TRANSIENT BRIGHTENINGS OF INTERCONNECTING LOOPS

II. Dynamics of the Brightened Loops

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Abstract. We discuss three different kinds of dynamic events related to interconnecting loops observed in soft X-rays aboard Skylab. (1) A newly born transequatorial loop that was either emerging from subphotospheric layers or gradually filled in with hot plasma. (2) Large-scale twists of interconnecting loops which never relax, and often only form, after the loop brightenings. (3) Three events where the loop that later interconnected two active regions had been visible long before one of the interconnecting regions was born. Several impacts this observation might have upon our understanding of the process of flux emergence are suggested.

1. Introduction

In an earlier paper (Švestka and Howard, 1979; referred to as Paper I) we studied the occurrence of sudden brightenings of interconnecting loops in relation to flares, newly emerging flux, and slowly moving disturbances from other active regions. We have also tried to estimate the lifetime of the brightenings and the density and temperature of the brightened loops. In this second paper, we want to discuss some dynamical effects associated with these brightenings:

(1) The process of birth of transequatorial loops;

(2) observed twists of interconnecting loops; and

(3) interconnecting loops that exist *prior* to the birth of one of the interconnected active regions.

2. The Process of Birth of Transequatorial Loops

As we mentioned in Paper I, we have been greatly interested in finding any dynamic effects propagating *along* the interconnecting loops which could indicate the nature of the process of the loop heating. However, with only one exception, no dynamic effects of this kind could be detected in any loop we studied, in spite of the fact that some loops were observed in the earliest phase of the brightening (cf. Section 4.1 in Paper I). This indicates that either the loops are heated homogeneously along their

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whole extent (with some preference of the flare tops in the initial phase, cf. Paper I), or the heating propagates so fast that the Skylab data are unable to detect it.

The only exception was a transequatorial loop observed on September 2, 1973 (BF-5 according to the notation adopted in Paper I), where the brightening extended gradually from region McMath 12512 on the southern hemisphere (16° S) to McMath12510 (15° N), forming thus a newly visible interconnecting loop. The loop could not be seen at 16:18 on September 2, it began to be visible at 22:52 on that day, and it extended along the full distance of about 30° at 04:48 on September 3 (cf. Figure 1).

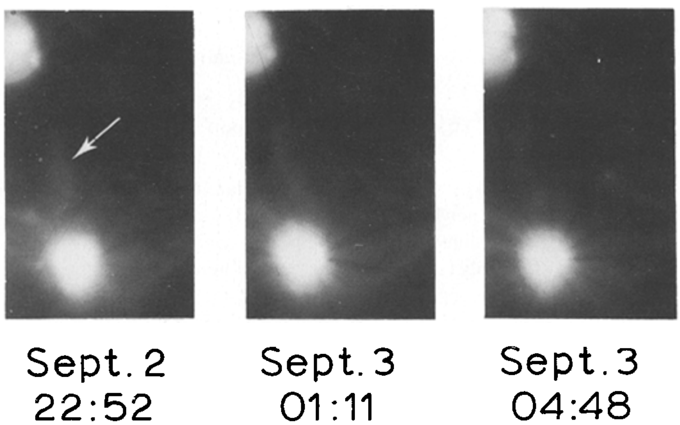

Fig. 1. Possibly the birth of a new transequatorial loop on September 2/3, 1973. The left picture, at 22:52 UT on September 2, shows the loop partly extending from the the newly born McMath region 12512 (below) toward McMath 12510 (above). The right picture, at 04:48 on September 3, shows the connection fully established. The central frame was taken at 01:11 on September 3. This figure also shows the event AF-5 discussed in Section 4: The brightened X-ray bright point can be seen on the right-hand frame. (AS&E photographs in soft X-rays: 2–54 Å, exposure 16 s.)

