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Evolution of Weak Solar Magnetic Fields*

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Abstract

We review studies of the evolution of weak solar magnetic fields with the Big Bear videomagnetograph. To all detectable limits, the field is clumped in small elements. The size of the smallest detectable intranetwork elements is probably 3×10^{15} Mx ($\equiv 3\times10^{7}$ Wb) and the field strength in these elements probably less than 10 G (1 G $\equiv 10^{-4}$ T). The general weak network fields are the remnants of ephemeral regions, which also play a role in field diffusion as proposed by Marsh. The intranetwork elements show a shorter lifetime and much more rapid motion than the network elements. In some cases they stream into existing network elements and may merge to form new elements, but many show no preferential motion to the network edges. Consonant with X-ray bright point counts, there appear to be fewer ephemeral regions in magnetically active areas.

1. Introduction

The Sun reveals three levels of magnetic activity: bipolar active regions, unipolar regions, and the general network of weak magnetic fields which covers the Sun and is always present whether there are sunspots or not. Since the third regime is always present independent of the level of the cycle, it owes its origin to a separate cause, and has generally been supposed to be created out of velocity fields in the network, as suggested by Leighton *et al.* (1962).

Recent improvements in the Big Bear videomagnetograph (VMG) have enabled us to study the evolution of both the enhanced network and the weak fields. The instrument was developed by R. B. Leighton and R. C. Smithson in 1971, and improved by a number of workers (S. Schoolman, A. Michalitsanos, J. M. Mosher and others). The old system has been described by Mosher (1976). A schematic diagram of the new system installed in 1979 is shown in Fig. 1. Images of the solar surface are obtained through a KDP modulator and a Zeiss Hα filter, retuned to 6103 or 6439 Å, installed as the spectral resolving device. The Ramsey (1971) scheme for recording both polarizations simultaneously is used. Images in the σ_1 and σ_2 Zeeman polarization are alternately recorded, 8-bit digitized and stored by a Quantex digital

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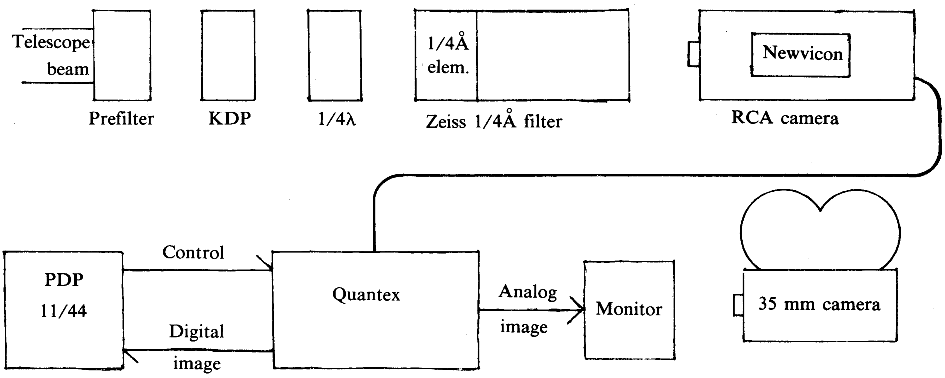

Fig. 1. Schematic diagram of the Big Bear videomagnetograph.

image processor in 12-bit memory. After a number of these have been added and subtracted at video rates, a final magnetic image is produced and recorded on disc, magnetic tape or film. A maximum of 4096 frames is utilized for the weakest fields. For comparison, about 32 or 64 frames are adequate to record the typical active region. The system is controlled by a PDP 11/44, but a small computer or hard-wired system would also work. Aside from its great sensitivity, the advantage of the system is that the fields are displayed in real time, so that the evolution of fields is easily studied.

2. VMG Observations

The weak magnetic fields recorded by the VMG have been studied by various members of the Caltech group (Martin 1984; Wang *et al.* 1985; Martin *et al.* 1985), including the present author. We have found that the smaller the magnetic element studied, the more rapid is its variation, and one often sees instances of magnetic reconnection, merging etc. There appears to be a general correspondence between lifetime and size in the hierarchy of magnetic fields: the large sunspots and active regions may last for months; the elements of the enhanced network will certainly last for days, while the unipolar regions themselves may also last for months; the elements of the weak network last a few days, and the weak intranetwork (IN) elements have a lifetime of only hours.

