

## The Counter-kink Rotation of a Non-Hale Active Region

M.C. López Fuentes <sup>1</sup>,

Instituto de Astronomía y Física del Espacio, IAFE, CC. 67 Suc. 28, 1428 Buenos Aires,  
Argentina,

P. Démoulin,

Observatoire de Paris, section Meudon, DASOP, URA 2080 (CNRS), F-92195 Meudon  
Principal Cedex, France,

C.H. Mandrini <sup>2</sup>,

Instituto de Astronomía y Física del Espacio, IAFE, CC. 67 Suc. 28, 1428 Buenos Aires,  
Argentina,

and

L. van Driel-Gesztelyi

Konkoly Observatory, H-1525, Budapest, Hungary

lopezf@iafe.uba.ar

Received \_\_\_\_\_; accepted \_\_\_\_\_

---

<sup>1</sup>Fellow of the CONICET, Argentina

<sup>2</sup>Member of the Carrera del Investigador Científico, CONICET, Argentina

## ABSTRACT

We describe the long-term evolution of a bipolar non-Hale active region which was observed from October, 1995, to January, 1996. Along these four solar rotations the sunspots and subsequent flux concentrations, during the decay phase of the region, were observed to move in such a way that by December their orientation conformed to the Hale-Nicholson polarity law. The sigmoidal shape of the observed soft X-ray coronal loops allows us to determine the sense of the twist in the magnetic configuration. This sense is confirmed by extrapolating the observed photospheric magnetic field, using a linear force-free approach, and comparing the shape of computed field lines to the observed coronal loops. This sense of twist agrees with that of the dominant helicity in the solar hemisphere where the region lies, as well as with the evolution observed in the longitudinal magnetogram during the first rotation. At first sight the relative motions of the spots may be miss-interpreted as the rising of an  $\Omega$ -loop deformed by a kink-instability, but we deduce from the sense of their relative displacements a handedness for the flux-tube axis (writhe) which is opposite to that of the twist in the coronal loops and, therefore, to what is expected for a kink-unstable flux-tube. After excluding the kink instability, we interpret our observations in terms of a magnetic flux-tube deformed by external motions while rising through the convective zone. We compare our results with those of other related studies and we discuss, in particular, whether the kink instability is relevant to explain the peculiar evolution of some active regions.

*Subject headings:* Sun: corona — Sun: interior — Sun: magnetic fields

## 1. Introduction

Solar active regions (ARs), as observed at the photospheric level, consist of large areas with a strong magnetic field concentration ( $\geq 1000$  G) as compared to the quiet-region average field. Since, in general, an AR is formed by two of such areas of opposite magnetic polarity, it has long been believed that they are the manifestation of the emergence of a flux tube formed from the toroidal magnetic field originated at the base of the convective zone (e.g. Parker 1993, Weiss 1994). The typical shape of this flux tube is that of the letter  $\Omega$ , which results from the rising of a buoyant magnetic flux-tube (e.g. Zwaan 1987 and references therein). As the flux tube crosses the photospheric surface, two flux concentrations of opposite polarity appear and progressively diverge from each other in an approximate East-West direction. Such bipolar ARs will, in general, obey the Hale-Nicholson polarity law (see e.g. Zirin 1988).

However, there are several observational examples of ARs, or emerging bipoles within ARs, disobeying the Hale-Nicholson’s law (e.g. Tanaka 1991, Lites et al. 1995, Leka et al. 1996, Pevtsov & Longcope 1998). The evolution of such photospheric flux concentrations has been explained in terms of the rising of very distorted flux-tubes. Tanaka (1991) proposed a model implying the emergence of a “knotted” flux-tube to explain the observed evolution of two very active  $\delta$  configurations. Though not explicitly mentioned in his paper, the shape of the tube resembled that of a kink-unstable flux tube (see Linton et al. 1998, 1999, and Fan et al. 1998, 1999, for theoretical developments). Van Driel-Gesztelyi and Leka (1994) and Leka et al. (1996) analyzed series of magnetograms corresponding to an AR, where strong flux emergence was observed, and concluded that the proper motions for several emerging bipoles were consistent with the rising of kink-deformed flux tubes. More recently, Pevtsov & Longcope (1998) interpreted the magnetic data and soft X-ray images of a pair of ARs, observed during two solar rotations, as an evidence of the emergence of

a single magnetic system resembling a kinked flux-tube. In the case of Lites et al. (1995), the evolution of a  $\delta$  configuration was explained as resulting from the ascension of a nearly closed system of twisted magnetic field, unrelated to the kink instability. More generally, Weart (1970, 1972) noticed the almost random distribution of the starting tilt of emerging bipoles, which subsequently became more parallel to the equator, and proposed that this was caused by the emergence of twisted flux-tubes.

We describe here the magnetic field evolution of a region formed by a pair of sunspots, which, at its appearance on the disk, disobeyed the Hale-Nicholson polarity law for solar cycle 22. For this analysis we used a set of magnetograms obtained at Kitt Peak National Solar Observatory (KPNO), and soft X-ray images obtained with the Soft X-ray Telescope (SXT) on board the *Yohkoh* satellite. We followed the region along four solar rotations, from its appearance on the solar disk in October 1995, until its decay and disappearance in January 1996. Along these three months, we observed that the following spot rotated relative to the preceding one in such way that by the end of this period both flux concentrations were aligned according to the Hale-Nicholson law. In §2 we describe the temporal evolution of the studied region, while in §3 we discuss a possible model to explain such an evolution. Finally, in §4 we summarize our conclusions and we discuss the role of the kink instability in the peculiar behavior of some active regions.

## **2. Non-classical evolution of the active region**

### **2.1. Description of the data**

A set of 23 line-of-sight magnetograms obtained at KPNO has been used to follow the evolution of the non-Hale region NOAA 7912. The magnetograph of KPNO (Livingston et al. 1976) provides daily full disk longitudinal magnetic field maps with a spatial resolution

of around  $1''$ . The maps used in the present study correspond to the months of October, November and December 1995, and January 1996. We chose approximately 6 magnetograms per rotation, when available, around the day of the central meridian passage (CMP) of the region of interest.