An estimate of the speed of growth of the brightening is difficult and inaccurate for several reasons: (1) We do not know how deep in the regions the loop was rooted (see the extensive X-ray emission of the active regions in Figure 1). (2) The loop was fairly diffuse. (3) Gaps between successive pictures are large: 2.3 and 3.5 hr, respectively. The only result we can give is that prior to 22:52 on September 2 the mean speed was >11.6 km s^{-1}, but it decreased to only 3 to 6 km s^{-1} between that time and 4:48 on September 3. This is a speed lower by two orders of magnitude than the sound speed or Alfvén speed for $n \sim 10^9$ cm^{-3} and $B \sim 10$ G.

We saw somewhat similar behaviour in the case of the transequatorial loop that connected McM 12474 and 12472 during its birth on August 4 to 6 (cf. Figure 2b in Švestka *et al.*, 1977). Therefore, it is probable that this event of loop brightening also was a case of the birth of a transequatorial loop. In contrast to the August event, however, where the newly formed loop system stayed visible for at least two days (cf. event AF-3 in Paper I and here Section 3), the loop of November 2 disappeared again after 12:10 on September 3. It might have become visible once more for a few hours on September 5 (cf. event BF-6 in Paper I); in any case, the system to which this loop belonged (and of which it was perhaps the first foundation link) subsequently survived in the solar corona for several solar rotations.

In Švestka *et al.* (1977) we arrived at the conclusion that the transequatorial loop of August 6 was most probably born through reconnection of magnetic field lines extending from the two active regions toward the equator. The reconnection was accomplished 33–49 hr after the time when the younger interconnected region was born. For the September event, the newly born region (McMath 12512) is mentioned in *Solar Geophysical Data* first on September 1, at 62° E. At 13:08 UT on the 1st the region could be seen in X-rays on OSO-7, where it was invisible 8 hr earlier. By 17–18 hr on that day it already developed three tiny spots and a small bright Hα plage. Hence its age, at the time when the loop was first seen fully developed, was 33–48 hr, which is another similarity to the event of August 7.

Of course, it is also possible that in both these cases the magnetic loops actually existed prior to the brightening, and that we have here an example of a slow brightening of a pre-existing loop. The shape of the portion of the loop that brightened first did not change as the brightening progressed, so there apparently were no drastic processes at work. However, the fact that one of the interconnected regions was born only shortly before, is an evidence that the connection had to be newly formed close to the time when the brightening was observed.

In any case, the gradual growth in brightness could be explained as due to progressive heating, or to progressive filling up of the loop with plasma, from the hotter or denser (in our case the younger) region. For example, Bessey and Kuperus (1970) and Craig and McClymont (1976) have shown that, with slow energy input, the velocity of a thermal wave along field lines can be approximated as

$$v_t \simeq \bar{v}(\lambda/l)\ \mathrm{cm\ s^{-1}}\,, \tag{1}$$

where $\bar{v}$ is the thermal speed of protons, λ the proton mean path, and l the scale length of the temperature gradient. Thus, if $l \gg \lambda$, we can have $v_t \ll \bar{v}$, i.e. the excitation along the loop can grow much slower than the sound speed, in agreement with observations.

However, if this were true, we should observe a similar phenomenon more often: Rarely are the temperature and density conditions at both ends of a newly reconnected loop identical. However, as we said before, such a slow growth in brightness has not been seen in the initial phase of any other interconnecting loop. Therefore, one has to consider also another alternative interpretation, suggested by Vaiana (1978), namely that the loop growth represents a gradual emergence of a subphotospheric loop into the corona.

According to Parker (1975) a magnetic loop rises through buoyancy with a speed

$$u = v_A(\pi a/C_D\Lambda)^{1/2}\,, \tag{2}$$

where

$$v_A = B/(4\pi\rho)^{1/2}$$

is the Alfvén speed, a is the radius of the tube, C_D the decay coefficient (of the order of unity and <3 for subsonic motion), and Λ is the atmospheric scale height. With a close to or slightly smaller than Λ, the speed of emergence is thus very close to the Alfvén speed for the value of B in the flux tube, B_T. Hence, a flux tube will rise with a speed close to 10^{-2} B_T km s^{-1} from the photosphere into the chromosphere. Because the interconnecting loops are never rooted in sunspots and connect spotless hills of magnetic field in the active regions (Howard and Švestka, 1977), the order of 100 G seems to be an appropriate estimate for B_T. Thus the speed of emergence would be of the order of 1 km s^{-1}, as observed.

