspot minimum $\sim$95% of the flux through the surface of the Sun emerges as bipolar ephemeral active regions, while at sunspot maximum the flux emerging in the normal active regions outweighs that emerging in the ephemeral regions (Golub, Davis, and Krieger 1979). Howard and Labonte (1981) and Wallenhorst and Howard (1982) describe the manner in which the flux spreads out from the active regions (in which flux first appears) as the regions age and decay (see earlier description in Bumba and Howard 1965*a*, *b*). But while some of the flux disperses, it is pointed out by Wallenhorst and Howard (1982), Wallenhorst and Topka (1982), and Gaizauskas *et al.* (1983) that most of the magnetic flux of a bipolar active region disappears rather than disperses. And this is a puzzling phenomenon which can only mean that somehow magnetic flux sneaks out of the picture in a state in which it is not observed. Wallenhorst and Howard note that "the opposite polarity portions of the regions have moved far enough apart that any large-scale cancellation of their fields seems unlikely." Wallenhorst and Topka remark that "... apparent decreases in photospheric flux also seem to occur in other regions far removed from the neutral line and any opposite polarity flux." "... we must conclude that flux is being removed from the photosphere. The processes of flux removal from the photosphere are still not understood. They may include fast reconnection ... and ejection, and/or sinking, or both."

It is the purpose of this paper to consider the implications of the observed disappearance of magnetic flux from the aging bipolar magnetic regions on the surface of the Sun. The first point is that flux cannot merely disappear in so highly conducting a fluid as the solar photosphere. The resistive diffusion coefficient η has a value 1×10^8 cm^2 s^{-1} at optical depth unity in the continuum in the quiet photosphere, and a maximum of 7×10^8 cm^2 s^{-1} (at optical depth unity) in the umbra of a sunspot (Kovitya and Cram 1983), for electric currents sufficiently weak that the electron conduction velocity is small compared to the electron thermal velocity (of $\sim$400 km s^{-1}). The velocity u with which resistivity allows fluid to diffuse across a magnetic field with characteristic scale l is of the orderof η/l, which is only 7 m s^{-1} for l as small as 10 km in a sunspot umbra and 1 m s^{-1} in the normal photosphere. Ambipolar diffusion of a field of 2×10^3 gauss under similar conditions ($l = 10$ km, neutral density 2×10^{17} cm^{-3}, ion density 2×10^{14} cm^{-3}) allows only the very small slip velocity of 1 mm s^{-1}. In the same environment the electron conduction velocity produced by the change of field strength of 2×10^3 gauss over a distance $l = 10$ km is of the order of 0.5 m s^{-1}, so there seems to be no way to conjure up anomalous resistivity.

It would appear, then, that the field is firmly tied to the gas which pervades it. It follows that isolated magnetic flux cannot disappear in situ. There are three ways in which flux through a region on the surface of the Sun may disappear. First of all, the individual flux tubes can be bodily transported out of the region. Second, two tubes of opposite sense can be brought together and merged so as to cancel one another. Third, the two footpoints of a tube arching above the visible surface may come together and disappear as the tube is pulled back below the surface. There are no known alternatives to these three obvious processes.

None of the above are directly observed in association with the decline of the magnetic flux in a bipolar region. We can only conclude that one or more of the effects goes on below the limit of observation. The simplest idea is that the individual flux tubes arching up through the surface are pulled back below the surface by the tension in the field—the reverse process of their earlier emerging. Wallenhorst and Topka

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discuss the disappearance of flux and point out that the decay of a bipolar region occurs with the reestablishment of the supergranule convection, temporarily suppressed by the earlier emergence of the region: "... the active region fields are swept to the edges of the emerging supergranules ... the network left after the spot has dissolved is long lived, persisting for more than a solar revolution." It would appear, then, that the retraction of flux tubes may involve motions of the footpoints along the supergranule boundaries, in which the fluid outside each magnetic footpoint need not take part. Footpoints with a diameter of 300 km carry a flux of 10^{18} maxwells, so that we require 20 of them "sneaking" out of a decaying magnetic region each hour to account for the observed decay of 5×10^{20} maxwells day^{-1}. At this point we can only conjecture that something of the sort happens because the active regions decay and Maxwell's equations require the bodily removal of the flux, presumably in the form of small flux tubes pulled back into the Sun.

