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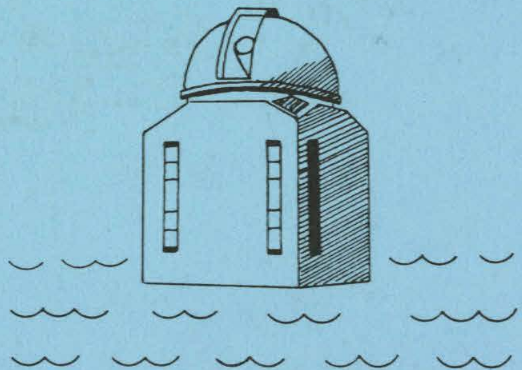

THE SOLAR CYCLE FIELD REVERSAL

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ABSTRACT

A non-mathematical model of the solar cycle field reversal is presented. The basic process producing the reversal in this model is surface reconnection of higher latitude p-flux with lower latitude f-flux. This picture differs substantially from the reversal aspect of the solar cycle field geometry presented by Babcock (1961), but the discussion is carried out entirely within the context of the flux ropes he originally considered.

1. Introduction:

Most current thinking on the underlying nature of the solar sunspot cycle is based on ideas which, while they had been tossed around to some extent by previous authors (e.g., Cowling, 1953, and Parker, 1955 a,b), were first put into a reasonably coherent picture by Babcock (1961). In his now classic paper on the subject he presented a simple geometric picture of sub-photospheric magnetic field lines being stretched by the action of differential rotation, and showed that this simple picture could explain many facets of the birth and evolution of spot groups. Owing to the wide familiarity of solar scientists with Babcock's picture, I will not try to recapitulate his ideas here, and I refer anyone unfamiliar with them to his original paper.

There is one facet of Babcock's paper, however, which is difficult to follow and rather unconvincing as it stands, at least to this reader (see also, for example, Piddington, 1972); namely, the mechanism of the field polarity reversal during every eleven year cycle. What we hope to do here is to present a modification of Babcock's picture of the field line topology associated with the field reversal, and to convince the reader that within this context the field reversal is not only possible but expected. This may seem to be reviewing ancient history, in light of the fact that many more papers on the solar cycle have appeared in the literature since Babcock's work (e.g., Leighton, 1964, 1969; Parker, 1972). But these later contributions have dealt with the magnetic field evolution without considering the large scale flux rope topology involved, probably because these models make use of magnetic field merging which is not readily susceptible to such description. In view of the objections that can be raised to such merging (Piddington, 1972) and in the interest of making the process seem more intuitively reasonable, the following discussion will be carried out entirely within the context of the flux ropes originally considered by Babcock.

2. Discussion of Babcock's Field-Reversal Arguments:

The principal argument given by Babcock is that as bipolar magnetic regions (BMR's) decay the f-polarity drifts poleward and the p-polarity drifts equatorward. Since the total amount of f-polarity flux erupting during an eleven year cycle is $\sim$100 times the total polar flux, only about one percent of this flux need actually reach the poles to produce a field reversal. Babcock then pictures the rest of the flux as disappearing via the following scenario: the p-polarity from one decaying BMR reconnects with the f-polarity from the next decaying BMR to the west, and the submerged flux connecting the two eventually surfaces, thus liberating flux loops into the corona.

This picture leaves one skeptical for two reasons. First, the actual topology of the subsurface flux tubes during the field reversal is very unclear in Babcock's description. The mechanism by which the subphotospheric field lines are turned around is only faintly hinted at; and one is left with the impression that all the flux tubes should eventually leak out of the surface, leaving the convection zone devoid of any field whatsoever. Secondly, and we think most disturbingly, it gives no explanation for the fact that the reversed field is always about the same strength as the original field; i.e., it is presented as largely a matter of chance that the total leftover flux happens to come out equal in magnitude and opposite in direction to the original polar flux. Such a coincidence is enough to try most peoples' credulity, as Piddington (1972) has pointed out. For more detailed arguments along these lines the reader is referred to Piddington's paper.

However, Leighton (1969) later produced a mathematical model of the solar cycle based largely on Babcock's simple picture and was able to reproduce the behavior of the cycle to a fairly impressive degree. Again, Piddington has raised objections as to the physical reasonability of the field merging necessary for producing the field reversal in Leighton's model: but the success of this model leads one to suspect that there may well be some underlying reason for the 'coincidence' in Babcock's flux cancellation and that the effect produced by Leighton's field merging may indeed be physically reasonable even though strictly speaking the merging itself is open to question. What we shall attempt to do now is to elucidate what we suspect to be the actual topology of the subsurface flux tubes during the field reversal, and to show why this should be expected to produce an equal and opposite polar field for each successive cycle. This model is in no way at odds with Leighton's mathematical model and is presented only as a possible geometric picture of the underlying field configuration represented by Leighton's averaged fields.

3. Basic Assumption:

We will attempt to show below that the solar field reversal follows in a straightforward way from one simple assumption: <u>on the average, the p-polarity (preceding polarity) flux from decaying active regions reconnects with f-polarity (following polarity) flux</u>

from lower latitude decaying active regions, and after (or perhaps during) this reconnection the field lines resubmerge into the convection zone. This assumption is schematically illustrated in Figures 1a-1c with the dashed lines representing subsurface flux tubes and the solid lines representing atmospheric flux loops. Note that the actual process by which the change from configuration 1a to configuration 1c occurs is probably quite different from the simple reconnection shown in 1b (see later discussion), but the net result is all we are concerned with here.

The above assumption is at the heart of everything that follows, and before proceeding we will make a few comments as to why we think it to be reasonable; but the strongest support that can be given for it is that it produces a field reversal in a straightforward way, whereas without it the production of a field reversal encounters definite problems. It should be noted that the net effect of this process is exactly the same as the production and merging of the magnetic doublet rings in Leighton's (1969) mathematical model.