If this interpretation were the correct one, it would imply that the two active regions on opposite hemispheres were interconnected in subphotospheric layers prior to the loop visibility in the atmosphere, and most probably also prior to the emergence of the newly born active region to the solar surface.

This leads first to the same question we raised with the interpretation through heat waves: Since it seems more likely that such subphotospheric connections would exist between active regions on the same hemisphere, why didn't we see any effects of such a slow extension of brightness in any other loop? There is, however, a possibility that only regions in opposite hemispheres are interconnected below the solar surface as a possible consequence of severing and reconnection of the magnetic fields of active regions. In that case it is always the preceding polarities that should be interconnected (Krieger *et al.*, 1971), and this indeed was the case on September 2.

However, many transequatorial loops connect following polarities; so, even if this interpretation were the correct one in this particular case, not all transequatorial loops could emerge from below the photosphere: The birth through reconnection of two shorter loops still remains a likely interpretation for many such loops.

3. Twisting of Interconnecting Loops

Several interconnecting loops were seen twisted during or after their brightening, as Figures 2a, b, c demonstrate.

The most interesting example of such a twist was observed on August 7, 1973 (Figure 2a; event AF-3 according to the notation in Paper I). The whole life-story of this interconnecting loop was described by Švestka *et al.* (1977): The loop was not twisted before its increase in brightness; it twisted only during the brightening while expanding, and it eventually disappeared. One can suppose that the twist was due to observed movements of the magnetic elements in which the loops were rooted while the whole loop system expanded upwards.

Also in case AF-2, on July 6, 1973 (Figure 2b), the loops were not twisted before the brightening; they twisted only after the event, probably due to the observed rotation of the new active region in which the loops were rooted. This loop system did not disappear after the twist, but the twist seemed to relax on July 8.

In two other cases the twist might have existed before the loop brightened. In the event CF-2, on August 4, 1973 (Figure 2b), the twist seems to be present in the loop

