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The evolution of intranetwork magnetic elements

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Abstract. We have studied the evolution of Intranetwork (IN) magnetic elements, using a particularly good series of very deep magnetograms obtained at Big Bear Solar Observatory. The magnetograms span an interval 10 hours long and cover an area of 310×240 arcsec^2. We are able to follow 528 intranetwork elements from birth to death. The analysis reveals the following results:

(1). The appearance of IN elements can be classified into the following categories: half of the total IN elements emerge as clusters of mixed polarities somewhere within the network cells, one fifth appear as ephemeral regions (tiny bipoles), one fifth result from the merging of several elements of a given polarity, and one tenth appear by fragmentation of larger elements.

(2). IN elements disappear in four ways: one third of total IN elements cancel with elements of opposite polarity, one third decay into weak fields without apparent interaction with other elements, one fourth merge with IN or network elements of the same polarity, and one tenth split into smaller IN elements below detecting limit.

(3). About one ninth (one sixth) of the IN elements merge (cancel) with network features, consequently, part of the flux in network features is built up from former IN magnetic flux, and part is eliminated by IN elements. The net effect of merging and cancellation is a gradual reduction of the total flux of network elements in the 10 hours observational interval. It seems that not all the network magnetic flux is the remnant of active region magnetic flux.

Key words: Sun: magnetic fields – Sun: photosphere – polarization

1. Introduction

Intranetwork (IN) magnetic fields are the weakest signals revealed by conventional magnetographs. They were first observed by Livingston and Harvey (1971, 1975) and Smithson (1975). In recent years progress was made in IN's morphology, dynamics, and some other aspects using time sequences of deep magnetograms obtained at the Big Bear Solar Observatory (BBSO) (Livi et al. 1985; Martin 1984, 1988, 1990; Wang et al. 1985, 1988, 1995 [Paper 1]; Wang and Zirin 1988; Wang et al. 1996 [Paper 2]; Zhang et al. 1998 [Paper 3]; Zirin 1985, 1987, 1993).

The first Stokes V line ratio measurement made by Keller et al. (1994) has placed an upper limit on the intrinsic strength of IN fields at 1000 G and with 68% probability at 500 G. By using infrared spectro-polarimetry, Lin (1995) found that the IN fields typically have field strength around 500 G. Lites et al. (1996) presented recent observations of quiet regions near the center of the solar disk. These observations revealed horizontal magnetic flux structures. Such magnetic fields were weak (significantly less than 1000 G) and might be largely horizontal. These horizontal fields may correspond to the emergence of small concentrated loops of flux carried upward either by granule convection or magnetic buoyancy. Sánchez Almeida et al. (1996) suggested that the IN fields are highly irregular over optically thin scales. In particular, a sizeable fraction of the IN signals show clear signs of mixed polarities within the resolution element. Kneer and Stolpe (1996) presented an image in which small-scale magnetic elements possess substructure and are dynamics, with gas flows and magnetic field strength varying in space and time.

In spite of the ongoing effects to understand the behavior of IN elements, much work remains. In particular, the overall evolution patterns of IN elements have not been studied, probably because of the limited number of available observations. Our studies of IN fields are based on observations obtained at Big Bear Solar Observatory. Magnetograph observations with high resolution and sensitivity are essential to help us in understanding the magnetic fields in the quiet Sun. The evolution of IN magnetic elements is very important. From the knowledge of IN's evolution, their appearance and disappearance patterns and their interaction with network elements, we will understand the properties of the weakest fields on the Sun. Yet no detailed description of the evolution of IN elements has been made. This is the purpose of the present paper.

In Sect. 2, we describe the observational data. In Sect. 3, we present how IN elements appear. In Sect. 4, we study how they disappear. Sect. 5 gives the statistics with regard to the various ways of appearance and disappearance. In Sect. 6, we discuss the results.

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2. Observational data

The magnetograms of a quiet region of the Sun, obtained on June 4, 1992, are among the best ever obtained at BBSO for the study of IN elements. The magnetograms were acquired by integrating 4096 video frames, and recorded in 16-bit memory. The 10-hour sequence consists of 83 images with an average temporal resolution of 7.2 minutes. The series of magnetograms have a gap of 35 minutes between 16:01 UT and 16:36 UT. From 15:47 UT to 19:44 UT, the seeing conditions are very good; the spatial resolution reaches 1.5″. We determine the spatial resolution as the site of the smallest magnetic elements which can be traced in successive magnetograms. The working wavelength of the magnetograph is 6103Å, and the bandpass of the filter is 0.25Å FWHM. The calibration of the magnetograms is such that 1% polarization equals 115 G in flux density. The whole field of view (FOV) is 310×240 arcsec^2. The magnetograms have been gathered near the disk center. The pixel size is 0.6″ in the X direction and 0.5″ in the Y direction. The sensitivity of apparent flux density is 2 G (Paper 1). The detection limit of magnetic flux is 10^{16} Mx (here we use 2 pixels as one resolution element, each pixel is 0.5″, 10^{16}Mx$=$2G$\times$[730$\times 10^5$cm]^2). Additional information has been given in Papers 1, 2 and 3. In particular, the identification of individual IN elements is described in Paper 1.

