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Emergence of a U-loop – sub-photospheric link between solar active regions

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Abstract. Using SOHO/MDI magnetic maps we present the first direct observational evidence for the emergence of a U-loop in the solar photosphere. We show that two active regions (ARs), i.e. two adjacent Ω-loops, which were emerging at the same time at the same solar latitude, about 150000 km distance in longitude from each other, emerged from at least partially the same toroidal flux strand, and we bring five independent arguments to prove this assertion. The opposite polarity legs of the two Ω-loops were connected below the photosphere by a U-shaped loop. Following the emergence of the Ω-loops, the U-loop started emerging, manifested by the fast proper motion of the leading spots of the eastern (smaller) active region, which, after forming an elongated channel, collided with the following spots of the westerly AR and started cancelling with them. The full cancellation could not be followed because the ARs rotated out of sight. The total magnetic flux of the two ARs was unequal, the flux in the smaller AR was a quarter of that of the larger one. We propose scenarios for the formation of such a U-loop and discuss the implications of the confirmed existence of U-loops for the solution of such puzzles as the in-situ disappearance of magnetic flux from active regions, active nests and the formation of inter-AR filaments.

Key words: Sun: activity – Sun: magnetic fields

1. Introduction

Although most of the large-scale magnetic flux is believed to emerge from the solar interior in the form of Ω-loops, the existence of other flux-tube geometries has long been suspected (O-loops, kinked knots and balls (Tanaka 1991; Lites et al. 1995) and U-loops (Parker 1984; Spruit et al. 1987). Zwaan (1992) pointed out that while the Ω loop concept is indispensable for the explanation of the emergence of ARs, the complementary U-loop concept is very important in the explanation of the decay of ARs. U-loops are the opposite of Ω-loops: they have two ends located in the photosphere but are still embedded in the convective zone. They may be created in various ways, e.g. between two adjacent Ω-loops that have emerged from the same toroidal flux strand, or by sub-surface reconnection between the opposite polarity legs of Ω-loops.

An important difference between Ω- and U-loops is that while an Ω-loop can rise rapidly by draining material down its legs, in a U-loop matter is trapped in the concave part of the loop and cannot leave the Sun without disengaging from the plasma (Parker 1984). However, the horizontally oriented field is constantly agitated by turbulent convection and is susceptible to a form of Parker instability (Parker 1966; Mouschovias 1974), which eventually results in the formation of heavy magnetic valleys and an evacuated buoyant field between them. The dense and heavy magnetic valleys may sink and break away by magnetic reconnection. Low (1996) estimates that the speed of this process could reach 1 km s^{-1} in the photosphere. Furthermore, small sections of the horizontal loop can be brought up by turbulent eddies, creating a mixed-polarity field (down to a few Gauss, e.g. the intranetwork field) through the "sea-serpent" process (Spruit et al. 1987). As a result of these processes, the horizontal field effectively disappears from the photosphere, resulting in a flux decrease in two opposite polarity areas (the legs of the U-loop). Spruit et al. (1987) pointed out that those two areas may be so far apart that they are not recognized as being related. The underlying sea-serpent process creates a pepper-and-salt magnetic field, which does not differ much from the rest of the background field, and thus remains unnoticed.

However, we can expect the process of U-loop emergence to be observable when the two connected Ω loops are close to each other and emerge at the same time. Then we have a chance that the emerging Ω loops lift at least part of the U-loop above the photosphere, preventing the formation of a long, truly horizontal part of the U-loop. Then we would see the unusual sunspot motion consisting of opposite polarity spots of two different active regions seeking each other out, followed by a "clean" cancellation of their magnetic fields (Low 1996).

Since the launch of SOHO the continuous 96-minute cadence of full-disc magnetic observations has provided excellent opportunities to discover finer details of the evolution of the magnetic fields in solar active regions. Between 30 May-7 June 1999 we observed the emergence and subsequent evolution of two ARs (NOAA 8562 & 8567), which, we believe, clearly show the emergence of a U-loop connecting them. We describe

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Table 1. Magnetic flux in the ARs

Time	AR1			AR2		
UT	Total unsigned (Mx)	Positive (Mx)	Negative (Mx)	Total unsigned (Mx)	Positive (Mx)	Negative (Mx)
1-JUN-99 12:00	$1.2\pm0.1\ 10^{22}$	$5.5\pm0.4\ 10^{21}$	-6.3 ± 0.510^{21}	$1.0\pm0.0\ 10^{21}$	$5.3\pm0.1\ 10^{20}$	$-4.7\pm0.1\ 10^{20}$
2-JUN-99 12:00	$1.3\pm0.1\ 10^{22}$	$6.2\pm0.4\ 10^{21}$	$-6.4\pm0.5\ 10^{21}$	$1.3\pm0.3\ 10^{21}$	$6.6\pm0.2\ 10^{20}$	$-6.0\pm0.2\ 10^{20}$
4-JUN-99 06:00	$2.0\pm0.1\ 10^{22}$	$9.1\pm0.6\ 10^{21}$	$-1.1\pm0.1\ 10^{22}$	$4.5\pm0.5\ 10^{21}$	$2.3\pm0.3\ 10^{21}$	$-2.2\pm0.2\ 10^{21}$

the observations in Sect. 2, show the motion of spots, magnetic flux measurements and the flare activity in the ARs in Sect. 3. In Sect. 4 we discuss the importance of U-loops in understanding the in-situ disappearance of magnetic flux and the formation of filaments, and in Sect. 5 we present five independent arguments to show that we have indeed observed the emergence of a U-loop.