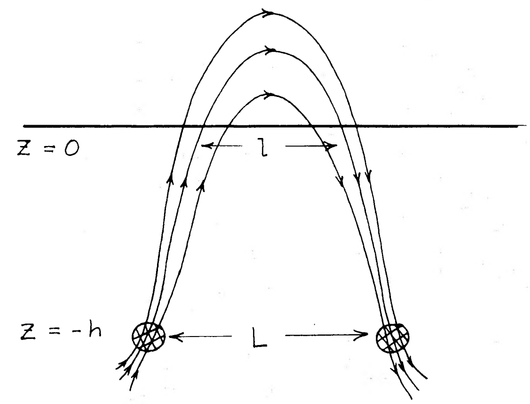

FIG. 1.—Sketch of the flux tube associated with an emerging bipolar magnetic region (of length l) at the surface of the Sun, with the hypothetical anchor points (cross-hatched) at a depth h below the surface and separated by a distance L.

II. RETRACTION OF FLUX TUBES

If we proceed on the hypothesis that the magnetic flux disappears by reversing the emerging process, i.e., retracts back into the Sun, then the dimensions of the normal and ephemeral active regions may be quantitatively related to their depth of origin, enabling the depth to be inferred from observations of the horizontal dimensions at the surface. The relation between horizontal scale and depth of origin comes about from the buoyancy of the field which must be overcome by the tension in the downward legs of the field if the field arching above the surface is to be pulled back into the Sun.

To provide some background for the discussion it should be noted that Golub *et al.* (1977) propose that the smaller size and different behavior of the ephemeral active regions are a consequence of their shallow origin, while the normal active regions are produced by magnetic flux coming up from the dynamo region deep ($> 10^5$ km) in the convective zone. The deep origin of the normal active regions is suggested by their breadth ($\sim 10^5$ km) and by the high rate of rotation of the complexes of activity in which they first emerge. Golub *et al.* (1977) argue that the ephemeral regions do not come from the same deep level, because their correlation with normal active regions is inverse. They propose an origin at an intermediate level.

Figure 1 is a sketch of the general structure of a bipolar magnetic region. The picture is based on the simple assumption that below some depth h the field is dominated by the convecting fluid, and above the depth h the gas density is so low that the field is not significantly influenced by the convecting fluid. The two cross-hatched circles at depth h in Figure 1 represent the anchor points—the highest level at which the field is held by the fluid. Above the anchor points the field is assumed to be more less in static equilibrium with its own stress, the pressure of the surrounding fluid, and the gravitational field of the Sun.

The observed fact that bipolar magnetic regions decay in situ, rather than dispersing over the face of the Sun, and disappear by pulling back into the Sun, indicates that the field is held on a short rein at some depth h. The concept of unique anchor points is the simplest representation of these facts. We look, then, for the simplest motion of the anchor points that can account for the observed behavior at the surface.

The static equilibrium of a slender flux tube has been worked out in the literature (Parker 1975, 1979*a*, pp. 136–141) and need not be repeated here. The basic fact is that the magnetic buoyancy (Parker 1955) of the flux tube cannot be held in check by the magnetic tension if the anchor points are too far apart. On the other hand, the tension overpowers the buoyancy and pulls the field back into the depths if the anchor points are close together. With L denoting the separation of the anchor points in Figure 1, let $L = L_c$ represent the maximum separation at which the tension can balance the buoyancy. Then, if $L > L_c$, the buoyancy carries the flux tube to the top of the atmosphere, where the field expands into the infinite space beyond, and the legs connecting to the anchor points are essentially vertical. The separation l of the two magnetic regions at the surface is equal to the separation L of the footpoints.

