MAGNETIC FLUX TRANSPORT OF DECAYING ACTIVE REGIONS AND ENHANCED MAGNETIC NETWORK

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Abstract. Several series of coordinated observations on decaying active regions and enhanced magnetic network regions have been carried out jointly at Big Bear Solar Observatory (BBSO) and Huairou Solar Observing Station of the Bejing Astronomical Observatory in China. The evolution of magnetic fields in several regions was followed closely for 3 to 7 days. The transport of magnetic flux from the remnants of decayed active regions was studied. Three related topics are included in this paper. (1) We studied the evolution and lifetime of the magnetic network which defines the boundaries of supergranules. The results are consistent with our earlier studies: network cells have an average lifetime of about 70 hours; 68% of new cells appeared by growing from a single network magnetic element; 50% of decaying cells disappeared by contracting to a network element. (2) We studied the magnetic flux transport in an enhanced network region in detail, and found the diffusion rate to be negative, i.e., there was more flux moving towards the decayed active region than away from it. We found several other cases where the magnetic diffusion rate does not agree with Leighton's model. The slow diffusion rate is likely due to the fact that the average velocity of larger magnetic elements, which carry most of the magnetic flux, is less than 0.1 km s^{-1}; their average lifetime is longer than 100 hours. (3) We briefly described some properties of Moving Magnetic Features (MMFs) around a sunspot (detailed discussion on MMFs will be presented in a separate paper). In this particular case, the MMFs did not carry net flux away from the central spot. Instead, the polarities of MMFs were essentially mixed so that outflowing positive and negative fluxes were roughly balanced. During the 3-day period, there was almost no net flux accumulation to form a moat. The cancellation of MMFs of opposite polarities at the boundary of the super-penumbra caused quite a few surges and Hα brightenings.

1. Introduction

Supergranulation was discovered by Leighton, Noyes, and Simon (1962), who found that the photospheric network, chromosphere network and network magnetic fields correspond to the boundaries of supergranules. Later, Leighton (1969) proposed that supergranules play an important role in the magnetic field evolution of the solar cycle, that the magnetic flux of active regions is transported into quiet regions by a random walk of supergranules. Two parameters are important in studying the supergranular convection pattern and the transport of magnetic flux: (1) the mean lifetime of supergranules and, (2) the magnetic diffusion rate.

In the pioneering study of Leighton, Noyes, and Simon (1962, also Simon and Leighton 1964), the lifetime of supergranules was found to be 20 hours. Other authors found longer lifetimes of 30 to 40 hours (Smithson, 1973; Worden and Simon, 1976;

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Duvall, 1980; Janssens, 1970). However, the above studies are based on the correlation study of velocity fields or network magnetic fields. In a previous paper (Wang and Zirin, 1989), we pointed out that a correlation study tends to underestimate the average lifetime of cells. Also, because of subtle changes of magnetic structures, it was difficult to identify cells from one day to the next. The round-the-clock magnetograph observation of BBSO and Huairou Observatory in China provides a new avenue to study the evolution of magnetic network and supergranule cells. Using the first nearly continuous data, Wang *et al.* (1989, hereafter referred to as Paper I) studied the evolution of supergranule cells and found the lifetime to be longer than 70 hours. In this paper, we study this subject further with several observing runs spanning 70 to 170 hours.

The magnetic diffusion constant is an important parameter to describe the decay of active regions. In Leighton *et al.*'s earlier studies (1962, Simon and Leighton, 1964; Leighton, 1969), they considered the magnetic flux transport from active region by the random walk of supergranules. Based on the average size (d) and lifetime (t) of supergranules, they estimated a diffusion constant (D) of 1600 km^2 s^{-1} by the formula $D = d^2/t/2$. Mosher (1977) constructed a diffusion model which, when applied to the cross-correlation curves of Hα and CaK network, gave a diffusion constant of 200 to 400 km^2 s^{-1}. Applying Mosher's technique to recent BBSO videomagnetograph (VMG) data, Wang (1988) found a diffusion constant of only 100 km^2 s^{-1}. However, all of the above studies were based on at most 12-hour series of observations. Continuous observation of a much longer duration on decaying active regions should provide more accurate information and shed light on the true diffusion constant. In Paper I, the authors found that during a 75-hour period, there was no net flux transported from the active region under study to the nearby quiet Sun. Instead, a substantial amount of flux flowed back towards the neutral line of the active region and disappeared there by cancellation. In that case, the diffusion constant was imaginary. In this paper, we present results of our further study on the subject of flux transport.

Finally, we discuss the roles of Moving Magnetic Features (MMFs) in the evolution of an active region. It has been suggested that MMFs are the initial step in transporting flux away from a decaying sunspot. Some flux from MMFs with the same polarity as the central sunspot usually accumulates in a ring-like moat around the central spot (Harvey and Harvey, 1973; Vrabec, 1974). An excellent movie of MMFs was obtained jointly by BBSO and Huairou Observatory. In this paper we briefly discuss some properties of MMFs and their chromospheric manifestations.

2. Data Collection

Two similar videomagnetograph systems at Big Bear and Huairou are the basic instruments for our coordinated observations. The telescopes and the VMG systems were discussed in detail in Paper I and the references quoted there. Besides the first observing run of September 1987 (Paper I), we have obtained and analyzed data for three more observing runs on six different regions in May 1988, July 1988 and March 1989. The March 1989 run observed the super-active region BBSO No. 1469, the results of which