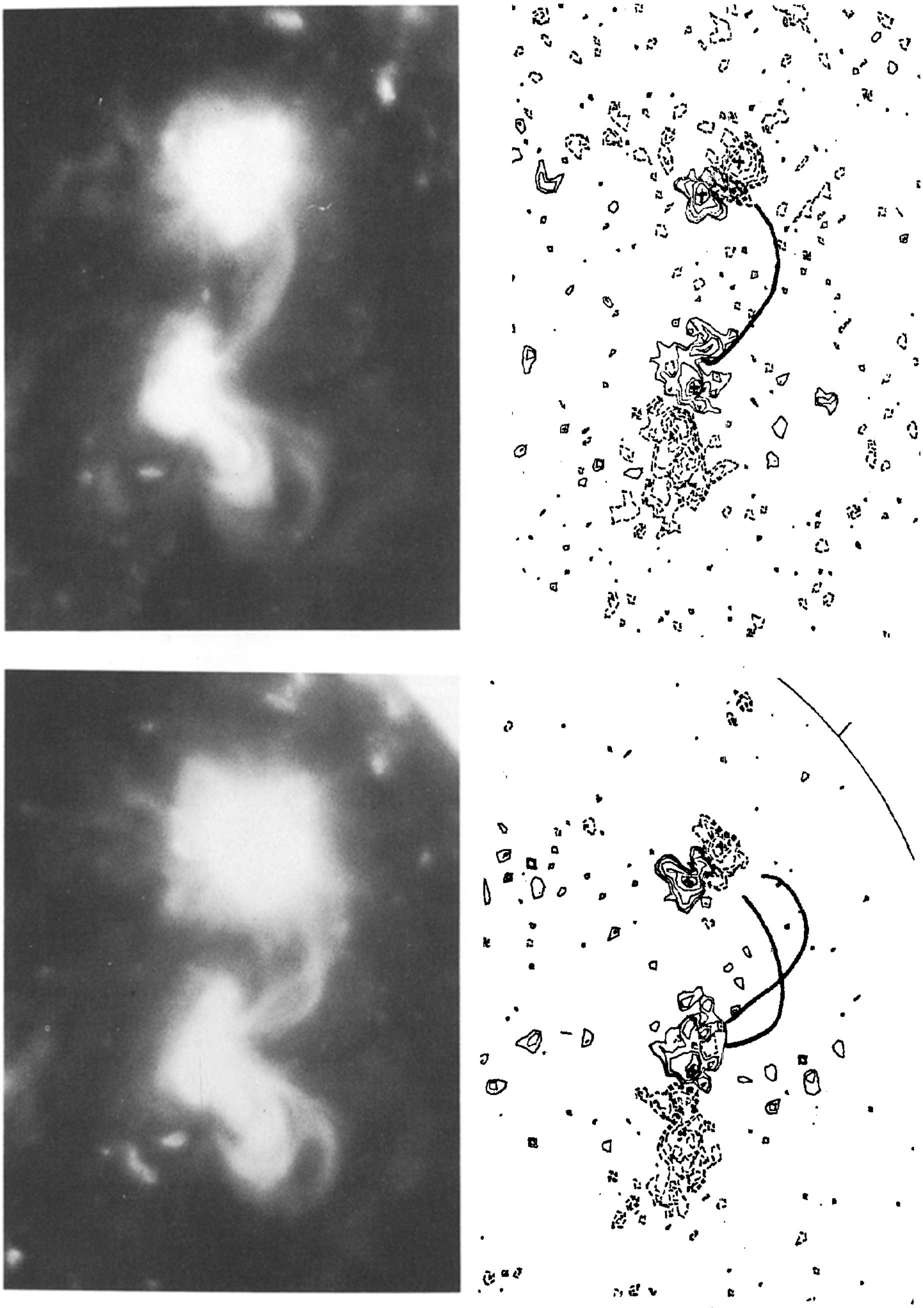

Fig. 2a. The transequatorial loop of August 7, 1973 (upper frame at 07:17 UT) twisted after its brightening (lower frame at August 8, 01:50 UT). Mount Wilson magnetic field maps indicate where the loop connections were rooted. (AS&E Skylab photographs in soft X-rays: 3–54 Å, exposure 64 s.)

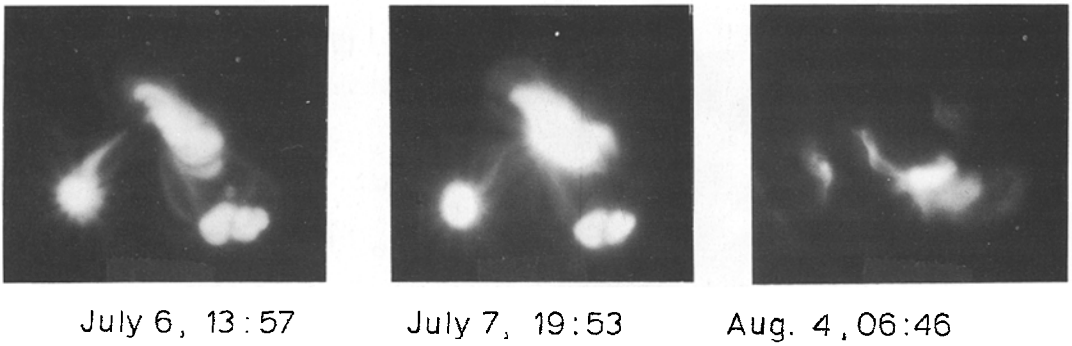

Fig. 2b The interconnection of July 6, 1973 (left frame at 13:57 UT) twisted as the newly born (left-hand) active region rotated (central frame at 19:53 UT on July 7). The right-hand frame shows the twisted interconnecting loops of August 4, 1973 (06:46 UT). (AS&E Skylab photographs in soft X-rays, left 2–54 Å, exposure 16 s, center: 2–17 Å, 256 s; right: 2–54 Å, 4 s.)

