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THE EVOLUTION OF SOLAR ACTIVE REGIONS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Ray N. Moses, P.E.

The Ohio State University
1974

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ACKNOWLEDGMENTS

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The patience, encouragement—and typing—given me by my wife will not be forgotten.
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"An Ultraviolet Filter," *Science Digest.*


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I. INTRODUCTION

Disturbances in the solar chromosphere and lower corona may lead to high radiation levels (several rem/hr) in the vicinity of Earth, causing astronauts' lives to be endangered (Brandt and Maran, 1968). The ultraviolet radiation and high energy particles associated with these events cause the required frequencies for short-wave transmission over intercontinental distances to change and sometimes induce short-wave fades which are sufficiently strong to prevent long-distance radio communications in the short-wave band. For these reasons the nations with extensive communication networks or space programs have supported flare studies.

But in addition to studying the sun for applied purposes, solar physicists hopefully can advance knowledge, i.e., pure research. In many ways the sun is our major guide to other stars. If we are to understand the magnetic fields and organized flows in typical main sequence stars then we shall probably begin with the sun.

The state of the art in these studies may be seen from the following quote from Ward (1972):

The passionate dream of the oppressed solar flare forecaster is the scientific discovery of the cause, the energy source, and the observable antecedent conditions for the solar flare. This "tunnel vision" has had a profound and deleterious effect on the state of the art. It has diverted attention from many promising
approaches and relegated them to limbo. More importantly, it has actually inhibited the scientific search for the underlying physical mechanisms. Examples of neglected aspects of the problem cover the entire range from observing techniques and equipment to the availability and accuracy of the archived data. A cursory inspection of this data leads to an obvious conclusion: there are at least two suns up there.

Solar flares are only one manifestation of solar active regions. The concentration on flares alone is probably not in the best interest of even the flare forecaster and almost certainly decreases the effectiveness of research on solar activity. Hence we should be concerned with the nature and evolution of solar active regions.

Only one model exists describing the evolution of solar active regions (Leighton, 1964), based on considerations of the diffusion of solar magnetic fields. The model was based on two assumptions.

1. The motion of a flux rope could be described by a two-dimensional random walk in which the step length and time were determined by the properties of the supergranular convection.

2. Magnetic fields were assumed to interpenetrate at neutral lines.

These conditions occurred because field elements were assumed to not interact with one another.

The model for describing the diffusion of solar magnetic fields proposed here was created by modifying Leighton's model in the following four ways.

1. The behavior of a random walk was replaced by a behavior analogous to the behavior of a two-dimensional compressible gas (shallow water theory) because of magnetic interaction between field elements.
2. Supergranular cell lifetimes are considered to be longer inside active regions than in quiet regions; hence diffusion is often slower inside active regions.

3. Reconnection and distortion, rather than interpenetration, occur at neutral lines.

4. The source regions—spots and faculae—of magnetic field elements are assumed to move in response to subphotospheric forces associated with their magnetic fields, as described by Foukal (1972).

Foukal (1972) interpreted "the shorter rotation period of active regions as observed by Howard and others (compared to the photospheric gas) as a result of direct coupling of the strong field to a more rapidly rotating solar interior." This motion was assumed to be due to magnetic attachment of the spots to subsurface layers (approximately 5000 km beneath the photosphere) moving west at a velocity of about 0.1 km/sec with respect to the photosphere.

The structure observable in hydrogen alpha has been treated as a map of solar magnetic fields (Zirin, 1972). Field elements spread out above the photosphere to form the chromospheric and coronal fields (Plates I and II). These elements also extend downward beneath the photosphere. The possibility that field elements slip with respect to the surrounding photosphere as a result of their attachments above and below should be included in a study of field element motions. Once a field element leaves its source region (spot or plage) it moves at a rate determined by the vector sum of the horizontal component of the supergranular flow and the rate of slip of the field element with respect to the surrounding photosphere.
PLATE I

OFF-BAND HYDROGEN ALPHA PHOTOGRAPH

(Structure in the Photosphere and Lower Chromosphere)
PLATE II

HYDROGEN ALPHA PHOTOGRAPH

(Structures Mainly in the Chromosphere)
Field elements of the same polarity interact with one another repulsively so that the elements in the interior of a unipolar region usually do not escape until those farther out have moved. The fields in AFS are relatively uniform in strength over regions on the order of 10,000 km across. Thus, the interior of a region assumes a relatively stable character with higher rates of expansion occurring on the periphery.

From hydrogen alpha photographs one might conclude that this flow tends to be similar to that of a viscous, laminar, two-dimensional compressible gas.

The rates described in this paper will, in general, be the mean velocity (km/sec) a field element would have at the location in question. In a quasi-steady situation such as a slowly decaying spot the behavior of isogauss lines is obviously entirely different from that of field elements. The field elements diffuse outward but the isogauss lines in the inner regions (measured on a low resolution magnetogram) slowly migrate toward the source regions while those farther out migrate outward. The behavior of isogauss lines is a function of the changes in the rate of decay of the spot.

An element of this model is the behavior of flux ropes in the vicinity of neutral lines. In Leighton's model (1964), fields interpenetrate and, therefore, the energy associated with the field remains spread over a large region. In the present model, on the other hand, stretching and twisting of magnetic fields and reconnection are assumed to lead to an appreciable fraction of the energy of the flux
ropes being stored in electrical currents near the neutral line rather than spread over an extensive region.

Sara F. Martin (1973) in describing the behavior of field elements has stated that adjacent fields of similar polarity merge together but that adjacent fields of opposite polarity never intermingle at the photospheric level. She further states that it appears as if the random walk process by which regions expand is inhibited at these boundaries and as if the energy that would have been expended in the random walk is available to assist in the formation of a filament. The observations are consistent with the model proposed here, but are not in agreement with the interpenetration of Leighton's (1964) model.

The destruction of the electrical currents is assumed to be the cause of solar flares and surges. Disturbances propagating from arch filament systems may be one cause to begin the current destruction process. Magnetograms seldom indicate sufficient photospheric field destruction for these currents to be photospheric. Following flares, spot decay rates often increase suggesting that some impediment to field element motion has been removed.

Some flares—possibly all—may be interpreted as chain reaction surges in which the flow from an initial surge triggers others. Since the flow cannot easily escape from the loops in the magnetic field it streams into the prominence along the neutral line and also down along the arches supporting the prominence. Plate III shows an example in which the dark lines between the two bright flare filaments
are field arches as seen from above. The dark material is flowing down the arches.

**Terminology**

A major, perhaps the major, limitation on communicating solar observation today is the lack of precise definitions which are operational in nature. For example, the words faculae, flocculi, plages, bright regions, and mottles are all so ill-defined that it is difficult to determine which one is appropriate with a given context.

Similarly, flares are classified into Classes 0, 1, 2, 3 and 4 by corrected area. Small flares, however, are not the same shape as large flares (large flares tend to be flatter) so a uniform correction factor will change the ratio of small to large flares as one approaches the limb. Flares are also classified into X-ray classes c, m and x which appear to be fairly well defined. It might be worthwhile to combine these two classifications, i.e., 2c or 3x flares, using a specific brightness contour to define flare area, although the problem of projected area is not subject to a simple solution since the three-dimensional structures of no two flares are alike.

The following terms will be used throughout this thesis.

**Active region:** a localized transient region (lifetime of a few weeks or months) of the solar atmosphere in which sunspots, plages, prominences, and solar flares are observed. All these events are assumed to be associated with the magnetic field which emerges from beneath the photosphere to form the region.
Chromosphere: the region immediately above the temperature minimum. It contains some features which are approximately at photospheric temperatures and others which are much hotter.

Flare: a localized, relatively sudden brightening of the chromosphere which then declines more slowly than it rose to maximum brightness, lasting at most a few hours, but typically only a few minutes.

Supergranule: a circulation cell about 25,000 km in diameter in the solar atmosphere. The borders of supergranules are often said to form a network. Flow at the photosphere is outward from the central portion of the cell to the walls at about 0.4 km/sec. This flow is the basic driving force for the random walk of field elements outside of active regions.

Field element: a hypothetical entity which is considered to be the basic quantum of solar magnetic fields. Field elements have been identified with spicules, bright points in the photosphere, moving magnetic features, running penumbral waves and intense fields observable with high resolution magnetograms. Field elements have, in several cases, been assumed to contain a total field of about $10^{18}$ Maxwell. A field averaging $10^3$ gauss in a region several hundred kilometers across will have this total strength.

Fibril: an elongated chromospheric feature which appears to be an approximately horizontal extension of the top of a spicule. Fibrils are often about 20,000 km in length and 2000 km in cross section.

X-ray event: a disturbance in the solar corona observable at the
**Chromosphere**: the region immediately above the temperature minimum. It contains some features which are approximately at photospheric temperatures and others which are much hotter.

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**Fibril**: an elongated chromospheric feature which appears to be an approximately horizontal extension of the top of a spicule. Fibrils are often about 20,000 km in length and 2000 km in cross section.

**X-ray event**: a disturbance in the solar corona observable at the
earth as an increase in the amount of X-rays. They occur in three
classes—Class c solar events associated with insignificant X-rays or
radio noise; Class m solar events which are accompanied by significant
X-ray production, greater than $10^{-2}$ ergs cm$^{-2}$ sec$^{-1}$ in the 0.8A band,
or $10^{-3}$ ergs cm$^{-2}$ sec$^{-1}$ in the 0.5-5A band, comparable sudden iono-
spheric disturbances or by 10 cm radio noise outburst of at least 75
flux units over background and of duration greater than one minute.
Class x solar events are accompanied by great X-ray production, greater
than $10^{-1}$ ergs cm$^{-2}$ sec$^{-1}$ in the 0.8A band, or $10^{-2}$ ergs cm$^{-2}$ sec$^{-1}$ in
0.5-5A band, comparably great sudden ionospheric disturbances, or by a
10 cm radio noise outburst of more than 1000 flux units over background
and of duration greater than 10 minutes.

**Disparitions Brusque:** the sudden disappearance of a prominence,
often preceded by prominence growth.

**Flare importance class:** classes 0 to 4 exist with areas less
than 2, 5.2, 12.5, 24.8 and greater than 24.8 square degrees in order
of increasing class. Seventy-five per cent of all flares are of im-
potence 0, 19 per cent of importance 1, and five per cent of impor-
tance 2.

**Prominence:** a region of increased density and lower temperature
in the lower corona. Densities are often around $10^{11}$ particles per
cubic centimeter and temperatures are often near $10^4$ degrees Kelvin
in comparison with the surrounding corona at about $10^9$ particles per
cubic centimeter and about $10^6$ degrees Kelvin.
Arch filament system (AFS): a group of low arches of plasma which represent the chromospheric manifestation of a newly emerging magnetic field. It is the first major observable stage in the evolution of an active region.

Modern Studies of the Evolution of Active Regions

Leighton's (1964) diffusion model for transporting solar magnetic fields was intended to describe the expansion of magnetic fields on a rather large scale. Schatten, Leighton, Howard, and Wilcox (1972) suggested several possible reasons for the lack of agreement between the model and observation of relatively small-scale solar field structures. One of those possibilities was that active region fields were not being properly represented. Originally Leighton (1964) had recognized a possible inadequacy in his model, stating that one often observes a rather well-defined and stable boundary between regions of opposite polarity in distinction to the mixed polarity region expected from his model.

Several review papers on the evolution of active regions have been written in the past decade. Kiepenheuer (1967) stated that the character of the solar network (e.g., the mesh width) never changes, not even in the center of an active region, and that the network is formed of magnetic knots at about the limit of resolution. Bruzek (1972) mentions magnetic knots with diameters of about 1000 km and field strengths of about 1000 Gauss. If these are identified with the bright spots emitted when running penumbral waves reach the edge of the penumbrae and with the moving magnetic features of Harvey and
Harvey (1973) then they may be considered to be flux ropes which would be significantly influenced by any magnetic fields greater than a few gauss.
II. BEHAVIOR OF THE MAGNETIC FIELD

The proposed model differs from Leighton's (1964) model in that in his model photospheric magnetic flux "disperses solely under the influence of solar differential rotation and a random walk, the latter being brought about by the supergranular convective cells," (Smithson, 1973). The proposed model, on the other hand, is based on the assumption that in addition to the effects of the supergranular flow, and differential rotation, field elements are moved by their interactions with each other and the photosphere (see Figure 1). Field elements are assumed to interact with the photosphere via hydrodynamic drag. An assumption of this model is that flux ropes slip with respect to the surrounding photosphere and that the rate of slip may be approximated by the following arguments (see Figure 2) which are often those Foukal (1972) used to describe the behavior of fields in active regions.

Strong photospheric magnetic fields (500+ Gauss) have been observed in tiny areas (less than two arc sec diameter) of the photosphere (Schroter, 1971). These magnetic knots (field elements) often move away from old isolated spots at about one kilometer per second. Identifying these field elements as the photospheric ends of flux ropes, let us assume that the interactions of field elements above the photosphere are similar to the ones which scaled down spots of similar horizontal dimensions and field strengths would have. Frazier and
FIGURE 1. The Forces on a Field Element ($F_m$ is the magnetic interaction between field elements and $F_H$ is the hydrodynamic interaction between a field element and the surrounding unmagnetized plasma).
FIGURE 2. The Assumed Structure of Active Regions
Stenflo (1972) have stated that the structure of field elements above the photosphere is similar to that of sunspots scaled down by a factor of about 20.

For several years Rust (1972), following a suggestion of Schmidt (1964), has been treating the photospheric portion of flux ropes as an array of fictitious monopoles. The region above the photosphere was assumed to contain relatively weak electric currents compared to those at and beneath the photosphere. This approach (photospheric monopoles and current free corona) was used in Aller's (1963) calculation of the force between sunspots. With this approximation elementary potential theory may be used to compute coronal fields. When compared with limb prominences in active regions this hypothesis has given good large-scale agreement with observation (Rust, 1972).