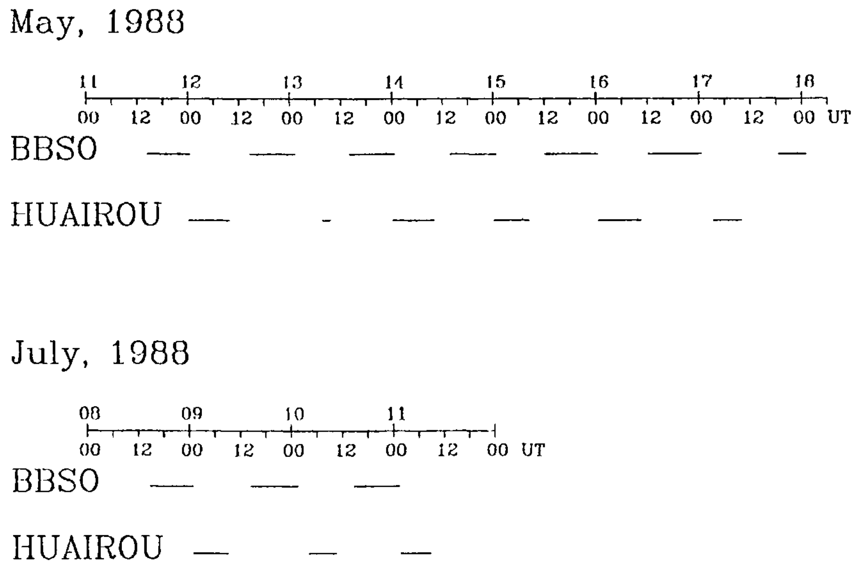


Fig. 1. The time table of the May 1988 and July 1988 runs. The horizontal bars show the observing periods of BBSO and Huairou Observing Station.

will be discussed in a separate paper. Figure 1 shows the time table of the May and July 1988 runs.

The target of the May 1988 run was an enhanced network region. The Kitt Peak daily magnetogram shows the region to have formed in the previous month. All the original sunspots had already disappeared when the region re-appeared on the East limb on May 10, 1988. The observing run spanned 155 hours with 6 night gaps of an average length of 5 hours. The time resolution was about 20 min. (The actual time resolution of BBSO magnetograms is 1 min, but we find this 20-min interval suffices for long-term studies.)

The July 1988 run observed 4 adjacent areas: an active region and 3 quiet regions. The telescopes were moved successively from area to area throughout the observing run. The period of one-cycle which covered all the four areas is 20 min. A total of 72 hours of observation were achieved for this run. The images are digitally recorded on magnetic tape.

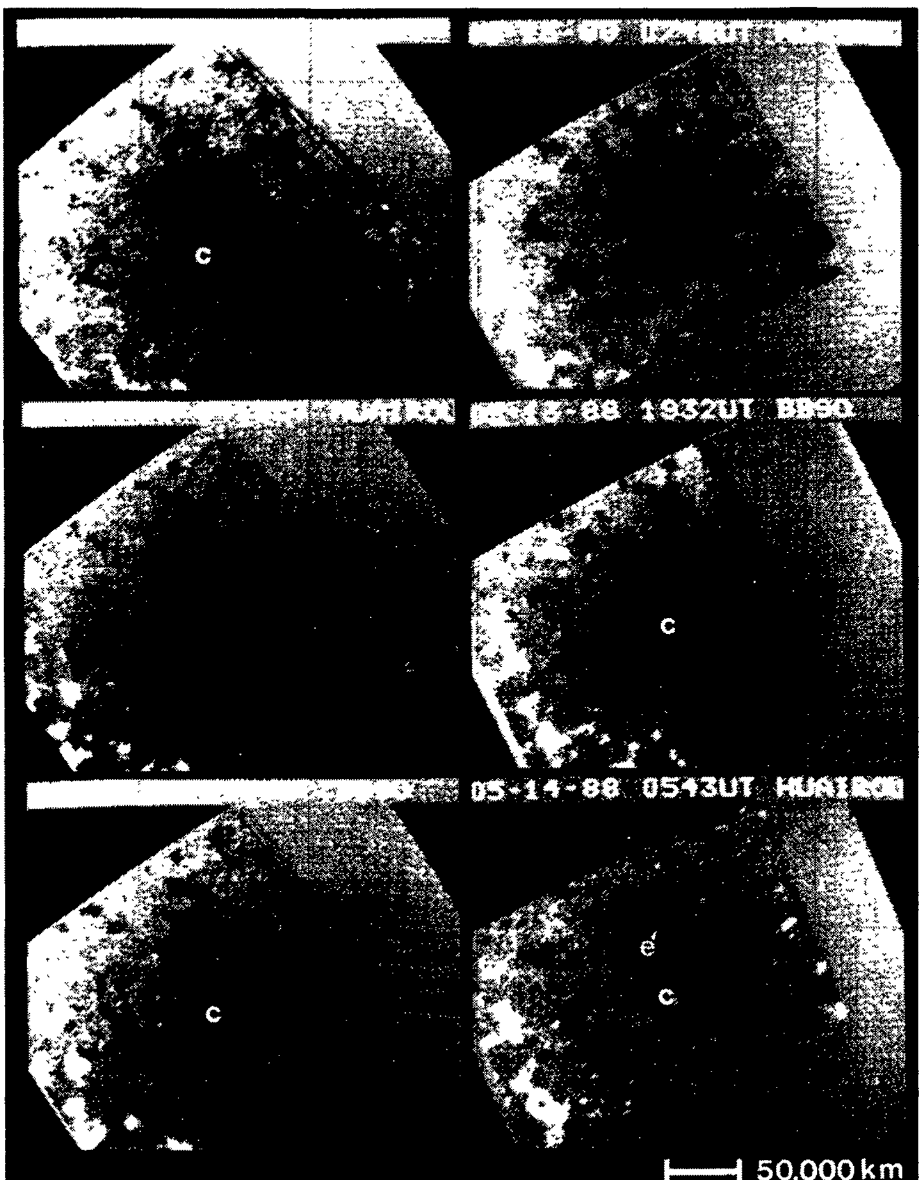
All the magnetograms then went through standard analysis procedures. (1) re-registration; (2) limb-darkening corrections; (3) geometric foreshortening correction, and (4) sensitivity correction. Details of the corrections were explained in Paper I. After the correction, the image scale is $0.75'' \text{pix}^{-1}$, and the overall field of view is 380 by 380 arc sec. Both the film and video movies were made from the processed images.

3. Evolution and Lifetime of Supergranule Cells

There are three possible methods to derive the lifetime of magnetic network which outlines the boundaries of supergranule cells. (1) Calculating the cross-correlation coefficients for the VMG images, and defining the e-folding time of the cross-correlation as the correlation lifetime of network cells (Simon and Leighton, 1964; Wang, 1988).