We complemented the magnetic data set with soft X-ray full disk images obtained with the Yohkoh/SXT (Tsuneta et al. 1991). We chose these images at times close to the KPNO magnetograms, and we coaligned these two data sets in order to follow changes in the coronal magnetic field structure as the region evolved.

## 2.2. Long-term evolution of the region

A bipolar sunspot group, NOAA 7912, was observed on the solar disk on October 10, 1995, at S10 E76. This AR had non-Hale polarity relative to the Hale-Nicholson polarity law for solar cycle 22. During its disk transit the negative polarity (located westward) appeared concentrated, while the positive one was more diffuse (see Fig. 1 right panel). CMP occurred on October 15, 1995. In the following solar rotation, at the same latitude and corresponding longitude according to the solar rotation rate, another non-Hale bipolar sunspot group was observed. This group was numbered as NOAA 7921, and we show in the next paragraph that it corresponds to AR 7912 of the previous rotation. During this second rotation the positive and negative polarities appeared to be closer together (see e.g. Fig. 3.a and b). Another particular feature of this AR 7921 is that the trailing (positive) spot lies closer to the solar equator than the leader (negative) spot, contrary to what is expected from Joy’s law (see e.g. Zirin 1988). During the third solar rotation (December 1995), we observe a bipolar AR (NOAA 7930) traversing the solar disk at the same latitude and corresponding longitude as AR 7912. In this case the leading and trailing spots obey the Hale-Nicholson polarity law, but the leading (positive) magnetic field concentration appears

much more dispersed than the trailing (negative) one. From the coincidence in location (see also next paragraph), we conclude that this is still the remnant of AR 7912 which we now observe in its decaying phase. In the fourth rotation (January 1996) no AR was identified at that position, though we observed a negative and a positive flux concentration oriented almost parallel to the solar equator with the leading positive field more dispersed than the trailing negative one.

We now argue, following similar arguments as Pevtsov and Longcope (1998), that AR 7921, AR 7930 and the subsequent positive and negative flux concentrations observed during January are the recurrences of AR 7912. In Fig. 2 we show the successive synodic longitudes for the three ARs, taken from the Solar Geophysical Data, and those for the bipolar flux concentrations observed during January, as measured using KPNO magnetograms. It is clear that all the points lie on a straight line, whose slope gives the value of the synodic solar rotation rate ( $\omega$ ) for the corresponding latitude ( $\approx 10$  deg). Thus, we conclude that during the four rotations the renamed ARs and flux concentrations were located at the longitude and latitude where the recurrent remnants of AR 7912 were expected to be. In our case  $\omega$  turns out to be  $13.25 \pm 0.02$  deg/day. Howard (1990), using Mt. Wilson magnetograms in the period 1967-1988, found for the latitude of  $10^\circ$  a synodic rotation rate  $13.015 \pm 0.038$  for all ARs and  $13.05 \pm 0.15$  for reversed polarity groups. The rotation rate we determined is around the upper limit for the latter. It is noteworthy that reversed polarity groups represent about 10 % of all ARs, and there is no evidence for a latitudinal dependence of their rotation rate (Howard, 1990).

Looking at the position of the AR closest to AR 7912, we find that during the first rotation this was AR 7910, located at the same latitude (S10) and 33 degrees to the West of AR 7912; this was a Hale region. Considering the errors bars, it appears very unlikely that we could confuse AR 7921 with the reappearance of AR 7910 (Fig. 2), even more

taking into account that AR 7921 is still a non-Hale region (Fig. 1, right panel). During the third rotation (in December) AR 7930 was practically the only active region in the southern hemisphere.

The lifetime of a sunspot both from an observational point of view (Petrovay & van Driel-Gesztelyi 1997), and according to the sunspot turbulent erosion model (Petrovay & Moreno-Insertis 1997), is around 41 days in the case it has a maximum area of 410 MSH (millionth of solar hemisphere), which approximately corresponds to the maximum area of the negative spot including its umbra and penumbra. Thus, the negative sunspot observed during the first rotation (AR 7912) is likely to have survived till the second rotation (AR 7921); then its magnetic flux progressively dispersed during the next rotations. This supports that the negative polarity observed in the four rotations is indeed formed by the same magnetic flux. Moreover, the lifetime of an isolated AR can be as long as 7 months; after that its dispersed magnetic field becomes indistinguishable from the background field (see the review by van Driel-Gesztelyi 1998). Therefore, we find it unlikely that AR 7912 had decayed and disappeared on the invisible side of the Sun, being then replaced by the emergence of another magnetic flux tube during the three consecutive rotations.

From the stringent coincidences in location, the recurrence and expected life span of active regions and sunspots of similar size, we conclude that, along these three months, we have been observing the growth, maturity and decay of the same AR, which we will call from now AR 7912. Its evolution is exemplified in Fig. 1 (right panel) in which we show one magnetic map per rotation at CMP. The most striking features of this figure are the way in which the positive polarity seems to rotate around the negative one, and the variable mean distance between the flux concentrations.

We extrapolated the observed photospheric longitudinal magnetic field using a linear force-free approach ( $\vec{\nabla} \times \vec{B} = \alpha \vec{B}$ , see e.g. Démoulin et al. 1997), where  $\alpha$  is determined by

the best fit between the soft X-ray loops and the computed field lines. We computed in the local orthogonal frame, that is  $(x, y)$  parallel to the photosphere and  $z$  perpendicular to it, the dipolar size of the AR ( $S_{AR}$ ) and the angle ( $\Phi_{AR}$ ) formed by the line joining the mean position of the positive and negative concentrations (see Eq.(3)) with the local parallel. We define the dipolar size of the region as the flux-weighted mean distance between opposite polarity fields which are stronger than some limit  $B_{min}$ ,

$$S_{AR} = \sqrt{(X_p - X_n)^2 + (Y_p - Y_n)^2}, \quad (1)$$

and  $\Phi_{AR}$  as

$$\Phi_{AR} = \arctan(Y_p - Y_n)/(X_p - X_n), \quad (2)$$

where  $X_p$  and  $Y_p$  ( $X_n$  and  $Y_n$ ) give the mean position of the positive (negative) concentration,

$$X_p = \frac{\sum_{B_z > B_{min}} x B_z}{\sum_{B_z > B_{min}} B_z}, Y_p = \frac{\sum_{B_z > B_{min}} y B_z}{\sum_{B_z > B_{min}} B_z} \quad (3)$$