Using the model of Harvey and Harvey (1973) (see Figure 2) one sees that flux emerging from one field element does not reconnect with the subphotospheric flux rope of the same field element. Hence the roughly vertical field element does not have a dipole field of its own but instead acts as a monopole at the photosphere.

Two typical sunspots of $0.6 \times 10^{22}$ Maxwells separated by 125,000 km act on each other with a magnetic force of $2.6 \times 10^{17}$ Newtons (Aller, 1963). A reasonable approximation to the force between two photospheric field elements (monopoles or equivalently the photospheric end of long dipoles in which the subphotospheric ends are not interacting to any significant degree) is
where $M_1$ and $M_2$ are the total fields of the field elements respectively, with the portion of the flux rope near the photosphere treated as a magnetic pole; and $k$ is a constant whose value is determined by the strength of the interaction between poles of known strength separated by a known distance.

The force between two field elements of $10^{18}$ Maxwells and separation $r = 10^4$ km may then be estimated. In this case

$$F_m = \frac{kM_1 M_2}{r^2}$$

Therefore, the photospheric portions of flux ropes often feel magnetic forces of to order of magnitude $10^{12}$ Newtons from other flux ropes. This force is mainly transmitted through chromospheric and coronal fields since the field at the photosphere is often quite restricted in horizontal extent. Field elements are surrounded by photospheric current sheets which effectively separate them from the surrounding regions whose field strength is very low ($< 5$ Gauss).

This magnetic force is countered mainly by hydrodynamic drag although spot and APS fields are tied to deep fields in the sun and are moved by these fields (Foukal, 1972). Flux ropes moving away from spots are not deep features. Harvey and Harvey (1973) have demonstrated
that these twisted flux ropes cross the photosphere several times.

The shallow subphotospheric interaction is mainly hydrodynamic since flux ropes have very small diameters and are separated by extensive regions containing small or zero fields (Harvey and Harvey, 1973; Foukal, 1972). Since the field from each rope does not extend into the surrounding flow it does not influence that flow.

The flux rope is sufficiently rigid so that it may be treated as an elastic cylinder in its reactions with the flow. The rigidity of a flux rope is similar to that of a stretched rubber band. At 1000 Gauss this "magnetic pressure" (i.e., tension) is 2500 times the dynamic pressure of the supergranular flow 600 km above the photosphere. It is also 80 times as large as the gas pressure at the photosphere. The subphotospheric portion of a flux rope will be approximately straight until the subphotospheric magnetic field pressures or gas dynamic pressures are an appreciable fraction of the flux rope magnetic pressure. That is, they will be approximately straight for the cases

\[ \frac{B_{fr}^2}{8\pi} \gg \frac{1}{2} \rho v^2, \]

where \( B_{fr} \) is the flux rope magnetic field strength, \( \rho \) is the density of the surrounding gas, and

\[ \frac{B_{fr}^2}{8\pi} \gg \frac{B^2_{\text{surroundings}}}{8\pi}, \]
where $B_{\text{surroundings}}$ are the fields outside the flux rope. Flux rope structures are determined mainly by their associated electric currents and not by the properties of the surroundings at the photosphere.

Foukal (1972) has used $F_h$ for the hydrodynamic drag force on this cylinder where $F_h = \frac{1}{2} C_d \rho u^2 A$, and $A$ is the cross-sectional area of the cylindrical flux rope, $u$ is the relative velocity of the flux rope and the surrounding photosphere, $\rho$ is the density and $C_d$ is the drag coefficient of order unity. But $F_m = F_h$ since the major force available to resist motion of the flux ropes is hydrodynamic drag. Foukal estimated that a flux rope $10^4$ km in diameter immersed in 0.1 km/sec flow would feel a hydrodynamic force of $10^{12}$ Newtons. Flux ropes may be estimated to be about $10^3$ km across (Frazier and Stenflo, 1972). Therefore, for $F_h = 10^{12}$ Newtons, $u = 0.3$ km/sec for the case of only two field elements $10^4$ km apart.

Foukal (1972) used similar arguments to show that flux ropes might be moved by fields beneath the photosphere. These conclusions are not in conflict with his, but merely show that these arguments apply to fields above the photosphere as well as below. Equal amounts of flux emerge from the top and bottom ends of a flux tube. Those which extend from the top expand and interact with one another whereas the bottom ends of flux ropes are controlled by subphotospheric flows and turbulence. Foukal's (1972) description appears to be appropriate for those regions of strong fields and relatively slow changes in the structure of the region. Obviously spots are not immediately destroyed by the photospheric random walk nor are they moved toward one another.
by their coronal fields which often supply attractive forces of order of $10^{17}$ Newtons. On the other hand, the moving magnetic features (MMF) (Harvey and Harvey, 1973) have velocities (approximately 1 km/sec) which are too high to be consistent with a deeply buried structure. A deeply extended field element with a velocity of 1 km/sec would experience a drag of much more than $10^{13}$ Newtons. MMF also appear to represent flux ropes which penetrate the photosphere several times. Spots and the more intense faculae early in the lifetime of an active region are controlled in their motions by relatively straight and deeply buried flux ropes (as Foukal suggested) but the dispersal process mainly occurs in flux ropes which are shallow for a considerable portion of their length.

If flux ropes may move with respect to the surrounding photosphere then it is necessary to modify Leighton's hypothesis concerning the spread of magnetic fields to account for this relative motion of flux ropes and the photospheric flow.

Let $C$ represent the velocity of propagation of a disturbance of the flux ropes relative to average velocity of the photosphere as determined spectroscopically. By the above argument

$$
\hat{C} = \left[ \hat{V}_{Rw} + \hat{V}_{slip} \right]/\sqrt{2},
$$

where $\hat{V}_{Rw}$ is the random walk velocity expected from Leighton's model and $\hat{V}_{slip}$ is the velocity produced by magnetic forces acting on the flux rope.
Observations (Harvey and Harvey, 1973) of minute regions of intense field and spot motions suggest that these arguments that slip is impossible because of the large magnetic Reynolds numbers are incorrect (Foukal, 1972). A succinct description of the argument against slip is contained in Gibson (1973). Arguments against slip appear to be based, in the main, on the assumption that fields in flux ropes are \( \ll 10^3 \) Gauss.

The propagation velocity, \( \dot{c} \), may be combined with shallow water theory, a modification of the theory of compressible gases appropriate for two-dimensional flows, to enable some predictions concerning the structure and evolution of active regions to be made.

A major element in the present model is that stretching and twisting of flux ropes occurs along neutral lines. If the flux ropes are unable to interpenetrate then the forces impelling fields to expand will lead to some changes in structure near neutral lines. This stretching and twisting represents storage of energy, which is in part released in flares, and therefore the flare probability along any portion of any neutral line is (to first order) proportional to the number of flux ropes accumulated along that portion of the neutral line.

A major difficulty for those who would solve the flare problem lies in the fact that almost all "solutions" to the flare problem depend upon either magnetic reconnection or upon current diffusion, which is another way of looking at the same problem. Most acceptable solutions to these problems today depend upon a scale of 100 km or less (Tandberg-Hanssen, 1967). The X-ray emission from at least one
flare has been shown to occur on this scale (Vorpahl, 1972).

But this sort of final solution is not required by the solar forecaster. He often assumes that there are, corresponding to the fine structures, coarser structures observable with existing equipment. Often he is satisfied, for the time being, with results which are to a great extent empirical correlations which may not have adequate theoretical explanation.

Prior to arch filament system (AFS) emergence we have only the beginnings of theories to guide us in determining when and where to expect new solar activity. Dodson and Hedeman (1968) have shown that activity tends to occur at longitudes approximately 180 degrees apart. Stanek (1972) has indicated that a 30 degree periodicity exists. Vitinski (1965) has described numerous approximate methods of predicting the heights of coming solar cycles. None of these methods, however, have been used to give a numerical estimate of AFS probability at a given time and location.

The probability of an AFS at any point on the sun appears to be related to the structure of the fields. Regions of high field strength tend to remain at relatively high field strength for many months. They could not retain these relatively strong fields without the injection of new fields nearby.

Active regions are born with the emergence of most of the magnetic field in a period of a few days. The magnetic field at this time is not connected to the surrounding fields. In the days following the arch filament system emergence a region of high contrast fibrils
spreads away from the new active region. Initially the region does not contain stable prominences and flares are quite improbable. During arch filament system emergence many small surges may occur and the plage at the ends of the arches is almost of flare brightness. In most cases material streams down the ends of the arches at about 30 km/sec (Weart, 1970). Our knowledge of this phase of solar activity is mainly due to the work of Weart (1970) and of Bruzek (1969).

Arch filament systems (AFS) initially emerge at almost any angle with respect to the solar equator (Weart, 1970). This has been interpreted as a locally induced random orientation due to supergranular convection. Another possible interpretation is that large-scale subphotospheric structure exists and that, at least in part, the initial orientation of arch filament systems reflects that structure. If a region is going to survive more than one or two days the AFS will usually rotate toward an east-west orientation (Weart, 1970).

Following arch filament system (AFS) emergence the development phase of an active region begins. During this phase cooling of the photosphere occurs at the ends of the arches of the field which were initially the ends of the arches of the AFS. The greatest cooling occurs in the locations of greatest field strength and within a week much of the field is tied up in the spots. While the central portions contract to form spots the outer portions continue the expansion which began when the AFS started to emerge.

The structure of an active region results from the migration of field elements. The leader spot is usually near the leading end of an
irregular region of plage. The leader spot area is typically somewhat larger than the follower. The writer has studied the rate of expansion and decay of spots and found that this rate has a slight positive correlation with their rate of motion away from the neutral line, as has been known for years (see Figure 3). The rate of movement of spots away from the neutral line has a slight positive correlation with their rate of growth. Normally growth stops when the rate of movement away from the neutral line slows from about 0.2 km/sec to a rate of less than one-fourth that large. This occurs at the end of the development phase. The rate of movement typically decreases steadily after spot formation begins.

Initial flare activity often begins three or four days after AFS emergence. The site of the activity is usually near the trailing spots. Other flares and disparitions brusque occur in relatively distant active regions simultaneously with this activity near the AFS site.

The mature phase of an active region is the time of greatest flare activity. The follower portion of the region has normally decayed into a large area of weak field containing at most a few scattered spots. The leader spot goes through its maximum size at this time. As follower spots decay the fibrils sometimes assume a more or less spiral structure about a relatively symmetrical leader spot. The development of this spiral structure appears to depend upon the region being both long-lived and isolated so that when the follower portion
FIGURE 3. Spot Motion and Growth Rate (NOTE: Spot velocity is measured with respect to the intersection point, p, of the neutral line and the line connecting the spots. Reference: Solar Geophysical Data)
of the region decays the leader spot will be surrounded by an approximately circular region of leader polarity.

The decay phase of a region is a time when it is strongly affected by new regions forming even at relatively great distances from the region. Disparitions brusque, changes in prominence size and structure, and movements of neutral lines all appear to be results of the displacement of older fields by newly emerged ones.

During the decay phase, prominences reach their greatest size and then decay. A prominence will often undergo one or more disparitions brusque prior to decaying.

Occasionally large flares, usually with long rise times, will occur during the decay phase of active regions.

An outline of the evolution of an active region is given in Figure 4.

A Criterion of Flare Forecast Accuracy

Flare forecasts should be judged by a more realistic criterion than per cent correct. Statements to the effect that one has 80 per cent accuracy when activity is low convey very little useful information in that a forecast of low activity made continuously throughout the two or three years of sunspot minimum would have an accuracy of about 83 per cent. Many existing flare forecast techniques are essentially statistical in nature. One observes radio and optical phenomena and estimates levels of activity and then combines the data to make a forecast of flare probability. In a large number of these
Arch filament system emergence

Formation of pores (the larger dots are pores; smaller dots are field elements and arrows denote field element motion)

Spot growth and prominence formation

Flare initiation by disturbance from nearby AFS

Conduction of disturbance along field lines to create two flare filaments

The mature phase

The decay phase

FIGURE 4. Evolution of an Active Region
cases the forecast techniques used are similar to those of a weather forecaster applying climatology. These techniques lead to spuriously high success rates during times of slow change and to random or worse rates during times of rapid change.

Dr. G. H. Newsom and the writer have developed a technique based on the concept of accuracy compared to random distribution. In measuring the effectiveness of any flare forecast technique, one must first determine the most probable random number of right guesses of significant events (for our purposes flares of Class 2 or greater or correspondingly important X-ray events) and compare it with the number of times significant events were actually forecast. The most probable number, $r_{\text{prob}}$, of random flare forecasts being correct is

$$r_{\text{prob}} = \sum_{k=1}^{n_{f}} \frac{t_{k}}{T} n_{g},$$

where $t_{k}$ is the time span of a single forecast, $T$ is the total time in which the forecasts occurred, $n_{f}$ is the total number of flares occurring in time $T$, and $n_{g}$ is the total number of guesses that flares will occur. If $t_{k}$ is constant and equal to $t$, then $r_{\text{prob}} = n_{f} n_{g} t / T$.

Let $r$ represent the number of right guesses, i.e., the number of times Class 2 flares were forecast and occurred. To determine the skill, $S$, of a flare forecast technique one should compare the number of correct forecasts with the most probable number of correct forecasts if the forecasts were random. Then skill may be defined as
so that for zero skill, \( S = 0 \). Given the constraint that one wishes to forecast a given time into the future then values of \( S \) for different forecasters may be compared.