3. Appearance of IN elements

3.1. Emergence as clusters of mixed-polarity elements

The IN magnetic elements mainly emerge as clusters of mixed-polarity elements in a localized area within a network cell (perhaps, if the angular resolution were good enough, we would observe all IN elements appearing as tiny bipoles). We call such an area a flux-emergence center (Paper 1). In Fig. 1a, an example of the emergence of IN element is shown. The figure is composed of 12 images with a mean temporal resolution of 7 minutes. The dynamical range of the magnetograms spans from -18 G to 18 G. (Unless we explicitly give it, the dynamical range of the magnetograms displayed in the forthcoming figures will be from $-$ 28 G to 28 G.) As we have mentioned above, from 15:47 UT to 19:44 UT, the seeing conditions are very good; the spatial resolution reaches 1.5″. We can easily trace an IN element from birth to death. An IN element looking like a cluster of mixed polarities emerges at 16:43 UT (see the brackets). From 16:43 UT to 17:06 UT, its flux increases continuously, then it decays into weak field below the noise level at 18:00 UT. We find the lifetime of this IN element to be 1.28 hour (from 16:43 to 18:00 UT). We also observe another IN element "C" emerging at 17:12 UT near an IN element "D" of opposite polarity. The flux of "C" increases, whereas that of "D" decreases. Fig. 1b shows the time variation of the flux of IN element "A". The flux measurements were made with an interactive data language IDL procedure. It allows one to interactively select an element, outline its boundary, and so measure its area, total flux and maximum flux density. The increasing and decreasing times are nearly equal.

It was thought that most of IN elements originated in the centers of supergranules (Martin 1990). In this series of magnetograms, however, we find that *IN elements emerge everywhere within the supergranular cells with no preferred location*. Fig. 2 gives some examples of the emergence of IN elements. In order to display the IN elements more clearly, the dynamical range used to display the magnetograms spans from -18 G to 28 G. IN element "A" (we take "A" as IN element according to the identificationn of individual IN elements described in Paper 1), pointed out at 20:02 UT, *emerges near the boundary of a network cell* (There are some regular network patterns which remain during the series of magnetograms. The boundary of the supergranular cell is determined by visual inspection of these network patterns). Emergence near the network boundary has not been mentioned in the literature. Within the supergranular cell, IN elements move to the boundary. In Fig. 3, another IN element "B" emerges close to a previously existing network element and separates from it. The mechanism guiding these emergences is not clear.

3.2. Emergence as ephemeral regions

Most intranetwork elements appear as a cluster of mixed polarities somewhere within the network boundary, however, some of them emerge as ephemeral regions (Martin 1990; see also Paper 1). Fig. 4 shows a pair of IN elements emerging at 16:01 UT (see the brackets); the flux of the positive polarity element (white) is smaller than that of the negative polarity feature (black). We also find an interesting example in Fig. 3: a pair of IN elements appear as an ephemeral region at the boundary of a network element (within the brackets at 16:36 UT). The positive polarity IN element overlaps a pre-existing network element; the negative polarity element separates from the positive one. First, the pair of IN elements move along opposite directions, then the negative polarity element changes the direction of motion. The arrows at 17:06 and 17:48 UT show the direction of motion of two poles of the ephemeral region.

3.3. Merging of some smaller flux elements

The emergence of IN elements, both as clusters of mixed-polarities and as ephemeral regions, builds up to the total flux on the solar surface. Merging of smaller flux elements, on the other hand, does not change the total flux (total flux means the total unsigned flux). Some smaller elements converge together and form a larger one. Observationally, the total flux does not vary after the merging. Fig. 4 shows how the negative polarity element (black) of a ephemeral region (the square brackets at 16:01 UT) merges with another negative polarity element (in the circle at 16:36 UT) and forms a larger element "A" at 17:00 UT. Fig. 5 also gives an example: "B" is formed by the merging of several IN elements at 18:13 UT. Sometimes IN elements form by merging of barely visible signal (e. g., the element inside the ellipse of Fig. 6.)