We computed  $S_{AR}$  and  $\Phi_{AR}$  for the 23 line of sight magnetograms included in our study. To be sure that the trend followed by  $S_{AR}$  and  $\Phi_{AR}$  is not affected by the value of  $B_{min}$  considered in the computations, we have taken field strengths  $|B_z| > 10$  G, 50 G and 100 G. To check the absence of any systematic bias introduced by the magnetic extrapolation, we repeated the analysis replacing  $B_z$  by the observed longitudinal field. We found the same kind of temporal variation in all cases. Fig. 3.a shows a polar diagram, for  $|B_z| > 100$  G, where the displacement of the positive polarity around the negative one is clearly seen along the four solar rotations. The angle  $\Phi_{AR}$  is measured from West to East (counterclockwise), the center of the polar plot corresponds to the mean position of the negative polarity, while the light grey squares give the successive locations of the positive polarity and the black squares represent the average  $\Phi_{AR}$  angle for each solar rotation. Moreover, the distance between the light grey squares and the center of the polar plot corresponds to  $S_{AR}$ , while the long arrows joining the black squares to the centre correspond to the average  $S_{AR}$  for



each rotation. We show the time evolution of  $S_{AR}$  and  $\Phi_{AR}$  in a more explicit way in Figs. 3.b and c, respectively. The rotation by half a turn during four solar rotations as well as the approach of two opposite polarities during the first two rotations, followed by the increase in their separation during the third and fourth rotations, are abnormal characteristics of the AR 7912. From this analysis we deduce below the possible origin of this peculiar evolution.

### 3. Interpretation in terms of a rising flux-tube

#### 3.1. Emergence of the flux tube

The photospheric magnetic evolution of the region allows us to deduce the shape of the corresponding emerging flux-tube, assuming that all four ARs were formed by a single  $\Omega$ -loop. Unfortunately, we have neither a way to estimate the velocity of the emergence nor its change with time, so the conclusions drawn below concerning the shape of the flux tube may be affected by an arbitrary factor implying an extension (or compression) in the vertical direction. This has, however, no influence on the handedness of the tube axis and, therefore, on our conclusions.

The evolution of the photospheric magnetic field during the four solar rotations is not compatible with the emergence of a simple planar  $\Omega$ -loop, but it has to be interpreted as the emergence of a magnetic flux-tube which is deformed as shown in the left panel of Fig. 1. The flux-tube is drawn as it was when in the convection zone. As it progressively emerges, the intersections of both of its feet with the photospheric level (positive and negative polarities) rotate as observed in the magnetograms (Fig. 1, right panel). The portion above the photosphere will relax to an almost force-free field state and expand to fill the available volume; this latter evolution is not shown in Fig. 1.

Provided that we have no information on the velocity of emergence, the observed flux

tube evolution may result from one of the two following scenarios. In the first one, only the top part of the flux tube is buoyant enough to emerge above the photosphere. When the upward evolution stops, the further observed rotation may result from the magnetic tension of the flux tube (such force tends to bring the flux tube back to the planar configuration defined by the flux-tube feet rooted deeply in the convective zone). A second scenario is that, in the upper part of the convective zone, the buoyancy of the flux-tube feet is still present (while lower than at its summit). As a result of this, the upward speed of the flux-tube decreases with time but does not vanish (until the flux tube is eroded by turbulence). Unless both processes have similar time scales, the continuous rotation of the positive polarity relative to the negative one (see Fig. 3) favor a scenario driven by the process of continuous emergence, though further data are needed to confirm this. With such hypothesis, the magnetic flux-tube is indeed emerging for a much longer time than the AR formation which, on average, is completed in about 5 days (Harvey 1993). The two cases analysed by Pevtsov & Longcope (1998) imply indeed flux emergence during two solar rotations.

At this point it is noteworthy that the usual expression “flux emergence” is, in general, used to refer merely to the increase of the vertical photospheric magnetic flux (for both polarities). However, in the scenario proposed by us, the flux tube keeps emerging for several months, well beyond the first few days during which the apex of the flux tube traverses the photosphere. The continuing upward motion of the flux tube will not change the magnetic flux in the photosphere (because  $\vec{\nabla} \cdot \vec{B} = 0$ ), thus no conventional “flux emergence” will be observed in the magnetic map. In order to emphasize this different meaning, we will use the expression “flux-tube emergence”, rather than “flux emergence”, to refer to the full evolution of the flux tube as it is rising through the photosphere.

### 3.2. Magnetic twist

Besides its global shape, another important parameter which characterizes a flux tube is the amount of twist it brings up. We have no transverse field measurements available to determine the direction of the electric currents, but SXT images obtained mainly during the first three rotations show S-shaped sigmoids at coronal heights. This may be an indication of the presence of positive twist in the magnetic field (see e.g. Fig. 4.a), although the loops corresponding to some particular potential (i.e. without twist) magnetic configurations can also display sigmoidal shape (Fletcher et al. 2000). From our linear force-free extrapolations, the value of  $\alpha$  turns out to  $0.03 \text{ Mm}^{-1}$  (positive sign) for the data shown in Fig. 4. Our results show that the S-shape is really determined by the coronal currents (and not by a particular distribution of the vertical component of the photospheric field). Therefore, AR 7912 follows the hemispherical chirality-rule: a positive twist is dominant in the southern hemisphere (Seehafer 1990, Pevtsov et al. 1995).