Numerical techniques for flare prediction based on field element motion do not appear to be possible until a general theory for the diffusion of solar magnetic fields is developed which is somewhat more accurate in active regions than Leighton's method is. Thus we need more detailed observations of the behavior of active regions.
III. OBSERVATIONAL TECHNIQUES

Approximately 2000 ultraviolet photographs were taken at Lowell Observatory during the period 31 August 1972 through 11 September 1972. Of these about 30 per day were taken with 649F film and the remainder with High Contrast Copy film.

The filter used was a combination of glass filters leading to a full-width band pass at half intensity of about 150 Å centered near 3800 Å (see Figure 5) as measured by a Cary 14 spectrophotometer. There are strong spectral lines throughout this region. This bandwidth was achieved by using two filters with much larger bandwidths in sequence. In order to prevent these filters from cracking an infrared absorbing glass filter was placed in the beam between them and the primary mirror. The telescope used was an f/5.4 16-inch reflector stopped to four inches. The aperture was slightly off axis. Photographs were taken at the prime focus with a 35 mm. camera body. Exposure times were usually about one-thousandth of a second.

In addition to the observations made at Lowell Observatory, several other sources were used. A major addition was the collection of Hydrogen alpha and Calcium K photographs taken at Sacramento Peak Observatory, and supplied by Lou Gilliam, covering the same time period.
FIGURE 5. Transmission of the 3800 Å Filter
as the ultraviolet photographs. Additional photographs for this period were sent by Manila Observatory.

Data for a much greater time period (1967-1973) with a time resolution of one day were also used. These data consisted of Fraunhofer Institute Maps, Rome Observatory photographs and The Solar-Geophysical Data bulletins (Jacobs, 1967-73).

To adequately interpret changes in supergranules which typically have lifetimes of a day or two one needs observations on a time scale of hours, and the photographs taken during 31 August-11 September, 1972, were separated in time by a few minutes to a few hours. Similarly, to interpret the behavior of active regions information was used from The Solar-Geophysical Data bulletins (Jacobs, 1967-73) which cover most of 1967 and 1968 on a daily basis. Fraunhofer Institute maps have been published daily for the past 15 years using data from many observatories. The Rome Observatory CaII K and hydrogen alpha photographs have been taken daily for several years, and published once per month.

Having collected these observations we are now able to outline in greater detail the evolution of active regions.
IV. CONDITIONS PRIOR TO ARCH FILAMENT SYSTEM EMERGENCE

Structures in Quiet Regions

The Network

CaII K spectroheliograms reveal a bright network composed of cells about 25,000 kilometers across and with lifetimes of approximately one day (Plate IV). Average field strengths on the cell borders are on the order of 25 Gauss. Within each cell the horizontal flow velocity of the photospheric gases toward the side of the cell is about 0.4 km/sec. These facts have been known for a decade (Leighton, 1964). If an improved understanding of the evolution of solar magnetic fields is to be achieved then a more detailed description of the solar network will probably be necessary since the motion of flux ropes appears to be related to the flow in supergranular cells. Studies of cell size, brightness, lifetime and structure as a function of location may be useful.

Cell Sizes

The mode of high contrast cell sizes appears to be nearly 25,000 km in CaII K photographs (see Figure 6), while the lower contrast cell walls, if treated like the high contrast walls, would lead to a cell size of about half that of the higher contrast cells. The lower contrast walls are not visible at times of poor seeing.
PLATE IV

CaII K NETWORK STRUCTURE
FIGURE 6. Histogram of Supergranule Diameters (for a sample of 41 supergranules with high contrast walls) NOTE: diameter measured parallel to equator on cells near central meridian.
Ultraviolet photographs (3800 Å) from near the temperature minimum give a smaller modal size because some walls appear only in the lower portions of the network. The ultraviolet photographs also show network structure deep in active regions where it is sometimes overexposed in CaII K and hydrogen alpha spectroheliograms. Supergranular sizes do not appear to have any significant dependence on solar latitude (see Figure 7). These observations were made of supergranules near the solar central meridian and measurements were made parallel to the solar equator.

Two peculiarities in cell sizes exist. In many CaII K and 3800 Å photographs a large cell, about 50,000 km across, surrounds the leader spot of a spot group. Often a similar cell exists near the site of the arch filament system after the AFS emergence. Frequently the interior side of the walls of these cells is sharply defined while the external walls are relatively ill-defined.

**Cell Lifetimes**

Cell lifetimes were estimated by eight graduate students at Ohio State University using CaII K photographs from Sacramento Peak and Manila Observatories and 3800 Å photographs by the writer. As field strengths increase so do cell lifetimes and the lifetimes in active regions are several times as long as those in quiet regions. These determinations were subjective but there was good agreement between different estimators (see Table 1).
FIGURE 7. Supergranule Diameters Measured Parallel to the Solar Equator and Near the Central Meridian

Source - Sac. Pk. Obs.
Call K Photographs
<table>
<thead>
<tr>
<th>Estimated Initial Mean Magnetic Field Strength Averaged Across Cell (Gauss)</th>
<th>Estimated Mean Cell Lifetime (days) With Probable Errors</th>
<th>Standard Deviation of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0 ±0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>1.2 ±0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>10</td>
<td>1.6 ±0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>20</td>
<td>2.5 ±0.5</td>
<td>1.8</td>
</tr>
<tr>
<td>40</td>
<td>5.0 ±1.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Cell Structure

Supergranular cells are only slightly elongated. On the borders of active regions cells often appear to form extended lines along and near to the neutral lines.

Sykora (1970) has shown that outside of active regions supergranules are elongated in the direction of solar rotation. His figures show supergranular diameters parallel to the solar rotation to be 34,600 km, while those perpendicular to solar rotation are 32,800 km.

Studies undertaken in the course of this research show that cells in active regions usually have bright walls approximately parallel to the nearest neutral line. The cell is slightly narrower perpendicular to the isogauss contour than it is in the direction parallel to the isogauss contour. The ratio of distance between brighter walls to distance between less bright walls appears to be approximately 0.8 (see Figure 8).

Orientations of supergranule cells in these two studies do not appear to be in conflict since outside of active regions neutral lines tend to become oriented east-west as a result of differential rotation.
Distance between fainter walls in 1000 km

Distance between brighter walls in 1000 km

FIGURE 8. Supergranule Cell Elongation
V. ARCH FILAMENT SYSTEM EMERGENCE

The arch filament system phase is that period from initial brightening until the first spot appears. Arch filament systems (AFS) emerge relatively suddenly from beneath the photosphere. Two or three days prior to the emergence there is no indication of the coming AFS. CaII K and 3800 Å photographs show no significant changes in structure in the network cells or in lifetime, and hydrogen alpha photographs show no significant brightening at the site. In many cases AFS appear in regions which were not previously active, although considered on a sufficiently large scale there appears to be a strong tendency for new activity to form near the sites of previous activity (Leighton, 1964). Whether this is a result of disturbances at the base of the supergranular layer, or results from the difference in properties of regions which contain large magnetic fields and those which do not, should be studied by plotting the locations of new active regions versus the age of older ones. This will be considered further in a later section.

Hydrogen alpha photographs from the years 1967, 1968 and 1969 were studied to determine whether the sites of AFS were any different from surrounding regions. The cell at the AFS site often grows somewhat and becomes longer lived after the AFS emerges but does not change prior to AFS emergence. AFS were usually preceded by elongated bright
features at the AFS site about one day prior to emergence of the main portion of the AFS. This feature was oriented in approximately the direction the coming AFS would occupy and in most cases took the form of an hourglass-shaped figure spanning a supergranule. The amount of brightening appeared to be related to the total quantity of field which was emerging but was normally quite inconspicuous until the main portion of the arch filament system started to emerge. The orientation, location, rate of brightening, and rate of increase of field strength of the magnetic field are the first data which may be used to predict the future behavior of the active region.

Regions of greater than average activity often appear to form from more than one arch filament system. In some cases the separate AFS may initially appear as separate brightenings or as a brightening which does not have the characteristic hourglass shape.

Because hydrogen alpha photographs are more sensitive than magnetograms as indicators of chromospheric structure, probably due to better spatial resolution, AFS emergence is usually well underway as seen in hydrogen alpha before major changes are observable in corresponding magnetograms, as first noticed by Weart (1970). There is every indication, however, that the emergence of the AFS and of the magnetic field is, in the main, simultaneous. The magnetic fields associated with arch filament systems appear to be hundreds of Gauss (Weart, 1970).

Arch filament systems have been studied from a structural point of view by Bruzek (1972). Roberts (1970) has made movies of the
motions of the arches and the small surges which often occur at this time. Weart (1970) found that these systems may appear with any orientation with respect to the solar equator. In a few cases orientation is difficult to determine. Some of these cases represent the simultaneous appearance of more than one AFS.

Weart and Zirin (1969) have shown that most of these systems rotate during the first two or three days following emergence. Following the rotation of the system, which occurs by new arches appearing at a different orientation than the older ones (i.e., individual arches do not rotate) (Frazier, 1972), the region has its long axis approximately parallel to the equator in most of those cases in which the region does not disappear almost immediately.

Observation suggests that some arch filament systems may have a helix structure with roughly one turn between the footpoints of the arches. This structure is observable in both hydrogen alpha and white light. In white light the arch filament structure appears somewhat similar in texture to spot penumbrae (Bray and Loughhead, 1965). In hydrogen alpha, on the other hand, arch filaments appear as relatively dense, slightly twisted arches.

According to Bruzek (1967) the lifetime of a single arch is about one-half hour. The material in the central portions of arches is normally observed to rise and the material in the ends normally observed to descend, although in some cases there is no flow reported (Frazier, 1972).
Until we develop a better understanding of the evolution of magnetic fields beneath the photosphere, AFS will provide the first key to the future evolution of an active region and its possible flare productivity.

Two tendencies may be noted when AFS locations are plotted in a coordinate system rotating with the sun, with a synodic period of 27 days (see Figure 9). The first is a tendency of active regions to clump in complexes. The second is the tendency of regions to appear in pairs near the same solar longitude. Figures 10 and 11 illustrate the tendency for regions appearing on the same day to appear closer to one another than regions appearing randomly in time.

Flares seldom occur in the new active region during arch filament system emergence. They are, however, likely to occur in the surrounding fields which have been disturbed by the expansion of the new active region as will be discussed later. Disturbances in the new region during the AFS phase generally manifest themselves as surges (Weart, 1970). Around the AFS a fibril mat forms as the optical manifestation of the disturbance of the surrounding magnetic fields. Figure 12 shows the expansion of an active region appearing as increased fibril contrast. Initially, the disturbance propagates at 0.25 km/sec or greater, but the rate slows considerably after a few days.
Coordinate system based on 27 day rotation period and 0 of longitude on central meridian on January 1, 1967.

FIGURE 9. The Location and Orientation of AFS in 1967
FIGURE 10. Histogram of Separations of 20 Pairs of Randomly Selected Active Regions in the North Hemisphere
FIGURE 11. Histogram of Separation of Twin Active Regions in the Northern Hemisphere (NOTE: Regions to the left of the dashed line were too close together to be clearly distinguished.)
FIGURE 12. Mean Radius of Fibril Mat
Flares in the mature regions surrounding a rapidly growing active region appear to be related to the rate at which the flux ropes are being compressed by the new field, as will be discussed in greater detail in a later section. An order of magnitude estimate of the probability of Class 2 flares in the older regions surrounding new active regions is that one Class 2 flare occurs per 20 arch filament systems and that that flare is associated with a large filament rapidly growing in height and density.

Class 2 flare counts made for the period between one week prior to and one week following the emergence of AFS which are predecessors of major active regions (defined to be regions having spots equal to or greater than 100 millionths of a hemisphere at maximum area) reveal a peak in flare numbers on the second day following the AFS (see Figure 13). Of a sample of 159 Class 2 flares occurring on the sun within plus or minus one week of AFS which lead to large active regions, 61 occurred during the week before the AFS, 10 on the same day and 88 during the week after.

Many Class 2 and 3 flares may be shown to be related to the appearance of new active regions (see Table 2). These occur when:

(a) a region of age 8 - 40 days with strong field gradients is

(b) followed at from 2 - 20° longitude heliocentric by an AFS which is becoming a large active region and is

(c) somewhat (0 - 10° latitude) toward the equator from the flaring region (see Figure 14). The numbers adjacent to points in the figure represent days from AFS emergence in external spot group.
FIGURE 13. Class 2 Flares and AFS Leading to Spot Groups of Greater than 100 Millionths Hemisphere (NOTE: $1\sigma = 3.2$ flares/day.)
**TABLE 2**

**FLARE TIMING FROM AFS TO LARGE FLARES WITHIN THE REGION FORMED BY THE AFS**

<table>
<thead>
<tr>
<th>Days From AFS Emergence Until Class 2 Flare</th>
<th>Days From AFS Emergence Until Class 3 Flare</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>14</td>
<td>27</td>
</tr>
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<td>30</td>
<td>30</td>
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<td>3</td>
<td>21</td>
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<td>28</td>
<td>20</td>
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<tr>
<td>11</td>
<td>8</td>
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</tr>
<tr>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

(Mean = 16 days) (Mean = 22 days)

**REMARKS:**

Some bias probably appears in these figures due to the great differences in visibility of features on the sun with distance east and west of disk center. This bias would appear as an excess of activity at about 30 day intervals. One or more hydrogen alpha photographic satellites on the other side of the sun would go far toward solving this problem.

These numbers are intended to be suggestive of typical intervals from AFS emergence until large flares occur in the plage. Additional significance should not be given to them. The difference between Class 2 and Class 3 flares in this table is not necessarily significant.
FIGURE 14. Distance and Direction to Nearest External Spot Group from Group Containing Class 2 Flares
(NOTE: the numbers adjacent to points in the figure represent days from the AFS in the external spot group until the Class 2 flare.)
In the case of the flares occurring after AFS emergence the delay time from AFS to flare averages about one day per 50,000 km separation of AFS and flaring region (see Figure 15). Arch filament systems within 40 degrees heliocentric longitude of older active regions occur in approximately equal numbers to the east and west of the older region (see Figure 16).