It is readily shown that an isothermal atmosphere yields $L_c = 2\pi\Lambda$, where Λ is the scale height $p/\rho g$ (Parker 1975). That is to say, L_c is independent of depth, and there is no relation between the separation of the two halves of a bipolar magnetic region and the depth of origin. The Sun, however, is not isothermal. The temperature increases approximately linearly with depth, as shown in Figure 2 (from Spruit 1974). To set up a simple computational model write

$$T(z) = T(0)(-z/\lambda) , \tag{1}$$

where z is the vertical coordinate and $T(0)/\lambda \approx 0.95 \times 10^{-4}$ K cm^{-1}. Then for a polytropic equation of state $p \propto \rho^\Gamma$, barometric equilibrium in a uniform gravitational acceleration g requires that

$$p(z) = p(0)(-z/\lambda)^{\alpha+1} , \quad \rho(z) = \rho(0)(-z/\lambda)^{\alpha} , \tag{2}$$

with $\Gamma = 1 + 1/\alpha$. In the Sun α has a value of ~ 2 at a depth of 10^4 km (with larger values near the surface), declining slowly to the fully adiabatic value 1.5 at the bottom of the convective zone, at a depth of 20×10^4 km.

The general equation for the path of a slender flux tube in hydrostatic and thermal equilibrium with an atmosphere with pressure $p(z)$ is (Parker 1975, 1979*a*, p. 139)

$$y(z) = \pm \int_z^{z_2} \frac{d\zeta}{\{[p(0)/p(\zeta)] - 1\}^{1/2}} , \tag{3}$$

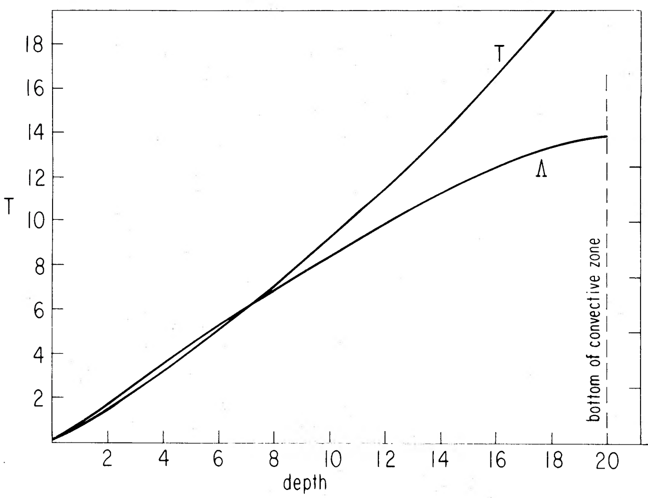

FIG. 2.—Upper curve represents the temperature (in units of 10^5 K, as measured up the right side of the diagram) as a function of depth (in units of 10^4 km) below the surface of the Sun. Lower curve, labeled Λ, represents the scale height (in units of 10^4 km, measured up the left side) as a function of depth, from the model of the convective zone computed by Spruit (1974).

if the coordinate system is located in such a way that the apex of the arched path lies at $y = 0$, $z = z_2$. Hence, for the polytropic atmosphere (eq. [2]), we have

$$y(z, z_2) = \pm |z_2| I(z/z_2, \alpha) , \qquad (4)$$

where

$$I(x, \alpha) = \int_1^x \frac{du}{(u^{\alpha+1} - 1)^{1/2}} . \qquad (5)$$

Note that $z_2 < 0$ because the apex lies below the top of the atmosphere at $z = 0$, except for the one solution $z_2 = 0$, reaching to the top, for which $y(z, 0) = 0$. The paths $y(z, z_2)$ are sketched in Figure 3 for a sequence of separations L for the present case that $\alpha > 1$ (precise plots for $\alpha = 1, 2, 3$ may be found in Parker 1979*a*, p. 141). The important point is that there are two paths connecting the anchor points for $L < L_c$. The lower path is stable, while the upper path is unstable (Parker 1981). Thus, if a flux tube in equilibrium along the upper path were perturbed upward, it would rise to the top of the atmosphere, where it would expand into the void above, producing a bipolar magnetic region (of the form sketched in Fig. 1) at the visible surface $z = 0$. If the tube were perturbed downward, it would retract into the lower equilibrium path.

For a given z_2 the separation of the anchor points at $z = -h$ is $L = 2y(-h, z_2)$. The maximum separation L_c is readily computed from equation (4) by setting $\partial y(-h, z_2)/\partial z_2$ equal to zero. The result is

$$I(\zeta, \alpha) = \zeta/(\zeta^{\alpha+1} - 1)^{1/2} , \qquad (6)$$

where $\zeta \equiv |h/z_2|$. The upper curve in Figure 4 is a plot of the real positive root ζ of this equation as a function of α. The lower curve is a plot of the associated value of the integral $I(\zeta, \alpha)$ which is equal to $y(-h, z_2)/z_2$.