2. Data

MDI (Michelson Doppler Imager) is one of the twelve experiments onboard SOHO, and which measures the photospheric manifestation of solar oscillations (Scherrer et al. 1995). Besides the dopplergrams, it records the line-of-sight magnetic field with a resolution of 4" in the full-disc mode. In this article we analyse 5-minute averaged full-disc magnetograms with a 96-minute cadence (15 day^{-1}) taken in the period of 30 May - 7 June 1999.

We made a co-aligned movie out of the MDI magnetograms, rotating them to the same position around the central meridian, thus removing the effects of the projection from the images. In the measurements of the magnetic flux we measured the disc position of the ARs and applied a correction for the projection effects on the magnetic fields, supposing that the magnetic vectors are perpendicular to the solar surface.

3. Results

3.1. Parallel history of flux emergences and spot motions in the two ARs

The first flux emergence was seen to start in AR1 (NOAA 8562) on 30 May at 11:12 UT. In AR2 (NOAA 8567) the first upcoming flux (B1) was seen about 10-11 hours later at 22 UT. The latter bipole reached maximal separation ($26''$, $\approx$ 19000 km) by 1 June 3 UT and decayed steadily after that; the separation of the opposite polarities slightly decreased and its flux became dispersed by supergranular flows (Fig. 1). Meanwhile, a second impulse of flux emergence started in the center of AR1 on 1 June at about 12 UT, which, through merging of several smaller negative flux concentrations, resulted in the formation of a second leading spot east of the first one and also created significant negative flux concentrations in the trailing part of AR1 (Fig. 1c). On 2 June at 20:51 UT a new episode of flux emergence started in AR2 (B2, see Fig. 1c). During the following 24 hours several negative (leading) flux concentrations formed in AR2, while the positive (trailing) polarities had a more dispersed appearance. The leading spots started moving westward, following the usual separation scenario of the opposite polarities of bipolar ARs (Fig. 2). However, their motion did not decelerate and cease as normally happens, but the spots kept moving with about the same velocity (0.3 km s^{-1}) for the following four days until the first of the spot "train" reached the main trailing spot of AR1 (Figs. 1, 3 and 4).

When the leading negative spot of AR2 reached the moat boundary around the trailing spot of AR1 on 5 June at about 21 UT, its flux quickly started to spread out along the boundary of that modified supergranular cell (Fig. 1f-g). The main negative spot of AR2 then approached and collided with the main trailing spot of AR1, rotating around the latter in a clockwise direction (Fig. 1h). At the same time, several negative polarity concentrations appeared in the trailing positive polarity region of AR1. The gradual disappearance of both positive and negative flux was very apparent in the magnetic movie. However, by then the ARs were too close to the limb for flux measurements and rotated out of view before the cancellation process was completed.

Fig. 1 can only provide a static presentation of the events described. More dynamical on-line versions are the compressed numerical movies (AVI format) located at *http://mesola.obspm.fr/gallery/mdi_i.avi* (white-light) and *http://mesola.obspm.fr/gallery/mdi_b.avi* (magnetic fields). A magnetic field movie in animated GIF format (with no compression) is also available at *http://mesola.obspm.fr/gallery/uloop.gif*.

3.2. Magnetic flux evolution of the ARs

The magnetic flux content of the two ARs is shown in Table 1 at different times. AR2 had two independent bipoles, B1 and B2. B1 emerged first and reached its peak flux on 2 June, after which time B2 started emerging at the same place, and having more than three times the magnetic flux of B1, started dominating AR2. The peak fluxes were reached on 4 June in both ARs. The fluxes were corrected for the projection effects on the magnetic fields, supposing that the magnetic vectors were perpendicular to the solar surface. The errors were calculated to be proportional to the area of the measured region taking ±10 Gauss error per pixel for both negative and positive fields, greatly overestimating the error introduced by instrumental effects. However, we kept the high error values because we wanted to account for other errors introduced by the inclination of the magnetic vectors in the ARs, which, in the presence of the U-loop geometry, can significantly differ from the normal to the surface.