Large flares occurring within a week after the appearance of a new region are about three times as likely to appear west of the new region as east of it (see Figure 17). Note the difference between flare probability for AFS appearing east and west of the older region.

Spicules

Spicules have been interpreted as shock waves in the solar atmosphere, as tongues of turbulence between granules, as a result of Rayleigh Taylor instability in the lower corona, as heat conduction along lines of high field strength, and as material condensing from the corona.

Spicules carry a significant mass flow into the corona, estimated to be sufficient to replace the coronal mass every few minutes (Greenstein, 1973). Spicules appear to supply much of the material which forms the prominences.

Fibrils

Away from neutral lines fibrils tend to form fan-shaped regions whose three-dimensional structure is probably that shown in Figure 18.

The fibrils approximately one day after AFS emergence form a large-scale pattern resembling a dipole structure. As regions age, the fibril structure becomes more and more wound up by differential
FIGURE 15. Separation Between Class 2 Flares and ARs Which Form Spot Groups

Distance from Class 2 flare to external (i.e., in another active region) spot group in thousand km

Days from AR to external spot group

1 2 3 4 5 6 7 8 9 10 11 12
FIGURE 16. Distance From Major AR With Spot Areas of a 100/10$^6$ Hemisphere to Arch Filament System (AR Denotes Active Region)
FIGURE 17. AFS and Class 2 Flares (NOTE: the numbers adjacent to each point are the number of days from AFS emergence to the flare. AFS locations are denoted by 0. Compare the strong asymmetry of flare distribution on this figure with the symmetry of AFS distribution shown on the previous figure).
FIGURE 18. Fibril Structure
rotation and flux rope migration. Often the fibril structure will join into a filament deep within the active region.

The complete fibril structure is probably a bright photospheric point over which there is a spicule that bends over at a few thousand kilometers to form the near horizontal fibril. If fibrils, spicules and bright points are all parts of the same structure in the magnetic field, then one would expect that they might have similar lifetimes. However, spicules often have appreciably shorter lifetimes than fibrils and bright points. Spicule lifetimes are on the order of 10 minutes but bright points last on the order of an hour or more. Fibril lifetimes appear to be on the order of an hour. Observational difficulties or the possibility that bright points may undergo pulsations with the production of several spicules during the lifetime of a bright point may explain these differences.

Location and Timing of New Active Regions

The writer's observations indicate that the location of a new active region does not appear to be influenced by the expansion of older active regions in the area. If such an effect were occurring, some bunching would occur when separation of active regions and AFS are plotted but this is not observed (see Figure 19). The distance between old regions and AFSs does not appear to vary with the age of old regions. This tends to suggest the need for a modification of Leighton's (1964) hypothesis that the emergence of new fields is influenced by the strength of preexisting surface fields. There is a tendency for new
FIGURE 19. Distance of New Active Regions from Older Ones
(NOTE: Solar rotation carries regions behind disk 1-15 days after AFS emergence. Therefore, gaps will result near 15 and 40 days.)
AFS to clump at certain locations known as active region complexes. Complexes have lifetimes of months. The behavior of these regions has been studied by McIntosh (1973), whose data suggest that there may be a tendency toward periodicity in the appearance of new active regions. These recurring active regions may be generated by the same subsurface disturbance rather than induced by surface fields.

New AFS appear at sites which suggest that the appearance is not random in longitude. Dodson and Hedeman (1968) have shown that complexes approximately 180 degrees apart in longitude exist and that these complexes often survive for months.

If active regions appear 180 degrees apart, then the next higher order of regularity would be 90 degrees. Plots of the spacing of central meridian passage of major active regions yield median spacing of 6.7 days (Figure 20), which corresponds to approximately a 90 degree rotation of the solar equator.

What (if anything) can be forecast before and during the AFS phase? It should be possible to considerably improve existing flare forecast techniques by forecasting the locations of new solar activity. Three techniques should be developed initially.

1. The large-scale structure should be drawn by using magnetograms. The rates at which different parts of the structure approach the equator should be studied. The changes in network structure should be forecast based on past motions and on predictions of network behavior. The type of activity which occurs on the sun varies somewhat with latitude. For example, reversed polarity regions are more probable near the equator than at higher latitudes. It may be worthwhile to check if the numbers of reversed polarity regions rise during the later portions of the sunspot cycle.
FIGURE 20. Histogram of Intervals Between Central Meridian Passage of Northern Hemisphere Major Active Regions in Year, 1971
(2) A strictly numerical technique based on rates of change of magnetic fields locally should be developed.

(3) A numerical technique based on the rate of appearance and size of active regions in a given location should be developed.

Once the hourglass figure has appeared, magnetograms and Hydrogen alpha taken on an hourly basis would probably enable the development of better techniques of predicting the subsequent evolution of active regions.

Hourglass figures which appear larger than usual, brighter than usual or unusual in shape may be indications of greater than usual activity.
VI. THE DEVELOPMENT PHASE

The development phase is that period from the initial appearance of sunspots until the spots reach their maximum size. The development phase has, in the past, been called the growth phase. That appellation is not entirely appropriate since the field is injected into the photosphere mainly during the AFS phase and expansion of the region (spreading of field elements) occurs during all phases.

At the end of the AFS phase the new active region consists of a bright plage whose field is rather sharply separated from surrounding fields and contains two clusters of tiny sunspots. These clusters usually are separating from each other with a relative velocity of approximately 0.25 km/sec (see e.g., Figure 21). As the spots move with respect to the surrounding photosphere they join to form larger spots. The rate of growth of these larger spots and rate of motion with respect to the surrounding photosphere appear to have some correlation (see e.g., Figure 3, page 26). In the case of typical active regions, spot motion and growth slows after five or six days. During this phase of the evolution of an active region, flare activity migrates toward the leader spots within the region and occurs along the outer border of the fibrils surrounding the region (see e.g., Figure 30, page 78). Flare probability in a young active region rises for about five days (see Figure 22).
FIGURE 21. Spot Separation During the Development Phase
(NOTE: the lines represent spot locations as a function of time for three spot groups.)
FIGURE 22. A Sample of 60 Flare-Producing AFS (Less than one-half of AFS lead to flares of Class 1 or greater.) All AFS in this sample occurred on the eastern half of the disk.
Faculae

Faculae are not symmetrically arranged in active regions. The leading edge of the facula often occurs at the wall of the cell surrounding the leader spot or, at most, the next supergranule to the west of the leader spot. The follower spot, on the other hand, is often located near the center of the facula. Frequently, follower spots decay into unobservability within two or three weeks of the formation of the region.

The centers of faculae and plages are offset from spots toward the poles by an amount which appears to increase erratically as the spot group ages (see Figure 23). One is seeing the poleward drift of the faculae with respect to the spots. Spots appear to be controlled in their motions by their attachment at relatively deep layers (i.e., about 5,000 km). Spot drift rates in latitude are low when compared with the drift rates of faculae.

The area, $A$, in which field elements lie following an AFS was assumed by Leighton (1964) to be

$$A = \frac{\pi L^2}{\tau} t,$$

where $L$ is a supergranule radius, $\tau$ is a supergranule lifetime, and $t$ is the time since AFS emergence. Leighton (1964) has evaluated $dA/dt = \pi L^2/\tau$ to be about $10^4$ km$^2$/sec.
Poleward distance the plage centroid is offset from the spot centroid in degrees

FIGURE 23. Plage Poleward Offset as a Function of Age of the Active Region (NOTE: McMath plage regions normally are abbreviated MM.)
Although measurements of supergranular cell diameters in active and quiet regions gave no statistically significant difference, cell lifetimes vary greatly with field strength (see Figure 24). This increase in cell lifetime had previously been noticed for newly emerged magnetic fields (Rust, 1972). In general, the increased brightness and additional structure inside active regions decrease the identifiability of cells and therefore the observed effect is real and not an artifact produced by the increased brightness. The rise in supergranular lifetimes inside active regions may be interpreted as a decrease in the diffusion rate. Smithson (1973) has observed such a decrease when following the motion of bright points in the CaII K plage.

Sunspots

Spots often originate as a scattered cluster of pores which merge to form a large spot. A rise in mean field strength from about 500 to approximately 2000 Gauss represents a four to one decrease in the area over which the field elements are spread. Thus, the formation of a spot may be treated as the migration of field elements to produce a region of greater field strength by overcoming their mutual magnetic repulsion.

When viewed in Hydrogen alpha, many spots display a crown-like extension of the penumbra. This crown-like structure often bends toward the rear with respect to spot motion through the photosphere.

Spot Behavior

Qualitatively there appear to be differences between leader,
FIGURE 24. Magnetic Fields (From Mt. Wilson Magnetograms) and Supergranule Lifetimes (NOTE: Each symbol represents the estimates of a single observer)
follower, and isolated spots which reflect their relations with their surroundings. The writer has observed that leader spots normally have more sharply defined penumbrae than follower spots and that the westward side of leader spots is usually more sharply defined than the east. They often have their long axis pointed approximately heliocentric east and west while for follower and isolated spots the orientation is somewhat more nearly random (see Figure 25). Leader spots are normally larger than follower spots but follower spots are often scattered across a larger area.

Large isolated spots are often round or slightly elliptical and at times may be surrounded by a characteristic whirl structure in Hydrogen alpha. This vortex structure around spots, which is quite rare, has been studied by Richardson (1941) and others.

Increasing spot size is associated with increasing spot separation during the growth stage (see Figure 26). Rapid growth and decay are often associated with spots which are elongated (see Figure 27). During the development phase of an active region the spots have a high probability of being elongated. As the region matures the spots become more nearly circular.

The neutral lines in active regions are normally displaced toward the follower spots with respect to the midpoint between the spots (see Figure 28).

**Flares**

The occurrence of flares following the appearance of an arch
FIGURE 25. Spot Orientation (NOTE: the vertical line represents the line connecting follower and leader spots and this line is well offset from the peaks of the spot orientation histograms, apparently due to the eastward motion of the spots with respect to the photosphere.)

Source - Solar Geophysical Data
Orientation measured clockwise from north
FIGURE 26. Leader Spot Diameter and Mean Distance to Follower Spots

Distance to center of follower spot group in 1000 km
$\frac{1}{A} \left[ \frac{dA}{dT} \right]$ fractional change in spot area per day

FIGURE 27. Spot Growth Rate and Elongation
Distance between major follower and leader spots in 1000 km rounded off to the nearest 20,000 km

FIGURE 26. Neutral Line Location

NOTE: n.l. = neutral line
filament system on the sun tends to follow a fixed pattern of development. Although numerous regions were studied the behavior of McMath region 8647 will be taken as typical of the larger regions considered.

Plots (Figures 29 and 30) illustrating the flare locations within 25 degrees of the arch filament system of MM 8647 during the period January 10 through January 22, 1967 show the evolution of a large active region. Some aspects of this evolution are the following.

(1) Flares tend to trail east of their associated spots (see Figures 31 and 32).

(2) Flares often appear near the follower spot longitude early in the lifetime of an active region.

(3) Flares tend to migrate a few degrees west during the first ten days following arch filament system emergence (see e.g., Figure 30).

(4) A relatively small number of flares occur at the edge of the mat of relatively high contrast fibrils which surrounds an active region. The site of the greatest likelihood of these flares moves outward from the center of the active region at approximately the rate the fibril mat expands (see e.g., Figure 29). Initially this rate is approximately five degrees per day but it soon slows to about two degrees heliocentric per day. This later rate is consistent with the Leighton random walk mechanism.
FIGURE 29. The Expansion of Flare Activity - MM8647
FIGURE 30. Flare Migration in the Flage - 198647
FIGURE 31. Number of Flares as a Function of the Longitude Relative to the Leader Spots for 14 Flares Occurring During the First Ten Days Following AFS Emergence
Flares to the east of spots  Flares west of spots

Longitude separation of flares and spots in degrees

FIGURE 32. Number of Flares as a Function of the Longitudes Relative to the Follower Spots for 32 Flares Occurring During the First Ten Days Following AFS Emergence
VII. THE MATURE PHASE

The mature phase of an active region is the period from spot maximum area until spot disappearance.

Structure

During the mature phase of an active region the major activity centers around the leader spot. Normally, the follower spots have either disappeared entirely or stabilized so that they have a very slow decay rate by this time. The leader spot may be quite large and, in fact, is of major interest to forecasters of large flares.

Large prominences often develop in the region during this phase. If these prominences are oriented approximately heliocentric north-south, then they may be associated with flares. Figure 33 illustrates that over half of all prominences have orientations between 20 and 130 degrees. In a sample of flares shown in Figure 34 no Class 2 flares occurred in prominences with these orientations. Hence prominences with approximately east-west orientations are much less likely to be associated with flares.

The relationship between prominence orientation and flare location is not just the obvious one that north-south oriented prominences are near spots. North-south oriented prominences are often flare associated even if the prominence is not within an active region. The
FIGURE 33. Orientations of 33 Prominences Near 25° N in 1964-1971
Mean orientation of prominence long axis measured clockwise from north through west

No. of class 2 flares near prominences

No. of class 1 flares near prominences

FIGURE 34. Prominence Orientation and Flare Class (25 Flares in Sample)
plage immediately to the east of these prominences is usually considerably brighter than that to the west. The prominences often appear to be moving west with respect to the photospheric plasma.