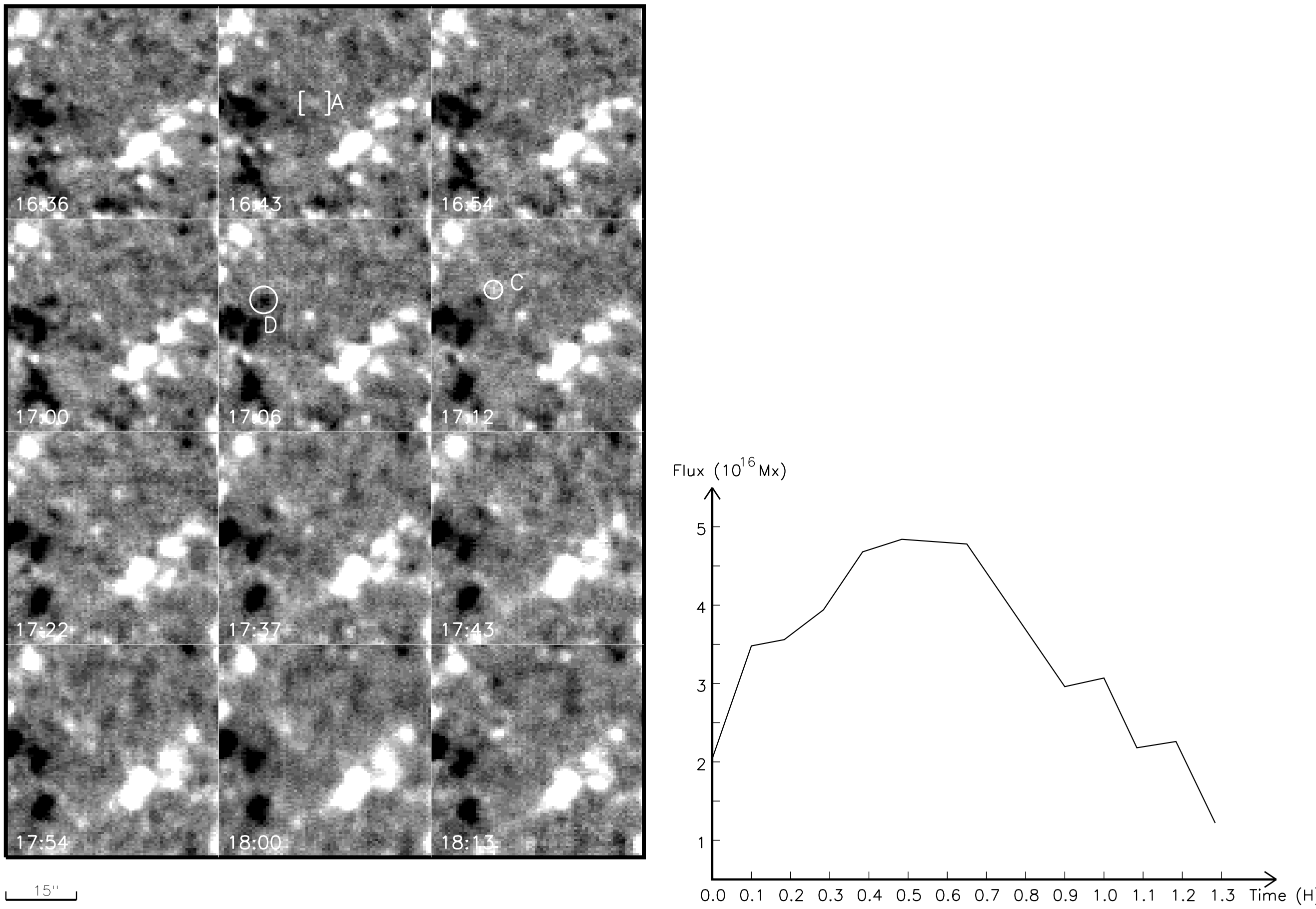

Fig. 1. a (left) Examples of emergence and evolution of IN elements are shown. The scale of the magnetograms spans from −18 G to 18 G. An IN element appears as a cluster of mixed polarity element at 16:43 UT (see the brackets). From 16:43 UT to 17:06 UT, its flux increases, then it decays into weak field at 18:00 UT. The IN element "C" emerges at 17:12 UT near the element of opposite polarity "D". The flux of "C" increases whereas that of "D" decreases up to its fade at 18:00 UT. **b** (right) The magnetic flux of the IN element "A" as a function of time. The units of abscissae and ordinates are hours and 10^{16} Mx, respectively.

3.4. Fragmention of larger elements

This mechanism is opposite to that described in Sect. 3.3. Some smaller features are formed by fragmentation of larger elements. If we were measuring the magnetic flux across the solar photosphere, and if the magnetic field vector of the fragments is the same as that in the original concentration, then we would expect that the total signal of the magnetogram is preserved by the fragmentation. We can see from Fig. 6 that IN element "A" breaks into two smaller elements "a" and "b", the flux of each element being much smaller than that of "A". We find also that IN elements can be formed from network elements, e. g., IN element "C" in Fig. 4 appears by splitting of the network element "N3".