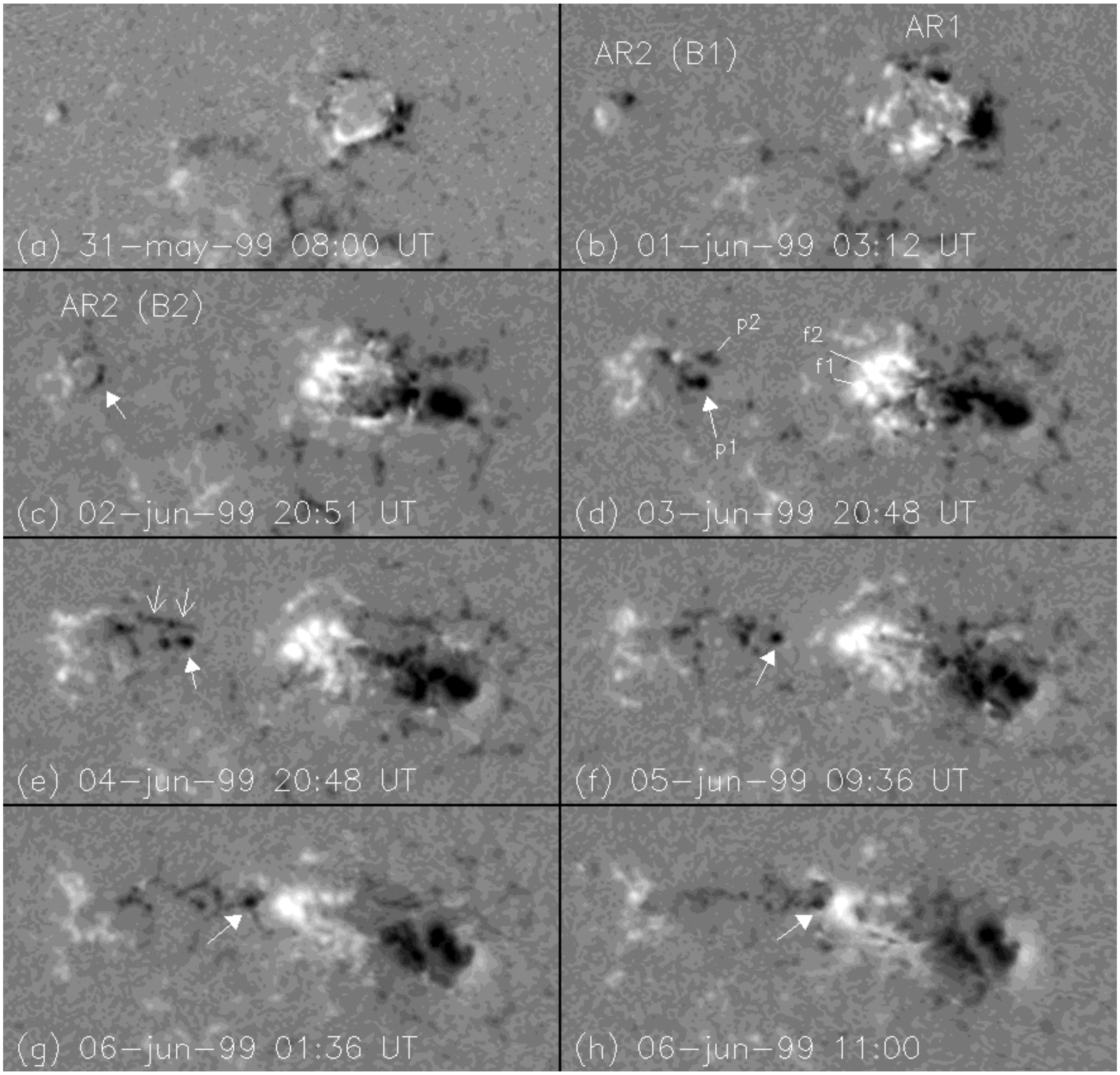

Fig. 1a–h. Evolution of the two active regions during seven days. Arrows point to the fast moving main spot of AR2 (p1), which, according to our interpretation, is a signature of the emergence of a U-loop connecting AR1 to AR2 (NOAA 8562 to 8567). The formation of magnetic flux concentrations elongated along the direction of proper motion (double arrow in **e**) as well as of chains of umbrae (**h**) suggest a highly inclined (almost horizontal) flux tube geometry on the leading side of AR2. B1 is the first bipole which emerged in AR2 (**a**–**b**); B2 appeared at the same place 2.5 days later (**c**).

In Table 1 we see that AR1 contained about four times as much flux as AR2. The magnetic flux was well balanced in AR2, while AR1 showed a significant flux inbalance: its leading (negative) polarity was about 18% higer than the amount of positive flux.

Active regions with larger fluxes have larger polarity separations. L. Tian et al. (1999) analysed 20 bipolar ARs, plotting the magnetic flux-weighted distance between the opposite polarities versus the total magnetic flux of the ARs. When plotting the total flux of AR1 and the two independent bipoles (B1 and B2) of AR2 versus their polarity separation, together with the sample analysed by the above authors, we find that AR1 and the first bipole (B1) of AR2 followed the rule, while B2 of AR2, especially by 6 June, showed at least three times more polarity separation than would be expected from its total flux content (Fig. 5).