**The CaII K Network**

If diffusion of field elements was given only by a random walk process some field elements would be transported toward the higher field strength region. Observations of MM011 in September, 1972 suggest, however, that flow of bright CaII K features was entirely away from the spot (Figure 35).

Another indication that diffusion is not the only manner in which flux ropes are moved is that the interior of active regions is not the smooth profile of field strengths expected from diffusion. Organized expansion and the random walk process appear to be related in the same manner that an expanding gas flow is related to the kinetic velocity of its molecules.

If a line is drawn through the centroids of the leader and follower plage this line may be thought of as determining the plage orientation. Plage orientation is related to flare probability. Groups in which Class 1 flares occur have a median orientation near 100 degrees, but for groups containing Class 3 flares the median orientation is near 120 degrees (see Figure 36). Therefore, faculae in spot groups in which large flares occur are more likely to have an orientation with the leading end pointing considerably closer to the equator than are groups in which smaller flares occur.
FIGURE 35. Estimated Flow Velocities of Chromospheric (CaII K) Features in the Vicinity of the Leader Spot in a Mature Active Region
FIGURE 36. Median Plage Orientation and Flare Importance Class
The orientation of the line between the follower and leader spots appeared to have some correlation with flare size. The line appeared to be oriented near 110 degrees for large flares and 90 degrees for small flares or none at all (see Figure 37). As can be seen from the figure the line between the centroids of the spots and the line between the centroids of the leader and follower plages do not differ greatly in direction. The line connecting the plage is slightly nearer north-south since the leader plage follows the leader spot while the follower plage often is centered slightly poleward of the centroid of the follower spots.

**Fibrils**

During the mature phase of active regions, fibrils from adjacent active regions are often brought into proximity. At this time they tend to rotate so as to form parallel bands (see Plate V). The ends of the large prominence below the center of the disk in the photograph divide into these bands.

**Prominences**

Aside from the estimates of drift toward the pole at about one degree per solar rotation and the qualitative opinions that prominences tend to move away from active regions there are, so far as the writer knows, no studies in the literature of prominence motion relative to associated active regions.

Active regions are frequently asymmetric in that faculae often tend to occur on opposite sides of the larger spots from prominences.
S - orientation of line between spots
P - plage orientation
ns - no spots
ls - 1 spot
P  | - plage and spots from
S  | same region

FIGURE 37. Plage Long Axis Orientation, Orientation of the Line Connecting Leader and Follower Spots — and Flare Class
PLATE V

HYDROGEN ALPHA SPECTROHELIOSGRAM
Large spots are seldom completely surrounded by plage. Prominences normally are found a few degrees poleward of their associated spots and, except for the large prominence which forms on the interior neutral line between the spots, they are much more likely to form to the poleward and west of an active region than to the east of the same region (see Figure 38). Prominences form on the advancing edge of the wave of fibrils which surround rapidly growing active regions and often, but not always, remain on the leading edge of that wave. (The large southern hemisphere region visible on May 14, 1967 illustrates this property.)

Prominence orientations from the years 1964-1971 were plotted as a function of latitude (Figure 39). Below 45 degrees latitude any prominence orientation is possible, but approximately three-fourths of all prominences in all latitudes have orientation angles greater than 90 degrees (i.e., the trailing end is nearer the pole than the leading end). This result is difficult to interpret if one assumes that prominences are long-lived features whose orientation is determined solely by differential rotation acting on a line with any orientation whatever. Acting over a sufficiently long period differential rotation should always cause the prominence orientation to be about 90 degrees.

Prominence locations in 25 north hemisphere isolated active regions in which the leader spot was somewhat closer to the equator than the follower (in other words, regions that were unusual only in being isolated) are shown in Figure 38. In these 25 regions the following conditions were found to exist:
FIGURE 38. Normalized Plot of Prominence Locations (Isolated Active Region with Spots About 100 - 280°) NOTE: the circles represent spot locations.
1. in every case the region's interior neutral line between the spots passed through the region closer to the follower spot than to the leader;

2. in most cases it was concave toward the west inside the plage;

3. on the poleward side of the active region it would often turn east or southeast. Several heliocentric degrees later it would turn back to a northeast-southwest orientation.

4. Prominences are observed more often on the poleward side of active regions than toward the equator.

We define the velocities of quiescent prominences with respect to nearby active regions to be the rate of change of the distance from the midpoint between the spots to the midpoint of the prominence. In a sample of 30 cases no velocity greater than 0.1 km/sec was found. Prominences associated with the follower portion of active regions usually move away from the region more rapidly than prominences associated with the leader polarity (see Figure 40).

At high latitudes the apparent solar rotation rate about the sun's axis as measured from the prominence locations is, in part, due to the poleward migration since rotation is measured at a constant latitude. Since rotation is measured on a given latitude the poleward moving prominence will place more and more westerly portions on a given parallel of latitude and, therefore, will be assumed to be moving west more rapidly than the gas motions. The apparent westward (or eastward) motion will then be a function of the angle the long axis of the prominence makes with the north-south heliocentric line (see Figure 41). If synodic periods less than 28 days are included a typical angle is about 100 degrees. Prominences are moving poleward
Radial prominence motion in km/sec

Distance from prominence midpoint to spot group midpoint

- prominences west of leader spots
- prominences east of follower spots

FIGURE 40. Prominences Adjacent to Isolated Active Regions
FIGURE 41. Synodic Period and Orientation Angle for Prominences Near 50° Latitude
at about one degree per rotation. The apparent mean westward prominence motion is about two-thirds degree per day with respect to the photospheric faculae (Howard, 1972). In linear distance the rate is about 500 km poleward per day and about 4000 km west per day.

Tandberg-Hanssen (1971) states that condensation of prominences occurs from preprominence matter because radiation losses in the optically thin preprominence matter are proportional to the density squared while heating is supposed to be proportional to the density. According to Hildner (1971) the process follows after an initial isobaric increase in density of about five per cent. In the past decade most cooling time estimates from coronal conditions to those in prominences have been in the range from a few thousand seconds to a few days. The sudden appearance of loop prominences following large flares suggests that in at least some cases all existing estimates are too long. Prominence formation time estimates were made for quiescent, not active, prominences, but none of the cooling time models made this explicit or made any such distinction. Flare loops form on the trailing edges of the bright flare ribbons. Their locations are such as to strongly suggest that the material condensing in the prominence is material which was injected into the corona from the bright portion of the ribbon a few minutes earlier.

If flux ropes are unable to propagate through the prominence and field strengths do not rise indefinitely then some sort of dissipative process must be occurring in the prominence since field elements are
continuously being carried toward the region of the prominence. If
the process is to be Ohmic diffusion in the absence of turbulence then
Kippenhahn and Schluter (1957) have calculated that material will des-
cend from the prominence with a velocity of a few hundredths of a cen-
timeter per second. However, material velocities as determined by
prominence spectra are often several kilometers per second.

The location of neutral lines is determined by the requirement
that equal amounts of flux approach the neutral lines from both sides,
which is required by the definition of neutral line. From this re-
quirement and the random walk process it is possible to predict ap-
proximately the motions of prominences which are in or near a steady
state with their surroundings.

There are, however, many prominences for which the random walk
process in its original form is inappropriate and modification based
on an analogy between the behavior of the random walk and the motion
of particles of a two-dimensional compressible gas appears more suit-
able. The prominences affected are the large prominences observed on
the outer edge of the fibril mat which forms around large, rapidly
growing active regions. The initial expansion of the new active re-
gion causes the formation of a region of high field strength. As
new flux emerges the region is kept at high field strength and the
equivalent of a shock wave advances away from the region (see model
section).

This disturbance moves outward until the field strength behind
the discontinuity drops to within a few Gauss of the mean solar field.
Each new AFS in the active region complex then gives a new impulse to the prominence (see Figures 42 and 43). Several weeks after the initial impulse the prominence slows sufficiently so that differential rotation begins to carry it east with respect to the spots.

Another common prominence situation occurs when a large active region is injected suddenly into the photosphere. The displaced older flux (around the current sheet dome surrounding the new flux) forms a region of high field strength which propagates away from the new active region. When the disturbance reaches a neutral line, the neutral line starts to move at a velocity which is usually approximately one-half the diffusion velocity of field elements. The rate of prominence motion is, in general, equal to the movement of the neutral line, which in turn is determined by the requirement that equal amounts of flux reach the neutral line from both sides. Prominences will form on these neutral lines and rapidly grow. If the displacement continues for several days for neutral lines distant from spots or for a day or two for closer ones, a disappearance brusque may result (Bruzek, 1952). When two mature active regions meet we do not observe structure from one penetrating into the other. We do often observe the formation of an approximately linear prominence along the line of contact.

The location and growth of prominences may be predicted based on the following assumptions:

1) the diffusion of field elements may be treated as an analog of the molecules of a compressible gas, and
FIGURE 42. Prominence Motion Poleward of an Active Complex

Prominence distance (N-S) from leader spot in 1000 km
Distance (N-S) of prominence from leader spot in 1000 km

300.

100.

HOTE: Both AES appeared on the back side of the sun.

FIGURE 43. MM Region 905 and Associated Regions
(2) reconnection and distortion rather than interpenetration occurs at neutral lines.

The second of these assumptions is based in part on the appearance of the plage near prominences. Plage near prominences tends to form into lines approximately parallel to the prominence. The plage structure does not extend across the prominence. The plage is often brighter on the western side of the prominence than on the eastern (see Plate V, page 89).

The location of prominences can be explained as the result of the spot velocity with respect to the photosphere, and the expansion of the facular region about the spot.

Flares

The class of the largest flares which may occur within the plage of large regions steadily rises for two or three weeks following AFS emergence (see Figure 44). The class of flares on the outer edge of the fibrils, on the other hand, remains roughly constant (see Figure 45).

The filaments associated with flares in active regions are normally quite low, as was estimated when the prominence was on the limb prior to the occurrence of the flare (see Figure 46). Out of 36 two-strand flares, the associated prominences were less than 20,000 km high in over half the cases.

Dodson and Hedeman (1970) have studied the occurrence of flares in regions of few or no spots. Their data lead the writer to conclude that these flares are located in the solar latitudes expected if they
FIGURE 44. Flares in Region 2103 (NOTE: APS emergence occurred on 30 June 1967)
FIGURE 45. Flares on Outer Border of Disturbance
MM 032, October, 1967
The diagram depicts a bar chart showing the number of flare-associated filaments at various heights in thousands of kilometers. The chart indicates that:

- At heights of 10 to 20 km, there are 12 filaments.
- At heights of 20 to 30 km, there are 10 filaments.
- At heights of 30 to 40 km, there are 8 filaments.
- At heights of 40 to 50 km, there are 6 filaments.
- At heights of 50 to 60 km, there are 4 filaments.
- At heights of 60 to 70 km, there are 2 filaments.
- At heights of 70 to 80 km, there are 0 filaments.

**NOTE:** These heights typically are underestimates by about 5000 km since on the day of limb passage they may be several degrees from the limb.

Source: Sac. Pk. Obs.

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**FIGURE 46. Filaments Associated with Loop Flare Systems**
were associated with spot groups (see Figure 47).

Active regions which are going to produce large flares appear likely to assume an east-west orientation quite early. Regions with a 10 to 70 degree orientation at the time the first spot appears are unlikely to produce anything larger than subflares prior to limb passage (see Figure 48).

Very long (greater than 40 minutes) rise times are often associated with X class X-ray events (see Figure 49). Flare rise times to maximum intensity are a function of the age of the region and whether the flare occurs in the newly injected field or the older displaced field. For at least the first few days after the injection of the AFS, most flares in the newly injected field are limited to rise times less than five minutes times the number of days since AFS injection (see Figure 50). Flares in the older displaced field generally take longer to reach their maximum intensity and appear not to observe the same rise time limit as flares in the newly injected field.
FIGURE 47. Class 2 Flares in Regions with Few or No Spots
(The contours enclose the regions where one has on an average 20 spot groups per five degree change in latitude.)

Source: Stenflo, 1972
FIGURE 48. Flares in Young Active Regions (1966)
FIGURE 49. X-Ray Class and Rise Time of Importance

≥ 1 Flares
FIGURE 50. Flare Rise Times
The decay phase of an active region is the period from spot disappearance until the region is no longer recognizable on magnetograms.

**Structure**

At this time the region has a large size but low mean field strength. Prominences often have their greatest size at this time. These regions are often unipolar, since by this phase the follower polarity has often dispersed.

**Evolution**

Flare activity in the region is in the main associated with the large prominences. Disturbances propagating from younger active regions may lead first to prominence growth, then to a disturbance in the prominence stability which will end in a large flare or disruption brusque.

This is the phase during which the moving magnetic features (MMF) are often most obvious. Harvey and Harvey (1973) describe these features as having the following properties:

1) are associated only with decaying sunspots surrounded by a moat (a zone without permanent vertical magnetic field);

2) move approximately radially at approximately one km/sec until they vanish or reach the network;
3) transport net flux away from the parent sunspots at the same rate as the flux decay of the sunspots; and

4) appear to contain a total flux several times that of the parent sunspots. This appears to result from each single flux rope crossing the photosphere several times (see Figure 51).

The sudden rise in flux rope density, drop in flux rope velocity, and relative stability of the outer border of a moat are all similar to properties of a hydraulic jump. The most familiar example is the circular wave which appears around the outflow from a faucet. Such behavior strongly suggests that organized flows are a property of active regions.