As suggestive justification for our basic assumption (admittedly falling far short of actually proving anything) we would note the following observed properties of active regions. First, active regions have a characteristic tilt such that the centroid of the p-polarity lies

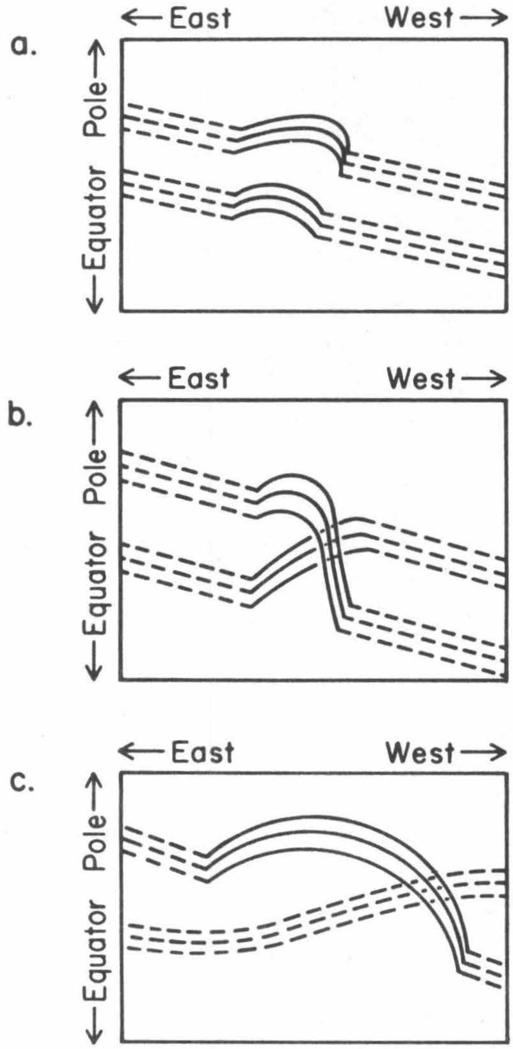


Figure 1

This sequence demonstrates the topology of the reconnection of two nearby active regions as implied by our basic assumption: the dashed lines represent subsurface flux ropes and the solid lines represent atmospheric flux loops. Note that the actual process by which the change from configuration (a) to configuration (c) occurs is probably quite different from the transition state shown in part (b) (see text), but the purpose of this figure is simply to clarify the net result implied by our assumption.

systematically equatorward of the f-polarity centroid, and the effect of this tilt will be to place the lower latitude f-polarity in close proximity to the p-polarity from higher latitude regions. This is just the effect responsible for the field reversal in Leighton's model. Secondly, as active regions decay the f-flux is observed to diffuse systematically poleward while the p-flux drifts systematically equatorward (Babcock, 1961). This may be related to the direction of twisting of the subsurface flux ropes (as suggested by Leighton, 1969) or it may have some other cause; but whatever the origin of this behavior may be, it is clear that it encourages the kind of merging noted in our basic assumption. Thirdly, in addition to random diffusion and the possible twisting of the flux ropes, there are two main influences on the motion of the decaying flux of an active region relative to its surroundings: i) the magnetic tension of the flux ropes to which it connects beneath the photosphere and ii) differential rotation. In the case of p-polarity flux both of these influences tend to make the flux rotate more rapidly than higher latitude flux (assuming the Babcock model to be correct); whereas in the case of f-polarity flux these two influences will be in opposite directions, thus making its velocity relative to higher latitude flux substantially slower. The net effect of this is that the relative velocity of higher p- and lower f-polarity flux will be much smaller than the relative velocity of higher f- and lower p-polarity flux. Hence, the former situation will offer significantly more time for the fields to diffuse together and reconnect, again encouraging the behavior implied in our basic assumption.

The arguments given in the previous paragraph all assume that when the opposite fields are brought into sufficiently close proximity they reconnect and resubmerge. We suspect a lot of readers will balk at this assumption so we will attempt a brief justification. We know that most of the flux surfacing during the solar cycle eventually disappears, and it has to go somewhere. There are basically two possibilities available to it; it can either resubmerge or it can peel off into the corona in the form of flux loops. Let us consider the latter possibility first.

For flux loops to peel out of the sun's surface it is necessary that the p and f flux regions which drift together on the solar surface already be connected by flux ropes beneath the surface. In the context of the Babcock-Leighton model the only way this can occur is if the p-flux from one decaying active region drifts together with the f-flux from the next active region to the west formed on the <u>same</u> subsurface flux rope. This is exactly the scenario pictured by Babcock in his field-reversal model and leads to all the same problems: namely, under such an assumption it is very difficult to understand why the sun doesn't simply lose all its flux, and an equal-and-opposite field reversal becomes highly unconvincing. We would argue that, while the above process may certainly occur, the average p and f regions brought together on the solar surface are unlikely to be already connected under the surface. It is true that the subsurface flux rope tension will favor the merging of p- and f-flux from successive active regions occurring on the same flux rope: but differential rotation will fight against it; and the greater the spacing between the two regions the more likely that differential rotation will win. Hence, we would argue that the bulk of opposite polarity flux pairs brought together on the solar surface are not already connected beneath the surface and are therefore unable to peel off as flux loops. Thus the only mode of disappearance left to them is reconnection and resubmergence.

It should be noted, however, that the actual process of resubmergence might occur by reconnection very near the surface, with the corresponding release of small closed flux loops into the corona. Figures 2a - 2f depict a possible scenario for such a process as two regions of opposite polarity drift together on the solar surface. Indeed, this may be exactly what is going on when a filament eruption occurs. But as far as our field-reversal model is concerned, such details are unimportant; the net