3.3. Flares in the AR

"Clean" magnetic cancellation is predicted to occur when a U-loop emergence brings two opposite polarities together (Low 1996), implying that high flare activity is not expected to accom-

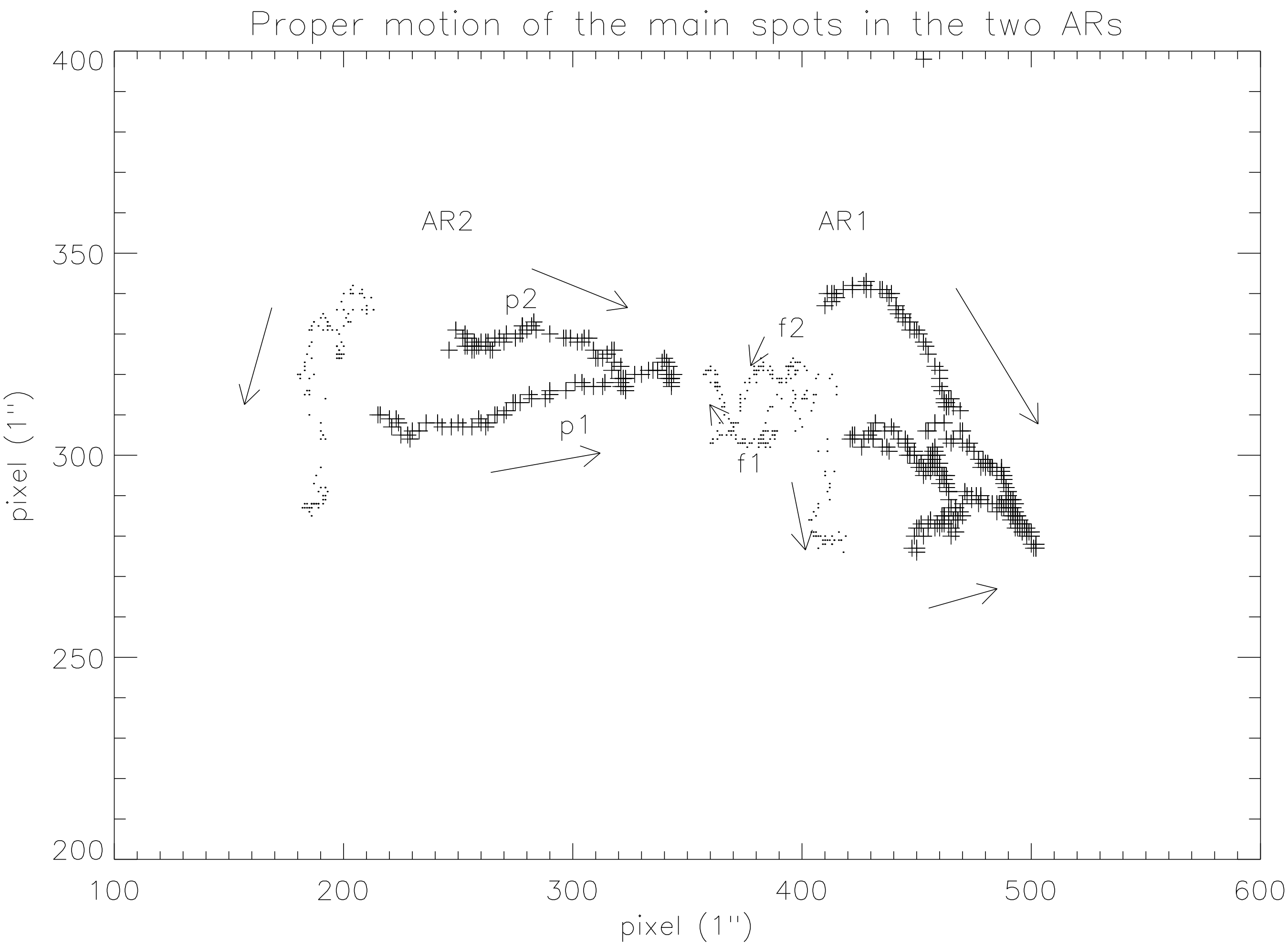

Fig. 2. Motion of the spots in AR1 and AR2 (NOAA 8562 & 8567, respectively). Arrows show the directions of the proper motion. Note that leading and trailing spots separate and the trailing spots of AR1 and leading spots of AR2 move towards each other. Leading (negative polarity) spots are marked by crosses, following (positive polarity) spots by dots.

pany such events, because the magnetic energy of the opposite polarities is not liberated (as in magnetic annihilation), but their magnetic flux instead simply moves above the photosphere.