Sheeley (1972) found the average outflow velocity around six old spots to be approximately 0.7 km/sec. This differs slightly from the Harveys' (1973) field element motion value of about one km/sec found by measuring the motion of 77 MMF. If the difference in gas and field element velocities is not due to errors in measurement, then field elements have (in this case) a slip velocity \( V_s \) of about 0.3 km/sec with respect to the surrounding photosphere. Since the field element velocities are higher it suggests the possibility that the field elements may induce the flow rather than the flow inducing the field element motion.
Source: Harvey and Harvey, 1973

FIGURE 51. The Structure of Moving Field Elements
Leighton's Model

Leighton has created a model in which magnetic flux "disperses solely under the influence of the solar differential rotation and a random walk, the latter being brought about by the supergranular convection cells" (Smithson, 1973). This model accurately describes very weak (< 5 Gauss) solar magnetic fields (Schatten, Leighton, Howard and Wilcox, 1972) except near neutral lines. It also is consistent with the propagation of fields to explain the solar cycle.

In a random walk the position of any particle follows on average the relation

\[ r = LN^{1/2}T^{1/2} \]

where \( r \) is the distance of a particle from its source region, \( L \) is a cell radius, \( N \) is the number of steps per unit time and \( T \) is the time since the particle left its source region.

An assumption of such random walk processes is that the particles do not interact with each other. As a result "a composite region is describable as a linear superposition of separate parts, each of which develops independently of the others; if two expanding regions overlap the resulting field will be taken to be the algebraic sum of the two
separate fields, whether these are of the same or opposite polarity" (Leighton, 1964).

This random walk process is modified by differential rotation to create bean-shaped unipolar regions with diffuse borders.

The degree of agreement of Leighton's model with observation is a function of field strength. Leighton's model requires that field elements move with the supergranular flow and that the properties of that flow are uniform over the sun. In very weak field regions (less than 5 Gauss) these requirements appear to be met. As field strengths rise the agreement steadily falls. The cells in the random walk have lifetimes of about one day, flow velocities of about 0.4 km/sec, and diameters of about 25,000 km. Cell sizes are uniform over the sun but cell lifetimes are not (see Table 1, page 39). Lifetimes are considerably greater in active regions than outside (Moses, 1974). A large cell which lasts for many days often appears around old spots during the mature phase. This cell (moat) has an outflow of field elements at about one km/sec (Harvey and Harvey, 1973) and gas at about 0.7 km/sec (Sheeley, 1972). These cells are about 50,000 km across and therefore do not match the properties of the supergranular cells in the random walk in:

a) size;

b) lifetime; and

c) flow velocities.

The diffusion velocity in active regions is observed to be only about one-third that predicted from Leighton's model (Smithson, 1973).
The structure near neutral lines of regions with field strengths greater than 10 Gauss is not the smoothly varying profile expected from the interpenetration of diffuse regions. To repeat Sara F. Martin's (1973) earlier comment—adjacent fields of the same polarity merge together but fields of opposite polarity never intermingle at the photospheric level. Hence neutral lines as observed are not the shape, location or diffuseness which are expectable from a random walk.

The flow velocity of field elements in Leighton's model is about 0.4 km/sec leading to a velocity of the leading edge of the disturbance of about 0.25 km/sec. A significant fraction of solar disturbances, however, propagate faster than this velocity. The velocity one km/sec appears to occupy a unique role since:

1) the disturbances (initiated by AFS) leading to flares and sudden disappearances of prominences in nearby active regions propagate at one km/sec (Bruzek, 1952; Moses, 1973).

2) field elements inside moats move at about one km/sec (Harvey and Harvey, 1973),

3) tongues of flux in old plages sometimes move at one km/sec (Smithson, 1973),

4) the fibril mat of new active regions expands at about one km/sec.

For these reasons it seemed reasonable to propose a compressible gas analog as an alternative to Leighton's diffusion model.

The Proposed Model

In order to achieve a matching between a diffusion model of the evolution of solar magnetic fields and the observations it was considered necessary to modify Leighton's (1964) model in four ways.
1) The rate of diffusion had to be decreased in active regions to account for the increased cell lifetimes and rigidity of structure observed there.

2) Fields were assumed not to penetrate one another at neutral lines. Reconnection was assumed to occur along neutral lines.

3) The random walk was treated as an analog of a two-dimensional gas due to interaction between field elements.

4) The source regions—spots and faculae—are assumed to move in response to subphotospheric forces associated with their magnetic fields as described by Foukal (1972).

Although the writer has not done so, it appears possible to use the model quantitatively. The model should be useful for computer forecasting of solar flares.

Properties of the Model

During the early expansion of an active region a disturbance of the magnetic field propagates away from the region. The initial velocity of this disturbance is approximately one km/sec driven mainly by magnetic repulsion. After a period of about two weeks the magnetic repulsion becomes negligible, and the disturbance slows to 0.25 km/sec, the diffusion velocity.

Photospheric field elements are concentrated regions of high field strength rather than a nearly uniform field. Field elements (features with diameters of a few hundred kilometers and fields of about $10^{18}$ or $10^{19}$ Mx total) may be identified with the moving magnetic features, MMF, of Harvey and Harvey (1973). They have also been identified with the bright points just above the photosphere at the borders of supergranules.
The velocity (about 1 km/sec), appearance in opposite polarity pairs, and total flux considerably in excess of spot flux are properties which suggest that bent fields a few thousand km in depth constitute the subphotospheric portions of the MMF which intersect the photosphere several times (Harvey and Harvey, 1973). Active regions are often $10^5$ km or more across. Hence the region is shallow in proportion to its diameter suggesting that the region may behave similarly to shallow water.

When the disturbance (a wave of increased field strength) reaches a preexisting neutral line the neutral line begins to move away from the new active region propelled by the field elements which are being swept forward by the disturbance. The neutral lines do not, in general, move at the flow speed of the field elements, since neutral lines can only remain neutral lines if equal quantities of flux reach the neutral line from both sides. Therefore, neutral lines will always achieve that velocity required to keep the quantity of approaching field equal on both sides, i.e., the product of the field strength and the velocity of approach on one side of the neutral line is equal to the product of the field strength and velocity of approach of the field elements on the other side of the neutral line, for an observer moving with the neutral line. Prominence velocities are consistent with this hypothesis.

This is not a model based on radial and uniform emission of field elements from regions of high field strength. Instead, the motions
of field elements in regions of high field strength are assumed to be influenced by the motions of spots with respect to their surroundings and by the magnetic structure in the corona and chromosphere over the region.

Mathematical Development of the Model

The motion of field elements under the influence of photospheric flow and magnetic interaction is treated as an analog of the flow of shallow water which may be described by relations similar to those for a two-dimensional compressible gas.

The photospheric field elements (and their extensions into the lower corona) are treated as the "particles" of this two-dimensional flow. Field element motions and the interaction between field elements together have many of the properties associated with pressure in a gas. (But it is not, of course, to be identified with the pressure of the gas in the lower corona.)

The analogy between the behavior of photospheric field elements and the behavior of shallow water may be expressed mathematically. Both may be treated as two-dimensional flows where the depth of the water is proportional to the water pressure and the magnetic field strength is proportional to the magnetic force felt by each field element.

Any motion, \( \mathbf{V}_{fe} \), of a field element may be expressed by

\[
\mathbf{V}_{fe} = \mathbf{V}_C + \mathbf{V}_s
\]
where $\overline{V_c}$ is the horizontal flow velocity in supergranules and granules relative to a coordinate system rotating with the mean velocity of the local photospheric plasma and $V_s$ is the rate at which that field element moves with respect to the surrounding flow. The average of these individual field element velocities is the field element flow velocity $u$ at any location.

A disturbance in a two-dimensional flow propagates with a phase velocity, $C$, where

$$C = \frac{V_{fe}}{\sqrt{2}}$$

with $\overline{V_{fe}}$ = the mean field element speed. Outside of active regions, where magnetic forces are relatively small, $\overline{V_s} \approx 0$, and an estimate of $V_c$ from horizontal flow in supergranules and in granules is $V_c \approx 0.4$ km/sec. Then $C \approx 0.25$ km/sec as is observed.

By contrast, in active regions $V_s \neq 0$. Foukal (1972) states that the relation for hydrodynamic drag, $F_h$, for a cylinder may be used to find $V_s$.

$$F_h = \frac{1}{2} \rho v_s^2 C_D A$$

where $\rho$ is the photospheric density, $C_D$ is a constant $\approx 1$, and $A$ is the width of the field element ($10^2 - 10^3$ km) times its effective depth ($10^3 - 10^4$ km). The drag force must be balanced by magnetic forces above and below the photosphere. Foukal (1972) has considered the
effects of subphotospheric fields on deep field elements such as spots and AFS plages. The result of his study is that spots move west with a typical velocity, $V_b$, of about 100 meters/sec with respect to the surrounding photosphere propelled by fields at the base of the supergranular layer. We now wish to scale Foukal's (1972) example to the weaker, shallower magnetic field elements in the expanding active region. For these shallower features the magnetic interaction is predominately in the lower corona and chromosphere since at the photosphere fields are confined to field elements which are not in contact with one another.

Frazier and Stenflo (1972) picture the structure of a magnetic filament (field element) as similar to a sunspot reduced in size by a factor of about 20. The field lines above the photosphere are assumed to fan out rapidly with height, from a photospheric diameter of about 0.5 seconds of arc.

Magnetograms indicate that most of the field in supergranules is concentrated in rosettes along the borders. After the formation of a supergranule most of the field elements inside will collect at the rosettes along the cell walls within a few hours. These may be then thought of as stationary field elements. During the subsequent evolution of the cell additional field elements will collect at the rosettes. Some field elements will, however, migrate through the cell without collecting at a rosette.

At some location, $P$, not in the vicinity of a rosette we wish to compare magnetic forces on field elements passing through this location at different times. From Schmidt's (1964) approximation that
electric currents do not appreciably modify magnetic fields above the photosphere the force, $F_m$, on a moving field element is seen to be

$$F_m \sim \bar{B},$$

where $\bar{B}$ is the mean field strength averaged over the cell. The field of the moving element is assumed constant.

But

$$p_m = -\dot{p}_h,$$

since the magnetic forces are dragging the field element through the photosphere. And from the drag relation

$$F_h \sim V_s^2.$$

Therefore, the average value of $V_s$ is related to $\bar{B}$ by

$$V_s \sim \sqrt{\bar{B}}.$$

The effect of a change in the location, $P$, and $V_s$ may be found using a simple assumption. Assume that rosettes are uniformly distributed around the border of a supergranule. The geometry of a field element, at $P$, moving within the cell is shown in Figure 52.
FIGURE 52. The Geometric Relation Between Moving Field Elements and Supergranular Cell Walls
Let D be the cell diameter and \( \theta \) be the angle between the line from the moving field element to the closest point on the wall and the line from the moving field element to the point on the wall being considered measured clockwise. If Schmidt's (1964) approximation is used the force, \( F_m \), on a moving field element due to the rosettes in the cell wall may be approximated by

\[
F_m = \int_{-\pi}^{\pi} \frac{k_1 B R_i}{R_i^2} \cos \theta \, d\theta ,
\]

since the field in unit distance along the wall is proportional to the mean field strength in the cell. Therefore, \( \int k_1 \frac{B}{R_i} \cos \theta \, d\theta = F_m \) where \( R_i \) is the distance from the moving field element to a given point on the wall and \( k_1 \) is a constant. The number of wall field elements seen in unit angle is proportional to \( B R_i \) and the flux composing the moving field element may be treated as a constant.

Very few elements are observed in the centers of supergranular cells. Therefore, a reasonable approximation is

\[
R_i \ll D ,
\]

for \(-\pi/2 < \theta < \pi/2\), and,
\[ F_m = 0 , \]

for \(|\theta| > \pi/2|\).

With this approximation the magnetic force becomes approximately that which would be felt from a straight wall. Let \( R \) be the distance from \( P \) to the closest point in the cell wall.

\[
F_m = \int_{-\pi/2}^{\pi/2} \frac{k_B}{R_1} \overline{B} \cos \theta \, d\theta ,
\]

but \( R_1 = R/\cos \theta \). Therefore,

\[ F_m \sim \overline{B} \frac{R}{R} . \]

Supergranular cells are about 25,000 kilometers across. The mean distance, \( R_m \), of a moving field element from the cell wall may be estimated as approximately 5,000 kilometers.

\[ F_m = k_2 \overline{B} \left( \frac{R_m}{R} \right) . \]

But

\[ F_n \sim v_s^2 . \]
Therefore,

\[ V_s = k \sqrt{\frac{B \left( \frac{R_s}{R} \right)}{}} \]

The constant, \(k\), which represents the relation between mean field strength and slip velocity in the above relation should be found. There are several ways of estimating \(V_s\), although exact values are not available. The force between two field elements of \(10^{18}\) Mx separated by \(10^4\) km is \(10^{12}\) Newtons as calculated in the introduction. The slip velocity required for a hydrodynamic force of \(10^{12}\) Newtons is about 0.3 km/sec (see introduction). If \(10^{18}\) Mx, the field felt by one of the elements, are spread evenly over an area \(10^4\) km in diameter the mean field strength, \(\vec{B}\), is approximately \(1/3\) Gauss. If no other field elements are present then \(k\) is approximately \(0.5\) km sec\(^{-1}\) Gauss\(^{1/2}\). Since additional field elements will contribute forces in other directions the vector addition will be less than the algebraic addition and \(k < 0.5\).

Near the supergranular border \(V_C = V_s = 0.4\) km/sec since field elements are held in place by the balance between drag and magnetic repulsion. A reasonable estimate of the mean field strength in the region near the cell border is about 32 Gauss, and \(R\) is approximately 5000 km. Thus, \(V_s = k \sqrt{B}\) yields \(0.4\) km/sec = \(k \sqrt{32}\); hence \(k = 0.07\). Then \(0 < k < 0.5\), and a reasonable order of magnitude estimate of \(k\) is 0.05.
Values of $V_s$ near 0.4 km/sec may be found in other ways. In the vicinity of an old spot the velocity of moving magnetic features is often about 1 km/sec (Harvey and Harvey, 1973). The gas flow is about 0.7 km/sec (Sheeley, 1972). Therefore, $V_s$ is approximately 0.3 km/sec.