Because the weak network elements are short-lived, there must be a source of their fields, since many parts of the Sun, especially the equator, are without enhanced fields often for periods of many months. At sunspot minimum many regions of the spot belts are similarly free of stronger fields, so there must be a source of the omnipresent network fields. This source appears to be the so-called ephemeral regions (ERs), which seem to correspond with the coronal bright points of X-ray regions, and were first extensively discussed by Harvey and Martin (1973).

Motion occurs at all levels of magnetic activity, primarily in connection with flux emergence. Although there is rapid motion in the early days of emergence of a new active region, the sunspots are generally rather static afterward, as are the surrounding fields. The ERs separate at about the same rate as emerging flux regions with a velocity of $0 \cdot 3\ \mathrm{km\,s^{-1}}$, but sometimes rapid motion occurs without flux emergence. The average speed of the network elements, however, is quite low, while the elements of the IN fields move as rapidly as emerging flux.

As is well known, there has been considerable discussion in recent years (Spruit 1976; Frazier and Stenflo 1978) on the possibility that the apparently weak fields away from sunspots are not weak at all, but rather strong. Because of the strong photospheric motions it seems reasonable that only strong fields could survive. Harvey (1977) however measured the IN fields at 10^{16} Mx. Wang *et al.* (1985) investigated the size of the smallest fields by studying gradually weakening and disappearing elements of the magnetic field, usually associated with reconnection by elements of ERs or the IN field. They found that the smallest elements measured by the Big Bear VMG were about 10^{16} Mx, in agreement with Harvey's estimate. There has been another increase in sensitivity since the data used by Wang *et al.*, and we believe that the smallest elements (see Figs 2 and 3) are about 3×10^{15} Mx. This value is about two orders of magnitude smaller than the values proposed by J. O. Stenflo, but it refers to the IN field, rather than possible elements of the network. If the network is made up of discrete intense elements, we would expect to see an abrupt disappearance of flux, which is not the case. This does not imply that the stronger fields are not clumped; even our most sensitive magnetograms, which show the IN fields quite clearly, never show continuous fields, only discrete elements. However, it does imply that fairly weak fields can survive the buffeting of the photospheric motions. If the total flux is 3×10^{15} Mx, then a field of 1000 G would be limited to an area of 10 km, which is probably too small for thermal isolation. A further argument against extremely small flux tubes is based on faculae. Faculae 1 arcsec across with a contrast of 20% have been observed at the extreme limb by Wang and Zirin (1986). If they were much smaller, say $0 \cdot 1$ arcsec, an unreasonably high brightness contrast of 2000% would be required to explain the observations.

The nature of the reconnection and merging phenomenon, which Martin *et al.* (1985) have referred to as cancellation, is not clear. It appears physically impossible for two poles to 'cancel' since they represent the intersection of lines of force with the surface, and the fields can only reconnect into lower energy configurations or submerge below the surface. Even reconnection requires submergence of the remaining flux, if the flux loops depart the Sun. Only if the fields are not anchored below the surface could cancellation occur, and in that case the fields would rapidly float up and away.

There has been some resistance to the concept of flux submergence. Even in sunspot groups submergence has been observed by Zirin (1985) and recently occurred in BBSO 451, a region under study by S. F. Martin. Most new dipoles emerge, separate and die away, but some dipoles are pulled back into the Sun by an unknown process. Further the process often called cancellation must involve flux submergence, if the roots of the field are to be explained. Regardless of how much flux escapes, the lines of force at the footpoints must be taken into account.