In Fig. 6 we plot the number of flares (the majority SF, and a few SN and F1 Hα classes) which occurred in these two ARs according to the listing in the Solar-Geophysical Data. All the flares, except for one on the 5th and 2 flares on 8 June, occurred in AR1. Flaring showed a peak on 3 June, when flux was vigorously emerging in AR1. These early flares do not appear to be related to the emergence of the U-loop. There was another flare on 3 June (max. at 07:45, 2B), which was listed in the SGD as an event in NOAA 8560, an AR just to the south of AR1 (NOAA 8562). This flare was observed by the THEMIS telescope on Tenerife, and had in fact some brightening in NOAA 8562 as well (Chambe et al. 2000). After the "collision" of the two opposite polarity umbrae of the two ARs on 6 June there was a minor enhancement in flaring in these ARs. However, these latter flares did not surpass the SN Hα and C1.3 GOES class levels. Normally, the collision and subsequent cancellation of such substantial magnetic field concentrations would lead to significant flaring (e.g. Gaizauskas et al. 1998). Thus we conclude that the cancellation we observed was indeed a "clean" one.

4. Discussion of the significance of U-loops

The demonstrated existence of U-loops can solve several old puzzles. Normally, the magnetic flux which emerged in the form of Ω loops is, at first, strongly concentrated in the photosphere. The concentrations (sunspots) are eroded by turbulent motions which slowly, through a random-walk process, diffuse the flux into the surrounding area. Meanwhile, the total flux slowly decreases due to small-scale cancellation processes as the diffused flux encounters opposite polarity concentrations in the network. However, there are several observations which show that not all the magnetic flux disappears in such way.

In active nests, where active regions (ARs) appear in close vicinity and succession (Brouwer & Zwaan 1990; van Driel-Gesztelyi et al. 1992), ARs appear to evolve differently; they decay faster than do isolated ARs. Even the gradual decay of

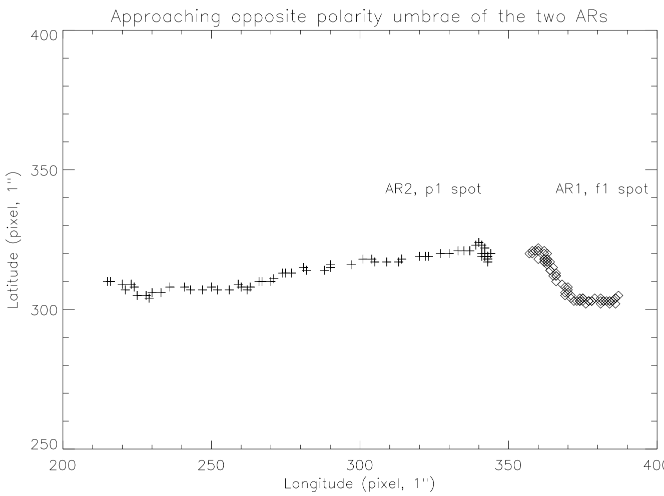

Fig. 3. As the trailing spot of AR1 (f1) and leading spot of AR2 (p1) move towards each other they move almost the same amount in latitude to meet. The velocity of approach is about 0.35 km s^{-1}.

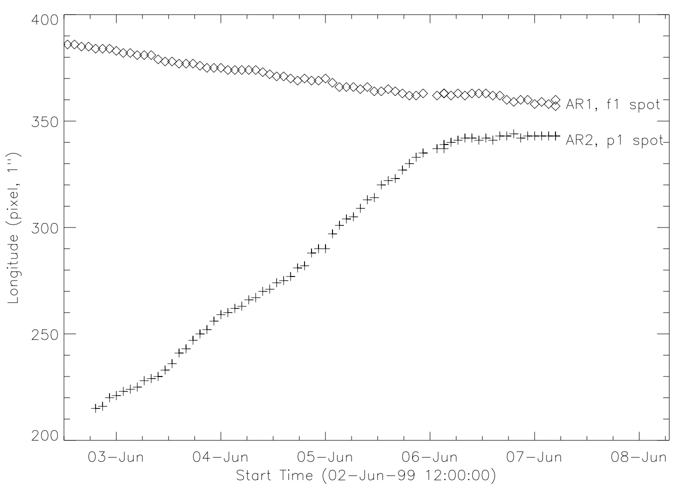

Fig. 4. Approaching motion of the opposite polarity spots of AR1 (f1) and AR2 (p1) in longitude versus time. The two spots collided on 6 June.