The analogy between field element motions and the behavior of shallow water is sufficiently close so that relations developed for shallow water may be used to make approximate predictions of the behavior of field elements by only a few modifications in terminology. The shallow water equations that follow are from Thompson (1972).

In shallow water theory waves propagate at

$$C = \sqrt{gh}$$  \hspace{1cm} (a)

with $h^2$ (the square of the water depth) corresponding to a pressure term and $g$ the acceleration of gravity. If the water flow is highly turbulent an additional term will be needed.

If mean convective $V_c$ and mean slip $V_s$ velocities are independent then a disturbance in the field propagates at

$$C = \sqrt{V_c^2 + V_s^2}$$

Therefore

$$C = \sqrt{(0.25)^2 + (0.05)^2}$$
or,

\[ C = \sqrt{(0.25)^2 + \frac{3}{400}} \quad (b) \]

Note that the magnetic repulsion term dominates the convective term for \( B > 25 \) Gauss. In this analogy \( B^2 \) (the square of the mean field strength) corresponds to a pressure term and \( (0.25 \text{ km/sec})^2 \) corresponds to a turbulence term.

In shallow water theory the ratio, \( F \), of the local flow speed, \( u \), to the local wave speed, \( C \), is

\[ F = \frac{u}{C} \quad (c) \]

or

\[ F = \frac{u}{\sqrt{gh}} \]

The analogous ratio applied to magnetic fields is \( N \), the ratio of the local flow speed, \( u \), to the local wave speed

\[ N = \frac{u}{C} \quad (d) \]

or

\[ N = \frac{u}{\sqrt{(0.25)^2 + \frac{3}{400}}} \]
In shallow water the expression for the steady flow of water from a reservoir is

\[ \frac{h_o}{h} = 1 + \frac{1}{2} F^2, \quad (e) \]

where \( h_o \) is the water depth at the source, i.e.,

\[ \frac{C_o^2}{c^2} = 1 + \frac{1}{2} F^2, \quad (f) \]

where \( C_o \) is the phase velocity at the source. In this approach

\[ \frac{C_o^2}{c^2} = 1 + \frac{1}{2} N^2 \quad (g) \]

for magnetic field flow.

A parameter, \( \gamma \), may be defined

\[ \gamma = \frac{d + 2}{d}, \]

where \( d \) is the number of degrees of freedom of a particle.

The maximum possible flow velocity from a reservoir is

\[ v_{\text{max}} = c \sqrt{\frac{\gamma + 1}{\gamma - 1}}. \]
As can be seen from the plot (Figure 53), $V_{\text{max}}$ is often close to one km/sec.

Whenever a sufficient number of field elements are released in unit time then the motion takes the form of an organized flow. The maximum velocity of such flows is an increasing function of the local field strength and, thus, falls with distance from the active center. The field elements in front of such a flow will tend to be compressed. A compression wave will be created by each element as it emerges.

A disturbance propagating at $V_{\text{max}}$ appears to be the source of the fibrils around rapidly growing active regions. Under these circumstances wave motion is possible with the possibility of structures analogous to weak and strong shocks as well as other structures corresponding to steady flows.

As the amplitudes of disturbances increase structures analogous to shocks will form. If the manner in which shocks form from large amplitude disturbances is to be determined then the development of a dispersion formula is necessary. An approximate relation may be found by analogy with the shallow water relation which is

$$c^2 = \left(\frac{g\lambda}{2\pi} + \frac{2\pi\sigma}{\rho\lambda}\right) \tanh \frac{2\pi\lambda}{\lambda},$$

where $\sigma$ is surface tension and $\rho$ is density. If $\lambda$ is very large ($i.e., \lambda \gg 2\pi\lambda$) and $\lambda \gg 2\pi (\sigma/\rho g)$, then
NOTE: — — — flow velocity of field elements \( \left( c_0^2/c^2 = 1 + 1/2 \pi^2 \right) \)

FIGURE 53. Steady Flow Velocity From A Source (Plage or Sunspot)
\[ \tanh \frac{2wh}{\lambda} = \frac{2wh}{\lambda} , \]

and

\[ c^2 = \left( \frac{g\lambda}{2\pi} \right) \left( \frac{2wh}{\lambda} \right) , \]

which reduces to

\[ C = \sqrt{gh} . \]

In the general case, \( C = \sqrt{gh} \). In the shallow water case, \( c \) is \( g \).

The solar relationships are by analogy

\[ gh \Rightarrow \left[ (0.25)^2 + \frac{B}{400} \right] \]

and

\[ c^2 = \left\{ \frac{a\lambda}{2\pi} + \frac{2\pi \sigma_8}{\rho \lambda} \right\} \tanh \left\{ \frac{2\pi}{\lambda \alpha} \left[ (0.25)^2 + \frac{B}{400} \right] \right\} . \]

The term \( \sigma_8 \) would represent a property of the solar magnetic fields which is similar to surface tension of a fluid. When field elements are of the same sign the forces between field elements are repulsive and therefore \( \sigma_8 = 0 \).
If

$$\lambda \gg \frac{2\pi}{a} \left( (0.25)^2 + \frac{\bar{B}}{400} \right),$$

then this relation reduces to the formula we have previously derived,

$$c^2 = \left( 0.25 \frac{\text{km}}{\text{sec}} \right)^2 + \frac{1}{400} \left( \frac{\text{km}^2}{\text{Gauss-sec}} \right) \bar{B},$$

where $\bar{B}$ is the mean magnetic field strength and $c$ is the phase velocity in km/sec.

The shallow water analog of a shock wave is the hydraulic jump. Water depths on the upstream side of the hydraulic jump, $h_1$, and on the downstream side, $h_2$, are related to the rate that water approaches the jump by

$$\left[ h_2 - h_1 \right] \left[ \left( \frac{h_2}{h_1} \right)^2 + \left( \frac{h_2}{h_1} \right) - 2F_1^2 \right] = 0.$$

This expression was found under the assumption that the pressure distribution away from the hydraulic jump is hydrostatic. Under the assumption that the magnetic pressure near a magnetic jump is similar in its behavior to the hydraulic pressure near the hydraulic jump the expression for the magnetic jump is
This relationship is reasonable in that the water depth is proportion-
al to the amount of water present and the field strength is propor-
tional to the number of flux ropes present. The term $c^2$ may be either
positive or negative depending upon the direction of application of
force. Since $c^2$ corresponds to the depth of the water in shallow
water flow this quantity must always be positive for shallow water.
Magnetic fields, however, may be opposite in sign and thus attract.
Under these circumstances only two solutions of equation (1) appear
to have physical significance. If

$$c_2^2 = c_1^2,$$

then

$$N_1 = \pm 1.$$

Since the negative root is not of interest here, $N_1 = +1$, and thus
an infinitesimal disturbance will propagate at

$$c_1 = c_2 = c.$$
Fields of the Same Sign

Now consider a "moat" which shows on magnetograms as a region of low field strength around old spots.

The random component, $V_c$, of the velocity of field elements at the photosphere is created by two processes; supergranular flow and granular convection. In a region of low field strength (the moat) the random component, $C_1$, is about 0.25 km/sec due to granular flow. The flow velocity, $u$, of field elements in a moat is about one km/sec (Harvey and Harvey, 1973). Since $N = \frac{u}{C_1}$, $N = 4$. Solving equation (i) for the positive root yields

$$\frac{C_2^2}{C_1^2} = -\frac{1}{2} + \sqrt{\frac{1}{4} + 2N^2}$$

i.e., $C_2 \approx 0.6$ km/sec which requires that $B_2 \approx 120$ Gauss.

To find the value of $B_2$ at which the flow discontinuity disappears one must again consider the flow, $u$, upstream from the discontinuity. There will be no discontinuity if $u_1 < C_1$, for the observed value of $u_1$ of one km/sec.

At $B_2 = 120$ Gauss $C_1$ is determined by granulation since there are no supergranular cells in a moat and random magnetic effects are small. But at $B_2 = 375$ Gauss $C_1 \approx 1$, a value resulting mainly from local interactions between field elements. At $B_2 > 375$ Gauss then no discontinuity exists. Thus, $120g < B_2 < 375g$ if a discontinuity exists.

The value of 375 Gauss is interesting in that it suggests that moats will not form around younger spots so long as this value is exceeded. These values are accurate to the extent that the shallow water approximations remain accurate at these moderately high field strengths.
FIGURE 51. Conditions for Observer Moving with Shock Within Unipolar Region

$u_2 < c_2$ \hspace{1cm} $u_1 > c_1$

downstream \hspace{1cm} upstream

$|u_2 B_2| = |u_1 B_1|$
Fields of Opposite Sign

Conditions near neutral lines (where most prominences occur) may be studied. Most prominences move west with respect to the average velocity of the nearby photosphere. The appropriate solution for the motion of a prominence, since $C_2^2$ and $C_1^2$ are of opposite sign, is

$$\frac{C_2^2}{C_1^2} = -\frac{1}{2} \sqrt{\frac{1}{4} + 2N_1^2}.$$

Since many prominences occur in regions of relatively weak magnetic fields, $C_1 = 0.25$ km/sec. A typical prominence velocity is on the order of 0.1 km/sec with respect to the nearby photosphere. Therefore,

$$N_1 = \frac{1}{2}.$$

Solving for $C_2$ yields $C_2 = 1.2C_1$, and, therefore, if $B_1$ is small then $B_2 = B_1 + 10$ Gauss. Hence the fields on the east side of prominences should usually be on the order of 10 Gauss stronger than the fields on the west.

We have considered the case of flow discontinuities when the magnetic field in front of the disturbance is approximately zero. Now let us consider more general conditions.

Supercritical flows cover only a relatively small portion of the photosphere at any one time. Since $V_{\text{max}}$ is of the order of 2C or
less the energy in these flows is not sufficient to drive the whole
photosphere into supercritical flow. Therefore, at some location the
flow velocity must drop from supercritical to subcritical. The situ­
atation along neutral lines is different since the flows are in opposite
directions. Negative pressure-like terms are possible in this analogy
since fields of opposite sign attract.

The equation analogous to a shock wave equation is equation (1)
which has been solved and plotted on the following page (Figure 55).

This graph then may be used to summarize our conclusions. The
rather surprising result which can be seen from this plot is that all
flows associated with neutral lines behave according to the supersonic
analogy. The strength of the disturbance, however, depends upon the
ratio of field strengths across the discontinuity in the magnetic field
or magnetic jump.

As can also be seen from the plot, magnetic jumps are possible
without the requirement of a change in field sign. The magnetic
"moat" which Harvey and Harvey (1973) observe around some old spots
appears to be an example of this phenomenon.

To equate the moat with the shock-like disturbance described
earlier one must first show that a moat has the behavior of a stand­
ing wave.

The moat and the bright circular region beyond, which often sur‐
round older spots, appear to be similar to standing wave phenomena as
may be seen from the following arguments. If the total magnetic field
in a spot is $10^{21}$ Mx, and each flux rope has approximately $10^{18}$ Mx,
NOTE: if $B > 50$ gauss then $\left| \frac{c_2^2}{c_1^2} \right| = \left| \frac{B_2}{B_1} \right|

FIGURE 55  Propagation Velocity of a Magnetic Jump with Respect to the Undisturbed Photosphere
then we have approximately $10^3$ flux ropes per spot. For a spot which
decays during a period of 25 days following its period of maximum size,
and since the total number of field elements is about five times the
net flux emitted (Harvey and Harvey, 1973), an average of 200 field
elements are emitted per day.

At one km/sec field element velocity and a distance of 22,000 km
to the outer edge of the moat the number of field elements present at
any given time should average about 50.

A reasonable mean field strength for the bright region beyond the
moat is about 150 Gauss. A reasonable estimate of the area is about
equal to that of the spot. Therefore, the bright region can contain
only one or two days' emission of field elements at any given time.
These bright regions survive for from several days to a week or two.

Since the elements forming the bright region are continually re-
placed, the bright region has, at least in this respect, a property in
common with the hydraulic jump observed in a kitchen sink.

The model was derived on the basis of flux ropes slipping through
photospheric flow, not a flow in which field elements and gas move
together. This model is intended to be applicable only in regions
with mean field strengths below 50 Gauss. When

$$\frac{B^2}{8\pi} > \frac{1}{2} \rho v_c^2,$$

where $\rho$ is the photospheric density and $B$ is the mean field strength
at the photosphere, then the motion of field elements is an organized
flow approximately along field lines. Thus, the character of the flow changes with location from nearly random in the outer portions of active regions to highly organized in the central portions. This model is not intended to describe the properties of the region in which high field strengths exist.

In this model many of the changes which occur in active regions result from the changing behavior of sunspots. Early in the lifetime of an active region the spots act as sinks. Flux ropes migrate toward the spots at a relatively slow rate (probably no more than 1/2 km/sec). As the region ages, the spots begin to emit field elements under repulsion and the partial coupling between field elements and flow sweeps the flux concentrations away from the spots.