(2) Counting the ratio of the number of surviving cells to the total number of cells as a function of time. The e-folding time of the ratio would give the average lifetime of the cells (Paper I). (3) If the observing run is long enough, identifying and tracking each cell from birth to death; then the average lifetime of these cells can be derived directly by averaging lifetimes of individual cells. The May 1988 run had continuous coverage of 155 hours, so we can apply method (3) in this case.

Since the magnetic network only defines the boundary of supergranule cells, changes in the shape of cells will cause the cross-correlation coefficient to decrease rapidly. Therefore, method (1) tends to underestimate the lifetime of supergranules. Methods (2) and (3) can give not only the average lifetime of network cells, but also the detail of magnetic network evolution. Furthermore, method (3) provides the distribution of supergranule lifetimes. However, the shortcoming of these two methods is that the criterion to define the birth or death of a cell is partially subjective.



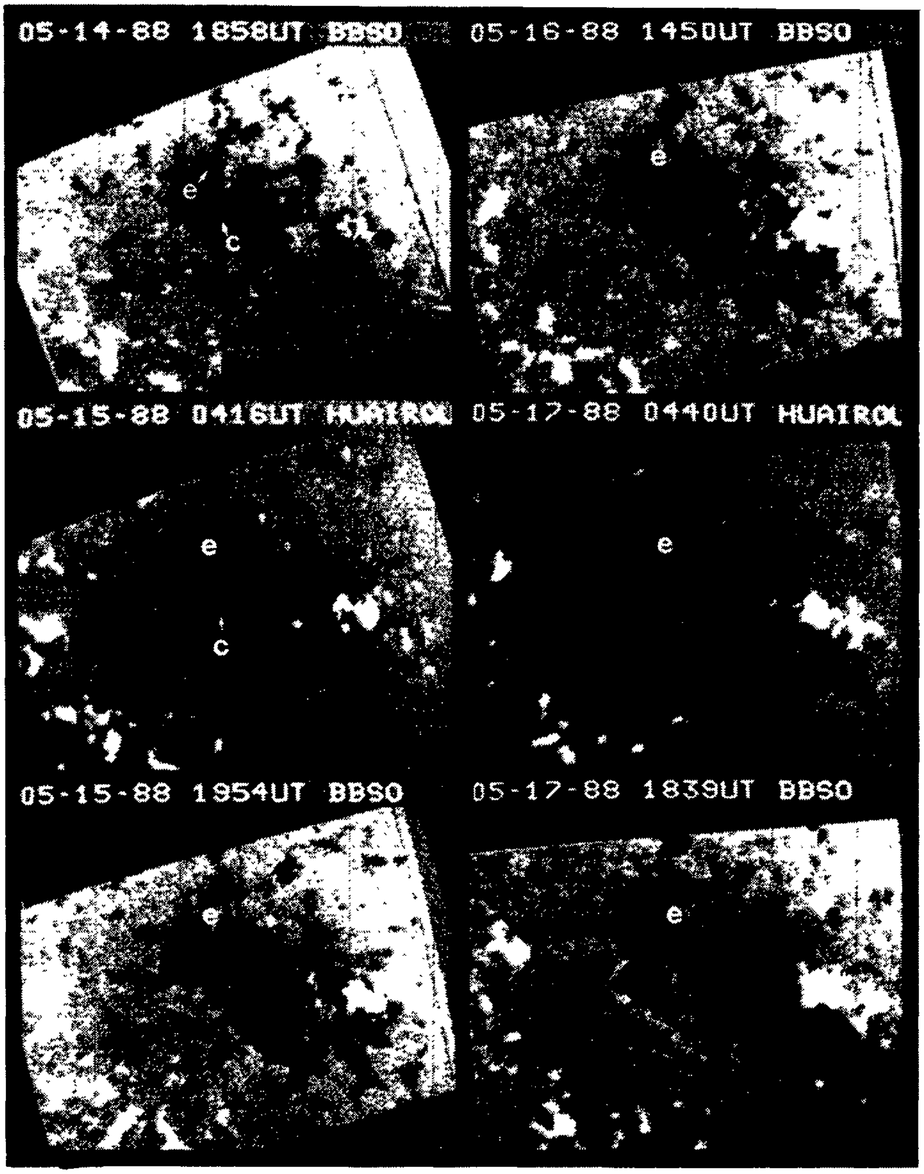


Fig. 2. Selected excepts of magnetograms show the magnetic field evolution of an enhanced network region from May 12 to 17, 1988. All the pictures shown in this paper have the following orientation: *top:* south; *right:* east.

Due to the scarcity of magnetic flux in quiet regions of mixed polarity, we experienced difficulty in defining the magnetic network. However, the magnetic network in the enhanced network regions can be defined quite well. In a previous study, we showed that the correlation times of supergranule velocity cells are similar in mixed polarity regions and in enhenced network regions (Wang and Zirin, 1989). We, therefore, expect that the lifetime-study of enhanced network would represent all the supergranules on the quiet Sun reasonably well.

Figures 2(a) and 2(b) show a sequence of selected magnetograms from the May 1988 run. We obtained the following results from the study of this region.

3.1. Evolution of the cells

3.1.1. *Decaying Cells*

We followed 32 magnetic network cells which disappeared during the observing period from May 11 to May 18, 1988. Figure 3 shows the various observed ways that cells disappear as well as the relative distribution of these categories.

