THE EFFECT OF AN INTERACTION OF MAGNETIC FLUX AND SUPERGRANULATION ON THE DECAY OF MAGNETIC PLAGES

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Abstract. This paper studies how the properties of large-scale convection affect the decay of plages. The plage decay, caused by the random-walk dispersion of flux tubes, is suggested to be severely affected by differences between the mean size of cellular openings within and around plages. The smaller cell size within a plage largely explains the smaller diffusion coefficient within plages as compared to that of the surrounding regions. Moreover, the exchange of flux tubes between the inner regions of the plage and the surrounding network is suggested to be modified by this difference in cell size, and the concept of a partially transmitting plage periphery is introduced: this periphery preferentially turns back flux parcels that are moving out of the plage and preferentially lets through flux parcels that are moving into the plage, thus confining the flux tubes to within the plage. This semi-permeability of the plage periphery, together with the dependence of the diffusion coefficient on the flux-tube density, can explain the observed slow decay of plages (predicting a typical life time of about a month for a medium-sized plage), the existence of a well-defined plage periphery, and the observed characteristic mean magnetic flux density of about 100 G. One effect of the slowed decay of the plage by the semi-permeability of the plage periphery is the increase of the fraction of the magnetic flux that can cancel with flux of the opposite polarity along the neutral line to as much as 80%, as compared to at most 50% in the case of non-uniform diffusion. This may explain why only a small fraction of the magnetic flux is observed to escape from the plage into the surrounding network.

1. Introduction

The first description of the supergranular velocity field was given by Hart (1954, 1956), soon followed by the statistical studies by Leighton *et al.* (1962) and Simon and Leighton (1964). Singh and Bappu (1981), Brune and Wöhl (1982), and Küveler (1983) estimate that approximately 10 000 supergranules cover the solar surface, corresponding to a typical diameter of approximately 28 000 km. Lifetime estimates for supergranules range from about 20 hr (Simon and Leighton, 1964; Rogers, 1970; Janssens, 1970), up to about 40 hr (Smithson, 1973; Worden and Simon, 1976; Duvall 1980). Many of the estimates of lifetimes for supergranules are 'deformation time scales', i.e., correlation times over which the feature used to trace the supergranule (e.g., the area of downdraft, or the chromospheric or magnetic network) is displaced by its own characteristic dimension. The cell may exist much longer as a feature traceable by eye. Mosher (1977, p. 210), for instance, notes that gradual distortions of cells in the enhanced network around active regions can be followed over periods of up to several days. Wang's (1988) study of velocity fields of a small number of supergranules indicates life times in excess

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of 50 hr. Network cells forming the enhanced network appear to live longer than cells in regions with a low flux tube density (Zwaan, 1978), perhaps as long as 3 days (Sheeley, 1969) or more (Livingston and Orrall, 1974).

Evolutionary changes of supergranules, including their formation and disappearance, have been suggested to cause the random-walk dispersal of photospheric magnetic flux tubes (first proposed by Leighton, 1964). In this process, the flux – that has been transported to the areas of downflow immediately after surfacing in the photosphere – shifts so that it always remains at the cell boundaries. The dispersion of magnetic flux over the solar surface on a scale much larger than a typical plage can indeed be modelled accurately by a random-walk diffusion process, provided differential rotation and meridional flow are taken into account (e.g., Sheeley *et al.*, 1985). The decay of magnetic plages, however, appears to defy a description by a simple, uniform diffusion process. For one thing, a simple diffusion process should result in a rapid decay of the plage with – at best – a very vague transition between the magnetic plage and the surrounding network. In reality, however, the transition between the main body of the plage and the surrounding network is often well defined (see the example given in Figure 1(a)), and occurs at a mean magnetic flux density of about 50 G when observed at $\simeq 1''$ resolution (e.g., Schrijver, 1987). The simple diffusion also fails to explain Schrijver's (1987) conclusion, based on the study of a sample of plages of different sizes and in different stages of evolution using Kitt Peak daily magnetograms ($1''$ resolution), that the mean magnetic flux density within the periphery of a plage (defined by a 50 G contour) is 100 ± 20 G. This mean flux density should have been found to decrease with the age of the plage if the decay of active regions were a simple diffusion process characterized by a single, constant diffusion coefficient.

This paper studies the consequences on the decay of plages of a proposed modified model for the diffusion of magnetic flux tubes in the solar photosphere: it addresses the effects that (1) the interaction of magnetic flux and supergranulation, and (2) flux transportation predominantly along supergranular boundaries could have on the decay of magnetic plages.

Zwaan (1978) has suggested that the local flux-tube density determines the size of network cells: within dense plages there is no cell structure except for some isolated, relatively empty patches with diameters up to several thousand kilometers, while rings of supergranular sizes are found only in the outskirts of active regions where the magnetic flux density is relatively small. Hence, convective cells seem to appear wherever the local magnetic flux density is sufficiently small, while the cells are larger where the magnetic flux density is smaller. An autocorrelation analysis by Foing, Bonnet, and Bruner (1986) of observations made with the Transition-Region Camera yields a characteristic diameter for the active-region 'network' of $\simeq 14000$ km. This is a factor of 2 smaller than the network in the quiet Sun. Simon *et al.* (1988) analyze observations made with the Solar Optical Universal Polarimeter (SOUP, Title *et al.*, 1986a), flown on Spacelab 2, in combination with a powerful technique to track the motions of granules (November *et al.*, 1986). They infer (center-to-center) cell sizes in plages from the flow-divergence maps of typically 10000 km to 15000 km, suggesting that not just