4. Disappearance of IN elements

4.1. Cancellation of opposite polarity elements

The disappearance of IN elements is mainly due to the cancellation of opposite polarity elements and to the decay of single polarity entities. If an IN element meets with another of opposite polarity, or with a network element, they can cancel each other. Under this condition, the total flux decreases. Fig. 4 shows how the IN element "A" cancels with the network element "N1". During the process of cancellation, the fluxes of both "A" and "N1" decrease. At 18:43 UT , the flux of "A" is already below the limit of sensitivity (10^{16} Mx), so that we consider "A" to be faded away. Consider the IN elements within the square in Fig. 5 (pointed out at 16:36 UT). In this region, many positive and negative polarities IN elements cancel each other, see, e. g., the pair of opposite polarities IN elements "A" and "B". The positive polarity element "A" disappears at 20:02 UT, the negative polarity element "B" separates into two smaller elements "a" and "b". The total flux of the IN elements in the square region at 21:28 UT decreases by an half at 16:36 UT. Fig. 7 also gives some examples of cancellation; the IN elements "A", "B", "C" cancel with network features sited on the boundary of network cell.

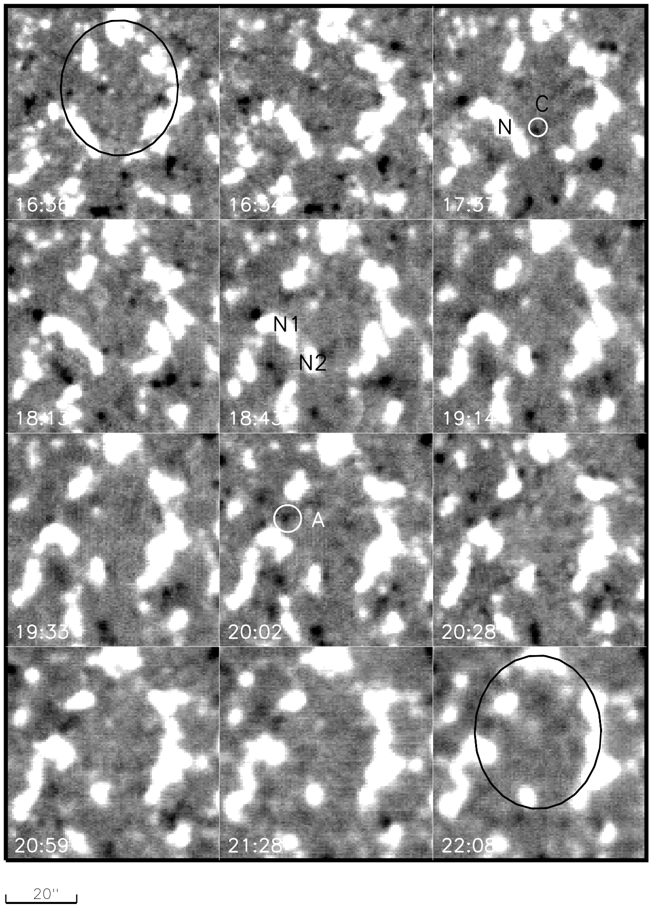

Fig. 2. Series of magnetograms including a whole supergranular cell. The large ellipse at 16:36 and 22:08 UT represent our estimate the cell's boundary (see maintext). The IN element "A" (20:02 UT) emerges at the boundary of the network cell. The IN element "C" emerges near the network element "N", which then splits into "N1" and "N2". From this series of magnetograms, we can see how the supergranular cell grows with time.