What is the magnetic signature of an emerging twisted flux tube at the photospheric level? To simplify the description, we discuss below the expected evolution for an AR located at disk centre, but this can be extended to regions in different locations on the solar disk as well. For the emergence of untwisted  $\Omega$ -loops, a series of magnetograms of the vertical field will show the classical appearance of a bipole, followed by the separation of the two opposite magnetic polarities. The magnetograms simply show the evolution of the vertical component of the magnetic field directed along the tube. However, when the flux tube is twisted an asymmetry appears in the magnetogram due to the contribution of the azimuthal component to the observed vertical component of the field. The result is schematically depicted in Fig. 5.c for the case of positive twist. The vertical projection of the azimuthal component produces two elongated polarities (“tongues”) which extend between the main ones. The strength of these “tongues” is directly proportional to the

magnitude of the twist and their position depends on the sign of the twist (the case with negative twist is a mirror image of the case with positive twist). The “tongues” are present only when the apex of the flux tube is crossing the photosphere (during the period of “flux emergence”). Later on, they disappear because the projection of the azimuthal field in the vertical direction becomes less important. Such picture was indeed present during the early evolution of AR 7912 (Fig. 5.a and b). The location of the “tongues” implies the presence of positive twist, in agreement with the independent determination done previously with SXT and magnetic field extrapolations. The retraction of the “tongues” with time is naturally explained by the emergence of the flux tube. This implies a positive rotation (counter-clockwise) of the mean position of the positive polarity with respect to the negative one from October 13 to 18 (Fig. 3).

The following negative (clockwise) rotation shows that the shape of the emerging flux-tube is not planar, though for the flux-tube portion which emerges during the few days of positive rotation the deviation from planarity is small; thus, when describing above the “tongues”, we have neglected the influence of non-planarity. It is only on the long-term (three months, so an order of magnitude longer in time) that the non-planarity of the flux tube becomes important.

### 3.3. How was the flux tube formed ?

The non-classical evolution of AR 7912 has called our attention as a probable candidate for a kink instability, since the flux-tube shape deduced in Fig. 1 is similar to what is expected from the non-linear development of this instability (Fan et al. 1999, Linton et al. 1998, 1999). However, the kink instability mode has certain properties that may be verified in the observations. In particular, the handedness of the magnetic twist ( $T$ ) and the writhe ( $W$ ) of the tube axis should be the same (e.g. Fisher et al. 1999). The twist is the measure

of the rotation of the field lines around the flux-tube axis and the writhe is the measure of the rotation of the flux-tube axis in space. In a kink unstable flux-tube the twist ( $T$ ) and the writhe ( $W$ ) should have the same sign because part of the twist is transferred into the writhe when the kink instability develops. For AR 7912, the three month evolution implies a flux-tube axis with a deformed helical shape (Fig. 1). The global negative rotation gives a negative writhe for the flux-tube axis (it is on a deformed left-handed helix). The sign of the writhe is opposite to the sign of the twist, thus a kink instability cannot be the origin of the non-Hale nature of this region !

Can photospheric or shallow sub-photospheric large-scale flows be the cause of the peculiar rotation of AR 7912 ? These motions may be a photospheric vortex (like an earth tornado) with a negative rotation, or they may result from the faster displacement of the positive polarity around the negative one (e.g. driven by the magnetic tension of the flux tube). However, this “surface” flow cannot explain why the AR was initially formed with a non-Hale orientation. Moreover, the dispersion of the positive polarity (which should be the leading in the southern hemisphere during solar cycle 22) is observed to be much faster than the dispersion of the negative polarity along these four rotations, as can be seen in Fig. 1 (right portion). This behavior is opposite to that of Hale regions. To quantify this we determined a flux-weighted mean size of both polarities,  $R_p$ ,  $R_n$ , with  $R_p$  defined by:

$$R_p = \frac{\sum_{B_z > B_{min}} \sqrt{(x - X_p)^2 + (y - Y_p)^2} B_z}{\sum_{B_z > B_{min}} B_z}, \quad (4)$$

and a similar expression for  $R_n$  (see Eq. 3 for the definition of  $X_p$ ,  $Y_p$  and  $B_{min}$ ). Table 1 shows the evolution of  $R_p$  and  $R_n$  for  $|B_z| > 10$  G (which we consider a value more representative of the relevant magnetic flux of the AR) for the four rotations. The values correspond to the averages of three days around CMP. We want to remark that the new small bipole appearing at the South of the region was not included in the computations.

Notice that the results of Table 1 are opposite to what is expected in Hale regions.

In such normal regions, the longer coherence of the leading polarity is explained by the evolution of the  $\Omega$ -loop through the convective zone: the Coriolis force in an ascending flux-tube pushes the plasma away from the preceding polarity towards the following one; the resulting decrease of the plasma pressure makes the leading spot more confined and with a stronger magnetic field (Fan et al. 1993). In AR 7912 we have observed just the opposite evolution because the positive polarity was indeed in a following position during the emergence (see Fig. 1)! This faster dispersion of which should be the normal preceding polarity shows that indeed the flux tube traveled through a significant part of the convective zone (as classical  $\Omega$ -loops do) in the reversed configuration, thus the peculiar rotation observed is not due to a vortex motion at photospheric level (or just below). Nevertheless, we cannot exclude the possibility that the rotation of the AR is due to the action of the magnetic tension force restoring the  $\Omega$  loop shape (without the need of the continuous emergence of the flux tube).

EDITOR: PLACE TABLE 1 HERE.

We propose that the origin of the peculiar evolution of AR 7912 may be a simple interaction with convective motions. As for other ARs, we suppose that a flux tube forms in the convective overshoot region and begins to rise as a normal  $\Omega$ -loop. During its way through the convective zone (including the bottom of the convective zone, but not its top) the flux-tube axis is deformed by external motions which have a rotational component (e.g. a cyclonic flow or a strongly sheared flow due to, e.g., an important local gradient of the differential rotation). From present data we cannot precise the delay between the initial development of the Parker instability and the deformation of the flux tube. This delay can range from zero to significantly less than the crossing time of the convective zone by the buoyant flux-tube. In any case, the motions are supposed to deform a finite section of the axis into a helical shape with a negative handedness, so a negative writhe ( $\delta W$ ). The

conservation of magnetic helicity implies that a positive twist ( $\delta T = -\delta W$ ) is induced in the flux tube (Moffatt and Ricca 1992, Berger and Field 1984). For simplicity, the case with no initial  $W$  and  $T$  is shown in Fig. 6. In this picture, the only peculiarity of AR 7912, compared to other ARs, is that it is formed by a rising flux-tube which encountered in its way convective motions which have a rotational component. All the peculiarities of AR 7912 (initial non-Hale configuration, a positive rotation followed by a negative one, a faster dispersion of what should be the leading polarity, a non-monotonic variation of the distance between the polarities, an opposite sign for  $W$  and  $T$ ) are the consequences of this interaction.