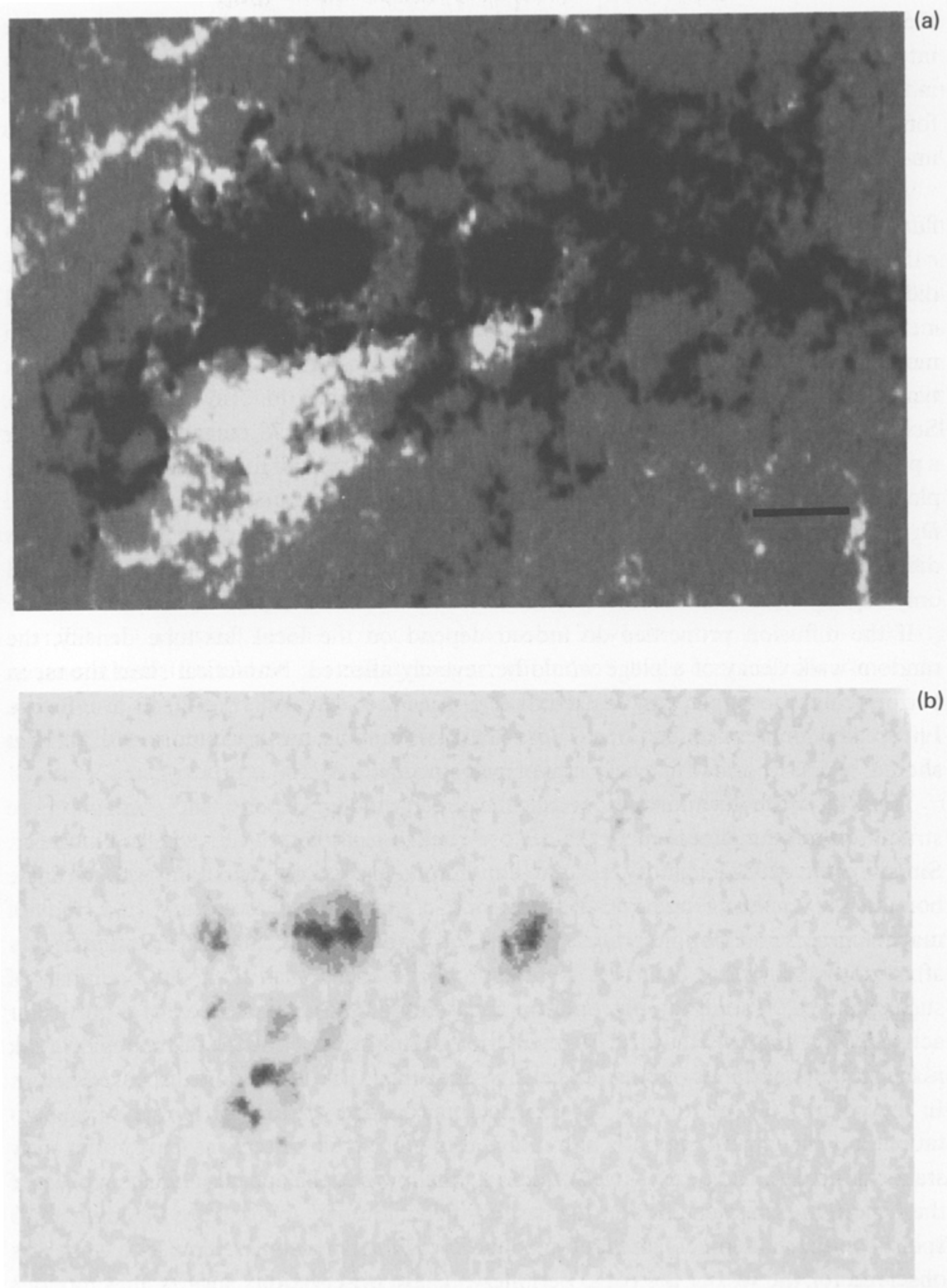

Fig. 1. Magnetogram (a) and line-intensity map (b, eight levels of intensity in the 8688 Å line) of active region No. 16850 (20 May, 1980), observed with 1″ resolution at Kitt Peak National Observatory. The field of view covers 330″ × 220″, i.e., 240000 × 160000 km. The bar in panel (a) shows a typical diameter of a supergranule (26000 km). Note the absence of large supergranular openings in the main body of the magnetic plage.

the network pattern but the flow pattern itself is modified. They also suggest that the interaction of magnetic flux and the supergranular flow velocity affects the flow velocity in the centers of the cells as well as the cell size; they find average horizontal velocities for granules caught in the supergranular flow around 400 m s^{-1} and 100 m s^{-1} in quiet and magnetic Sun, respectively.

A change in the convective properties should be reflected in the diffusion of magnetic flux. The diffusion constant in a random-walk process in given by $D = \langle r^2 \rangle / 4\Delta t$, with r the observed displacement after a time interval Δt. Note that the expression for the diffusion coefficient can be approximated by $D = \lambda^2/4\tau$, with λ a typical step length, and τ the typical time step. The inferred diffusion constants associated with the random motions of the traceable magnetic features in quiet regions and in enhanced network typically range between 200 and 400 km^2 s^{-1} (e.g., Mosher, 1977; DeVore *et al.*, 1985). Schrijver and Martin (1989) study displacements of some 170 magnetic features over a period of five days. They show that the diffusion coefficient of magnetic features within plages is smaller by a factor of about 2 than in the surrounding regions: they find $D_{\text{plage}} \simeq 120$ km^2 s^{-1} for the plage and $D_{\text{quiet}} \simeq 280$ km^2 s^{-1} for the quiet region. This difference is shown to be largely associated with the difference in the length scale and only slightly with a difference in velocities.

If the diffusion properties do indeed depend on the local flux-tube density, the random-walk decay of a plage would be severely affected. Numerical simulations, as performed in this paper, can be used to determine precisely what the effects are. Before I proceed with these simulations, I note that there may be another important effect that should be incorporated in the study of plage decay.

The SOUP observations show that the supergranular velocity field contains more structure than the simple model of a close-packed grid of convective cells allows for. Simon *et al.* (1988) identify several continuous lanes of flow along supergranule boundaries, some as long as 50–100 Mm or 2–3 supergranule diameters. In a study of magnetograms and Dopplergrams, Wang (1988) finds that flux cancellation often occurs after the two opposite polarities have approached each other along the boundary of supergranules. A study by Martin, Livi and Wang (1985) of the decay of a particular active region suggests that the fragmentation around the periphery of the region took place at the boundaries of network cells, in agreement with the model discussed above. In the polarity-inversion zone between the main concentrations of flux, the fragmentation and ensuing migration is not confined to a network pattern, at least in the early stages of decay. In the late stages of decay, when large cells appeared in the middle of the region, the fragmentation at the polarity-inversion line appeared to be confined to specific paths that coincided with the boundaries of supergranules, similar to what was observed for the rest of the plage periphery. These observations suggest that motions along supergranular lanes contribute substantially to the random walk of magnetic features. If the flux tubes move along the supergranule boundaries with a mean velocity of 100 m s^{-1} (Tarbell, 1987), a supergranule lifetime in excess of 50 hr allows the flux tubes to travel 18000 km without experiencing major displacements caused by the evolution of supergranules. The process of flux displacement along supergranular lanes could therefore form a major contribution to the random walk of magnetic flux tubes. Section 2 argues that this mode of flux-tube displacement would affect the evolution of magnetic plages severely. In subsequent sections I develop a model for the random-walk decay of plages that allows a study of the effects of a variable diffusion coefficient and of flux transport along cell boundaries on the decay of plages.