With these principles in mind, then, imagine the situation in which horizontal flux is confined at a depth $z = -h$ by anchor points that are close together ($L \ll L_c$), represented by the lowest, shortest arch sketched in Figure 3. Then imagine that

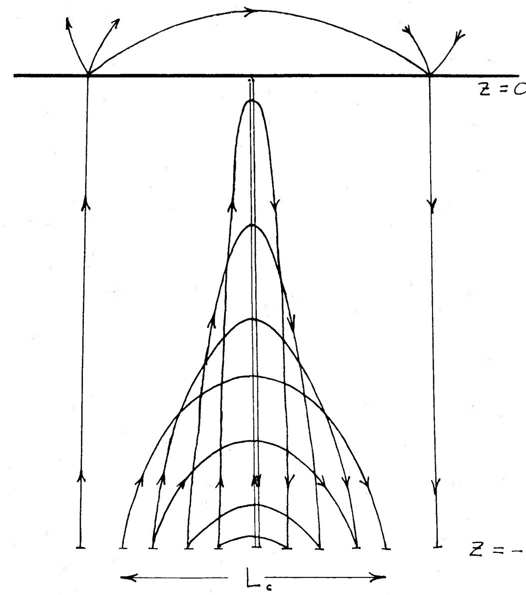

FIG. 3.—Sketch of the equilibrium paths of slender flux tubes with anchor points at a depth h separated by various amounts L. The outer path ($L > L_c$) with vertical legs leads to a potential field above the surface $z = 0$.

the separation of the anchor points slowly increases with time. The field arches increasingly upward, as indicated by the sequence of curves sketched in Figure 3, until L reaches the critical value L_c. Further separation allows no equilibrium paths between the anchor points. The buoyancy carries the flux tube up through the top of the atmosphere, from where the apex of the tube expands into the void above. Indeed, the flux tube is no longer slender at the top of the atmosphere where p falls to zero, taking on a potential form where its expanded state means that the total magnetic stress is slight. Hence, the flux tubes connecting either end of the potential field to the anchor points are nearly vertical. The configuration is outlined in Figure 3 by the lines with $L > L_c$.

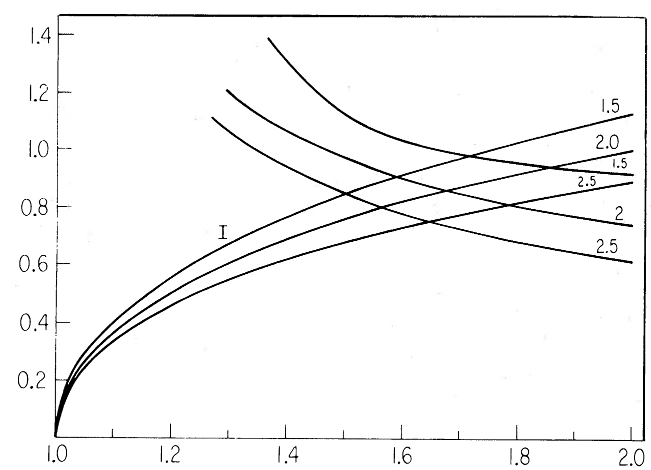

FIG. 4.—Curves labeled I give the integral $I(x, \alpha)$ as a function of x for the indicated values $\alpha = 1.5$, 2.0, and 2.5. Unlabeled curves are a plot of $x/(x^{\alpha+1} - 1)^{1/2}$ for the indicated values of α. Intersections of these curves provide the roots ζ to eq. (6), plotted in Fig. 5.

We presume, then, that shortly after $L > L_c$ the flux tube emerges through the surface of the Sun, to provide a bipolar magnetic region, with the system soon reaching a steady state with approximately vertical legs sketched in Figure 3. When that point is reached, the separation l of the tubes at the surface is approximately equal to the separation of the anchor points. Hence, $l \approx L_c$.

Suppose, then, that the separation decreases, becoming less than L_c again and declining toward zero. Nothing much happens at the surface as L declines below L_c, because the flux tube is extended vertically beyond the unstable upper equilibrium paths, whose apexes lie a distance z_2 below the surface. Only the special case $z_2 = 0$ reaches to the top of the atmosphere.