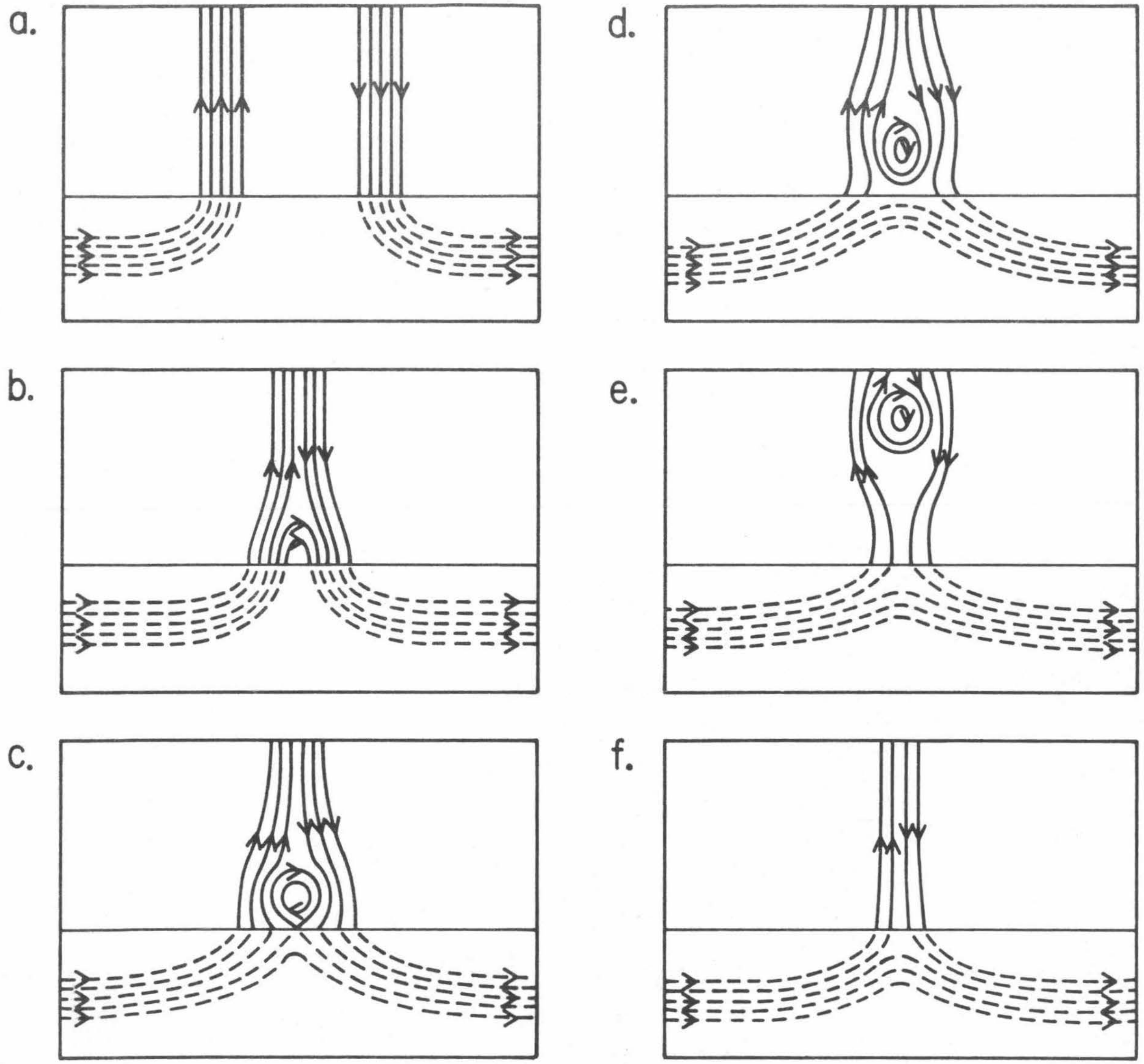


Figure 2

This figure represents a schematic time sequence showing how reconnection with the release of flux loops may occur as two opposite polarity regions drift together on the solar surface. The horizontal solid line in each diagram represents the photosphere while the other solid lines represent atmospheric flux tubes and the dashed lines represent subsurface flux tubes.

result is still the same as if atmospheric flux loops had actually submerged in the manner depicted in Figure 1.

In any case, it is expected that reconnection will occur across magnetic neutral lines (see, for example, the prominence model of Kuperus and Tandberg-Hanssen 1967). We also know that field lines generally penetrate the photosphere at supergranule boundaries; and we therefore expect that, as two opposite polarity regions drift together on the solar surface and reconnection occurs, the two sides of a reconnected tube will eventually be brought together at a supergranule boundary. Inasmuch as the convective gas flow is downward at supergranule boundaries, it is reasonable to expect that the reconnected flux will then sink back into the convection zone.

4. Geometry of Field Reversal:

a) General Comments on Diagrams

In Figures 3a - 3e are a series of highly schematic diagrams illustrating how the application of our basic assumption produces a field reversal. Again, the subsurface sections of the flux ropes in these diagrams are pictured as dashed lines while the sections above the photosphere are drawn as solid lines, and the arrows indicate the direction of the magnetic field along the flux ropes. Before discussing these diagrams sequentially, however, we would like to emphasize a few general points about them.

i) This sequence shows the field reversal occurring at all latitudes at the same time, whereas in reality the activity necessary to produce the reversal starts at higher latitudes and gradually works its way equatorward. The reason for this simplification was to make the overall topology of the field reversal as clear as possible. The modifications of this picture introduced by the gradual equatorward shift of solar activity will be discussed in Section 6.

ii) The individual subsurface flux ropes in these pictures are shown as emerging from the photosphere at the polar crown with their identities intact (i.e., still in the form of single ropes); whereas in reality this flux would be spread over the entire polar cap. The reason for this simplification is that it makes it much easier to follow the quantitative disposition of the flux; that is, to see just how the polar flux is quantitatively related to the active region flux to which it eventually reconnects and why this leaves a reversed field of approximately equal magnitude. It must be borne in mind, however, that the actual process of flux reconnection will involve diffusion over the entire polar cap. This means that there will be a significant time lag between the point at which sufficient active region flux for polar field reconnection has been produced and the point at which the polar field is actually reversed.

iii) In the early stages of the life of an active region its p- and f-flux will be connected to each other by atmos-