Observation and Theory

The purpose of this model is to attempt a closer correlation with observations than that found using Leighton's (1964) model. Let us then compare the predictions of the model to observations. Bruzek (1952) has shown that a disturbance associated with spot formation and propagating at about 1 km/sec is responsible for disparitions brusque. The initial expansion of the fibrils around large active regions also occurs at about 1 km/sec. Moving magnetic features in the vicinity of old spots also have velocities near 1 km/sec. A velocity of about 1 km/sec is then associated with large changes in field strength—as is predicted by the model.
The writer’s research suggests that some flares even at distances of 30 degrees heliocentric from large APS are induced by a disturbance traveling at about one km/sec. These flares are more probable in regions poleward and west of the AFS (see e.g., Figure 17, page 57). In the model this direction should be favored since the effect of differential rotation and spot motion would be to steepen the gradient of the disturbance in that direction. If spots were motionless with respect to the nearby photosphere then the greatest "compression" would occur at 45 degrees poleward from west. For spots moving west the maximum compression would occur at less than 45 degrees—and this is what is observed. The points in Figure 56 occur in pairs representing the line between adjacent active regions. Obviously such a diagram will have symmetry about its center. The points in Figure 57 represent the direction of the nearest active region from a flaring region. This plot is not symmetric. The maximum of flares actually occurs for regions about 20 degrees poleward from west from the AFS. In other words the flare occurrence probability is more sensitive to compression by spot motion and differential rotation than is the location of active regions.

Within active regions flow rates are often less than expected from Leighton’s model. Smithson (1973) estimates that they are about one-third the rate expected from Leighton’s model. The writer’s research shows that supergranule lifetimes increase with field strength, and the step time in Leighton’s random walk is determined by supergranular cell lifetimes. Therefore, a model with $C = \text{constant}$ is not
FIGURE 56. Line Between Centers of Nearest Adjacent Active Region Pairs (Each Point Represents One Member of Pair)
FIGURE 57. Direction From Flaring Region to Nearest Active Region
adequate for these regions. This behavior of active regions is consistent with flow from a source.

The writer's observations of magnetograms have shown consistently that for isolated active regions the magnetic field near the north-south oriented prominence is stronger on the east side of the prominence as was predicted by the model.

These north-south oriented prominences are much more likely to be associated with flares than are east-west oriented prominences. This is consistent with the hypothesis that fields are being swept up by north-south oriented prominences (see e.g., Figure 34).

Bright points in the plage outside of a moat in an old active region were observed to be moving at velocities less than or equal to 0.25 km/sec (most were less). Thus, a moat represents a discontinuity in the flow velocity of field elements. During the lifetime of a moat the field elements in the outer border are changed several times. Therefore, it is more appropriate to think of the moat as a stationary wave than as a fixed feature.

Flare activity tends to migrate toward the leader spot as regions age. The location and time are consistent with a correlation between the rate of approach of field elements to a neutral line and the rate of occurrence of flares near that location.

Neutral lines are usually found nearer follower spots than to leaders. This is consistent with the hypothesis of westward moving spots if field elements away from spots are assumed to move with the surrounding photosphere and not with the spot.
Spots have a tendency to be elongated east-west. Follower spots are more likely to have random orientations than are leaders. Elongated spots are not oval but instead usually have a rounded leading edge and a more pointed trailing edge. The difference in behavior between follower and leader spots appears to result from differences in the velocity of the spots with respect to the nearby photosphere. Such relative motion is an essential element of the model.

An appreciable fraction of all prominences (about 1/4) have their westward ends closer to the pole than the eastward end. These prominences usually define the poleward-eastward corner of the fibrils around an active region. Around many complexes there are large prominences which move poleward for months, receiving a new impulse each time a new active region forms in the complex (see Figures 42 and 43, pages 99 and 100).

If photospheric fields are to interpenetrate (as in Leighton's model) then fields a few thousand kilometers above the photosphere must interpenetrate as well. This means that the random walk process must operate through prominences. For this model (in distinction to Leighton's) field elements may only pass through prominences with difficulty since the prominence itself in the model has the mathematical character of a shock wave and, thus, should represent a discontinuity in the field. If random motions occur in the chromosphere near the prominence they will tend to destroy this structure. Kleczek (1964) has studied random motions of chromospheric structures in the vicinity of a large quiescent prominence. He found that these velocities are
suppressed and that the suppression appears to increase with height in the chromosphere.

Speculations and Suggestions for Future Work

Since the solar network appears to give no indication of the emergence of new active regions until they actually begin to penetrate the photosphere, precise prediction of specific AFS is not possible with our present understanding of solar physics. At best, then, one can estimate the probability of new activity at any location by averaging the mean field at that location over two consecutive three-month periods. Then new active regions are expected at those locations with the greatest field strength and with the greatest increase in field strength between these two periods. Since roughly 100 AFS occur per year (depending on the phase of the sunspot cycle), new active regions should be forecast during most weeks. The persistence of repeated activity at and near the same sites suggests that quantification is possible. This problem of determining the time of appearance and location of new activity is the most critical problem at present if we are to improve flare forecast accuracy. Computer-generated maps of AFS-prone regions would be of use as an initial step in the development of improved forecast techniques.

No one is at present forecasting AFS using any technique. The reason is that some studies suggest that AFS times and locations are, at least in part, random.

A significant improvement over the assumption of randomness is
the assumption that AFS probability, \( P \), at any location may be estimated from

\[
P = k_3 \bar{B} + k_4 \frac{\Delta \bar{B}}{\Delta t},
\]

where \( k_3 \) and \( k_4 \) are constants, \( \Delta t \) is the time interval (> one month) used, and \( \bar{B} \) is the local mean field strength averaged over a ten degree square and the time interval.

Obviously, \( k_3 \) and \( k_4 \) require evaluation. Their value depends upon the size distribution of AFS and the mean interval between AFS in an active complex. The logic behind this approach is persistence. The rate of approach of new flux to the photosphere is assumed to be similar to the past rate corrected for the change in rate. Persistent processes appear to be associated with the very long-lived giant cells and with the active longitudes which appear to result from the giant cells.

The model may be used to assist in the flare forecast process following AFS emergence.

A good approximation may be found by one of two approaches.

1) One can empirically estimate the interval from the time a prominence is first influenced by a propagating disturbance until a flare or disparition brusque occurs.

2) The probability of a flare is a function of the stored energy (as a result of the flow of flux near the neutral line) and the strength of a disturbance.

The distortion of field from a potential field is a measure of
the amount of electric current present. As field elements move toward
the neutral line electric currents are created which tend to twist the
field. The distortion is a cumulative effect, essentially proportion­
al to the total flux brought to the neutral line minus the amounts
destroyed by previous flares and by reconnection.

Two methods of applying the second approach to predict flares
are:

(1) The numerical approach in which rates of approach of flux
ropes to neutral lines are calculated.

(2) The qualitative approach in which results which should fol­
low from (1) are used without calculation. Some of these
are:

a. Flare activity occurs in prominences outside of ac­
tive regions as a result of a disturbance propagat­
ing away from an intense active region which may be
many degrees heliocentric from the flare. This ac­
tivity is preceded by increased prominence growth
and increased prominence density prior to the flare.
In any case, this interval from the passage of the
disturbance is, at most, one or two days.

b. Many Class 2 and larger flares occur in regions which
are from two to four weeks old whenever new active
regions form approximately five degrees toward the
equator and approximately 15 degrees east of the older flar­
ing regions. The probability of a Class 2 flare in
the older region rises steadily with the rate of ex­
pansion of the new region. The flare in the older
region is initiated by a disturbance traveling be­
tween one km/sec and 0.25 km/sec propagating from
the new AFS.

Numerical Forecasting

Assume that in regions of average fields less than five Gauss
and away from neutral lines, relatively small changes in field strength
propagate precisely as Leighton (1964) has stated. As field strengths
rise the structure of the region becomes longer lived and more rigid. This implies a change in the step time of any random walk process dependent upon supergranulation and thus implies a change in the propagation velocity of disturbances in the field. Two attitudes toward this problem are possible. If one takes the point of view that the field propagation velocity changes as a result of changes in the cell lifetimes then it is possible to devise diffusion rates which vary smoothly from 0.25 km/sec in regions of low field strength to almost zero at the spots. On the other hand, one may treat the problem as one of flowing flux ropes among relatively fixed features, as has been done here. The flow velocity of the moving elements then becomes of greater significance than the lifetimes of cells. In fact, the very existence of a coherent network becomes irrelevant so long as the scale of the flows and the time scale for changes in the flow may be estimated.

A very simple study which would require a minimum of equipment would be to draw or photograph spots on as large a scale as possible for a period of several months and then to plot spot motions versus the motion of the photosphere as determined from Doppler studies. Studies of spot motions relative to other spots are not adequate for flare prediction in that field element motions are, at least in part, determined by the motions of the photospheric plasma. The major result of such a study would be to give us enough spot motion data so that spot motions could be better related to other solar phenomena.
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than at present. Old spot data are not suitable since the related flare data are usually incomplete. The relations between spot motion and prominence locations, spot motion and the occurrence of flares, and spot motion and plage structure are not always clear at present. A computer solution of this or some similar diffusion model should be tried. To be useful for flare forecasting such a model must include some of the interactions between flux ropes. The model used might begin with the region just after the spots had moved enough so that the rates and direction of movement could be determined. The total flux present would be estimated using magnetograms of the region. Then computer generated magnetograms of the region would be made for a period of several days with the amount of flux reaching different portions of the neutral lines determined. A technique for estimating the storage capacity of that portion of the neutral line would be developed. The maximum possible flare size appears to grow for several weeks after AFS emergence exists but the time interval between the larger flares becomes greater as a region decays. Older regions have relatively few small flares. As an example, consider region 21034 (Brueck, 1969) (plotted in Figure 44, page 102).

Very large prominences oriented north-south heliocentric and located across the equator or in active region latitudes often appear near the site of large flares. In some cases the flare occurs in the prominence but often in an associated active region.

Observation suggests that there is a definite decrease in major flare activity of regions following large flares (see Figure 58).
(Note the increase in flare activity preceding the Class X flare)

FIGURE 58. Short-term Flare Development Pattern of Class 2 Flares in August 1972
This decrease to a low level of activity takes several hours during which a second flare may occur near the site of the first, apparently triggered by changes in the region associated with the first flare. Smaller flares do not appear to significantly deplete regions.

The descending branch of the sunspot cycle shows considerably more proton flare activity than the ascending branch (Krivsky, 1972). In the course of plotting Figure 13, page 51, the writer noted some tendency for flares late in the cycle to be related to AFS in the opposite hemisphere.

The model may be related to the problem of the inconsistent rotation rates of the sun when different techniques are used. For example, spots give a rotation rate about 100 m/sec faster than Doppler measurements of the surrounding photosphere (Foukal, 1972). The upper portions of prominences often rotate more rapidly than the lower (Dodson-Prince and Mohler, private communications, 1973). The upper portion appears to be strongly influenced by coronal magnetic fields while the lower parts are more strongly influenced by the local photospheric flow. Foukal (1972) argues that the westward motion of enhanced field features is caused by magnetic coupling to a layer some 5000 km below the photosphere. The tendency of the upper ends of prominences to lean west with respect to their bases suggests another possibility, that the upper portions are being pushed west by magnetic fields associated with the spots and that the bases are being dragged eastward, relatively speaking, by the relatively slowly rotating photosphere.
A possible interpretation of flare growth patterns may be given by modifying the frustrated surge hypothesis of Roberts and Billings (1955). They assumed that the strong fields over an active region were capable of stopping a surge. The kinetic energy of the surge would then manifest itself as heating of the coronal gas. If, instead, a flare is assumed to be a chain reaction of surges in which each surge tends to disturb its surroundings, then it is possible to interpret such flare features as (1) the strong tendency of flares to be associated with vertical magnetic fields; (2) the tendency of flare activity to occur simultaneously at the ends of magnetic arches; and (3) the large amounts of plasma sometimes observed over flares, in some cases leading to the formation of large loop prominences.

The points at which a flare may be first expected to brighten are those at which the magnetic field structure is most similar to that at the base of a surge.

Flare brightness and rise time are to some extent related (see Figure 59). Rise time and X-ray class are to some extent related (see Figure 49, page 108).

McIntosh (1970) has indicated that in one complex several regions appeared at 56 day intervals. The writer's studies (see Figure 60) confirm the relatively long intervals between the appearance of major activity. Major active regions in a complex are usually separated by 25 to 60 day intervals. Complexes in which the time interval between AFS is growing and simultaneously larger spot groups are appearing may be evolving toward the appearance of a large region. Conversely, the
FIGURE 59. Flare Brightness and Rise Time
FIGURE 60. The Interval Between the Occurrence of Major Active Regions and Previous AFS in a 20 Degree X 20 Degree Area.

REMARKS: Estimates made of regions appearing behind disk.

Moses + McIntosh 0 (McIntosh, 1970)

Note: Moses' sample is of larger regions than McIntosh since not all small regions were included in it.
appearance of smaller regions more closely spaced in time represents a typical mode of decay for an active complex.

Smithson (1973) and Moses (1974) have shown that under some conditions the rate of diffusion of flux ropes in enhanced field regions is less than 0.25 km/sec. Thus, any model should account for variations in the rate of spreading of fields.

This model is in no sense complete. It does not adequately describe spots, or regions with strong electric currents. Although the spreading of field with height is implied, the effects of twisted fields are included only implicitly and only near neutral lines. The model represents an attempt to describe the moderate and low field strength portions of active regions with sufficient accuracy so that initial attempts at forecasting some flares will be possible.

Although viscosity in the chromosphere has not been included in the expressions it probably does have observable effects.

It is hoped that eventually a program will be developed (based on Leighton's) in which a diffusion process will be modified by interaction as a function of properties of the region. The results of such a program (neutral line locations, local field strengths) would then be compared with observation until a function adequately describing the interaction was found.
APPENDIX I

Approximately two thousand photographs were taken using the filter system described in the observation section. Plate VI is one of those photographs. The limb brightening observed on Plate VI is due to dodging in the printing process. The photographs were used in conjunction with CaII K spectroheliograms and off-band Hydrogen alpha spectroheliograms in order to make estimates of supergranular cell lifetimes.
PLATE VI

A 3800 Ǻ SPECTROHELIОGRAM
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