Figs 2 and 3 present frames from a particularly clear series of VMGs of a quiet region from 16:39 to 00:02 on 13 October 1984. These frames are the differences for 4096 images in the 6439 Å line of Ca I ($g \sim 1 \cdot 28$). The region is close to the centre of the Sun, and of mixed polarity, although there is a tendency for black elements to dominate at the right of the photograph (east) and white toward the left. The IN field displays the characteristic 'pepper and salt' appearance first noted by Harvey, that

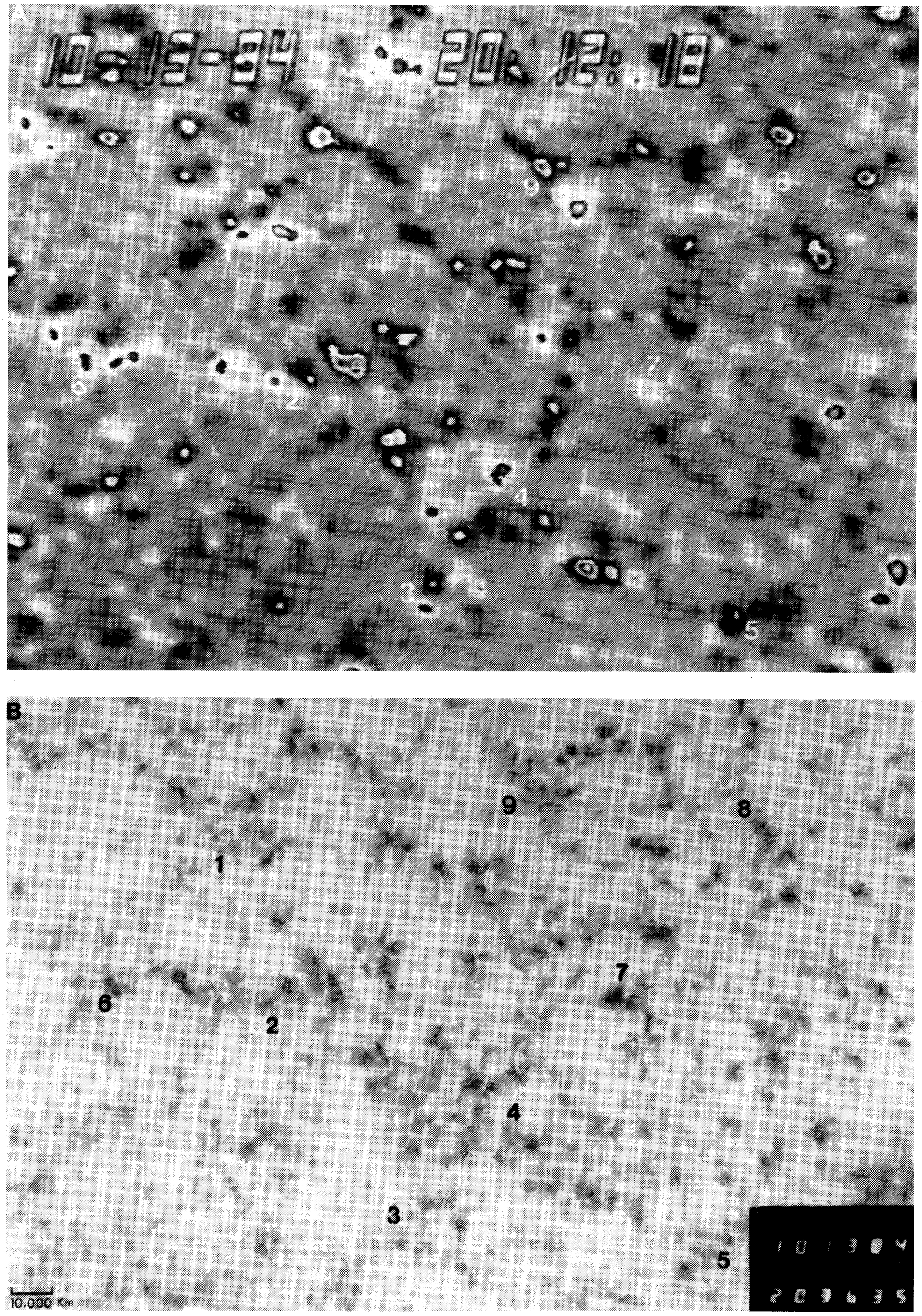

Fig. 2. A quiet Sun field taken on 13 October 1984 showing the magnetic field (top) and $H\alpha - 0 \cdot 7$ Å (bottom) (with south at top and west at left). (See Section 2 for details.)