Earlier, Longcope et al. (1998) developed a model describing the creation of magnetic twist in a flux tube from its interaction with helical turbulence. The convective flows are coupled to the flux tube by the drag force and they progressively introduce an helicoidal deformation in the flux-tube axis (writhe). By conservation of magnetic helicity a twist of opposite magnitude is introduced in the flux tube. Such effect, named the  $\Sigma$  effect, predicts a hemispherical rule, a magnitude as well as a statistical dispersion of the magnetic twist similar to what is observed. We suggest that the evolution of AR 7912 follows the model developed by Longcope et al. (1998).

We have given above a simple explanation of the behavior of AR 7912 supposing implicitly no initial  $T$  and  $W$  (Fig. 6.a) in order to explain the main effects. We make this view more precise below. The observations show that the flux tubes forming most active regions have both significant magnetic writhe and twist at the photospheric level (e.g. Canfield and Pevtsov, 1998). The writhe is thought to come from the effect of the Coriolis force (leading to Joy’s law) and from the interaction with the helical turbulence on the ascending flux tube (Longcope et al. 1998). The sub-photospheric origin of the twist is thought to be at the core-convection zone interface (e.g. Gilman and Charbonneau, 1999).

An initial twist is indeed needed so that the buoyant flux-tube is not destroyed by the hydrodynamic vortex, which develops behind it during its transit through the convective zone (Emonet & Moreno-Insertis, 1998; Fan et al. 1998).

The conservation of helicity then simply writes:

$$T_t + W_t = T_0 + W_0 = H_0 \quad (5)$$

where  $T_t$  and  $W_t$  (resp.  $T_0$  and  $W_0$ ) are the twist and the writhe at time  $t$  (resp. initial time). Taking a positive initial helicity  $H_0$  to study a typical flux tube in the southern hemisphere (the negative case is symmetric), we have the following possibilities:

- **Case a:**  $W_t < 0$ , so the writhe created by the convective motions is negative and the twist of the emerging flux tube is positive ( $W_t T_t < 0$  and  $T_t > H_0 > 0$ ),

- **Case b:**  $0 < W_t < H_0$ , so the added writhe is not enough to create a negative twist and both are of the same sign ( $W_t T_t > 0$  and  $H_0 > T_t > 0$ ),

- **Case c:**  $W_t > H_0$ , so the writhe created by the convective motions is large enough and positive to create a negative twist ( $W_t T_t < 0$ ,  $H_0 > 0$  and  $T_t < 0$ ).

The observable photospheric evolution of the longitudinal magnetic field resulting from the emergence of the twisted flux-tube is determined by the twist ( $T_t$ ) and the writhe ( $W_t$ ) of the flux tube. As the apex of the twisted flux tube emerges, two elongated magnetic polarities (“tongues”) appear (see Sect. 3.2). This phenomenon, which is determined by the twist of the flux tube, gives a relative rotation of the mean position of the photospheric magnetic polarities and lasts approximately as long as the period of “flux emergence” (several days) (see Démoulin et al. 2000). Once the apex of the flux tube has fully emerged, the tongues disappear, and as the flux tube continues emerging, the flux tube shape, so its writhe, determines the long-term evolution of the magnetic polarities (Sect. 3.1). Then we have:

- **Case a:** an initial short-term positive rotation of the mean positions of the polarities



followed by a long-term negative rotation (case of AR 7912),

- **Case b**: a continuous positive rotation,

- **Case c**: an initial short-term negative rotation followed by a long-term positive rotation.

In all these cases, the long-term rotation brings back the polarities to the Hale orientation. Case c would appear as an exception to the hemispherical rule for the sign of  $\alpha$  (while the flux tube is initially formed in the same way at the bottom of the convective zone). Finally, in Case b, the origin of the peculiar geometry of the tube can be confused with a kink instability.

#### 4. Conclusion

We have shown that AR 7921, AR 7930 and the bipolar field on January 1996, at  $\approx$  S10, are in fact the re-appearances on the solar disk of AR 7912. Emphasizing this fact, we use the same NOAA number (AR 7912) for all four regions.

We have focused this study on the long-term (4 rotations) evolution of AR 7912 because it is a non-Hale region, which showed unusual rotation of the positive polarity with respect to the negative one, making approximately half a turn. Apart from that, AR 7912 is a simple active region from the point of view of the magnetic complexity, since it is basically a bipolar configuration. Thus, AR 7912 gives us the possibility to analyze the emergence of one simple magnetic flux-tube which undergoes unusual motions. From the photospheric evolution of AR 7912, we deduce that the flux-tube axis has a helical shape. A possible interpretation of this evolution may be a non-linear development of the kink instability, although further analysis does not support that, since the writhe of the flux tube and its internal twist do not have the same sign (as they should have for a kink instability mode). Next we exclude the photospheric (or shallow sub-photospheric) vortex motions, because

faster dispersion of positive polarity implies that the flux tube has traveled through at least part of the convection zone in such an helical shape (Sec. 3.3). The most likely origin of the peculiar flux-tube geometry of AR 7912 is an interaction, deep down in the convective zone, of the rising flux-tube with plasma motions having a rotational component. Such motions would bring the flux-tube axis in a left-handed helix-like shape, giving a negative writhe to the axis. This writhe is observed as a negative (clockwise) rotation of the photospheric polarities as the flux tube emerges. The conservation of magnetic helicity induces a positive twist which adds up to the initial twist (probably, also positive due to the hemispheric rule for the helicity). With the hypothesis of the deformation of the flux-tube axis by convective motions, all the peculiarities of AR 7912 (initial non-Hale configuration, a positive rotation followed by a negative one which brings back the region to the Hale orientation, a faster dispersion of which should be the leading polarity, a non-monotonic variation of the distance between the polarities, an opposite sign of writhe and twist) are explained in a logical way.