The small tension in the field above the top of the atmosphere pulls the upper ends of the legs slightly toward each other, so that as $L \to 0$ the tube picks up the upper equilibrium path for $z_2 = 0$, represented by the hairpin path drawn up the middle of Figure 3. That path is unstable, but with $L \to 0$ the instability can grow only downward (there is no equilibrium with $l > L$). So the hairpin path soon retracts downward to the lower solution, placing the field into its original horizontal position if L remains close to zero.

As a matter of fact, the fibril state of the magnetic field at the surface of the Sun suggests that these arguments should be applied to the individual fibrils rather than to the overall bundle of flux whose emergence makes up a bipolar active region. Thus, some of the vertical fibrils may be moving together (with $L \to 0$) and retracting at the same time that the anchor points of others are still widely separated. And, of course, the close packing of the expanded fields above the surface of the Sun means that the individual fibrils get in each other's way to some degree (sunspots represent an extreme case). One can see, then, how the active region may maintain its overall dimensions during the decay phase while fibrils are retracting into the Sun near the neutral line across the middle. Altogether, it appears that the observed confinement of the bipolar magnetic regions during their decay phase (wherein much, if not all, of the flux disappears back into the depths) follows directly from the idea that the flux, perhaps in the form of individual fibrils, is anchored firmly at some depth h, while the separation of the individual pairs of anchor points increases beyond the critical value L_c, and then decreases again to some small value $L \ll L_c$.

III. DEPTH OF ANCHOR POINTS

Now, insofar as the emergence of a bipolar active region is the result of free flux tubes above moving anchor points at some well-defined depth h, the separation l of the centroids of the two magnetic regions at the surface gives a more or less direct measure of L_c at the depth h. Since L_c is a known function of depth h, it is a simple matter to compute h. It is evident from Figure 5 that with α in the range 1.5–2.5, the ratio $\zeta = |h/z_2|$ providing the maximum width $L_c = 2y(-h, z_2)$ has a value of ~ 1.7. It follows from equation (4) that

$$L_c = 2hI(\zeta, \alpha)/\zeta .$$

Hence,

$$h = \zeta l/2I(\zeta, \alpha) ,$$

upon setting L_c equal to the separation l at the surface.

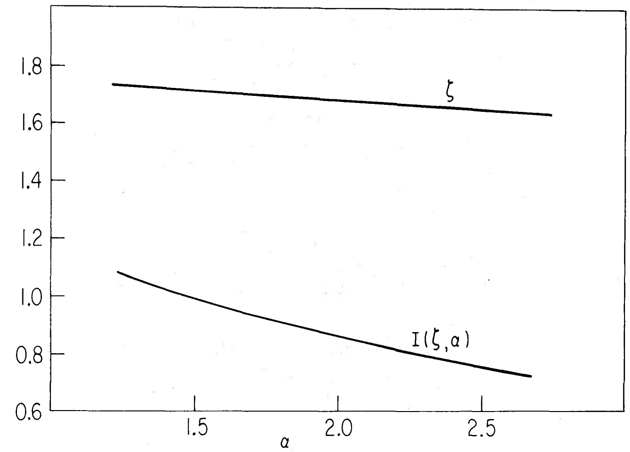

FIG. 5.—Upper curve is a plot of the real positive root ζ of eq. (6) as a function of α. Lower curve is the corresponding value of the integral $I(\zeta, \alpha)$.

For the ordinary active regions with deep origins (as we shall see) the effective value of α is close to 1.5. It follows from the lower curve in Figure 5 that $I \approx 1.0$, so that

$$h \approx 0.9l . \quad (7)$$

For the ephemeral active regions, with origins at intermediate depths, the effective value of α is close to 2, from which it follows that $I \approx 0.85$ and

$$h \approx 1.0l . \quad (8)$$

To a first approximation, then, the depth of origin of both normal and active bipolar regions on the Sun is equal to the separation l of the centroids of the two monopolar halves of the bipolar region.