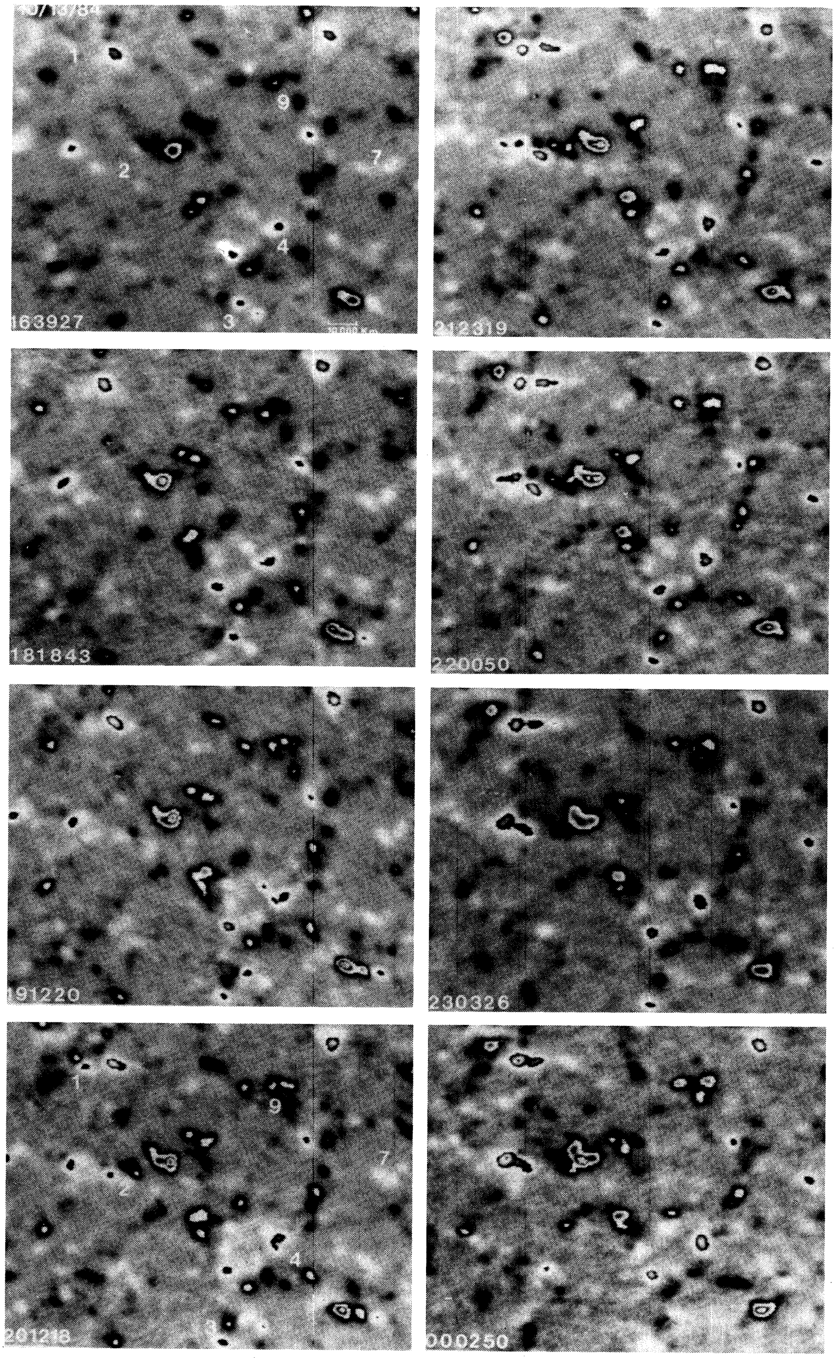

Fig. 3. Eight frames of a portion of the same region as in Fig. 2, showing the evolution of the magnetic elements. The numbers are the same as in Fig. 2, but some elements are outside the frame. The ERs 1, 2 and 3 can be seen to erupt starting with the second and third frames.