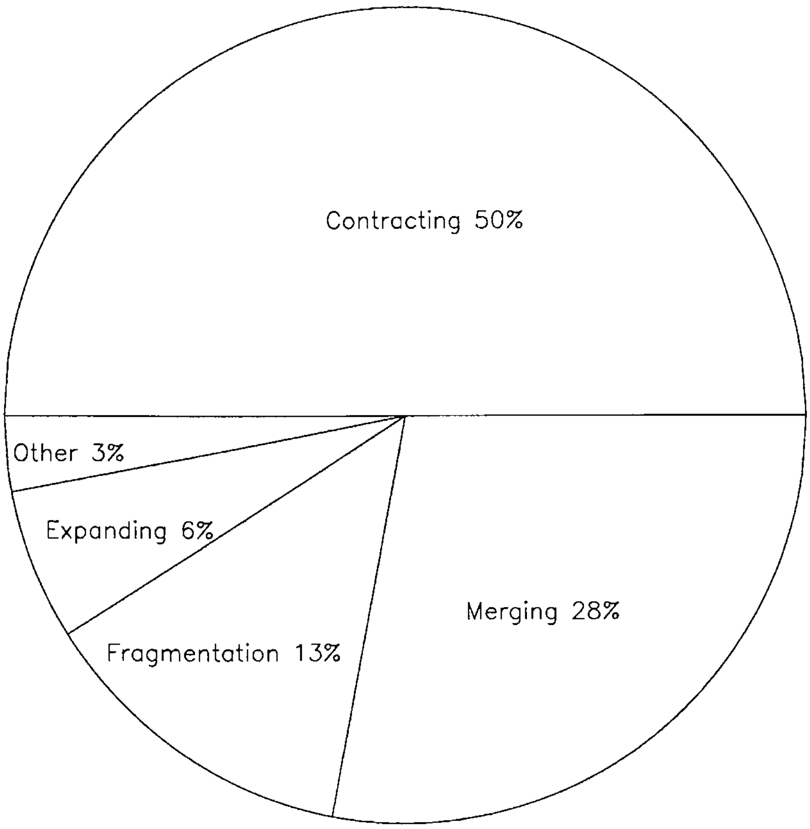


Fig. 3. Relative distribution of the ways that supergranule cells decay.

(1) Contracting. The opposite sides of the network cell collapse, the area of the cell decreases continuously, and finally the cell is replaced by converging pieces of magnetic network elements. The typical rate of contraction for a cell is 1000 $km^2 s^{-1}$. The cells may contract after a decrease in the convection velocity, reducing the total pressure within a cell. Other cells push in with a greater pressure. Fifty percent of cells disappeared in this way. The cell marked as 'c' in Figures 2(a) and 2(b) gives an example of a contracting cell.

(2) Merging. The magnetic flux elements located at the boundary dividing two cells gradually move away, so that the two cells apparently merge into a new cell. Note, the magnetic network defines only the boundary of the cells. The disappearance of the dividing boundary between two cells does not necessarily mean that the two cells change their flow patterns and become one cell. In this case, we might underestimate the lifetime

of some cells. A simultaneous continuous velocity observation would answer this problem. In the present study, we found that 28% of cells became unidentifiable in this way.

(3) Fragmentation. A cell is apparently fragmented to two or more smaller cells. Thirteen percent of cells belong to this category.

(4) Expanding. A cell keeps expanding, until it becomes too big and the field at its boundary becomes too weak to define the cell. Six percent of cells belong to this category.

We then analyzed the network cells which survived as a function of time. The result, plotted in Figure 4, is based on the May 11–18 observation. The master frame (the frame

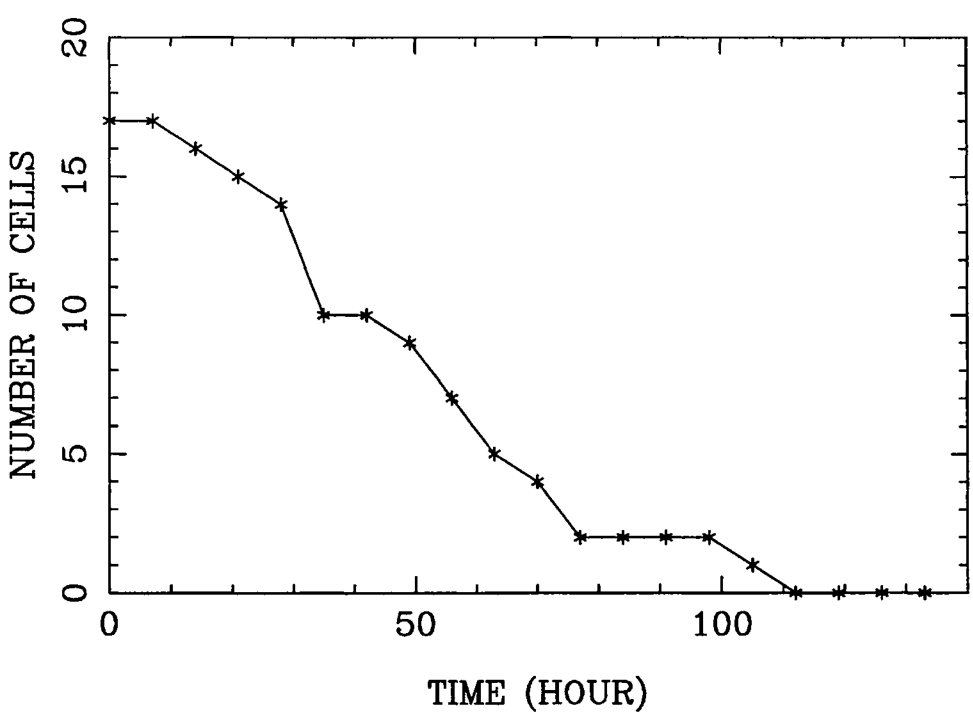


Fig. 4. Number of cells which survived as a function of time. The e-folding time gives the average lifetime of magnetic cells.

at time 0 in Figure 4) was obtained at 14:00 UT May 11. The e-folding time is 66 hours, which is slightly smaller than the value (80 hours) given in Paper I.

3.1.2. *Growing Cells*

We study the properties of growing cells in a manner similar to our study of decaying cells. However, if we ran the movie forward, we usually find more features disappearing than appearing. In order to avoid any bias, we ran the movie backward instead of forward to study the growing cells. In a backward-running movie, any cell which disappears during the period covered by a movie is actually a growing cell.

Using this technique, we identified 25 new cells in this region. Figure 5 shows the relative distribution of the observed ways that new cells form.