Throughout this paper I shall use the term 'flux-tube density' (N) as an equivalent for the mean magnetic flux density ($\langle fB \rangle$ or, more accurately, $\langle f|\mathbf{B}| \rangle$, the product of the photospheric area filling factor f for flux tubes and the intrinsic field strength B) as observed with sufficiently low resolution (say $1''$–$10''$). The use of that term should avoid confusion with the intrinsic magnetic flux density (or field strength) within individual flux tubes (which is commonly suggested to be 1–2 kG, e.g., Howard and Stenflo, 1972; Stenflo, 1973). The term also implies that the entity that is being transported by the (sub-)photospheric velocity field is in fact the flux tube. I do not wish to imply that all flux tubes are identical, although for the purpose of this paper the concept of a 'typical magnetic flux tube' may be used: the random-walk diffusion of flux tubes can be envisaged as the diffusion of otherwise identical 'atoms' through another medium. The term 'magnetic plage' is used for large-scale, coherent regions with a high flux-tube density and a well-defined periphery. The surrounding low-density regions are referred to as 'quiet' (even though the flux-tube density may be higher than in areas of minimal activity).

2. A Model for the Decay of Plages

2.1. The semi-permeable plage periphery

A possible feedback between the local flux tube density and the mean size of the convective cells would be very important in the decay of plages if the displacement of flux tubes (or small bundles of flux tubes) is caused to a large extent by motions *along* cell boundaries. This can be illustrated by tracing the path of a bundle of flux tubes originally located within the plage in the idealized grid of rectangular cells sketched in Figure 2. After a certain amount of time this bundle ('A' in Figure 2) reaches the periphery of the plage. In order to escape from the plage, the flux tubes must move along the periphery to find an appropriate exit in the form of a supergranular lane leading away from the plage into the 'quiet' region, because they cannot move against the opposing flow of the supergranulation. Since the cells within the plage are smaller than in the quiet region, the probability to encounter a path leading back into the plage is larger than the probability to find a path leading out of the plage. Consequently, if the flux is predominantly transported by flow along supergranular boundaries, the periphery of the active region acts as a semi-permeable '*membrane*' that preferentially *turns back parcels trying to escape from the plage*. A similar argument shows that the plage periphery preferentially *transmits parcels moving into the plage* (see the path of flux parcel 'B' in Figure 2). The paths along which bundles move into or out of the magnetic plage possibly alternate along the periphery; this does not affect the calculation of the probabilities of escape or capture.

The above model assumes that flux transport occurs predominantly along supergranule boundaries both in the magnetic plage and in the quiet Sun. This assumption can be relaxed: it is sufficient to assume that the flux escaping the plage travels along supergranule boundaries (as suggested by Martin, Livi, and Wang, 1985, see Section 1)

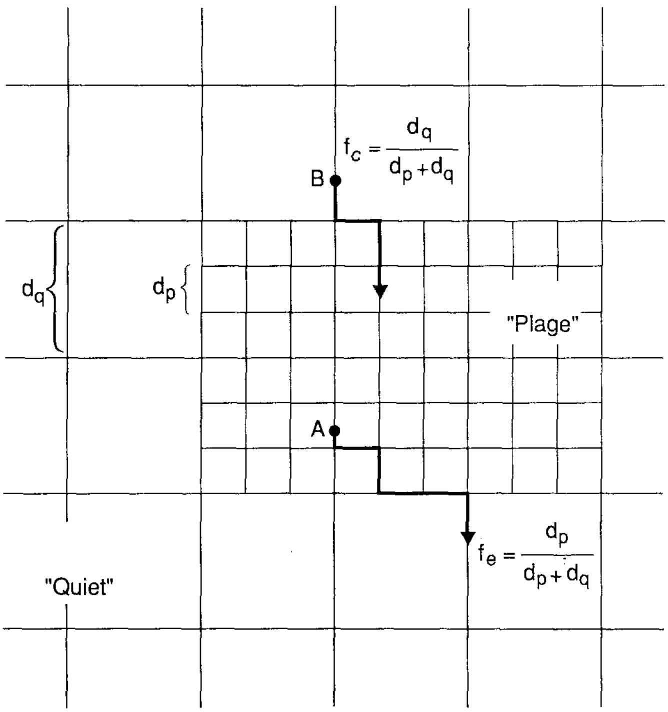

Fig. 2. Idealized rectangular grid of 'convective cells'. The typical size d of the velocity cells is suggested to be determined by the flux-tube density N: d_p at $N \geq N_c$, and d_q at $N < N_c$. The flux tubes (or small bundles of flux tubes) labelled A and B outline possible paths of flux tubes that escape through or are captured by the plage periphery, respectively. The escape probability f_e and the capture probability f_c (see Section 2.1) are determined by the size of the velocity cells. Note that in reality a spectrum of cell sizes is observed both in quiet regions and in plages.

into the quiet region, while the transport within the plage may be due to random displacements with a time scale much smaller than the life time of a supergranule in a quiet region. In this case the probability of escape, f_e, through the plage periphery should be computed as the ratio of the width of the supergranular lane to the supergranule diameter (while the probability of capture of a flux tube into the plage is $f_c \simeq 1$), which basically gives the fractional width of the 'slots' through which the flux tubes may escape. With this relaxed assumption, the model does *not* necessarily require a change in the convective velocity field within a plage, but assumes only that the *transport properties* of the flux tubes depend on the flux-tube density (see Section 5), as required by the observed dependence of the diffusion coefficient on the flux-tube density (see Section 1).