Turning to the observations one finds a range of values for l, particularly for the normal active regions. It must be remembered that we are interested in the separation l of bipolar regions that are newly emerged and have reached at least a temporary steady state. Such individual regions tend often to move off from their point of origin in a complex of activity as newer regions emerge, so that a magnetic map at any instant in time shows a smeared bipolar region, which is, in fact, a superposition of many old individual bipolar regions. We want the dimensions l of the individual normal active regions, which are typically 6–10° in longitude or $0.7–1.2 \times 10^5$ km. The depth of the anchor points follows from equation (7) as $0.6–1.1 \times 10^5$ km, suggesting that the flux is anchored near the middle of the convective zone. This corroborates the suggestion by Golub *et al.* (1977) that the flux that makes up the normal active regions originates in the lower half of the convective zone, immediately below the level at which the flux is anchored. Golub *et al.* (1977) had previously noted that the depth from which the fields emerge can hardly be less than the width of the magnetic regions they produce at the surface. The present analysis provides a more explicit context, allowing a quantitative statement of the relation.

Now, for the ephemeral active regions the separation is typically $l \approx 8–16 \times 10^3$ km, indicating anchor points at depths h of the same magnitude. This depth, of $\sim 10^4$ km, would appear to define the "intermediate depth" ascribed by Golub *et al.* (1977) to the ephemeral regions. Presumably, the flux for the ephemeral regions comes from somewhere not far below this level. We note that this depth is approximately the estimated depth for the supergranules, leading one to conjecture that the supergranules may play a role in confining the flux under their "feet" as a consequence of topological pumping (Drobyshevski and Yuferev 1974; Moffatt 1974; Drobyshevski, Lokesnikova, and Yuferev 1980) or other effect (see list in Parker 1984).

IV. DISCUSSION

We have made some simple assumptions and have derived from them the result that $h \approx l$, from which we deduce that the normal active regions are controlled at a level about halfway down through the convective zone, with their magnetic flux originating from somewhere below that level. The same analysis suggests that the ephemeral active regions are controlled at a depth of the order of 10^4 km, with their flux originating from below that level.

We may worry that our assumptions have oversimplified the real situation in some essential way. For instance, is there a clearly defined level at which the flux is anchored, or is there convective interference with the field at all levels, so that there is no unique depth h at which the field is anchored? In that case the dimensions l of the bipolar regions at the surface are a product of convection over the entire range of depth, and the confinement and retraction of the flux during the decay phase is a direct product of an evolving convective pattern throughout the convective zone. That is to say, the evolution of the magnetic regions at the surface is less a consequence of magnetostatics and the simple widening and narrowing of the separation of anchor points than it is a direct manipulation by the evolving hydrodynamics (see formal example in Akasofu 1983). After all, it has been argued elsewhere (Meyer *et al.* 1974; Parker 1979*b*) that the sunspot is a product of unseen subsurface convection, at depths of the order of only 10^4 km. However, such convection, if it exists, operates independently in the two halves of the bipolar region and so need not vitiate the magnetostatic footpoint picture elucidated here. The principal point to be made is that the separation and approach of the anchor points is a simpler concept than a general time-dependent convective pattern. It remains to be seen whether the simpler view is the correct one.

We suggest that, in any case, the detailed quantitative behavior of bipolar magnetic regions on the Sun contains essential information on the nature of the dynamics beneath the surface. The quantitative relation between the size and total flux of individual bipolar regions is an important feature. The present study raises the question of the distinction between normal and ephemeral active regions. Do they really come from such widely separated, clearly defined levels as the conventional numbers for their sizes would indicate? Is there a strong correlation between the total flux Φ and the scale l of the individual bipolar regions, suggesting either a variety of depths of origin or a tendency for the stronger bundles of flux to expand at the surface in response to their magnetic pressure $B^2/8\pi$? In the latter case, l is not a direct measure of at the depth of origin.

Then we may ask why the flux tubes that form the ephemeral active regions are anchored at a depth of 10^4 km while the flux tubes of the normal active regions extend more or less freely through that level without being seriously impeded? Perhaps it is merely a matter of size and strength.

The ultimate question, of course, is the dilemma posed by the observations that bipolar magnetic regions decay rapidly without the observer seeing the bodily departure of the flux from either half of the bipolar region. Until the departure can be detected, any physical interpretation of any aspect of the evolution of magnetic regions is subject to grave uncertainty. If the field can sneak away unseen, who can say what else it does unseen.

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