is, both dark and bright elements are found within each network cell. There are no chains of magnetic field, as found in the enhanced network, but isolated relatively weak poles of either sign. The contour-like curves in these images are caused by wrapping the signal around to the opposite sign when the 12-bit memory is filled. Thus, successive contours will represent one, three or five times the original field. This gives a considerable dynamic range, and also enables an estimate of the relative intensity of the weakest and strongest fields on a magnetogram. There is some change in sensitivity due to solar zenith angle and seeing, but relative changes are clear. The magnetograms reveal striking instances of field constancy and field change. Out of 43 stronger magnetic elements (all those with one wrap around), five disappeared and six new ones appeared in eight hours. Thus, we could expect all the elements to change in 50–100 hr. All of the contoured elements correspond to Hα rosettes, as do several of the weaker ones. Almost all of the weaker elements changed.

If the Leighton model of the sunspot cycle is correct, the rate of field diffusion is the critical parameter. Leighton (1964, 1969) required that magnetic fields diffuse by one network cell per day, which corresponds to a diffusion parameter of 10^4 km^2 s^{-1}. The actual rate of motion measured in the weak network elements corresponds to one-third of that value (for a lifetime of 1 day), and if a length of 20 000 km is ascribed to the spatial change connected with the disappearance of one element, we again obtain 330 km^2 s^{-1}, the value obtained by Mosher (1977). However, even this low value is for the relatively transient weak network, whereas it is the enhanced network fields which must be transported for the Leighton model to be correct. Our observations of the enhanced network show very little change from day to day. Virtually none of the strong elements move in an eight-hour run. Only the IN elements move fast enough to produce adequate diffusion, but they are always bipolar, and so it is difficult to see how they could transport unipolar flux.

In Figs 2 and 3 several features and their counterparts in the Hα wing have been marked. The dipoles above the numbers 1 and 2 were ERs which first appeared at 19:12:20 (third frame at left in Fig. 3) and then separated rapidly to merge with counterpart polarities on either side. In the eighth and last frame we can see that although 2 enhanced the existing dipoles, the ER 1 only enhanced the white (right) pole, and replaced the dark pole (just visible at the top of the frame). The ER 3 appears in the second frame, expanding north–south and cancelling the white element above it, leaving the new white pole further north (down). This is an example of Marsh's (1978) mechanism. Number 4 separates a dipole which may have been an ER, since the lower dark pole moved away at a peak speed of 0·4 km s^{-1}, covering 8000 km in the eight-hour observation period. In the last frame it is a dark patch near the network pole to the lower right. Number 5 is a pair of dark poles which have split from a single pole and moved apart at the high speed of 0·72 km s^{-1} (numbers 5, 6 and 8 are not shown in Fig. 3). Number 6 is a counterexample, a group of white poles which do not change at all during our observation period, while 7 is a group of IN elements which merge to form a stronger pole (note that even at this time there is a spicule bush over 7). Number 8 is a pentagonal figure of network elements which was substantially unchanged all day, while 9 is an element which merged with most nearby IN elements as they converged on it at 0·3 km s^{-1}.

The IN fields are of interest because they are the weakest fields observed and presumably the most easily affected by photospheric motions. On the films the IN elements almost all move fairly rapidly from one place to another, eventually disappearing or merging with other elements. The IN structure is completely changed in a few hours; however, very few of the elements disappear, but rather move a considerable distance or merge with other elements. The motion is quite rapid compared with the network poles. The motions of 37 identifiable elements of the network over eight hours were measured and an average motion of only $0 \cdot 06$ km s^{-1} was found. Five elements disappeared and six new ones appeared. A total of 33 IN elements were measured over 90 min and a mean motion of $0 \cdot 35$ km s^{-1} was found, a considerably higher value.

It has generally been thought that IN elements are swept to the edges of the network by the supergranular flows. For element 9 this was obviously the case with IN elements of both polarity converging on it. Further, as noted, the ERs also seem to move to existing elements. However, for the other IN elements no pattern has been found; motion vectors marked for each of them show no favoured direction. Some network elements also emit IN fields, which is the opposite of the predicted behaviour.