2.2. A NUMERICAL MODEL FOR THE DECAY OF MAGNETIC PLAGES

The analytical study of the decay of a plage with a semi-permeable periphery and density-dependent diffusion properties is very complicated so that instead a numerical simulation was made. First the evolution is modelled of a circular, monopolar 'plage' with a radius of 38 000 km, typical of an average-sized plage. Because of the symmetry of the problem, only the first quadrant of the plane is included in the simulation, with flux tubes reflecting against the horizontal and vertical boundaries at $y = 0$ and $x = 0$. The first quadrant of the plage initially contains over 5300 homogeneously distributed 'flux tubes' (a mean magnetic flux density of 120 G and an intrinsic field strength of 1500 G in the tubes implies a mean flux-tube diameter of 150 km, and a total flux of about 6×10^{21} Mx). Another 4700 flux tubes of the same polarity are distributed homogeneously over the area of the quadrant outside the plage, within a radius four times that of the initial plage (with an equivalent mean flux density of 7 G).

In each time step (equivalent to 24 hr) each of the flux tubes is moved in a random direction, with a specified step length λ (the mean free path length) and velocity v. The 'grid-structure' of cells is thus ignored, but this structure only affects the transition of flux across the plage periphery. In order to simulate these transition effects at the periphery, transition probabilities f_e and f_c are introduced. Although the model discussed in Section 2.1 links the ratio of cell sizes in plage and quiet Sun with the probability to move through the periphery (and that $f_c = 1 - f_e$, see Figure 2), the values of f_e and f_c can be varied independently in the computer code so that the effects of density-dependent diffusion and the effects of a 'semi-permeable' periphery can be studied separately.

The well-defined transition between plage and quiet Sun suggests that the change in the characteristic size of supergranular convection occurs suddenly, at some critical flux tube density N_c. Hence, the velocities (v) and step lengths (λ) are assumed to change in a step-wise fashion at a specified critical flux-tube density N_c. Additional random steps are made if the available time interval is not fully used after travelling the previous free path length. This ensures that the mean free path length is always completely covered. If more than the available time step of 24 hr is used by covering the (last) mean free path length, the excess time is subtracted from the next time step.

After each time step the flux-tube density $N(r)$ is determined as a function of distance r from the origin by integration over concentric circular segments of 90°. Azimuthal fine structure is thus disregarded. The largest radius, R_{N_c}, at which the flux-tube density drops below the critical value N_c is taken as the periphery of the plage. Thus, small regions within the plage may have a density below the critical density, which is usually caused by statistically allowed fluctuations. On statistical grounds, the largest density fluctuations are expected near the origin where the number of flux tubes that determines the flux tube density is rather small owing to the small area of the concentric circular segments used to determine the density profile. Note that the model allows such low-density areas to exist within the plage, as long as their scale is smaller than, say, an unperturbed supergranule. The circular shape of the plage periphery at $r = R_{N_c}$ prescribes a cylindrically symmetric evolution.

If a step would take a flux tube across the periphery of the plage at R_{N_c}, it is given a certain transition probability to cross the periphery: it has a probability f_e to escape from the plage into the quiet region, and a probability f_c to be captured from the quiet region into the plage (compare Figure 2). If the flux tube crosses the periphery, the direction of motion is maintained, but the velocity and step length are adjusted at the periphery to the values specified for the relevant region. If the flux tube does not cross the periphery, it bounces back along its original path while completing the remaining part of the step.

Simulations of the evolution of a bipolar plage are also made. The introduction of the second polarity breaks the cylindrical symmetry, so that the flux-tube density has to be determined more or less locally. The computer code was revised to determine the flux-tube density $N(r, \phi)$ in segments of $\Delta\phi = 15°$ as a function of distance r from the origin. The plage is assumed to consist of two identical halves: one polarity occupies the space at $x > 0$, the opposite polarity the space at $x < 0$. Again only the first quadrant is simulated, but the reflection at $x = 0$ is modified: if a parcel reaches $x = 0$ it is assumed to cancel with a flux parcel of opposite polarity. In reality not all flows between convective cells may direct flux tubes towards the neutral line, while also other factors may make it harder for a flux parcel to actually reach a flux parcel of opposite polarity at the neutral line. In order to study the results of such effects on plage evolution a 'cancellation probability' f_{cl} is introduced that measures the fraction of flux tubes that meets a tube of opposite polarity and cancels upon reaching $x = 0$. A fraction $1 - f_{cl}$ of the tubes bounces off the 'polarity-inversion line' back into the first quadrant.

The cancellation of flux tubes reduces the flux-tube density near the 'polarity-inversion line' drastically, which would result in a switching to the diffusion properties of quiet regions, but ordinary supergranulation should not develop there because of the lack of space where $N < N_c$. In reality, supergranulation is not observed around the polarity-inversion line unless the regions of different polarity are widely separated. Therefore, the distance $R_{N_c}(\phi)$ of the periphery to the origin is taken to be constant for $\phi > 45°$, regardless of the actual flux-tube density for $\phi > 60°$.

3. The Random-Walk Decay of a Unipolar Region

If the velocity and step length are chosen independent of the magnetic flux density ($v_{\text{quiet}} = v_{\text{plage}}$ and $\lambda_{\text{plage}} = \lambda_{\text{quiet}}$) and the transition probabilies to cross the plage periphery equal unity ($f_c = f_e = 1$), the situation is a simple two-dimensional diffusion problem. Its characteristic properties (Figure 3) are a rapid smoothing of the initial discontinuous change in density at the plage periphery, and a rapidly decreasing flux-tube density in the original plage area. The unipolar plage (defined as the coherent body of flux with a local flux density above 80 G) has a life time of about 10 days (Figure 4(a), curve 1). Note that the life time would be even shorter for a bipolar plage with internal cancellation of magnetic flux.