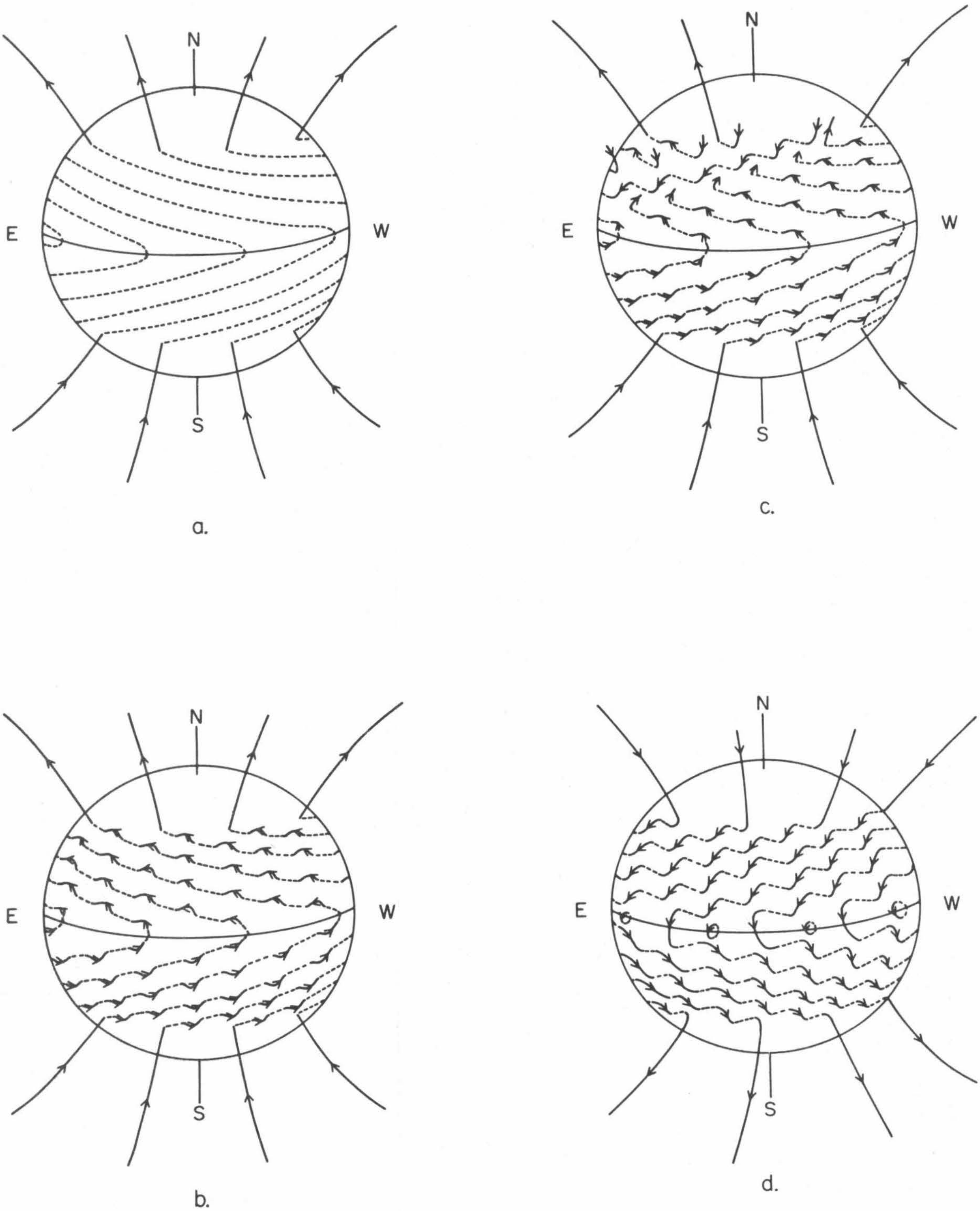
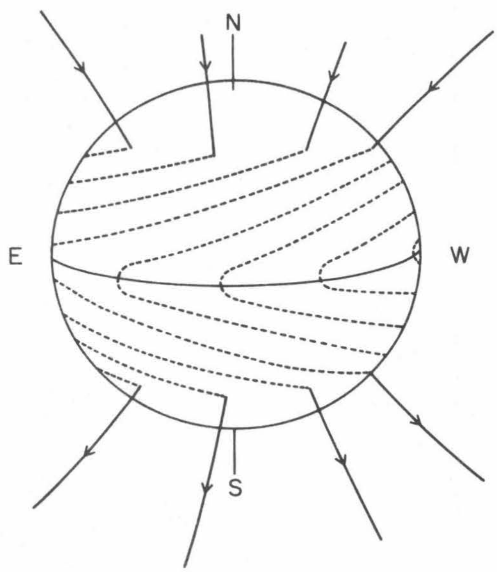


Figure 3 (continued on next page)



e.

Figure 3 (continuation)

Sequence showing how application of our basic assumption to solar active regions produces a polar field reversal. Solid lines represent atmospheric flux tubes while dashed lines represent subsurface flux ropes. For a more detailed explanation see text.

pheric flux loops. When the p-flux from a higher latitude region reconnects to the f-flux from a lower latitude region, it is clear that other flux reconnections must also be occurring in the atmosphere in order to keep everything balanced (e.g., the higher f- may temporarily reconnect to the lower p-flux, as shown in Figure 1c). These coronal flux connections are not pictured in this sequence of diagrams in order to preserve clarity, but they will be discussed briefly in Section 6. Let it be said here, however, that the magnetic stresses due to these coronal connections are probably small compared to photospheric stresses and that the details of the connections are therefore unimportant to our arguments.

iv) It is clear from a casual glance that the number of active regions on each flux rope and their positions in the diagrams have been carefully chosen to make the reversal occur in a straightforward way. The details of the field line topology on the real sun will doubtless be considerably more complicated; but we will try to convince the reader in Section 5 that they can reasonably be expected to have the same net effect.

b) Description of Field Reversal Sequence

With the above comments in mind we will now proceed to describe the basic sequence of events producing the field reversal in this model. In Figure 3a is a schematic diagram of the sun with its subsurface flux ropes wound up as envisioned by Babcock (1961). Following his arguments we will assume that when the field gets wound up to a sufficient strength, loops in the subphotospheric flux ropes will begin to erupt into the solar atmosphere forming active regions and bringing about the situation pictured in Figure 3b (keeping in mind comment i above). At this point we apply our basic assumption that the p-part of higher latitude regions reconnects to the f-part of lower latitude regions. Figure 3c shows the result of applying this assumption to a selected sequence of the erupted flux loops shown in Figure 3b. It is clear that the resulting flux rope (including its atmospheric connections) has a net north-south component opposite to that of the original flux ropes. This step is at the heart of the whole field reversal process and is worthy of looking at with some care.