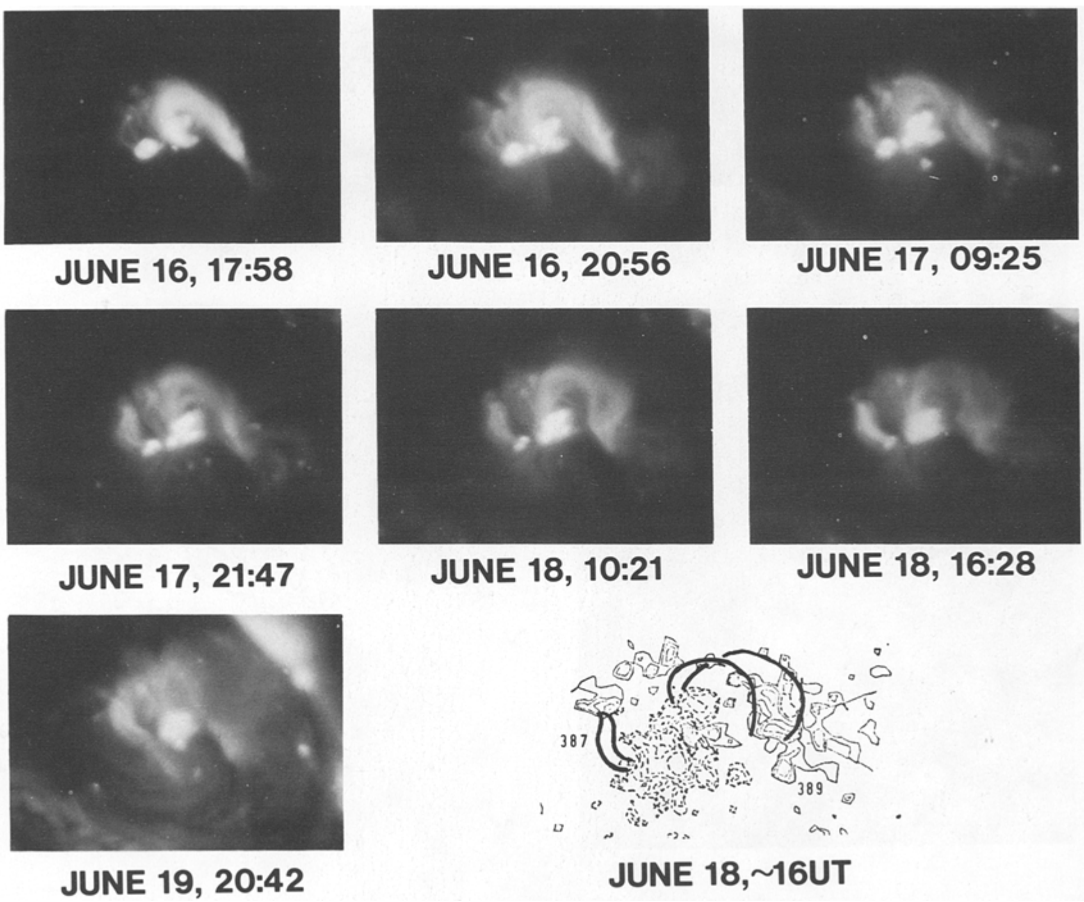

Fig. 2c. The untwisting loop of June 16–19, 1973. A major flare occurred in the region McMath 12387 at 14:03 UT on June 16. (AS&E Skylab pictures in soft X-rays, 3–54 Å, exposure 16 s except the first frame (4 s) and the last one (64 s).)

system before the brightening, but – as far as the low-quality pictures on August 5 reveal – the loops also stayed twisted after the event. The twist disappeared only later, on August 6, some 30 hr after the brightening. We do not know, of course, whether the loops really untwisted, or whether the twisted loops simply ceased to be visible at the time.