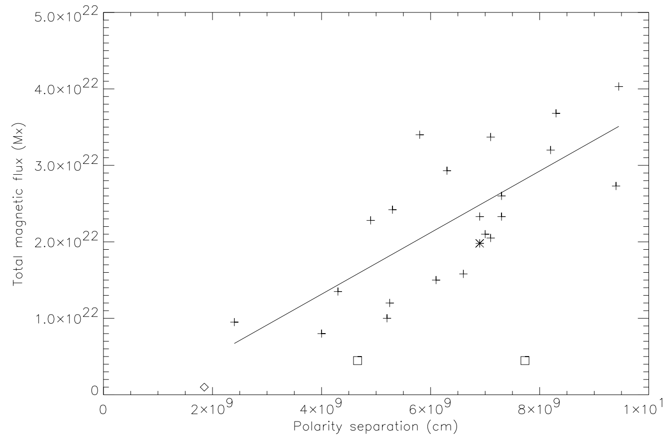

Fig. 5. Active regions with larger fluxes have larger polarity separations. When plotting the total flux of AR1 and AR2 versus their polarity separation together with the sample analysed by L. Tian et al. (1999) we find that AR1 (*) and the first bipole (B1) of AR2 (◇) followed the rule, while B2 of AR2 (□), especially by 6 June, showed at least three times more polarity separation than would be expected from its total flux content.

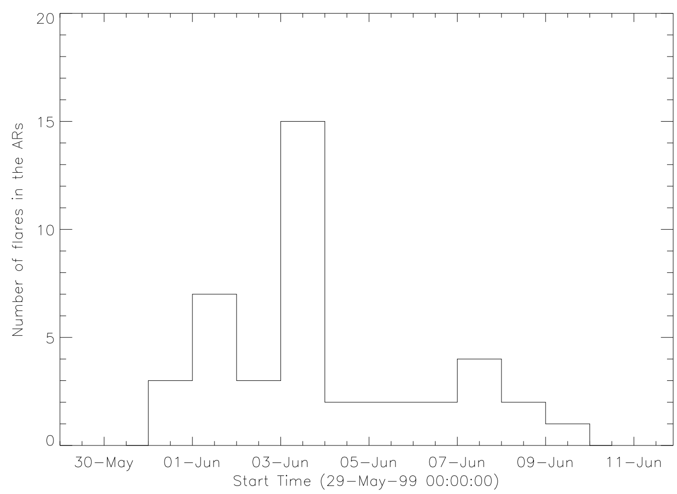

Fig. 6. Number of flares in the ARs as they evolved show a peak on 3 June, when flux was vigorously emerging in them. These early flares do not appear to be related to the emergence of the U-loop. The second peak in flare activity appears on 7 June, when the magnetic cancellation was going on between the opposite polarity umbrae of AR1 and AR2. However, these flares were small, they did not exceed the C1.3 and Hα SN level. The figure is based on the flare list published in the Solar-Geophysical Data (1999).

spots seems to be fastest in nests and flux seems to disappear *within* the periphery of the nest (Gaizauskas et al. 1983; Zwaan 1992).

Wallenhorst & Howard (1982) and Wallenhorst & Topka (1982) observed decaying ARs using Mt. Wilson magnetograms and found no increase in the surrounding field regions as spots decayed; the flux seemed to fade away with no signs of where it went. Furthermore, Wilson & Simon (1983), Liggett & Zirin (1983), Simon & Wilson (1985), and Topka et al. (1986) reported "in situ" flux disappearance from isolated ARs. The flux did not noticably leave by diffusing into surrounding quiet areas, but seemed to diminish within the AR by about 10% per day. These results are very puzzling, though one has to keep in mind that flux seems to disappear when its strength or scale drops below the observational threshold.

Rabin et al. (1984) observed that 4×10^{20} Mx of magnetic flux concentrated in an area of 30 arcsec disappeared overnight. Their vector magnetograms show that all components of the magnetic field weakened together. They estimate that if the field had weakened through diffusion or fluid flow, 90 % of the original flux would still have been detected by the magnetograph within a suitably enlarged area. In fact they detected a threefold decrease in flux. Since the disappearing flux was located in a region of low magnetic shear and low activity, they found it unlikely that the field dissipated through reconnection.

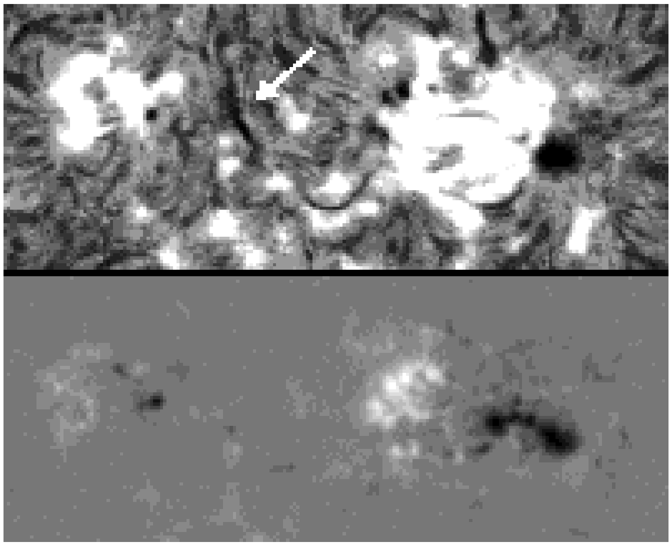

Fig. 7. The presence of the filament, indicated by an arrow, between the two ARs supports the scenario that an emerging U-loop was connecting the ARs, see discussion in the text. The Hα image was taken by Big Bear Observatory on 03 June at 15:38 UT, the MDI magnetogram was taken 22 minutes later.