If the random-walk properties are independent of the flux-tube density but an escape probability f_e through a periphery (defined by the contour at $N = N_c$ equivalent to 80 G)

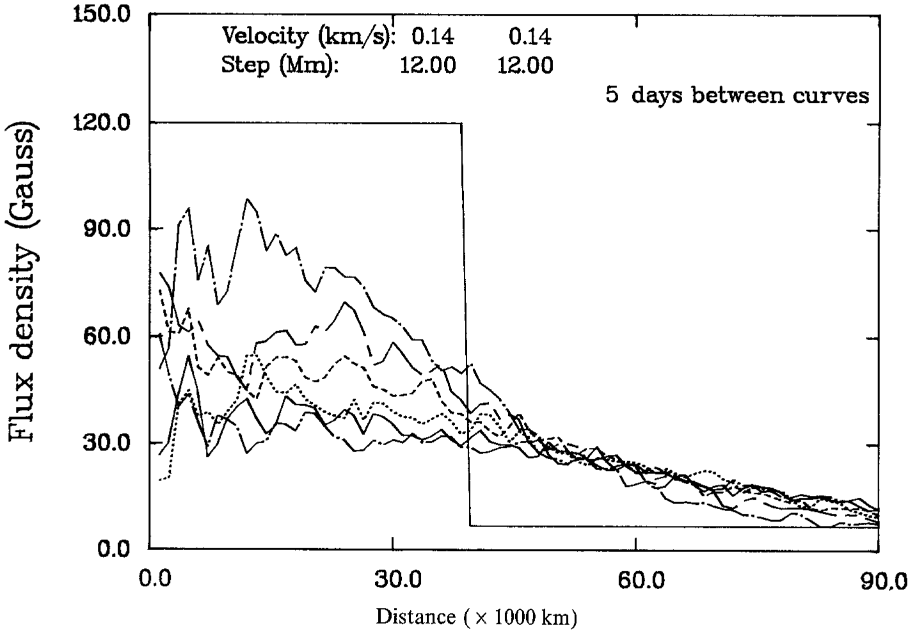

Fig. 3. Simulated evolution of a monopolar plage (see Section 2.1), in the case of uniform diffusion. The fractional flux loss as a function of time is shown in Figure 4(a), curve 1.

is specified sufficiently smaller than 0.5 (with $f_c = 1 - f_e$), a steep density gradient is maintained at the periphery (Figure 5). The mean flux-tube density within the plage decreases only slowly, and the flux density profile can be almost independent of radius if the escape probability is small enough. Even with a density-independent diffusion coefficient, the introduction of a semi-permeable plage periphery drastically increases the lifetime of the monopolar plage: Figure 4(a) (curve 3) shows that only some 50% of the flux is lost after four weeks with diffusion properties typical of a solar quiet region.

If the diffusion coefficient in the high-density plage is much smaller than in the low-density surroundings (in the simulation: $v_{\text{quiet}} \simeq v_{\text{plage}}$ and $\lambda_{\text{plage}} \ll \lambda_{\text{quiet}}$), a steep density gradient can be maintained at the periphery of the plage even if $f_e = f_c = 1$. In this situation the density profile within the plage can be virtually independent of radius, but the mean flux-tube density does decrease rather rapidly with time (Figure 6) (an analytical solution to a similar problem is discussed by Crank, 1986). The existence of a steep gradient appears to be related to the rapidity with which flux tubes can be moved away from the plage periphery in the quiet region: if the removal is slow, the density change at the periphery is kept smaller, resulting in a lower net loss of flux from the plage per unit time. For typical solar diffusion properties, the monopolar plage looses all its flux in about a month (Figure 4(a), curve 2).

If the plage diffusion coefficient is much smaller than the diffusion coefficient in its surroundings, and the escape probability f_e through the periphery is much less than unity (with $f_c = 1 - f_e$), an abrupt transition in flux-tube density is maintained at the periphery of the plage, the mean flux-tube density within the plage decreases only slowly,