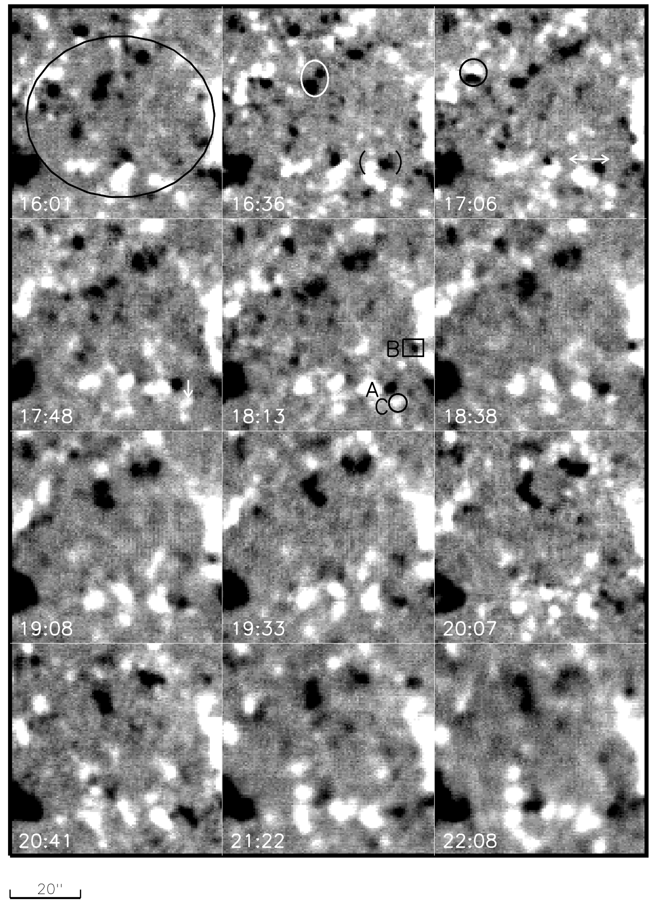

Fig. 3. Similar to Fig. 2. The large ellipse at 16:01 UT is the boundary of a supergranular cell. The two IN elements in the circle at 17:06 UT cancel each other, and the two IN elements in the ellipse at 16:36 UT merge together. An IN element ("B") emerges close to a network element previously existing and separates from it; a pair of IN elements appears as an ephemeral region (within the brackets at 16:36 UT). The positive polarity IN element overlaps with a network element. This ephemeral region separates and rotates. The arrows at 17:06 and 17:48 UT show the direction and distance travelled by the ephemeral region.

4.2. Decay below the detectable flux density

Some IN elements disappear by decaying into weak fields without apparent interaction with other elements. Fig. 1a gives a typical example. There seems to be no obvious magnetic structures near the IN element "A". "A" stays there over an hour, and then it decays into fields below the detectable flux density. The IN element "C" in Fig. 5, formed by merging of some smaller elements, also disappears by decaying. The observed decays can be due to the following processes: buoyancy upwards, submergence or diffusion; which one is actually going on is still very uncertain.

4.3. Merging with same polarity elements

Both cancellation and decaying of IN elements decrease the flux. The merging of smaller IN elements, on the other hand, does not change the total flux, but changes the IN's morphology and dynamics. The two IN elements in the small ellipse in Fig. 3 merge at 19:08 UT. After the merging, the flux of the newly formed element nearly equals the flux of the two original IN elements. Fig. 4 shows the IN element "B" merging with the network element "N1": "B" moves quickly to "N1" (the arrow at 17:22 UT shows the direction of motion of "B"), with a peak speed about 0.65 km/s (the motion patterns of IN elements is studied in Paper 4). We can deduce from these and the later example the following conclusion: the flux of IN elements contributes to the built-up of the flux of the network or, in other words, not all the flux of the network elements comes from the decay of active regions.

4.4. Fragmentation into smaller IN elements

This other mechanism should also preserve the total flux. A large IN element, at the center of the supergranular cell in Fig. 6, separates into several smaller elements. This mechanism destroys