More generally, applying our assumption to all of the erupted loops shown in Figure 3b produces the result shown in Figure 3d. Resubmerging the atmospheric connections shown in 3d and smoothing out the wiggles in the subsurface flux tubes (as magnetic tension would be expected to do) then produces the configuration depicted in Figure 3e. This final configuration can be characterized as one in which the north-south field is reversed in direction and the subsurface flux ropes are wound backwards, so that the initial effect of differential rotation will be to unwind them, thus reducing the field strength and eventually bringing the configuration back to the point where it starts to wind up again and a new, opposite-polarity cycle can commence.

Several further comments should be made at this point. First, it should be noted that the evolution of each subsurface flux segment as the field reverses is exactly the same as depicted by Leighton in his earlier paper (Figure 10 of Leighton, 1964). What is different here is that the reconnection makes it possible in the large (i.e., over the whole sun at once) without incurring the objection raised by Piddington that rotating one piece of subsurface flux counterclockwise must necessitate rotating adjacent flux in the opposite direction.

Secondly, it can be seen that the reversed field depicted in Figure 3e has exactly one reversed flux rope for each original flux rope in Figure 3a. This is largely an artifact of the way the diagrams were drawn; i.e., had we chosen to space our active regions less carefully we might have produced a different result. We shall try to convince the reader in the next section, however, that while this sort of precisely one-for-one field reversal is not generally to be expected, we can none the less expect the field strength to have a preferred value to which it will always tend to return.

Thirdly, the higher-p to lower-f flux connections in Figures 3c and 3d appear to be excessively large and not all that credible. This is largely an artifact of the small number of flux rope windings pictured in Figure 3a, necessitated by the fact that if more windings had been put into the diagram it would have looked hopelessly cluttered. In a more realistic picture the flux ropes would have been much more nearly parallel to the equator when activity erupted, and as a result the reconnections would have looked much less strained.

And finally, it is not at all necessary that atmospheric flux loops actually connect the higher-p and lower-f flux regions before they resubmerge. In terms of the net result, all that is required is that the regions drift together and that reconnection occur at the neutral line, either above or below the photospheric surface. The reason for the regions drifting together is unimportant. It may be related to the direction of twisting of the subsurface flux ropes as suggested by Leighton (1969), or it may be due to something entirely different (e.g., the cyclonic motions of Parker, 1955b); but whatever the cause may be, the observations enumerated in Section 3 suggest that it happens, and that is enough for our purposes.

5. Generalization of Model:

The purpose of this section is to attempt to convince the reader that the simple schematic picture of the solar field reversal presented in the previous two sections is likely to be relevant to the real Sun, in spite of the fact that the actual field configuration is undoubtedly much more complex. As far as our basic assumption is concerned, all we can add to the previous discussion is to say that the action of differential rotation combined with the observed poleward and equatorward drifts of decaying f- and p-flux, respectively, would be expected to push lower f-regions into higher p-regions from below and behind. This would be expected to produce neutral lines with a characteristic tilt going from north-east to south-west (in the northern hemisphere), which is just the characteristic orientation observed for solar filaments (this characteristic orientation can be seen very clearly in the synoptic diagrams of Hansen and Hansen 1975). Inasmuch as filaments are known to occur along magnetic neutral lines (Howard, 1959), the observed filament orientations provide some support* for our basic assumption.

The next question we have to address here is whether reconnection of a realistically random collection of active regions will be likely to produce a field reversal of the sort shown in Figures 3a - 3e. There are two character-

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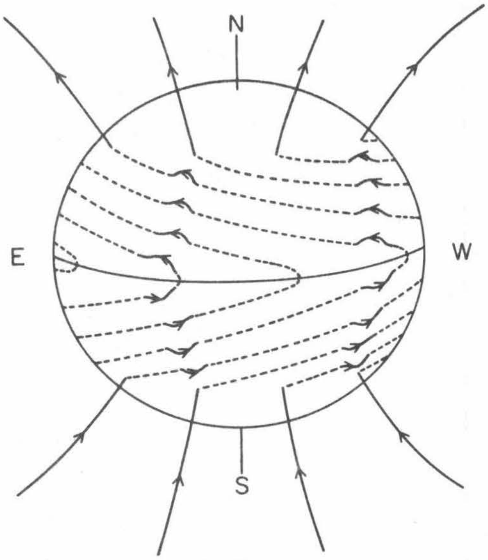
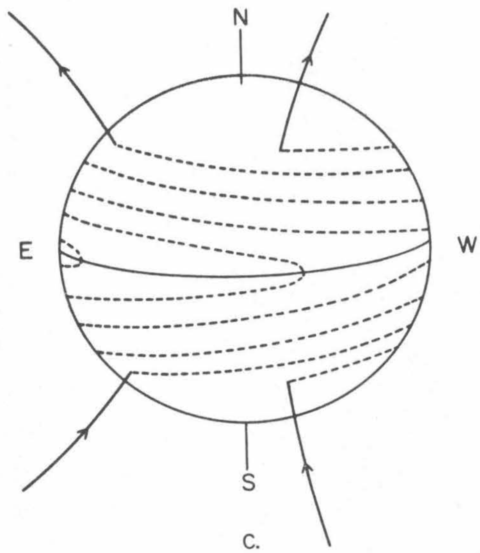
FOOTNOTE*: This observed characteristic orientation of filaments is often cited as evidence of differential rotation of the filaments. However, the median lifetime of filaments is only about four days (Adams and Tang 77); and if filaments were actually born with random orientations, differential rotation over such a short time span would be very unlikely to produce the observed preponderance of tilts.

istics of this set of diagrams that allow the reversal to occur so neatly: i) the relative positioning of the active regions on neighboring flux ropes, and ii) the density of active regions along each flux rope; i.e., the number of active regions available for reconnection. There is no reason to expect decaying active regions on the sun to be so neatly arranged, and we are faced with the obvious question of whether or not a more random distribution will still produce a field reversal.