Elements of the IN field are created by splitting from opposite fields (dipole emergence) or from similar fields, and they can disappear by the converse process. Both occur with small elements merging into larger ones or splitting from them, and many small pairs appearing, with ERs just on the edge of detectability. Some also appear from a variation in sensitivity, to which we attribute the occasional appearance and disappearance of monopoles. Not all the ERs separate; some weak ones move together and maintain their separation. It is surprising that the weak IN elements can move through 5000 km of photosphere with little change. Because the nearest opposite poles are often 5000 km away, they must have roots of the same order of magnitude, and these roots must either move with the field or stretch. We note that motion produced by flux emergence does not require field line stretching, the arch simply emerges and the intersection of the field lines with the surface simply separates or comes together. The IN motions cannot be explained in this way and must be shared by their roots.

How do we distinguish a network from an IN element? Since one may merge into another, they can only differ quantitatively. The IN elements move faster and of course are weaker; when they form a network element they stop moving and grow bigger spicules. In Fig. 2 we can see that the stronger poles are generally associated with prominent Hα rosettes.

It is interesting to speculate on the subsurface ties of the IN elements. Because they move so rapidly and have virtually random sign, they must have shallow roots. However, the concept of shallow roots is difficult to picture, since a flux loop closing just below the surface would be unstable against buoyancy and float away. Although the IN elements only exist for a few hours, their behaviour does not match that to be expected from buoyancy. Further, the IN elements seem freely interchangeable through split or merger with the network, so they must be able to attach to the network flux elements, which must be deep and at least as deep as the scale of the network.

As we can see in Fig. 3 the ER emergence took place rapidly, within an hour, and within three or four hours the dipole had separated and merged with the previously existing dipole element. The velocity of separation of the dipole elements was about $0 \cdot 6$ km s^{-1}, each moving at about one-half that amount. We note that each ER emerged between two elements of opposite polarity, and that the elements moved towards the region of the same polarity. These are the best examples we have of this type of ER emergence, but there are not yet enough cases to estimate how often this pattern is followed. In the case of region 1, the dark polarity did not reach the other element of the dipole, growing strong instead while the other weakened, and resulting in a net shift of magnetic polarity. The merging of similar magnetic field poles is a well-known phenomenon, which commonly occurs when new sunspots appear in an emerging flux region. These invariably occur as the merging of many tiny pores. The density of network fields must of course be a balance between production of pairs of new elements by ERs, or by merging of IN fields and destruction or fading of elements into IN elements. Cancellation of existing elements by ERs, as in element 3, does not play a role because we still have the same number of elements.

In addition to the sequence illustrated, enhanced network fields observed for a full day on 23 September, 28–9 September and 24 December were studied. These show at most one ER per field for an eight-hour period, three times less than our quiet region. There appears to be a definite shortage of ERs in enhanced networks, more than can be explained by confusion. If we examine Fig. 1 of Harvey *et al.* (1975) we see relatively few ERs marked in the areas of enhanced network.

3. Summary

The results of the present study can be summarized as follows:

(1) The quiet Sun network elements seem to have a lifetime such that about 15% are completely changed after eight hours, implying a average lifetime of 50 hours if they are all uniformly long-lived. Thus, they cannot be remnants of active regions, but must be regenerated by local phenomena. This occurs as local flux emergence, either in ERs or with smaller dipole emergence in the IN field. The enhanced network is much longer lived, and appears to have fewer ERs.

(2) Elements of the IN field are everywhere of mixed polarity and move rapidly during their brief lifetimes. They appear through local dipole emergence and splitting of network elements. They continually merge with the elements of the network, sometimes enhancing them and sometimes weakening them.

(3) In some cases the IN fields flow into network elements, but most show random motion. There is a tendency for ER elements to flow to existing poles.

(4) Magnetic fields are concentrated at every level of intensity.

(5) The magnetic elements of the weak network are not concentrated in linear features as is the enhanced network, but rather concentrated in point-like structures. They correspond to the 'rosettes' of spicules, first described by Beckers (1963), in contrast to the bush structures pointed out by Cragg *et al.* (1963).

Acknowledgments

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