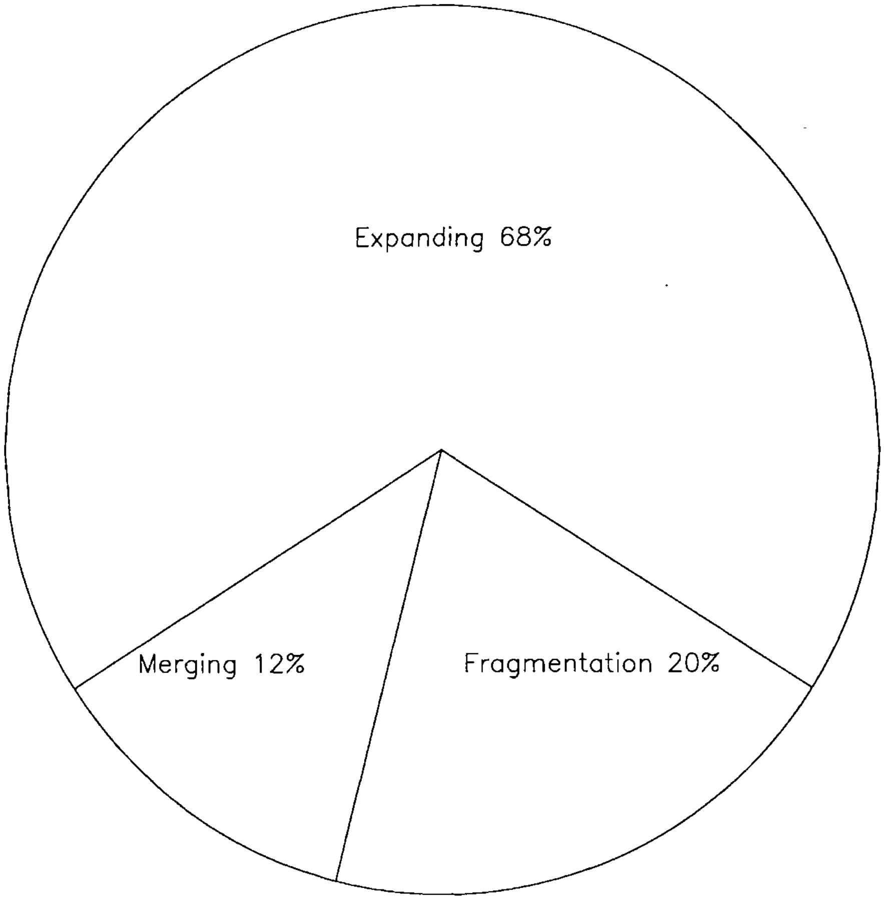


Fig. 5. Relative distribution of the ways that a new supergranule cell forms.

(1) Expanding. A cell appears in the midst of a piece of network magnetic element and grows steadily until it becomes a normal size network cell. This is opposite to the contraction process of decaying cells. 68% of cells formed in this way. The cell marked '*e*' in Figures 2(a) and 2(b) gives an example of an expanding cell.

(2) Fragmentation. A cell is formed by subdivision from a parent cell. Twenty percent of cells are formed in this way.

(3) Merging. A cell is formed from the merging of two original cells. Twelve percent of new cells belong to this category.

It is interesting that a majority of new cells are formed by expansion from a magnetic element. This agrees with the Hα network study by Janssens (1970). This means that most cells (possibly all cells) originate at the network boundary of pre-existing cells.

We found that more than half of the cells disappeared by contracting, and on the other hand, more than half of the cells appeared by expanding. However, these two categories try to avoid each other; i.e., an expanding cell usually does not decay by contracting.

3.2. Lifetime of the Cells

Our previous studies show that the average lifetime of magnetic network cells is between 60 to 80 hours (Wang and Zirin, 1989; Wang *et al.*, 1989). However, none of the observing runs were long enough to follow individual cells from birth to death. During the 155 hours of observation in May 1988, we were able to follow 16 cells for their entire lifetimes. Figure 6 shows the distribution of the lifetimes of these cells. The lifetime of cells ranges from 20 to 130 hours. The average lifetime is 66 ± 28 hours, consistent with the result of Section 3.1.