A somewhat similar case was seen on June 16, 1973 (event CF-1). The extensive, very bright loop was clearly twisted since the first time we saw it brightened; also loops preceding it (which, however, need not be quite identical with that one seen bright) appear to be twisted. The twist, however, definitely did not disappear, nor relax, after the brightening. The loop was untwisting only very slowly during the following three days, and it finally completely dissolved on June 19 (Figure 2c).

All these observations indicate that the twists have no direct relation to the loop brightenings. Note that both the events when the loops appeared to be twisted before the brightening, were old loops. All the young loops (cf. the classification in Paper I, Section 2) were either not twisted, or the twist formed only after the brightening. The twisting was produced by motions of the magnetic elements in which the loops were rooted. This also explains why we may see twists in old loops prior to the brightening: The long-existing magnetic connections are distorted because of rotation or shift of the photospheric magnetic elements in which they are anchored.

Thus there is no contradiction to an assumption that the loops are nearly current-free when they are formed. This is to be expected if the loops originate through field-line reconnection: With newly emerging flux in the case of one-hemisphere loops, or between two loops if the interconnection crosses the equator (cf. Figure 1 in Švestka *et al.*, 1977). The reconnection process tries to build a connection with the minimum amount of energy, i.e. a current-free loop. After that, relocations of magnetic polarities and coronal motions may induce currents into the configuration. As we have seen in two events of young loops, the sudden brightening can speed up the twist of the loops; at least in one event (AF-3) to the extent that the loops system became unstable and disappeared.

However, we did not see any case where the brightening could be the result of a twist, preexisting and relaxing during the brightening. When the twist relaxed, it happened over a period significantly longer than the duration of the event.

4. Loops Seen Prior to Newly Emerging Flux

Usually one first detects new flux emerging into the corona (an X-ray bright point) and only after that does this newly emerged region begin to be visibly interconnected with another old region in its vicinity. (In this section we will assume that the X-ray brightening is always associated with emerging small bipolar magnetic flux. Although this is generally observed to be the case, we do not have magnetograph observations showing the emerging flux in these particular examples.) Sometimes (within the time resolution of the Skylab sequence of photographs) the new flux and the interconnecting loop appear at the same time (cf. Paper I, Table III). However, there were three events where one could see the interconnecting loop earlier than the new flux became visible at its footpoint.

Two examples are shown in Figure 3. In case AF-1 (on June 26, 1973) the loop was seen in X-rays 58–78 hr prior to the flux emergence. Careful examination of the frames taken on June 24 indicates that already at that time the interconnecting loop consisted of two separate parts, with the point of separation being *exactly* (i.e. within a few arc sec) at the place where the new flux emerged on the 25th (cf. Figure 3).

In case AF-4 (on September 2, 1973) the loop was seen in X-rays 23–36 hr* prior to the flux emergence. Whereas the loop was first seen on August 31 at 06:45, the newly born X-ray region appeared only on the frame taken at 12:06 on September 1. This region was discussed also by Sheeley *et al.* (1975, their Figure 2) and Sheeley (1976, his Figure 3).