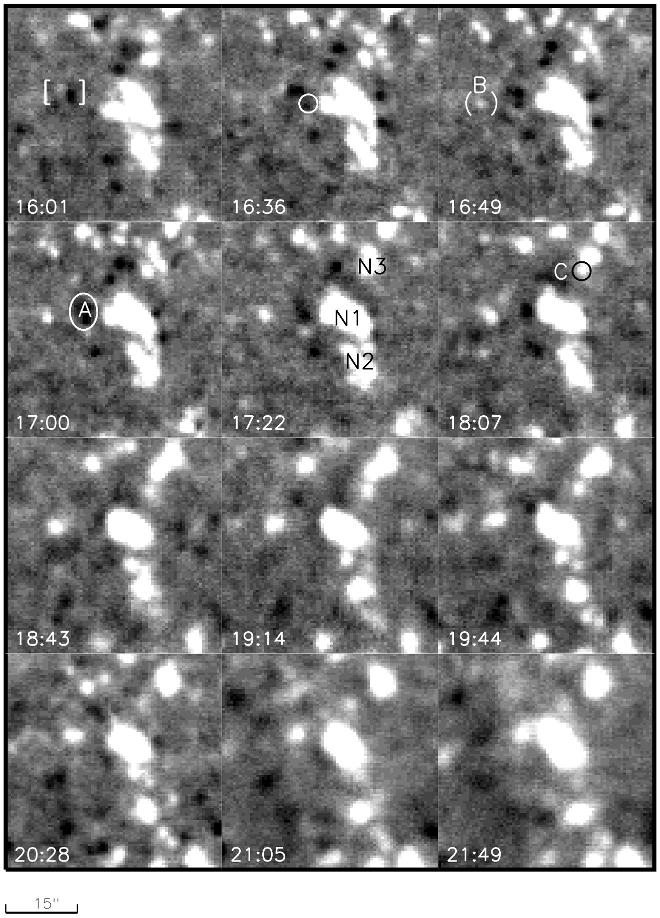

Fig. 4. Merging of IN elements with network elements and interaction between IN elements. The dynamical range of the magnetograms spans from −18 G to 28 G. A pair of IN elements emerge at 16:01 UT (within the brackets). The positive polarity element (white) disappears at 17:00 UT without apparent interaction with other elements. The negative polarity element (black) merges with another negative polarity element (in the circle at 16:36 UT). Then the merged negative polarity element cancels with a network feature "N1" at 19:14 UT. At 16:49 UT, another IN element "B" (within the parentheses) emerges and moves quickly to "N1" (the arrow at 17:22 UT shows the direction of motiom of "B"). The peak speed, which occurs near 19:14 UT, is about 0.65 km/s. Finally, the element "B" merges with "N1". The network element "N2" moves down along the lane of the supergranule and, simultaneously, its flux decreases. The IN element "C" (at 18:07 UT) appears by splitting from the network element "N3".

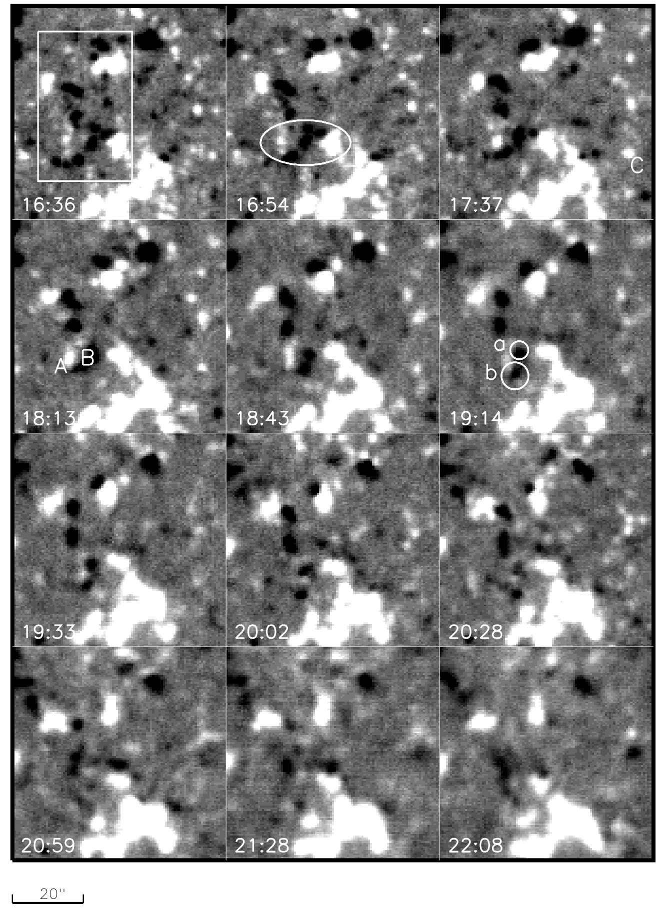

Fig. 5. Series of magnetograms showing evolution patterns of IN elements. We mainly consider the region in the square. In this region, almost all the IN elements of positive and negative polarities decay. The negative polarity elements in the ellipse converge together and form "B". "A" cancels with "B" and "B" splits into "a" and "b". "C" decays into weak field without apparent interaction with other elements.

the element "C". Fig. 7 gives a similar example; "H" in the circle at 19:14 UT splits into three small fragments. We find that if the flux of an IN element is large and the flux density (i.e., the apparent magnetic field strength) is relatively weak, this IN element appears to split into several smaller fragments. These fragments usually diffuse quickly as the flux of each fragment is small.

5. Statistical results

In the 10 hours run of magnetograms, we are able to follow 528 intranetwork elements from birth to death. If an element diffuses into weak fields below the noise level, we define it as a death. Similarly, if an element emerges into strong fields over the noise level, it is defined to be born. On the other hand, when an element A breaks into elements B, C and D, A is said to die, while B, C and D are born. When elements E and F merge together and form another element G, E and F die, G is born. The lifetime of an element is the duration from its birth to death over the noise level (Paper 3). The appearance mechanisms of IN elements can be divided into two classes: emergence and transformation. Emergence also includes two categories: emergence as a cluster of mixed polarities, and emergence as ephemeral regions. Transformation means that the IN elements evolve into other IN or network elements, without an obvious change of the total flux. We have found two sorts of transformation: merging with the same polarities and breakup. Merging means that the IN element is formed from smaller or barely visible features. Breakup