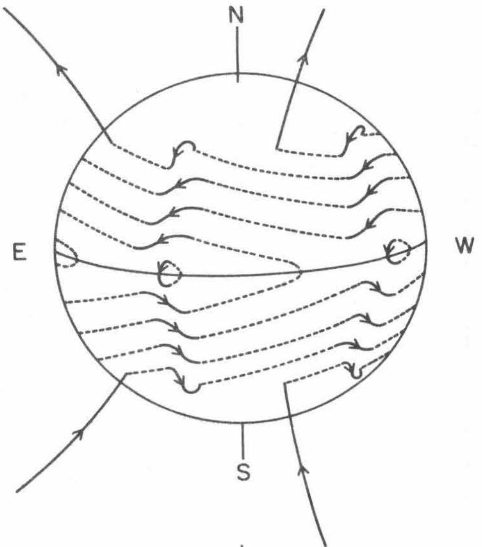
As far as the relative positioning of active regions on neighboring flux tubes is concerned, there is no particular problem because, regardless of the initial positions, differential rotation will eventually bring appropriate pairs of regions together. Whether or not there will be enough active regions to produce a reversal is less obvious. Consider a situation similar to that shown in Figure 3b, but with considerably fewer active regions, such as the example shown in Figure 4a. Reconnecting the regions according to our basic assumption (as illustrated in Figure 4b) would then not produce a reversed field but simply what would appear to be a more tightly wound field (as shown in Figure 4c). That is, the effect of reconnecting flux ropes according to our basic assumption is to allow counterclockwise (in the northern hemisphere) rotation of the subsurface flux rope sections: a small number of reconnections will result in only a small amount of such flux segment



a.



c.



b.

Figure 4

Sequence showing the effect of reconnecting a smaller number of active regions (than in Figure 3) according to our basic assumption. It can be seen that in this case, while the subsurface flux ropes are still caused to rotate counterclockwise (in the northern hemisphere), the magnitude of this rotation is insufficient to produce a reversal. Note, however, that the flux ropes are still forward wound (in the sense of Figure 3a) and hence differential rotation will continue to produce new active regions until a reversal <u>is</u> produced. As before, the solid lines represent atmospheric flux loops while the dashed lines represent subsurface flux ropes.

rotation and the resulting flux ropes will still be forward-wound (i.e., wound up in the sense of Figure 3a). Hence, they will still be subject to amplification by differential rotation and new active regions will keep on forming. Further reconnections will continue this process until the subsurface flux segments have rotated far enough so that their north-south component is reversed in direction. At this point the field will be reverse-wound (i.e., wound up in the sense of Figure 3e); and differential rotation will start to unwind the field, thus reducing its strength and stopping the production of new active regions. Hence, the sun will naturally tend to produce the correct number of active regions to produce a field reversal, and then stop.

The most important question to discuss in this context is whether or not the reversed polar flux produced by our process will necessarily tend to be roughly equal to the original polar flux. To answer this question we will have to consider the process outlined in the previous paragraph in somewhat more detail. First, we will assume that once the eruption of active regions commences, the strength of the subsurface field remains approximately constant until such activity ceases. This is based on the assumption of the Babcock-Leighton model that once the field reaches some critical value, magnetic bouyancy (Parker, 1955a) or other hydromagnetic effects will cause it to erupt, thus producing active regions. The field strength is unable to go much above this critical value because the formation of active regions relieves the field to some degree. On the other hand, as long as activity continues the average field must not be far below this critical value. Since this critical value presumably remains constant from cycle to cycle, the average subsurface field strength at the phase when reversal occurs must be approximately the same from cycle to cycle.

Given this fixed average value for the subsurface field as reversal occurs, let us follow the evolution of the net polar flux during the reversal process. Our basic assumption obviously can't apply to the topmost ring of f-regions produced during a solar cycle because there will be no higher latitude p-regions for them to reconnect with. Hence they will diffuse toward the pole and reconnect with the general polar field (which is of p-polarity). Any left-over f-flux in excess of the original polar p-flux will go toward producing the new, reversed polar field. To see just how much of such left-over flux there is likely to be let us consider how the polar flux balance evolves as a function of the tilt (with respect to parallels of latitude) of the subsurface flux ropes.

Starting with a configuration such as shown in Figure 3a, the production of active regions and their consequent reconnection according to our basic assumption will initially reduce the tilt of the subsurface flux ropes to a configuration such as shown in Figure 4c. Note, however, that this change in tilt involves no further winding of the field and that the number of flux ropes crossing any meridian of longitude has remained the same. So the geometry of the new situation consists of having a smaller number of flux ropes each having a larger number of windings (as can be seen, for example, by comparing Figures 4a and 4c). If we have fewer flux ropes with more windings, we have fewer flux rope ends emerging from the polar cap, and hence a smaller amount of net polar flux. Again, the mechanism by which this has actually happened is that part of the original polar flux has been canceled (or at least balanced out) by the topmost ring of f-flux produced during our reconnection process. The point all this is leading up to is that, for a given average field strength in the subsurface flux ropes, the net polar flux is solely a function of the average tilt of the subsurface flux ropes with respect to parallels of latitude. Indeed, this is easily seen because the net polar flux is just equal to the north-south component of the subsurface flux, and this in turn is determined by the tilt angle.