We bring now the case of AR 7912 in a broader context to analyze whether such evolution has been reported in other cases. We concentrate now, in particular, on the possible origin of these peculiarities: kink instability or interaction with convective motions (photospheric motions are unlikely to be the origin as discussed above). Pevtsov & Longcope (1998) show two examples where a Hale AR is associated with a non-Hale AR. The latter appears in the consecutive solar rotation. In Fig. 7 we show a 3-D perspective of the scenario proposed by them. These authors do not explicitly address the mechanism which created this kinked flux tube, but an a priori possibility may be the development of the kink instability (e.g. Fan et al. 1999, Linton et al. 1999, Matsumoto et al. 1998). However, the observational results of Pevtsov and Longcope rather show that the magnetic flux tube has not an helical shape, but is simply a classical  $\Omega$ -loop bended down close to its center (see Fig. 7). The magnetic linkage shown in Fig. 7 is deduced from the degree of dispersion of the polarities, but we notice that our conclusion would be the same if we

exchange the linkage of each positive polarity to the other alternative negative polarity. We suggest that the origin of this configuration may be the interaction of the rising  $\Omega$ -loop with plasma motions in the convective zone, a similar scenario to the case presented by us. A first possibility is that the Parker instability developed successively at two nearby portions of the same toroidal flux-tube, and that the non-Hale region was formed by the same mechanism as for the AR studied in this paper. A second possibility is that one rising  $\Omega$ -loop interacted with downward convective motions along its central portion. One side of the loop was pushed down more efficiently than the other one leading to a shift in the emerging time (of about one solar rotation) between the two sides (so, the two linked ARs). Both examples that Pevtsov and Longcope provide can be interpreted by one of the above possible mechanisms. The only minor differences between their two examples are: first, that the sign of the polarities is opposite because the ARs are located in different hemispheres, and, second, that the southern part of the  $\Omega$ -loop is emerging less rapidly than the northern part in the first example (AR 7918 and AR 7926), while the reverse is true in the second example (see Fig. 7).

Other case studies have been carried out on much shorter time scales (few days compared to the four solar rotations described here). Tanaka (1991) presented two cases of peculiar active-region evolution. The first one (July 1974) is characterized by showing both directions of rotation (clockwise and counter-clockwise), it is a complex case which cannot be easily explained by the kink instability mode. The second case (August 1972) presents a negative (clockwise) rotation of the main bipole, so a writhe of the same sign as the twist (as deduced from the shape of the  $H\alpha$  fibrils and flare ribbons). This is a good candidate for the kink instability mode. Other studies have been rather focused on the short-term evolution (few days) of small bipoles within an active region. Evidences for the emergence of twisted flux tubes have been found in several active regions (Kurokawa, 1987; Ishii et al. 1998). Lites et al. (1995) have interpreted their observations in terms of an ascending

closed ball of twisted field. From these papers it is difficult to draw any conclusion on the writhe and twist. Leka et al. (1996) found at least four small bipoles which emerged twisted and have the same sign for the writhe and the twist, thus being good candidates for the kink instability.

Canfield and Pevtsov (1998) have investigated the statistical relationship between the twist and the writhe of 91 ARs following the Hale law (8 non-Hale ARs of the sample have been eliminated from the statistics). The twist is determined by the best fit of the vector magnetic field data with a linear force-free extrapolation, and the writhe is deduced from the tilt of the active region axis with respect to the solar equator. In the south hemisphere they found that the majority of the ARs have a negative writhe (Joy’s law) and a positive twist based on independent statistics (note that the sign defined from the writhe is opposite by definition to the sign of the tilt angle). But surprisingly, the correlation between writhe and twist was found to be direct, so that an AR with positive twist has more chances to have a positive writhe than a negative one; the opposite of what is expected from the two independent statistics in function of latitude mentioned above. This is in favor of the above Case b (where the added writhe is not sufficient to reverse the sign of the initial twist) or of the kink instability (where the writhe comes from the initial twist). However, the statistical laws are weak (a large dispersion is present); a fact which may explain their apparent incompatibility. Such large dispersion probably comes from the interaction between ascending flux tubes and turbulent motions (Longcope et al. 1998).

Looking at all the cases listed above, the basic characteristic of the kink instability ( $WT > 0$ ) is only present in some examples; which can also be interpreted as examples of our Case b (where the writhe is not sufficient to reverse the sign of the initial magnetic helicity). Moreover, there are cases which do not have the characteristics of the kink instability. Our studied case (AR 7912) has opposite writhe and twist, and the two

examples of Pevtsov and Longcope (1998) are likely to be explained also by an interaction of the rising flux-tube with convective motions. With so few examples studied in detail, we certainly cannot confirm that all cases have a common origin, that is the interaction of a normal rising  $\Omega$ -loop with convective motions, even if such interpretation is attractive (see also Longcope et al. 1998). Clearly, an extension of the study of peculiar cases (non-Hale active regions) is needed. The cases which show the same sign for the twist and the writhe need a further analysis to confirm or not that they are indeed caused by the development of the kink instability. Then, following Pevtsov and Canfield (1998), a further statistical analysis of a large sample of ARs is needed.

Finally, we note that if it would be shown that the kink instability is not the origin of the formation of non-Hale ARs, this will have a positive outcome in helping to determine more precisely the twist in buoyant flux-tubes at the base of the convective zone. The threshold to reach the kink instability decreases like the inverse of the flux-tube radius (e.g. Linton et al. 1998); then, the kink instability is easier to achieve as the flux tube moves upward and expands (by at least a factor of 10). So, in order to prevent the kink instability to develop during the ascent in the convective zone, the initial twist should be low enough. On the other hand, the flux tube needs to be slightly twisted initially to keep its coherence through the convective zone (Emonet and Moreno-Insertis 1998 and Fan et al. 1998). Thus, if the kink instability does not develop, it is probable that the initial twist of flux tubes emerging at the photosphere lies in a narrow range, just above the minimum twist needed to maintain the coherence of the tube. To test precisely this conclusion, present numerical simulations need to be extended to follow a flux tube through many gravitational scale-heights (from the bottom of the convective zone to the photosphere). Then, even if careful examination of the observations would show that the kink instability is less important than it is presently thought, further investigations in this area are clearly needed.