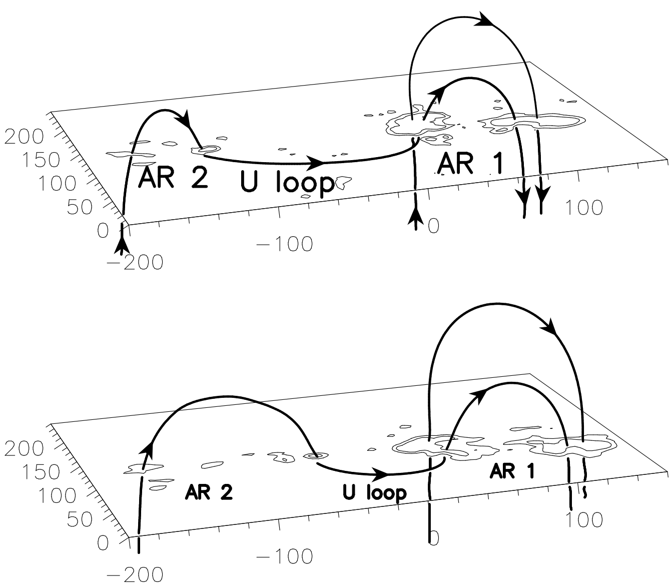

Fig. 8. Flux tube topology in the two ARs on 3 June (upper panel) and 5 June (lower panel). Note that only a part of the magnetic flux of AR1 was extended eastward and emerged to form AR2.

A popular interpretation of the above observations is the submergence of magnetic flux. Submergence is certainly a process which can remove flux from the photosphere in small-scale cancellation processes (e.g. Harvey et al. 1999). However, it is doubtful that large-scale flux can submerge. Low (1996) pointed out that if two photospheric patches of opposite polarities are connected by the traditional Ω loop in the atmosphere above, it is unlikely to have the ability to force the entire magnetic field back down to submerge it below the photosphere.

Theoretically, the buoyant rise of a U-loop is more a simple geometric explanation of why, at the photosphere, two magnetic elements of the opposite polarities should seek each other out in order to annihilate. Low (1996) proposed that many such clean cancellation events (e.g. Rabin et al. 1984; Zirin 1985) which had been attributed to flux retraction (submergence) were, in fact, rather due to emergence of U-loops through the photosphere.

A possible manifestation of the emergence of U-loops is the moving magnetic feature (MMF) phenomenon. MMFs are small, often bipolar, magnetic concentrations which move radially outward across the moat cell surrounding decaying sunspots, carrying magnetic flux away. Spruit et al. (1987) proposed that if ARs are formed at least partially of the same magnetic flux bundle, U-loops may emerge between them and peel off flux from the spot. The presence or lack of U-loops may cause the intrinsic spread in sunpot decay rates (Zwaan 1992).

Another possible consequence of the emergence of U-loops is the formation of filaments. Martin (1989) observed that the formation of filaments is accompanied by a systematic converging drift of opposite polarity magnetic elements toward the inversion line. An emergence of a series of U-loops can be the result of the rise of a quadrupolar configuration (Titov et al. 1993) or of a horizontal twisted flux rope, with a quiescent filament forming in it (Rust & Kumar 1994; Low 1996). In this case the magnetic field along the inversion line would be concave upward, consistent with the inverse configuration observed in the majority of prominences (Leroy et al. 1984; Bommier et al. 1994). Note that the majority (65%) of quiescent filaments form between two ARs (Tang 1987). Our observation that a filament appeared between the two emerging ARs, at the place of the rising U-loop, supports this scenario (Fig. 7). Deng et al. (2000) recently observed small-scale flux emergence in the centre of a mature AR. They observed two evolving small arch filament systems which were seen occasionally connected by alongated U-shaped chromospheric fibrils. According to their interpretation the two small-scale flux-systems were formed of the same magnetic flux tube and the U-shaped fibrils were signatures of the emergence of U-loops between them. This process led to the formation of a filament.

5. Conclusions

We propose that the two ARs we observed to emerge at the same latitude in about 150000 km distance at the same time were formed at least partially of the same magnetic flux tube (Fig. 8). To be more precise, only a quarter of the magnetic flux of the larger AR was extended eastward and emerged to form AR2 (cf. Table 1).