As this tilt passes through zero the net polar flux passes through zero; but presumably, owing to a certain amount of randomness in the flux rope geometry (they are not all perfectly smooth straight lines), the average tilt must continue to rotate to some finite positive angle before differential rotation can significantly unwind the field and stop the production of new active regions. It is the value of this angle at which activity (and the consequent reconnection it implies) stops that determines the net reversed polar flux. There is no reason that this reversed flux should be exactly the same as the initial flux (as it was in Figure 3d), but presumably the activity-cut-off angle (of the flux rope tilt) is approximately the same from cycle to cycle and therefore the net polar flux is always approximately the same.

6. Additional Considerations:

The purpose of this section is to discuss briefly a few further aspects of generalizing the model to the real Sun. They are not as essential as those discussed in the previous section, but are included for the sake of completeness.

As previously mentioned, one unrealistic aspect of our model is that it shows solar activity as erupting equally at all latitudes at the same time, whereas in actual fact we know that activity starts at higher latitudes and gradually works its way equatorward. This means that in actual fact the field reversal occurs first at higher latitudes and gradually works its way equatorward. Figures 5a - 5d show a schematic sequence of how the subsurface flux rope topology probably evolves as the solar cycle progresses.

Also shown in Figures 5a - 5d are coronal flux loops,

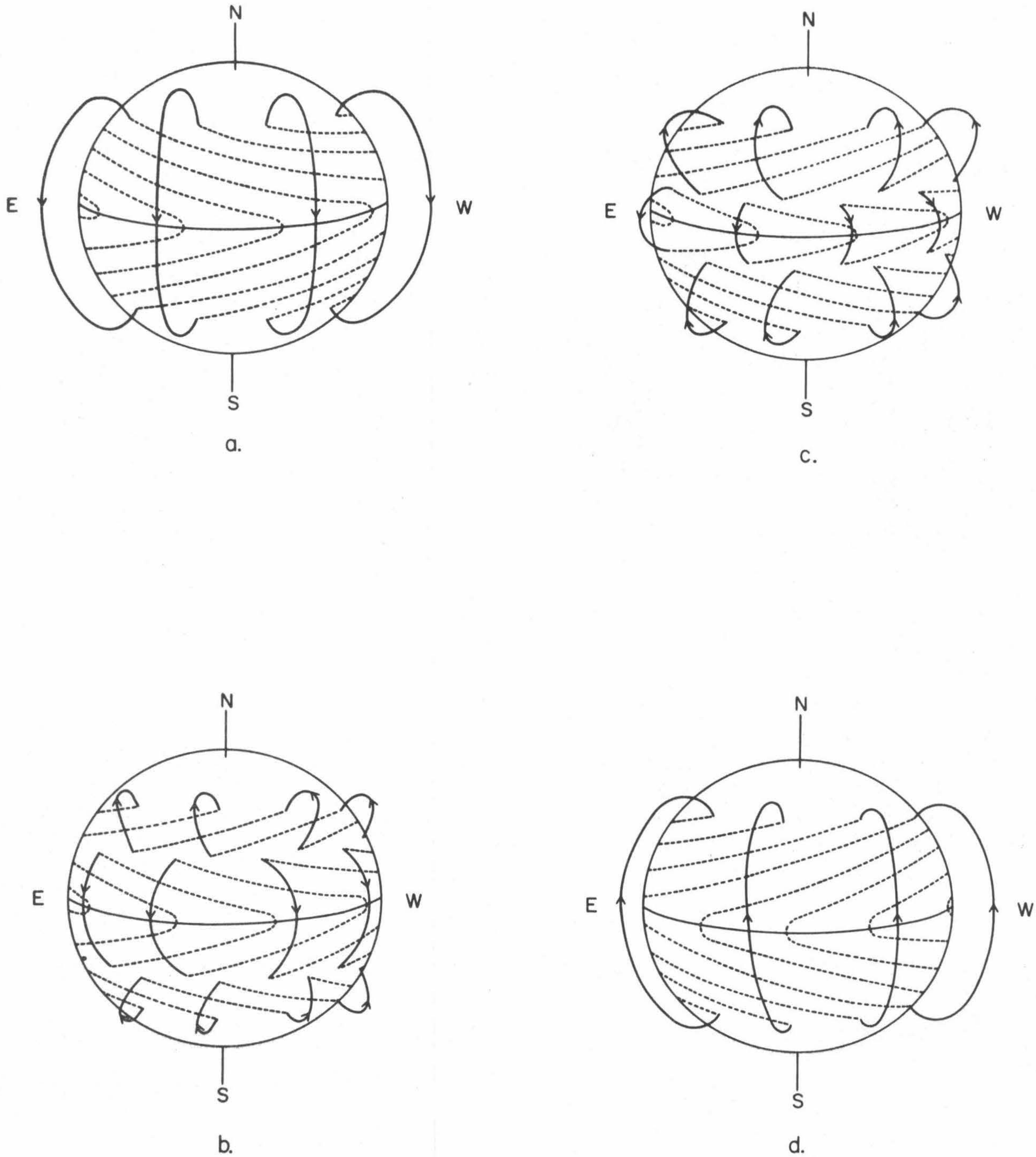


Figure 5

Sequence showing the time evolution of the solar field reversal as active regions reconnect at successively lower latitudes. Solid lines represent atmospheric flux tubes while dashed lines represent subsurface flux ropes. See text for further details.

indicating the simplest form they might take as the cycle proceeds. In reality, of course, many of these flux lines would open into the solar wind; but for the purpose of demonstrating how the overall flux balance is maintained it seemed better to draw them as closed.

It can be seen from the sequence of diagrams in Figure 5 that the net effect of the reconnection process is equivalent to gradually driving the original polar flux down toward the equator, at which point it escapes from the Sun in the form of flux loops. This may seem to be somewhat at odds with our assumption in Section 3 that reconnection is usually followed by resubmergence of the flux; but inasmuch as the total polar flux is only a very small fraction of the total active region flux produced during a cycle, there is not necessarily any contradiction. The real question is why flux loop escape should selectively predominate in the equatorial region while resubmergence predominates elsewhere. The answer is that, while the opposite polarity regions that drift together elsewhere on the solar surface are not expected to be connected by subsurface flux ropes (see Section 3), the pairs that drift together from opposite sides of the equator <u>are</u> expected to be so connected. Hence flux loop escape in equatorial regions is a natural expectation.