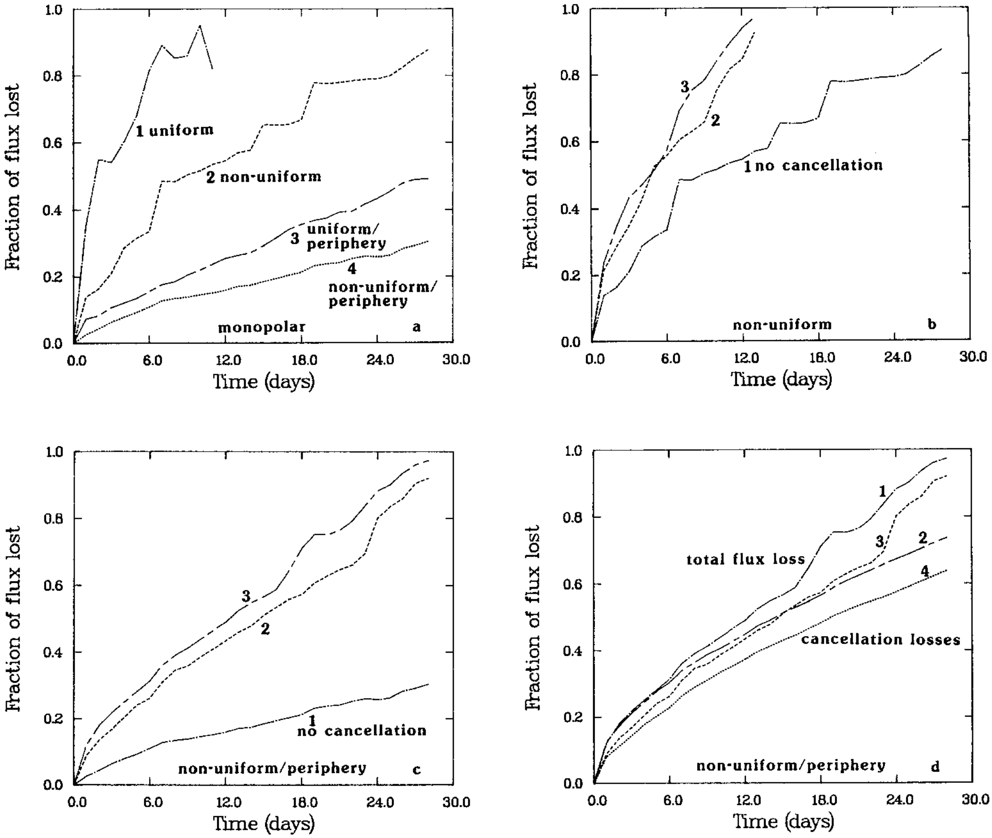

Fig. 4. Fractional flux loss from the plage as a function of time. The flux loss is measured by the number of flux tubes that have crossed a contour at a flux-tube density N_c equivalent to the critical flux density $\langle fB \rangle_c \simeq 80$ G. (a) shows losses for the simulated evolution of a monopolar plage: (1) uniform diffusion (parameters given in Figure 3), (2) non-uniform diffusion (Figure 6), (3) uniform diffusion, but with a semi-permeable periphery (Figure 5), (4) non-uniform diffusion and semi-permeable periphery (Figure 7). (b) shows the flux losses for the evolution of a two-polarity plage, with non-uniform diffusion but without a semi-permeable periphery: (1) no flux cancellation (same as curve 2 in (a)), (2) cancellation probability $f_{cl} = 0.5$ (see Section 2.2), (3) $f_{cl} = 1.0$ (remaining parameters as in Figure 6). (c) shows flux losses in the case of the evolution of a two-polarity plage with non-uniform diffusion and a semipermeable periphery (parameters as in Figure 7): (1) no flux cancellation at the polarity-inversion line (same as curve 4 in panel (a)), (2) $f_{cl} = 0.5$ (cf. Figure 8(a)), (3) $f_{cl} = 1.0$ (cf. Figure 8(b)). In (d) curves 1 and 3 repeat the total flux losses in situations 2 and 3 in (c), and separately shown is the loss associated with cancellation at the polarity-inversion line at $x = 0$ (curves 2 and 4 for cancellation probabilities 0.5 and 1.0, respectively).

and the plage density profile is virtually independent of the distance from the origin (i.e., independent of the proximity to the flux leak at the periphery). For typical solar conditions ($\lambda_{\rm plage} = 4000$ km, $\lambda_{\rm quiet} = 12000$ km, $v_{\rm plage} = 100$ m s^{-1}, and $v_{\rm quiet} = 140$ m s^{-1}) the plage life time depends strongly on the escape probability f_e. A mean plage flux density of about 100 G is maintained if N_c is equivalent to ≈ 80 G. If $f_e = 1$, the plage looses all of its flux in a month, while at $f_e = 0.25$ the plage still has 70% of its initial flux after that time (Figure 4(a), curve 4).

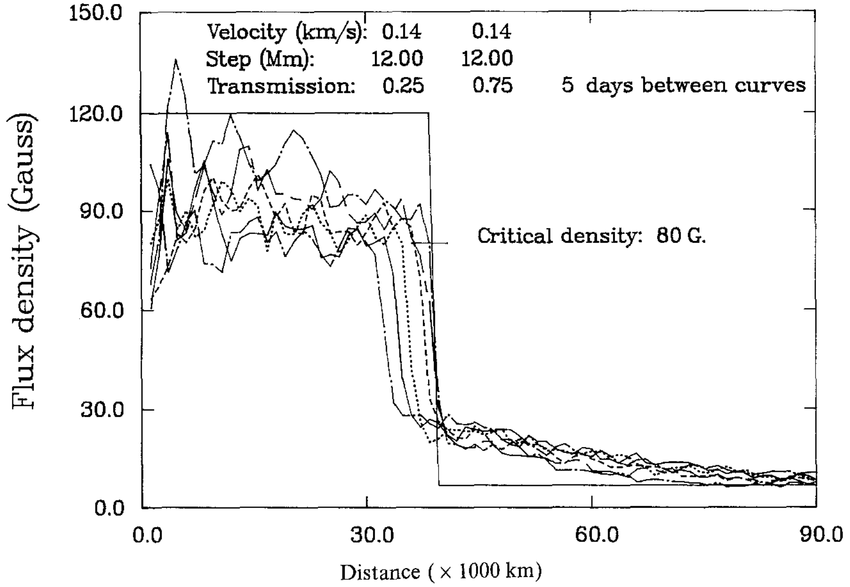

Fig. 5. Simulated evolution of a monopolar plage with uniform diffusion, but surrounded by a semi-permeable periphery (see Section 2.1). The critical flux density at which the diffusion properties change discontinuously is $\langle fB \rangle_c = 80$ G. The numbers at the top of the panel show the diffusion properties above and below the critical density (values at left and right, respectively), and the escape probability f_e (left) and capture probability f_c (right). The fractional flux loss as a function of time is shown in Figure 4(a), curve 3.

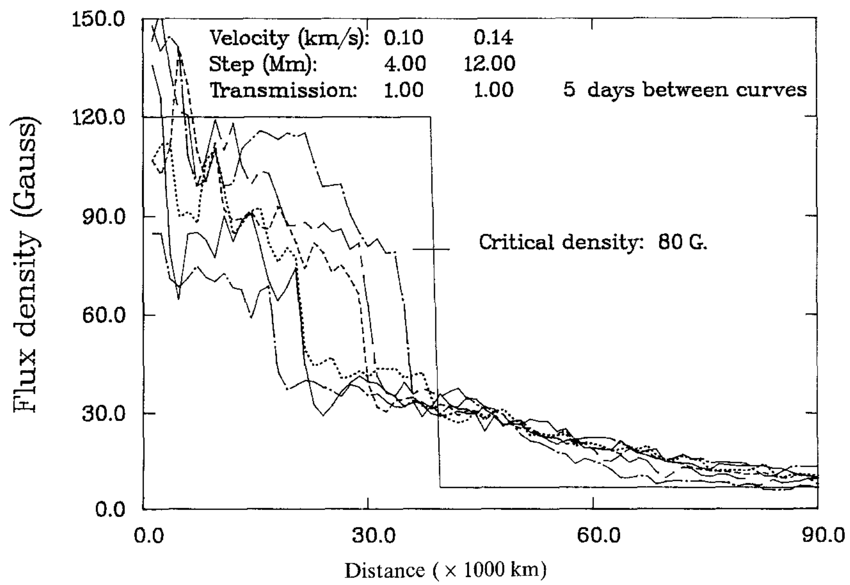

Fig. 6. Same as Figure 5, but for non-uniform diffusion and a completely transmitting periphery ($f_e = f_c = 1$). The fractional flux loss as a function of time is shown in Figure 4(a), curve 2.