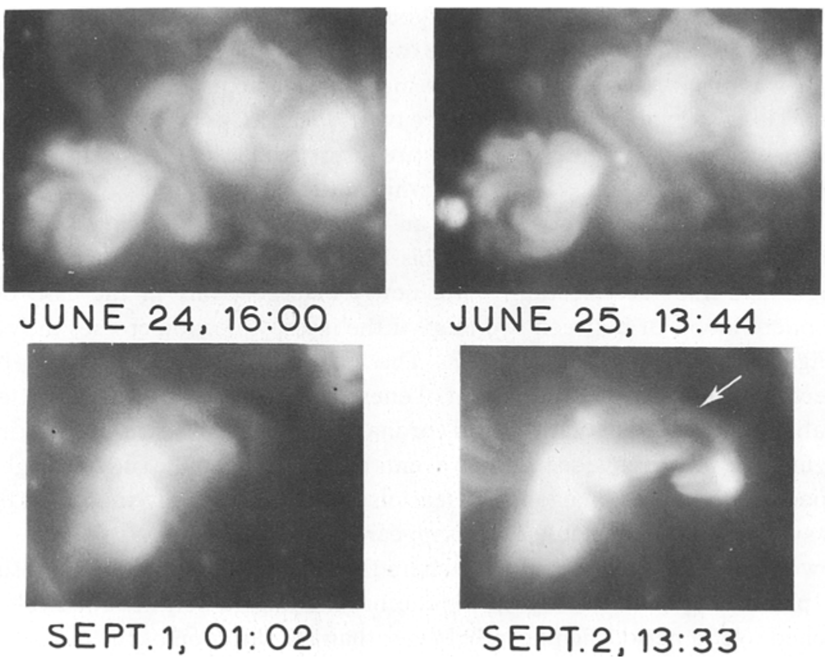

Fig. 3. Two events (AF-1 above and AF-4 below), when a newly appeared loop presaged the occurrence of a new flux near its footpoints. (AS&E Skylab pictures in soft X-rays, 2–54 Å, exposure 64 s.)

In the third case (AF-5, on September 3, 1973) the loop interconnected a newly emerged X-ray bright point with an old active region (cf. Figure 1). The interconnecting loop was visible for more than 5 hr before the bright point emerged.

In all these cases the new flux emerged *exactly* (within less than 4000 km) where the preexisting loop was rooted (cf. Figures 1 and 3). We have shown (Howard and Švestka, 1977) that the interconnecting loops become visible as a consequence of

* By mistake, 24 hr more were added to this time difference in Paper I.

variation in magnetic field near their footpoints; in the case of young loops this variation is the emergence of new magnetic flux. Therefore, in these three cases it is as if the loops were affected by the emerging flux tens of hours before the flux reached the upper atmospheric layers and became visible in X-rays.

The brightenings of the interconnecting loops in these cases are very definite and strong events. It may be that the case of the activity eruption and loop brightenings in the active region McMath 12628 on November 26, 1973, represented a similar situation (Howard and Švestka, 1980). This was one of the most outstanding events of the whole Skylab period, so it seems unlikely that these cases represent chance association of flux eruption and brightening. How, then, can we explain the fact that at times we see some apparent consequences of flux eruption long before the flux itself is seen?

Equation (2) shows that the speed of emergence of a flux tube is close to the Alfvén speed for the magnetic field strength in the flux tube, B_T. On the other hand, any disturbance of the interconnecting loop propagates along the loop with the Alfvén speed corresponding to the value of B in the loop, B_L. If the loop is seen excited through contact with the emerging flux deep below the photosphere several tens of hours before the flux reaches the upper atmospheric layers, there must be in (2) either

$$u \ll B_L/(4\pi\rho)^{1/2}\,, \tag{3}$$

i.e.,

$$B_L \ll B_T\,, \tag{4}$$

or the radius a in (2) is very much smaller than the scale height,

$$a/\Lambda \ll 1\,. \tag{5}$$

Eventually, of course, Equation (2) may prove to be incorrect, with strong fields rising much slower than envisaged by Parker.

Since we cannot observe what goes on below the surface before the arrival of flux from below, we can only speculate at this time. Possibilities that seem reasonable are:

(1) The rising magnetic flux may be in the form of very small, filamentary, high field strength, flux tubes, as some observations indeed indicate (Vrabec, 1974; Zwaan, 1978). Then the inequality (5) will be fulfilled, the ratio a/Λ in Equation (2) will be small, and the rise of the emerging flux tube to the surface will be slower than the Alfvén velocity corresponding to B_T.