Our suggestion is supported by the following five independent arguments:

1. The proper motion of the leading (negative) polarities of AR2 indicates a flux tube geometry different from Ω-loops. The usual evolution of proper motions in an emerging bipole involves a separation of the opposite polarity spots which is fast at first (0.1-0.7 km s^{-1}), reflecting that the top of the

Ω-loop is crossing the photosphere, but decreases quickly as the more vertical parts of the flux tube are surfacing (for a typical example see e.g. van Driel-Gesztelyi & Petrovay 1990). In the case of AR2 the leading spots moved with an almost constant speed of 0.3 km s^{-1} until they collided with other umbrae of opposite polarity (Fig. 4). Such non-decreasing speed rather suggests a concave-up flux tube geometry (however, in the concave-up case we would instead expect an acceleration of the sunspot motions). However, an emerging U-loop may get heavier as it has problems with draining material, which may slow down its rise.

2. In the leading (negative polarity) part of AR2 magnetic concentrations became highly elongated in the direction of their proper motion and they formed an elongated chain (e.g. Fig. 1e,h). Such deformation is expected to occur when the emerging flux bundle is highly inclined to the vertical, i.e. when it is "flat" as a U-loop.
3. The polarity separation in AR2 was about three times larger than in other ARs with the same magnetic flux content (Fig. 5). Since the relationship between polarity separation and magnetic flux of ARs should reflect the physics of the usual Ω-loops (the balance between the magnetic tension force and the buoyancy), the deviation of AR2 from the rule suggests a different flux tube geometry.
4. The opposite polarity umbrae of AR1 (f1) and AR2 (p1) moved towards each other both in latitude and longitude to meet (Figs. 3 & 4). There was another pair of umbrae (f2 & p2, c.f. Figs. 1 and 2) which were moving towards each other in a similar way, but their collision occurred (presumably) after they rotated out of sight. It is very improbable that two pairs of magnetically unrelated umbrae would seek each other out by pure coincidence. However, if we consider that the two pairs of spots were parts of a rising U-loop, their approaching motion and collision is natural.
5. When the first two opposite polarity umbrae collided and started cancelling, their cancellation was "clean": it was not accompanied by important flare activity (Fig. 6). The small number of minor flares observed during the flux cancellation process, we believe, were due to the fact that the emerging U-loop was fragmented and among the separated flux tubes and the ones belonging to the normal Ω-loop of AR1 separatrices formed and reconnection events took place. However, these flares did not exceed the C1.3 GOES class level, supporting the idea that we simply witnessed flux emergence of a concave-up structure without major reconnection processes and annihilation of substantial amount of magnetic flux.

We then conclude that the two ARs we analysed were magnetically linked by a U-loop. A similar conclusion was reached by Pevtsov & Longcope (1998) for two other pairs of ARs, though they never mentioned the term "U-loop" and their main aim was to explore the geometry of an "Ω-loop with a stitch". They argued that each of the pairs of ARs analysed was formed by a severely kinked flux tube, one of which emerged about one month after the other (a difference with our observations, where the flux emergences were co-temporal). In our case the high and continuous MDI magnetogram cadence permitted us to bring more independent arguments to prove the existence of a sub-photospheric magnetic connection and the subsequent emergence of a U-loop between the two ARs.

Why was the emergence of this U-loop asymmetric? We observed that the approach between the f spots of AR1 and the p spots of AR2 was mainly achieved through the fast motion of the latter, while the f spots of AR1 moved much less. Since the magnetic flux of AR1 was four times that of AR2, only a fraction of the flux of the bigger AR belonged to the U-loop, while the rest was part of a normal Ω-loop (Fig. 8). We propose that the trailing part of AR1 flux tubes belonging to the U-loop were entangled with the ones of the Ω-loop, providing an "anchor" for the U-loop there.

What was the origin of this U-loop? A U-loop possibly could form if, in the convective zone during the emergence of an Ω-loop, external flows would be able to separate a considerable part of the flux bundle from the rest and then push a part of the separated flux tube down thus forming two Ω-loops connected by a U-loop. Another, more plausible scenario is that the two ARs were formed by an extended Parker instability at the bottom of the convection zone, triggering several impulses of flux emergence. Since the episodes of flux emergence occurred in the two ARs very close in time, they seem to have the same origin. It is plausible that the initial instability, modifying the surroundings, can trigger a near-by instability when the field strength is close to a critical value. Such nearly simultaneous instabilities may be the cause of activity nests. The observation that magnetic flux seems to disappear faster in active nests than in isolated ARs and that most of it disappears inside the boundaries of the nest, besides an enhanced cancellation rate, suggests the presence of U-loops.

If U-loops are such common features, why were they not noticed in magnetograms earlier? We believe that the movie representation of the coaligned, de-rotated and de-projected high-cadence MDI maps made it possible for us to recognise the U-loop emergence, which was not at all obvious when we looked at the daily unprocessed individual magnetograms. With the wealth of the MDI data base and the necessary software readily available, we believe that many more such events will be found.

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