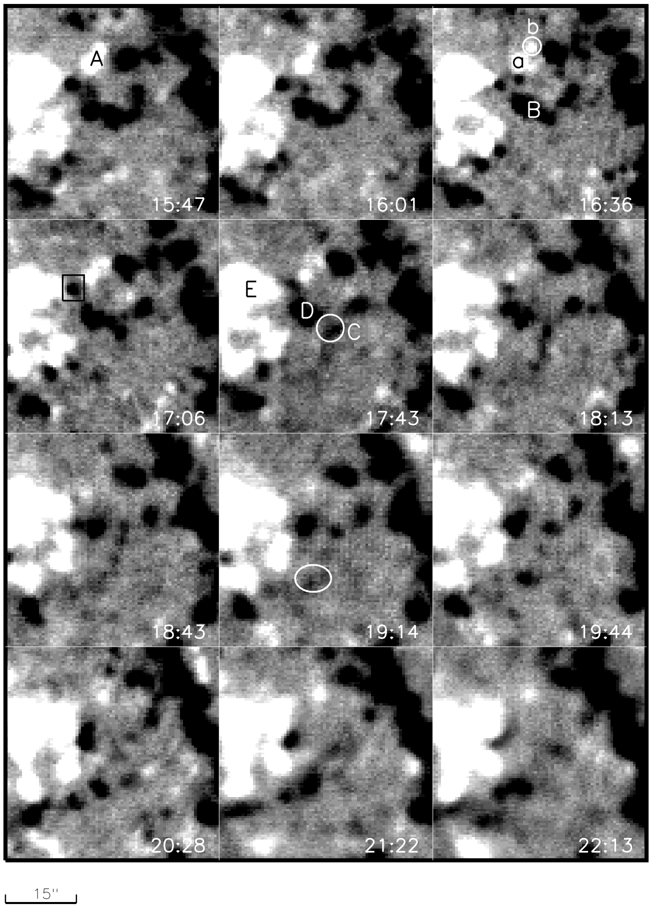

Fig. 6. Series of magnetograms showing a whole supergranular cell. The element “A” at 15:47 UT splits into “a” and “b”; “a”, “b” cancel with other elements of opposite polarity. “B” separates into “C” and “D”. First, “D” moves along the radius of the supergranular cell. When it reaches the network element “E”, it changes the direction of motion to move along the edge of “E” and then cancel with it. “C” splits into several smaller elements.

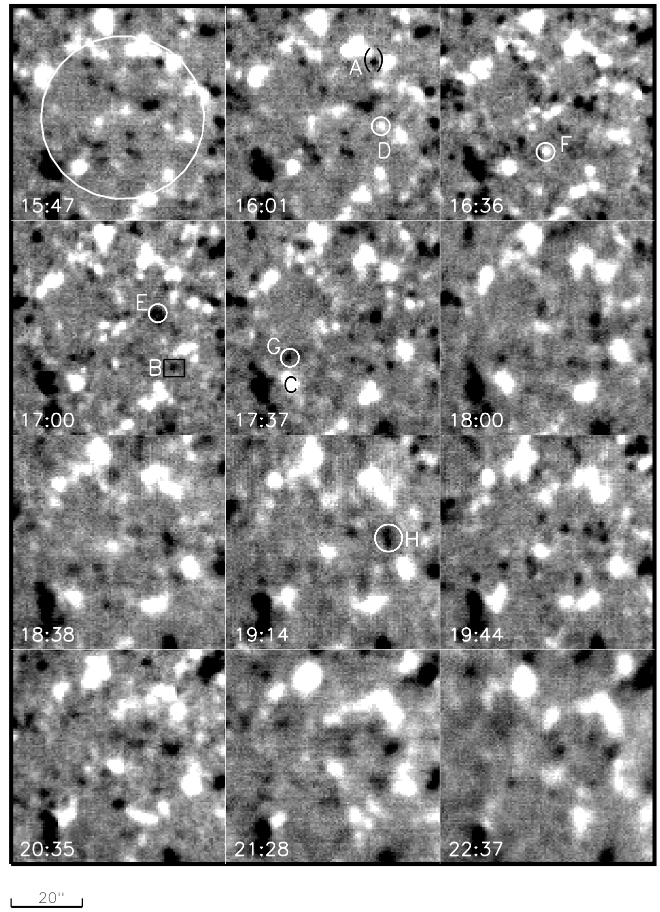

Fig. 7. Similar to Fig. 6. The large ellipse 15:47 UT outlines a very regular supergranular cell. Almost all of the IN elements move radially to the boundary of the cell. Some IN elements cancel with IN or network elements (“A”, “B”, “C”); some merge with other elements (e. g., “D”), and a few split into smaller elements (e. g., “H”).

Table 1. Appearance patterns of IN elements

Categories	N	ML
Clusters of Mixed Polarities	271	1.62±1.09
Ephemeral Regions	97	2.10±1.28
Merging (same polarity)	95	3.75±1.49
Breakup	65	1.72±0.98

Table 2. Disappearance patterns of IN elements

Categories	N	ML
Cancellation (opposity polarities)	190	1.80±1.25
Decay (no interaction with others)	158	1.68±1.23
Merging (same polarity)	123	2.66±1.58
Breakup	57	2.87±1.30

N: Denotes Number, ML: Denotes Mean Lifetime (hour).

means that smaller IN elements appear by splitting of larger IN or network elements. Example of merging and breakup has been given in Sect. 2. Table 1 summarizes the frequencies of the different mechanisms of formation of IN elements. It also shows the mean lifetime (in Paper 3, we gave a detailed description about how to obtain the lifetime).