(2) Whereas the field strength in all elements of the interconnecting loop may have the standard value of ~1500 G (Stenflo, 1973; Harvey, 1977), the field strength in the newly erupting flux might be lower (below 600 G at the top of the convection zone) because of the reason suggested by Zwaan (1978): Everywhere inside the convection zone B_T remains below the local equipartition value B_E defined as $B_E/8\pi = E_k$, where E_k is the kinetic energy density in the convection. In that case the inequality (4) is fulfilled.

(3) The flux tube starts to rise to the surface because of changes in the thermal or convective properties of the atmosphere between the flux tube and the surface. Thus effects at the surface can occur, triggered by these changes, before the flux arrives at the surface.

(4) A change in the surface magnetic field configuration brightens the loop, and Alfvén waves propagate downward from the surface and trigger the rise of the flux tube.

(5) The flux tubes rise actually much slower than Parker's Equation (2) predicts. This might be the case, e.g., if some turbulence persists within the tube (Zwaan, 1978). Only when B_T exceeds the equipartition value B_E, does the effect of buoyancy become significant enough to make the tube rise. However, because of very little lateral heat exchange, the rising loop adiabatically expands which brings B_T once again below the B_E value. Thus B_T is kept all the time close to B_E and in this way the process of emergence may be slowed down, far below the Alfvén speed.

It is doubtful that any of these effects (1) through (5) could delay the loop emergence by several tens of hours, as we have observed. However, if two (or more) such effects contribute, the observed delay could be accomplished. In any case, it is a subject worth detailed study, since it may give us valuable information about the real conditions of the flux emergence.

5. Conclusions

In Paper I we have shown that at least in some cases the top (or most curved) part of an interconnecting loop is the site of the most intense brightening in the initial phase of a loop enhancement; no fast-propagating disturbance could be seen in any loop in which the early phase of development could be followed. However, in one case, on November 2/3, 1973, the brightening gradually extended along a transequatorial loop, invisible before, with a slow speed of only 3 to 6 km s^{-1} in the later phase of the loop growth. We suppose that this might have been the birth of this transequatorial connection, because at that time one of the interconnected regions was younger than two days, and later on the two regions stayed interconnected for at least two rotations. The loop was either emerging from subphotospheric layers (connecting the preceding polarities as some models of the solar cycle predict), or we have witnessed here a progressive heating and/or filling up of a newly formed loop with plasma.

In a few cases the loop brightening was followed by a large-scale twisting of the brightened loop. In two cases a twist might also precede the brightening. However, we never found any evidence for a case of brightenings caused by a large-scale twist that relaxed after the brightening had occurred. All the twists we see appear to be caused by motions of the photospheric magnetic elements in which the loops are rooted, and loop brightenings either have no effects upon them, or increase the twists as the brightened loops grow (as in the event of August 7, 1973). Of course, we cannot say anything about possible small-scale, internal twists of the loops which might be below the resolving power of the Skylab instrumentation.

In three events the loop that later interconnected two active regions had been visible before one of the interconnected regions was born (preceding it by 5, >23, and >58 hr, respectively). A similar case may be the striking outburst of flare activity and loop brightenings in McMath region 12628 on November 26, 1973, which started at least twenty five hours before one could see the newly emerging flux that possibly caused it (Howard and Švestka, 1980). If one takes Parker's (1975) Equation (2) as strictly valid, such cases can hardly happen, since both the flux emergence and any disturbance propagation toward the solar surface move with Alfvén speeds. However, the speed of emergence may be lower than Equation (2) predicts if some turbulence persists with the emerging tube (Zwaan, 1978). The emergence will slow down also in the case that the rising magnetic tube is in the form of small, filamentary, high field strength flux tubes. Or, both the flux rise and loop brightening are caused by a common agent between the flux tube and the surface which influences the loop before the flux arrives at the surface (and possibly even before the rope begins to rise).

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