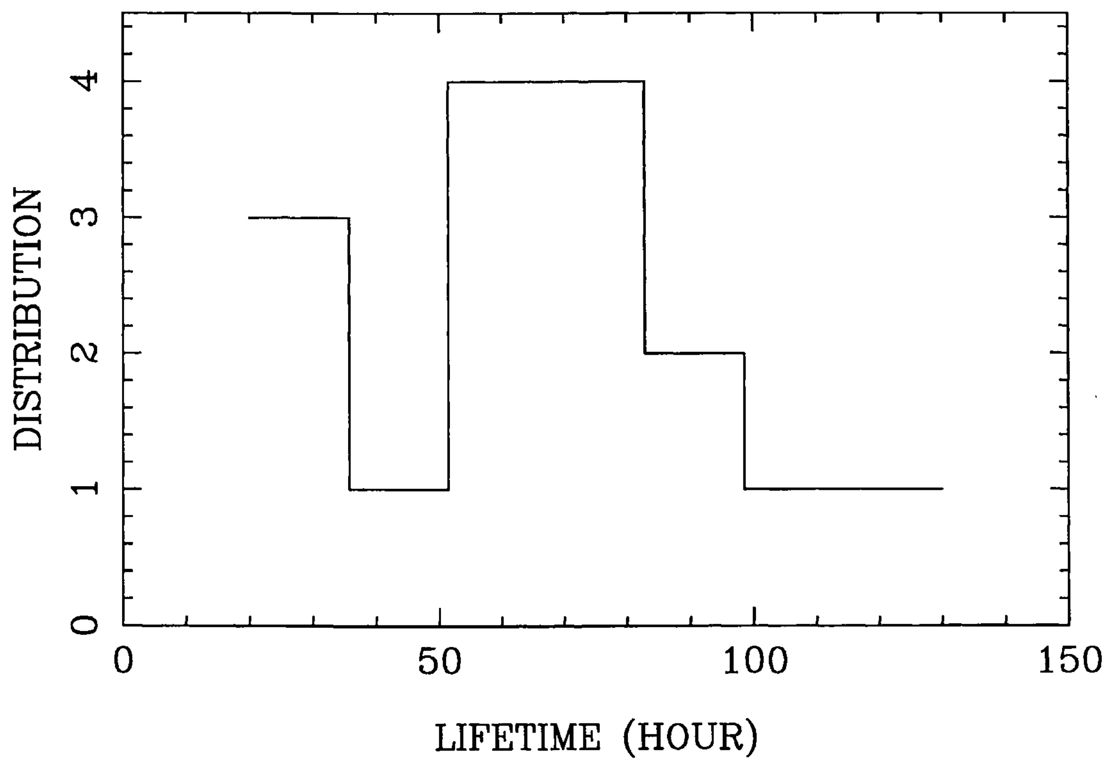


Fig. 6. Histogram to show the distribution of supergranule cell lifetime. The result was obtained by following individual cells from the beginning to the end of their life.

Our studies once again show that the lifetime of magnetic network cells is much longer than 24 hours. If the magnetic diffusion is principally due to a random walk of supergranules, then a longer supergranule lifetime means a slower magnetic diffusion rate.

In Figures 2(a) and 2(b), there are two other features worth noting. (1) Continuous flux cancellations across the neutral line dividing large scale positive and negative magnetic fluxes. This subject has been studied by Martin (1990). (2) An Emerging Flux Region (ER1 in Figure 2(b)) appeared during our observing run. It provides a good opportunity to follow the EFR from a very early stage. This EFR is under study by Martin and Kong (1990).

4. Magnetic Diffusion Rate

The magnetic diffusion constant is an important parameter in understanding the breakup and transport of active region magnetic fields. In Leighton's (1969) solar cycle model, he proposed that the magnetic diffusion is principally due to a random-walk process by the supergranulation. A diffusion constant of 1000 km^2 s^{-1} would fit Leighton's model. However, Mosher (1977) found a diffusion rate of 300 km^2 s^{-1} and Wang (1988) found a value of 100 km^2 s^{-1}. In Paper I, we followed magnetic elements of a decaying active region for three days, and found that no magnetic flux was transported away from the active to the quiet region. Instead, a substantial amount of flux retreated to the neutral line which divides the leading and following polarities of the active region, and cancelled there. The cancellation was the major source of flux disappearance in that region. In the May 1988 run, we followed magnetic elements in an enhanced network region for 155 hours, so we can study the transport and the diffusion of magnetic fields in more detail.

In this section we use the data from the May 1988 and July 1988 runs and concentrate on the following topics: (1) and estimate of how much flux transported was towards and away from the enhanced network region. (2) The evolution and motion of individual magnetic elements. Their average lifetime and velocity provide the basic information on the diffusion rate.

Figure 7 shows a magnetogram obtained at 19:52 UT, May 15, 1988 on an enhanced network region. Two white lines in Figure 7 roughly outline the boundaries of the enhanced network region and the undisturbed quiet Sun.

We counted all the flux elements and measured their fluxes as they moved inward and

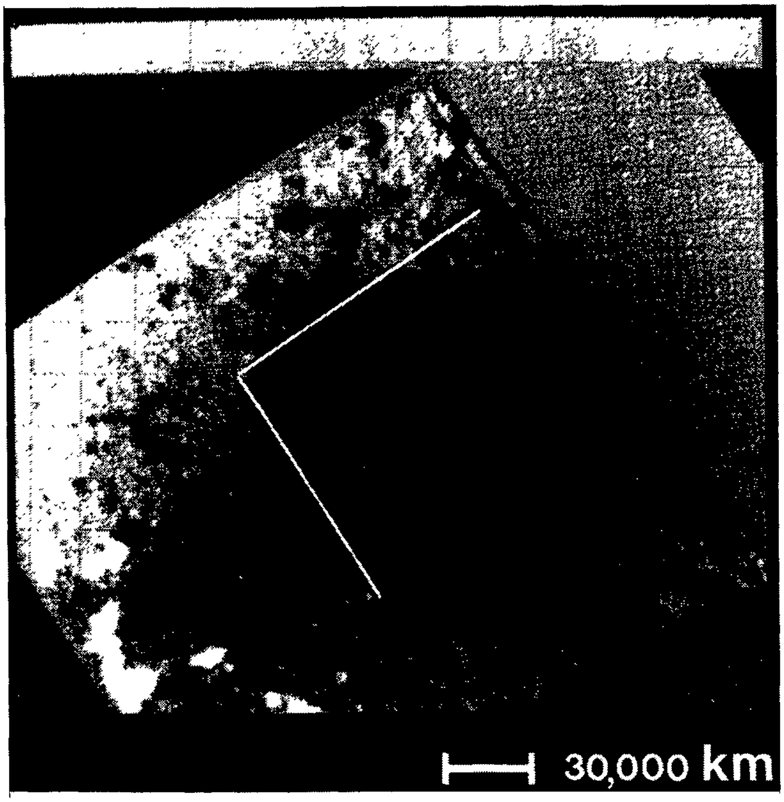


Fig. 7. A magnetogram at 19:52 UT, May 12, 1988. Two lines show the assumed border between the enhanced magnetic network (a newly fragmented active region) and the undisturbed quiet region.

outward across the borders shown in Figure 7. During 155 hours, the total flux crossing the borders moving outward and away from the enhanced network region is 3×10^{20} Mx; however, the total flux crossing the borders and moving into the region is 8×10^{20} Mx. So the enhanced network region gained 5×10^{20} Mx of flux from the quiet-Sun background during the 155-hour period.