One other aspect that has not been discussed previously is the fact that, while we believe that most reconnections result in the effective resubmergence of the flux loops, even at non-equatorial latitudes there may well be some cases in which flux tubes actually peel out of the Sun in the fashion envisioned by Babcock. An important question is whether or not occasional instances of this process will interfere with out basic reconnection process. The answer seems to be that each such event will effectively remove one active region from our reconnection process and therefore require that more active regions be produced in order to effect a reversal. Other than that it in no way interferes with the basic process, at least not if the number of subsurface flux segments escaping by such a route remains a small fraction of the total.

7. Remarks on Piddington's Arguments:

Piddington (1972) wrote an entire paper on the difficulty of producing a field reversal in Babcock-type models of the solar cycle and concluded that it could not be done. It therefore seems worthwhile to examine his objections in the light of our model.

Piddington's objections to previous models can be roughly divided into two catagories: l) arguments that the magnetic field merging required in Leighton's (1969) model is not physically reasonable, and ii) arguments that most of the field in such models would be expected to peel out of the Sun altogether. The arguments on merging are basically that a) in the region of the Sun where most of the field resides the conductivity is too high for ohmic diffusion (i.e., resistive reconnection) to occur and b) if turbulent diffusion were sufficient to merge the fields it would destroy the observed order that the fields show on a global scale. We accept both of these arguments as being sound but point out that in the model presented here it is reconnection at or near the surface that makes field reversal possible. The conductivity at the surface is considerably lower than in the middle of the convection zone and it is widely accepted that reconnection of some sort does occur above magnetic neutral lines in the photosphere (see, for example, the quiescent prominence model of Kuperus and Tandberg-Hanssen 1967). Piddington's arguments on field merging are therefore not applicable to the picture presented here.

Piddington's arguments on loss of flux through escaping loops are as applicable to our model as to previous models; but we would like to point out what we believe to be flaws in those arguments. One of his arguments is that since most of the flux produced by active regions eventually disappears it must escape upward in the form of loops; as we pointed out in Section 3, we believe it to be more likely that most of this flux resubmerges. He also argues that each toroidal flux rope must be broken in about 15 places around the solar circumference during the course of a cycle and that this places successive active regions quite close together, thus encouraging the formation of escaping loops. However, the period of time over which most of these active regions form (a few years) is quite large compared with the average lifetime of the flux produced by each eruption (a few months by Piddington's own estimate). Consequently, any given piece of active region flux is unlikely to have the opportunity to escape in a flux loop before it reconnects to some other flux rope and resubmerges.

Piddington's other basic argument on the probability of most of the flux escaping is that as each field eruption twists by some mechanism akin to Parker's (1971), it layers the reversing flux on top of underlying flux and therefore gradually moves the centroid of the flux closer to the surface, where it eventually escapes (see Figure 3 and accompanying text of Piddington's paper for a clearer statement of this objection). What seems to us to be the principal flaw here is that, while one flux rope may be layered above a second in one region of the Sun, the second is just as likely to be layered above the first in another part of the Sun. Hence, the net effect of such field line crossings will be to braid neighboring flux ropes together to some degree, thus tying them all the more strongly into the subsurface field structure.

Of course, most of the arguments on both sides of the question of flux loop escape are basically heuristic, and the reader will have to choose for himself which he wishes to believe.

8. Closing Remarks:

We have presented a picture of the solar cycle field reversal in which selective reconnection and resubmergence of lower latitude f-flux with higher latitude p-flux allows sufficient rotation of subsurface flux rope segments to reverse their north-south component and consequently reverse the general polar field. This model is substantially different from the description of the field reversal given by Babcock (1961). It is, however, much closer to the model of Leighton (1964, 1969), with our subsurface fields undergoing exactly the same evolution as envisioned in Figure 10 of Leighton (1964). The only real difference here is that we do not conceive of this field evolution as occurring through subsurface merging of field components but rather through a genuine rotation of subsurface flux ropes made possible in the large by surface reconnection.

While our model is, indeed, little more than a minor variation on the Babcock-Leighton legacy, it has the virtue that it is not subject to the objections raised by Piddington (1972) to the field merging used in other models. In that respect it provides further support for the correctness of the basic mechanism of field amplification by differential rotation underlying the Babcock-Leighton model. It also provides an intuitively comprehensible picture of how field reversal occurs, an aspect which some felt to be lacking in previous descriptions.

Our intention in this discussion has been to present a simple idea which is basically non-mathematical, and for that reason we have deliberately avoided the use of equations and numerical estimates in this initial presentation. There are many areas of this discussion, however, that could fruitfully be explored on a quantitative basis; and we hope to pursue this aspect in later work.

And last, but far from least, we come to the question of observational testing. This entire discussion has been nothing more than an extensive elaboration of the implications of our basic assumption that higher-latitude p-flux selectively reconnects to lower-latitude f-flux and that the resulting flux tubes resubmerge. If one could follow the evolution of the flux from a decaying active region up until the point when it actually disappears, one might be able to demonstrate (or disprove) this assumption observationally. Inasmuch as old active region flux spreads itself quite thin before finally disappearing, however, such tracking would not be an easy task; but it is probably not completely beyond possibility.

A partial test of the basic assumption which might be less difficult from an observational point of view would be the careful study of the field structure around magnetic neutral lines to see if there is any direct observational evidence of reconnection followed by resubmergence. Such behavior might be difficult to sort out if the usual mode of reconnection at neutral lines involves flux loop release in a fashion akin to that depicted in Figure 2, but it is worth looking for. Also, as discussed in Section 6, while in most of the Sun's active zone we expect the flux to resubmerge, in the equatorial regions we expect a significant quantity of flux to actually peel out of the surface. This means that there may be observable differences between neutral line behavior patterns in the two regions, which might be reflected in the characteristics of filament formation, filament lifetimes, and/or filament eruptions in these regions. This might well be the most fruitful area for investigation.

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