M.L.F, C.H.M. and P.D. acknowledge financial support from ECOS (France) and ANPCYT (Argentina) through their cooperative science program (A97U01). LvDG acknowledges the Hungarian Government Grants TP 096 OTKA T026165, T032846 and AKP 97-58 2,2. We thank the anonymous referee for the constructive and helpful comments which improved our paper. The NSO/Kitt Peak data used here are produced cooperatively by NSF/NAO, NASA/GSFC, and NOAA/SEL. The *Yohkoh* Soft X-ray Telescope is a collaborative project of the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo, supported by NASA and ISAS.

Table 1. Evolution of the mean size of the polarities.

Rotation Number	$R_p$ (Mm)	$R_n$ (Mm)
1st.	37.	24.
2nd.	48.	24.
3rd.	58.	34.
4th.	62.	51.

## REFERENCES

- Berger, M. A. 1998, IAU colloquium 167, eds. D. Webb, D. Rust and B. Schmieder, A.S.P. Conf. Ser., 150, 102
- Berger, M. A., & Field, G. B. 1984, *J. Fluid Mechanics*, 147, 133
- Canfield, R. C., & Pevtsov, A. A. 1998 in *Synoptic Solar Physics*, ed. K. S. Balasubramaniam, J. W. Harvey, D. M. Rabin, ASP Conference Series, AGU, Vol 140, p. 131
- Démoulin, P., Bagalá, L. G., Mandrini, C. H., Hénoux, J. C., & Rovira, M. G. 1997, *A&A*, 325, 305
- Emonet, T., & Moreno-Insertis, F. 1998, *ApJ*, 492, 804
- Fan, Y., Fisher, G. H., & De Luca, E. E. 1993, *ApJ*, 405, 390
- Fan, Y., Zweibel, E. G., & Lantz, S. R. 1998, *ApJ*, 493, 480
- Fan, Y., Zweibel, E.G., Linton, M.G., & Fisher, G.H. 1999, *ApJ*, 521, 460
- Fisher G. H., Longcope, D. W., Linton, M. G., Fan, Y., & Pevtsov, A. A. 1999, in *Stellar Dynamos: Nonlinearity and Chaotic Flows*, ed. M. Numez, & A. Ferriz-Mas, A.S.P. Conferences Series, vol. 178, 35
- Fletcher, L., López Fuentes, M. C., Mandrini, C. H., et al. 2001, *Sol. Phys.*, 203, 255
- Gilman, P. A., & Charbonneau, P. 1999, in *Magnetic Helicity in Space and Laboratory Plasmas*, ed. M. R. Brown, R. C. Canfield & A. A. Pevtsov, *Geophys. Monogr. Ser.*, AGU, Washington, D.C., vol. 111, p. 75
- Harvey, K.L. 1993, PhD Thesis, Univ. Utrecht, Chapter 3
- Howard, R.F. 1990, *Solar Phys.*, 126, 299



- Ishii, T. T., Kurokawa, H., & Takeuchi, T. T. 1998, ApJ, 499, 898
- Kurokawa, H., 1987, Solar Phys., 113, 259
- Leka, K. D., Canfield, R. C., McClymont, A. N., & van Driel-Gesztelyi, L. 1996, ApJ, 462, 547
- Linton, M. G., Dahlburg, R. G., Longcope, D. W., & Fisher, G. H. 1998, ApJ, 507, 400
- Linton, M.G., Fisher, G. H., Dahlburg, R. G., & Fan, Y. 1999, ApJ, 522, 1190
- Lites, B.W., Low, B. C., Martinez Pillet, V., Seagraves, P., Skumanich, A., Frank, Z. A., Shine, R. A., & Tsuneta, S. 1995, ApJ, 446, 877
- Livingston, W. C., Harvey, J., Slaughter, C., & Trumbo, D. 1976, Applied Optics, 15, 40
- Longcope, D. W., Fisher, G. H., & Pevtsov, A. A. 1998, ApJ, 507, 417
- Matsumoto, R., Tajima, T., Chou, W., Okubo, A., & Shibata, K ApJ1998493L43
- Moffatt, H. K., & Rica, R.L. 1992, Proc. Roy. Soc. Lond., A 439, 411
- Parker, E. N. 1993, ApJ, 408, 707
- Petrovay, K., & Moreno-Insertis, F. 1997, ApJ, 485, 398
- Petrovay, K., & van Driel-Gesztelyi, L. 1997, Solar Phys., 176, 249
- Pevtsov, A. A., Canfield, R. C., & Metcalf, T. R. 1995, ApJ, 440, L109
- Pevtsov, A. A., & Canfield, R. C. 1999 in Magnetic Helicity in Space and Laboratory Plasmas, ed. M. R. Brown, R. C. Canfield & A. A. Pevtsov, Geophys. Monogr. Ser., AGU, Washington, D.C., vol. 111, p. 103
- Pevtsov, A.A., & Longcope, D.W. 1998, ApJ, 508, 908

Seehafer, N. 1990, *Solar Phys.*, 125, 219

Tanaka, K. 1991, *Solar Phys.*, 136, 133

Tsuneta, K., Bruner M., Lemen, J., et al. 1991, *Solar Phys.*, 136, 37

Weiss, N.O. 1994, in *Lectures on Solar and Planetary Dynamos*, ed. M.R.E. Proctor & A.D. Gilbert (Cambridge: Cambridge Univ. Press), 51

van Driel-Gesztelyi, L. 1998, in C. E. Alissandrakis & B. Schmieder (eds.), *ASP Conf. Ser.* 155, 202

van Driel-Gesztelyi, L., & Leka, K. D. 1994, in K.S. Balasubramanian & G.W. Simon (eds.), “Solar Active Region Evolution: Comparing Models with Observations”, *ASP Conf. Ser.* 68, 138

Weart, S.R. 1970, *ApJ*, 162, 987

Weart, S.R. 1972, *ApJ*, 177, 271

Zirin, H. 1988, *Astrophysics of the Sun* (Cambridge: Cambridge Univ. Press), 308