On the other hand, let us estimate the flux transported away from the enhanced network region in accordance with Leighton's diffusion model. Roughly, the total magnetic flux transported from the active/enhanced network region to the quiet region per unit time is

$$\frac{\mathrm{d}F}{\mathrm{d}t} = D\overline{B} ,$$

where D is the diffusion constant and $\overline{B}$ is the average magnetic flux density near the boundary between the enhanced network region and the undisturbed quiet region. The two lines drawn in Figure 7 roughly define $\frac{1}{3}$ of the border, so during the period of ΔT, the total flux transported outward across the two lines should be

$$\Delta F = \tfrac{1}{3}\Delta T D\overline{B} .$$

With $\Delta T = 155$ hours, $D = 1000$ km^2 s^{-1} and $\overline{B} = 100$ G, the expected total flux transported away from the region should be

$$\Delta F = 2 \times 10^{20}\ \mathrm{Mx}.$$

The observed and theoretically calculated magnetic diffusion rates disagree in sign and magnitude. The observed diffusion is towards the enhanced network region, while the calculated diffusion is away from the enhanced network.

We then apply an independent method to study the diffusion rate of the May 1988 region. We measured the area of the enhanced network from the digital Kitt Peak magnetograms, which cover a much larger area then the BBSO magnetograms. We analyzed one Kitt Peak magnetogram per day from May 11 to May 18. After correcting for geometric effects, we found that the actual area of the enhanced network decreases about 5% in 8 days, with an error range of $\pm 5\%$. Again, this means a slight 'negative' magnetic diffusion rate. If the diffusion rate is 1000 km s^{-1}, the area of the enhanced network should increase almost 20% in this region during the 8-day period.

It is not clear how to explain this 'negative' diffusion rate. A recent study of Schrijver (1989) shows that the observed slow decay of plages may be due to the characteristic motion of magnetic elements: the magnetic elements tend to move around the boundary of supergranules and concentrate in some convergent areas. This kind of motion is not 'random' at all. It tends to concentrate flux instead of dispersing it.

To study the motion and evolution of individual network magnetic elements, we analyze the data of three quiet regions of the July 199 run. We measure the velocities and the lifetimes of all the measurable magnetic elements and find the following:

(a) The larger a magnetic element, the smaller is its velocity. If the magnetic element has a flux of 10^{17} to 10^{18} Mx, typical for intranetwork elements, the speed is about 0.3

to 0.4 km s^{-1}. These elements move towards the network boundaries and are consistent with supergranular flow (Wang and Zirin, 1988). If the flux is in the order of 10^{19} Mx, the speed is 0.1 to 0.2 km s^{-1}. These elements usually move along the network boundaries. If the flux is greater than 10^{20} Mx, the magnetic element is immobile.

(b) As we learned in Paper I, the lifetime of magnetic elements is almost always longer than 20 hours. The larger the magnetic element, the longer is its lifetime. For the magnetic elements with a flux of 10^{17} to 10^{18} Mx, the typical lifetime is 20 to 30 hours; for flux in the order of 10^{19} Mx, the lifetime is about 70 hours; if the flux is larger than 10^{20} Mx, the lifetime is longer than our observing period of 155 hours. Thus the 0.5 km s^{-1} velocity used by Leighton only applies to the weak intranetwork fields.

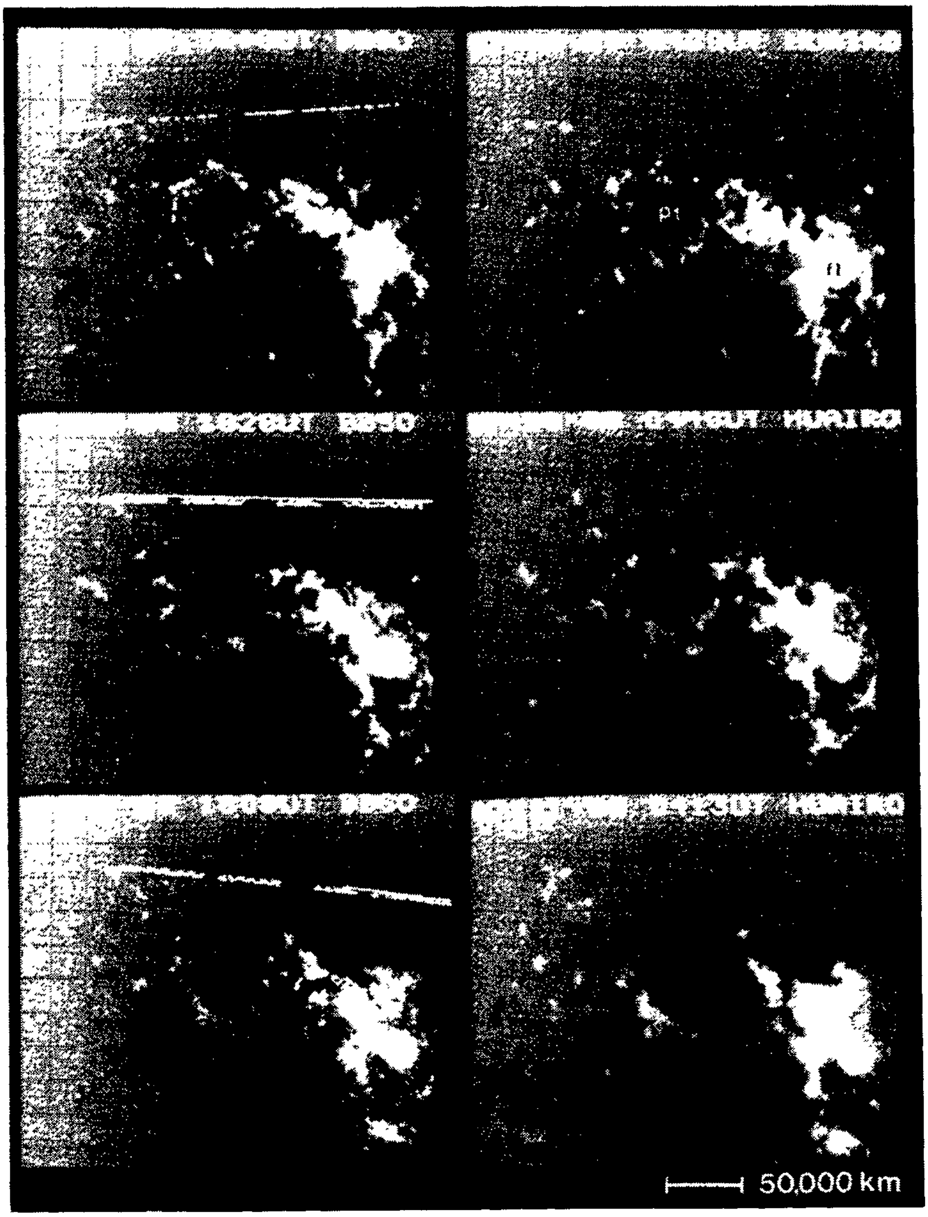


Fig. 8. Select images for July 1988 run, region A, a still growing active region. There are MMFs ejected from two main sunspot bodies ($f1$ and $p1$).