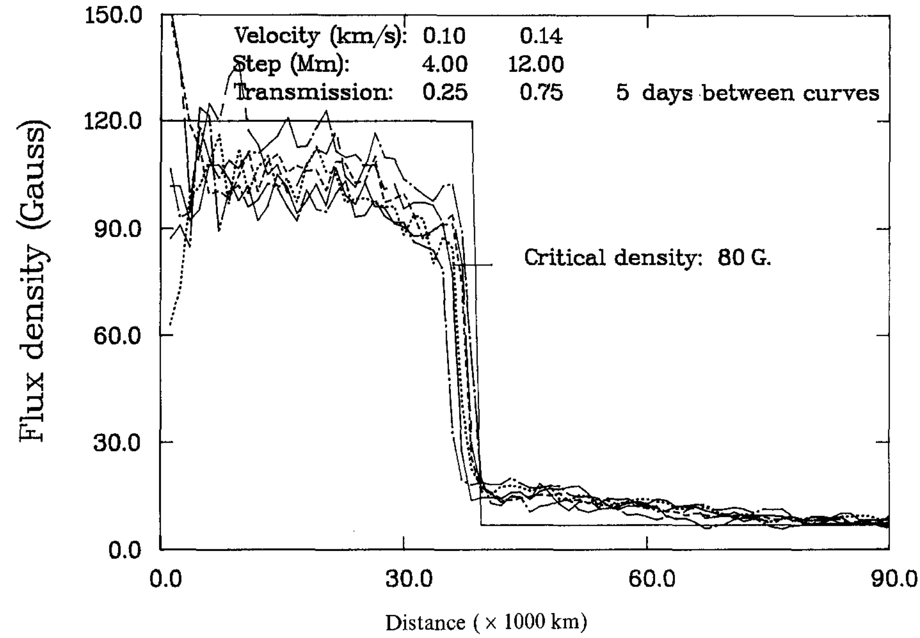

Fig. 7. Same as Figure 5, but including a semi-permeable periphery. The fractional flux loss as a function of time is shown in Figure 4(a), curve 4.

4. The Evolution of a Bipolar Magnetic Plage

The simulated evolution of a bipolar plage is shown in Figure 8(a) for a cancellation probability at the polarity-inversion line of $f_{cl} = 0.5$ and in Figure 8(b) for complete cancellation ($f_{cl} = 1.$). Despite the fact that a strong sink now occurs within the plage, the mean flux density of the plage remains at about 100 G while the periphery receeds towards the center of the plage. This is of course related to the fact that the flux density must remain just over the critical flux density of 80 G in order for the plage to survive: as soon as N drops below N_c the strong increase in the diffusion coefficient from D_{plage} to D_{quiet} would quickly erase the plage.

Figure 4(c) shows that the flux loss in the plage is strongly increased by the cancellation at the polarity-inversion line: while the monopolar plage still has 70% of its original flux after a month, the bipolar plage has all but disappeared after this time. While the typical life time of a medium-sized bipolar plage with non-uniform diffusion and a semipermeable periphery is about one solar rotation (Figure 4(c), curves 2 and 3), a bipolar plage with a fully transmitting periphery would completely disappear in less than two weeks (Figure 4(b), curves 2 and 3).

The plage evolution is very sensitive to values of the cancellation probability $f_{cl} < 0.5$, while the flux loss at $f_{cl} > 0.5$ shows a much weaker dependence on the value of f_{cl}: as f_{cl} approaches unity the critical factor becomes the supply of flux from the body of the plage, rather than the cancellation probability. Figure 4(d) shows that at $f_{cl} > 0.5$, approximately two thirds of the total flux initially contained in the plage is lost by internal

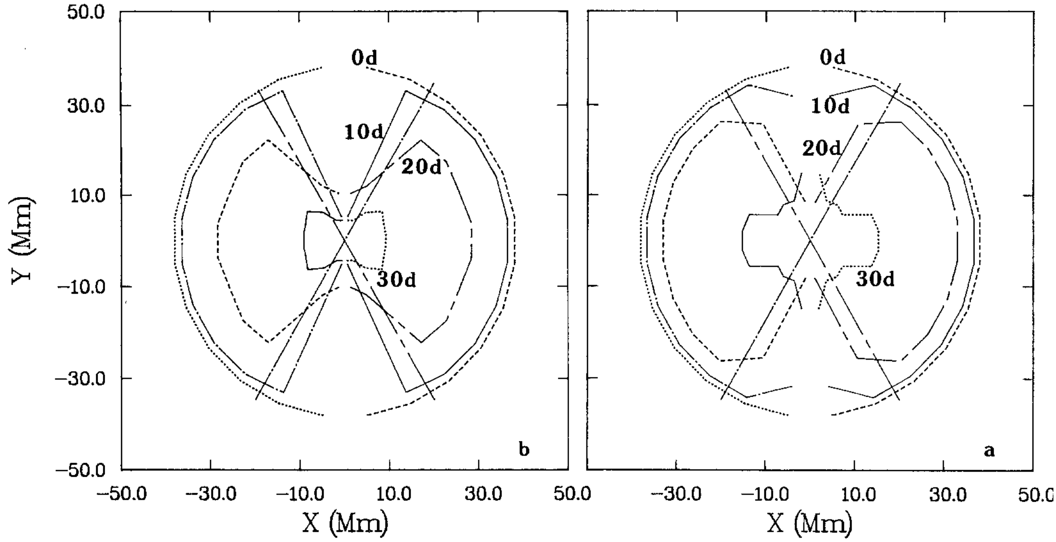

Fig. 8. Simulated evolution of a bipolar plage with flux cancellation at the polarity-inversion line. Opposite polarities occupy the space at $x > 0$ and $x < 0$. The contours are drawn at the critical flux density of 80 G at which the velocity v and the mean free path length λ change discontinuously: $v_{\text{plage}} = 100 \text{ m s}^{-1}$, $v_{\text{quiet}} = 140 \text{ m s}^{-1}$, $\lambda_{\text{plage}} = 4000$ km, $\lambda_{\text{quiet}} = 12000$ km. The escape and capture probabilities are $f_e = 0.25$, $f_c = 0.75$, respectively. In the simulation the distance $R_{N_c}(\phi)$ of the periphery to the origin is taken to be constant for $\phi > 45°$ (see Section 2.2), regardless of the flux-tube density for $\phi > 60°$ (the region near $x = 0$ enclosed by the diagonal lines); i.e., no ordinary supergranulation is allowed to develop within the plage near $x = 0$. Contours outline the plage after 0, 10, 20, and 30 days. Note that only the outer 80 G contours are drawn: the depletion of flux near the polarity-inversion line is not shown. The probability of cancellation f_{cl} at $x = 0$ is 0.5 in (a) and 1.0 in (b). The fractional flux loss as a function of time is shown in Figure 4(d) by curves 1 and 2, and the loss due to cancellation are given by curves 3 and 4.

cancellation, leaving only a third of the flux to escape into the surrounding quiet regions. In the case of non-uniform diffusion without the partial confinement caused by the semi-permeable periphery, more than half the flux would eventually escape into the surrounding quiet regions (not shown in Figure 4) within the plage life time of two weeks.