About 70% of the total IN elements appear by emergence, and 30% by transformation. Table 2 provides the frequencies of the different ways of disappearance of the IN elements.

According to Table 2, we find that 66% of IN elements dissolve (i.e., disappear by cancellation or decay), which is comparable to the emergence rate (70%, Table 1). This satisfies the balance of total flux on the solar photosphere, if the mean emerging IN element carried the same flux as the mean decaying IN element. As the identification and classification of the different structures of magnetograms was carried out by visual inspection of the set of magnetograms, the statistical results in Table 1 and 2 may exist some uncertainty (i.e., the statistical results may be affected by the dynamical range of the presentation, seeing change etc.).

As we have followed the evolution of 528 IN elements, we can estimate the lifetimes. The results are presented in paper 3. In order to deduce the relationship between the flux and lifetime,

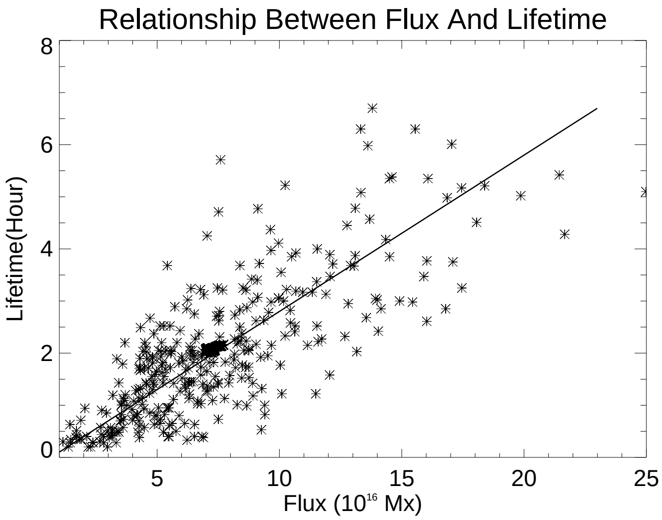

Fig. 8. Relationship between flux of IN elements and lifetime. The solid line represents a linear fit.

we have also measured the flux of each element. Fig. 8 shows the plots of lifetime versus flux. As we can see, the larger the flux, the longer the lifetime, so that there is a dependence of lifetime on flux. We have fitted the relationship by the function:

$$T = 0.3\Phi - 0.1 \quad (1)$$

where T is the lifetime in hours and Φ the flux in 10^{16} Mx. The peak of the flux distribution of IN elements is at the 6×10^{16} Mx. This indicates that most IN elements have lifetimes of some 2 hours.

6. Discussion

Although we have been mainly concerned with the evolution of IN elements, it is important to emphasize the strong interaction existing between IN and network elements. We find that IN elements tend to interact with nearby network elements. Usually the interaction between IN and network elements is in the form of cancellation or merging. Most of the IN elements move towards network elements which seem to represent convergence centers. We have also noticed that, when IN and network elements approach each other, they do not instantaneously interact. Usually, the IN elements move along the peripheries of the network elements for some distance. This may be a manifestation of the magnetic field suppression of convection. The supergranular flow carries IN elements from cell's centers to the borders. When IN elements reach the neighbourhood of a network element, the strong network fields modify the flow and so the IN element motion. This effect explains why IN elements tend to move along chains of network elements.

We found in Paper 1 that, in the region analyzed here, 22% of total flux was in the form of IN magnetic flux (6.3×10^{20} Mx), and 78% in the form of network magnetic flux (2.2×10^{21} Mx). The IN magnetic elements are possibly generated by a small-scale dynamo operating somewhere not much deeper than the base of the supergranule (Petrovay & Szakály 1993; Durney et al. 1993). The subsurface converging motion of the supergranule gathers them together at the supergranular center; supergranular upflow and magnetic buoyancy bring them up to the solar surface. Once in the photosphere, they may be swept to the network boundaries and then dragged down once again to the base of supergranules to start yet another life cycle (Paper 1).

In this paper, we find that 36% of total IN elements cancel with IN or network features of opposite polarity, whereas 23% merge with elements of the same polarity (see Table 2). The frequency of cancellation is higher than that of merging. About half of the cancellation (merging) mentioned above corresponds to IN elements cancelling (merging) with network features. If we assume each IN element carries the same flux, the net effect of cancellation and merging is a gradual reduction of magnetic flux in network elements.

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