Based on the above discussions, we may understand some of the reasons why the network magnetic diffusion rate is small. Larger magnetic elements carry more flux than smaller ones. We should give larger elements more weight when we calculate the magnetic diffusion rate. However, since the larger elements do not show a significant random walk, the overall magnetic diffusion rate is reduced. This is consistent with the argument of Schrijver (1989).

5. Moving Magnetic Features

We now examine some properties of Moving Magnetic Features (MMFs) which have been interpreted as the initial step of sunspot breakup (Vrabec, 1974). We do not intend to study MMFs in detail in this paper. We wish to make only two points which are inconsistent with the traditional concepts of MMFs.

(1) MMFs appear not only in the decaying stage of sunspots, they also exist in the growing stage of spots, usually as soon as the penumbra of a spot forms.

(2) In some cases, MMFs do not carry net flux away from the central spot. MMFs are mixed in their polarities. Positive and negative fluxes are roughly balanced and cancel out at the boundary of the super-penumbra.

Figure 8 shows selected pictures of the active region of the July 1988 run. Two sunspots ($p1$ and $f1$) showed obvious MMF patterns. $f1$ is a following spot which has a well defined moat with the same polarity as the center spot. However, $p1$ does not have a well-defined moat. We will concentrate the study on the sunspot $p1$. The overall evolution and MMFs of both $p1$ and $f1$ will be studied in a separate paper.

The active region is still in its growing stage. In between the sunspots $f1$ and $p1$, new flux is emerging. The new flux has the same polarity orientation as the older spots ($p1$-$f1$). Flux of the same polarity joins spot $p1$ continuously from the east side (right side of p^1). The momentum of MMFs seems much weaker than that of emerging flux, so no MMFs are ejected from the east side of $p1$. However, MMFs appear in the rest of the circumstance around $p1$. As we pointed out in Paper I, the apparent polarity of moving magnetic features depends critically on the location of the region relative to the solar disk center. In the present case, on July 8, the target is east of the central meridian, the MMFs in the west (left) side of $p1$ are dominantly negative dominant (same polarity as the sign of the spot); on July 10, the region was west of the central meridian, so the polarity of the west side of $p1$ changed its dominant polarity to positive. Only on July 9, when the region was near the central meridian, did the apparent sign of MMFs represent the real magnetic polarities of the flux elements.

Measurement of July 9 data shows that the magnetic polarities of the MMFs are mixed and that approximately equal amounts of positive and negative flux are carried by the MMFs. During this 70-hour period, the magnetic flux of $p1$ is not reduced due to the MMFs. Positive and negative elements meet at or near the boundary of super-penumbra, where flux cancellation (Martin, Livi, and Wang, 1985; Livi, Wang, and Martin, 1985) occurs continuously. So there is no net magnetic flux accumulation of one polarity. The total flux-cancelling rate at the boundary of the super-penumbra is about 9×10^{21} Mx day^{-1}.

The large amount of flux cancellation might cause a substantial amount of energy release to the upper atmosphere. To study possible effects of energy release, we made a special Hα movie. For each observing day at BBSO, we selected 56-frames (56 is the memory limit of our image processor) from the 11–12 hours of observed data. The images are digitized from the film, re-registered and matched with VMG images. Figure 9 shows a pair of a magnetogram and its matched Hα image. When we run the Hα and VMG movies alternatively, we see a number of surges during the observing

Fig. 9. Comparison between a VMG and an Hα image for July 9, 1988. It shows the relationship between the flux cancellation of MMFs and the chromospheric surges. The contour-like wraps in the magnetogram are due to the overflow of the 8-bit memory of the BBSO MG system.

period. The feet of these surges are located at the boundary of the super-penumbra where continuous flux cancellation occurs. Some Hα brightening is often associated with the surges. The flux cancellation of the MMFs also results in several small flares. This subject has been discussed in detail by Livi *et al.* (1990).

6. Summary

Studies of data from several coordinated observations on active regions and enhanced magnetic network regions reveal the following conclusions:

(1) The lifetime of magnetic network cells is about 70 hours, much longer than the previously accepted 24-hour value. This result is consistent with both the result of Paper I and that based on velocity observations (Wang and Zirin, 1989). Most of the new cells are formed by expansion of existing large elements of flux. On the other hand, more than half of the cells decay by means of cell collapse and contract to a single magnetic element. The growth and decay of the network cell may represent the strengthening and weakning of supergranular convection flows.

(2) During a 155-hour period, there is more flux moving into an enhanced network region than away from it. This is consistent with the result found in Paper I, in which we also found that the flux did not move away from an active region but rather cancelled across the neutral line which divided the leading and following polarities. The transport of flux may be undergoing a more complicated process than a simple random walk. We find that magnetic flux elements with flux stronger than 10^{20} Mx do not show an obvious random walk.

(3) MMFs appear as soon as the penumbra forms, usually in less than one day after the new region emerged. For the sunspot studied in this paper, the MMFs are not responsible for net transport of magnetic flux from the sunspot for the duration of the observing period (70 hours). The total amount of positive and negative flux of MMFs is roughly balanced. The flux disappears at the boundary of the superpenumbra by cancellation, so there is no net flux accumulation at the boundary of the super-penumbra to form a moat. The energy release by the cancellation causes a number of surges.

In order to study the decay of active regions and the transport of its magnetic flux further, we plan future simultaneous velocity and magnetic observations on decaying active regions and enhanced magnetic network.

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