5. Discussion and Conclusions

Section 1 discusses evidence for the interaction of the magnetic field and the photospheric velocity field: the mean size of cellular openings that are observed in magnetograms of regions with a mean magnetic flux density above about 50 to 80 G (when observed at 1″ or 2″ resolution) which extend over a semi-coherent area larger than that of a few unperturbed supergranules, is a factor of two to three smaller than a typical supergranule in regions with a mean flux density below that critical value. This suggests a corresponding change in the size of the convective pattern, which has as yet been verified only by the flow-divergence maps of the brief sequence of SOUP observations. The change from one mean cell size to another associated with the change in flux-tube density appears to be rather abrupt (e.g., Figure 1(a)). The critical flux-tube density N_c

at which the change occurs probably corresponds to about 50 to 80 G, i.e., to a photospheric filling factor of about 5%.

The typical mean flux density in plages is 100 G (Schrijver, 1987). With an intrinsic field strength of 1–2 kG inside flux tubes, this implies an area filling factor in the photosphere between 5 and 10%. Such a large filling factor may affect the transportation of flux tubes by convective motions either because the convective motions themselves are affected, or because the convective flow looses its grip on the closely spaced flux tubes that resist being displaced. The resistance of magnetic flux tubes against displacements may be caused by an anchoring of flux tubes deep in the convection zone. Alternatively one may speculate that it is caused by the contiguous character of the upper-chromospheric magnetic field over the photospheric plage. Parker (1986) noted that flux tubes of the same polarity repel each other due to the expansion of their fields above the solar surface until the expanded fields of the flux fibrils crowd firmly against each other. Shuffling of footpoints by granular motions may still occur (a mechanism that has been suggested to cause the heating of the corona, e.g., Parker, 1979a, b), but the rigidity of flux tubes (caused by the curvature force or tension) may prevent them from being pushed much closer together than a filling factor that corresponds to the equipartition field strength for the supergranular motions. The typical flux density of $\simeq 100$ G of the upper-chromospheric field is somewhat larger than the equipartition field strength of 50 G for the unperturbed supergranular motion (Parker, 1963, 1974). Hence, the flux tubes may slip in the photospheric flow, resulting in a drag force which may react back on the convective flow.

If the magnetic flux of a plage escapes into the surrounding network predominantly along the boundaries of convective cells (as discussed in Sections 1 and 2), the decay of plages is severely affected by a difference in cell size: the plage periphery will function as a '*membrane*', that preferentially *turns back flux tubes trying to escape from the plage*, and preferentially *transmits flux tubes moving into the plage*. Diffusion through a partially transmitting periphery maintains a steep density gradient at the periphery (because the flux-tube density on the low-density side is kept smaller and on the high-density side larger than in the case of a fully transmitting periphery by the action of the periphery), and an almost constant flux-tube density within the periphery. This agrees with the remarkable observed property that all plages appear to have an average flux density of $\simeq 100$ G.

Two interdependent processes compete in the simulated decay of a monopolar plage in the presently proposed model: the flux leak at the periphery lowers the flux density everywhere in the plage, while the periphery 'retreats' toward the centre of the plage because of the 'evaporation' of flux tubes into the quiet region. Whether the mean magnetic flux density in the plage can drop near the critical flux-tube density N_c before a large fraction of the flux tubes has 'evaporated' from the periphery depends on the transmission probability of the periphery and on the ratio of diffusion coefficients in the high and low flux-density regions. With typical observed values for cell size and step length, the mean flux density within the unipolar plage decreases only slowly. At some point in time the mean flux-tube density will drop below the critical value N_c, and supergranulation is predicted to occur suddenly everywhere within the remaining part of the plage. This may result in a rapid decay of an old plage into enhanced network after a relatively stable early life.

The reflection of flux tubes internal to the plage and capture of external flux tubes by the plage periphery serves to contain the plage flux much longer than would be expected in a simple, uniform diffusion process. Consequently, flux in a bipolar plage has a relatively long time available to cancel against flux of the opposite polarity at the polarity-inversion line. This explains observations by Martin, Livi, and Wang (1985), who find that during the early stages of decay of a plage fragmentation and subsequent losses of flux seemed to happen more frequently in the polarity-inversion zone in the middle of the active region than within any equivalent area around the periphery of the region. The flux confinement and the correspondingly large flux cancellation along the polarity-inversion line also explains the observation by Harvey (1988) that at most 30% of the flux that surfaces in plages escapes into the plage surroundings. The simulations yield a typical life time for a medium-sized bipolar region of about one solar rotation. Small magnetic plages with very few supergranular 'escape routes' suffer an even more effective confinement of magnetic flux, so that flux cancellation may be even more important in these small regions.

Note that the model does not necessarily require a change in the convective velocity field within a plage, but requires only that the *transport properties* of the flux tubes depend on the flux-tube density. Perhaps the observed openings in plage magnetograms and spectroheliograms do not correspond to velocity cells (although SOUP observations suggest this to be the case, see Section 1) but merely to evacuations of flux from a small area of a cell that has little grip on the flux tubes permeating it. If alternatively the convective flow is itself affected by the presence of magnetic flux tubes, it is still not clear what actually happens: is the cell size of the supergranulation reduced, or is the supergranulation suppressed completely so that only the mesogranulation (November *et al.*, 1981; Title *et al.*, 1986a, b) is left to operate? This question, and the possibility of a slipping flow, can be studied by direct observations of the horizontal photospheric velocities. The study of time-sequences of high-resolution magnetograms (or spectroheliograms at suitable wavelengths) can reveal how flux is transported within plages, and allows a direct study of the role of the periphery in the evolution of a plage.

The currently proposed model explains some of the observed characteristics and the time scale of the decay of solar magnetic plages by making a few assumptions about the photospheric velocity field that appear to be supported by observations. The decay of plages may of course be linked to subphotospheric processes, but the present model suggests that no assumptions concerning such processes are required. Hence, the validity of the model can be verified by detailed observations of the photospheric super- and mesogranular velocity field.

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