Zwaan, C. 1987, *Ann. Rev. Astron. Astrophys.* 25, 83

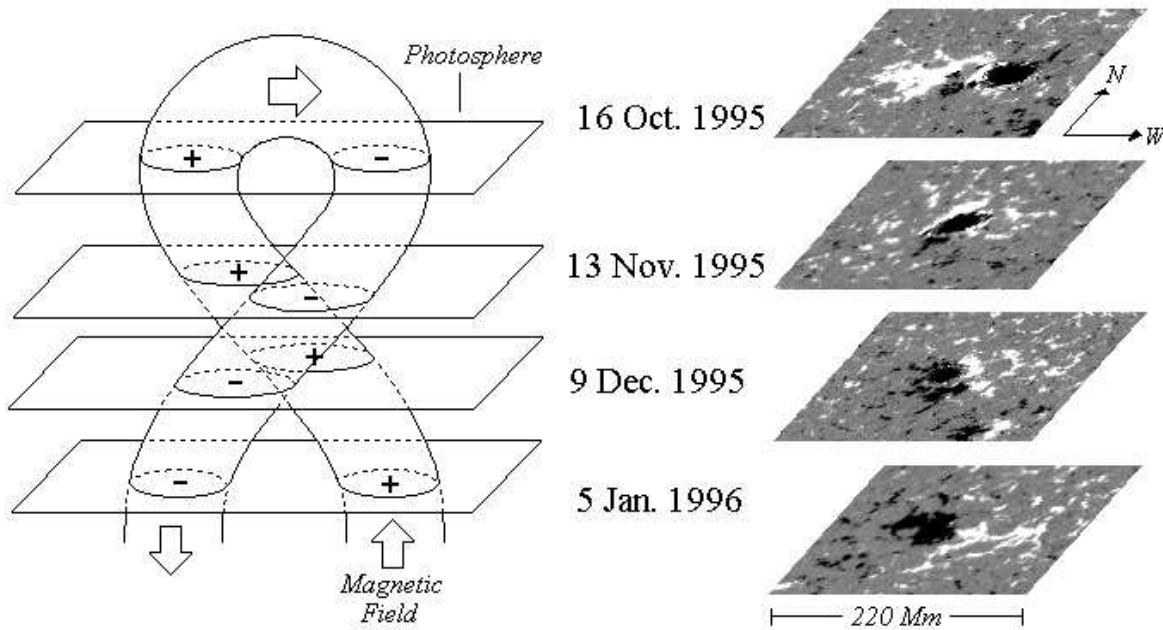


Fig. 1.— Evolution of AR 7912 during four rotations. On the right, photospheric longitudinal magnetograms are shown for each rotation close to central meridian passage (CMP), positive (negative) values of the field which appear in white (black) are saturated above (below) 50 G (-50 G). The four frames have the same size ( $\approx 220$  Mm). On the left, a sketch of the magnetic flux-tube as deduced from the observations. The cuts by four horizontal planes show the approximate location of the photosphere at the time of the magnetograms.

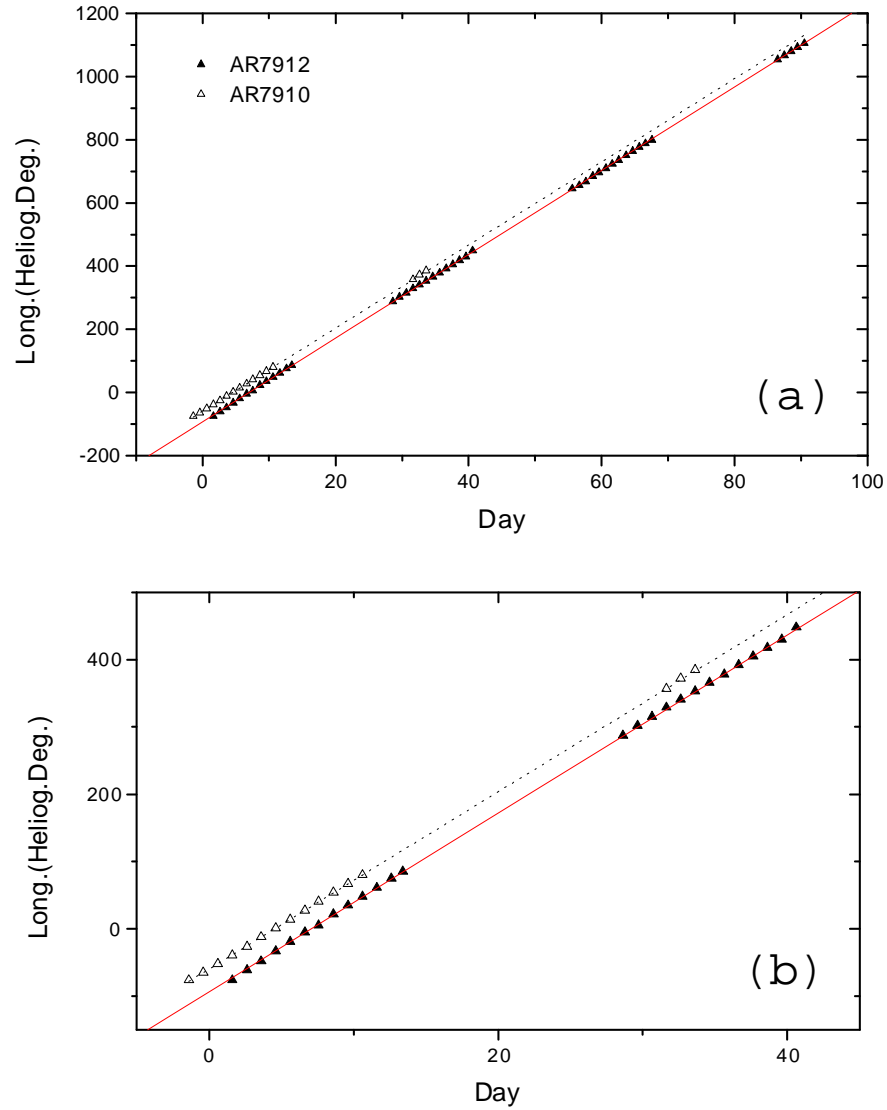


Fig. 2.— Synodic longitudes for the ARs 7910 and 7912 and their subsequent appearances on the solar disk, as a function of time (only few days around the CMP are plotted in the case when no AR was identify at that location). Day number one corresponds to October 10, 1995. A least square fit with a constant rotation speed is added. (a) four rotations, (b) zoom on the first two rotations.

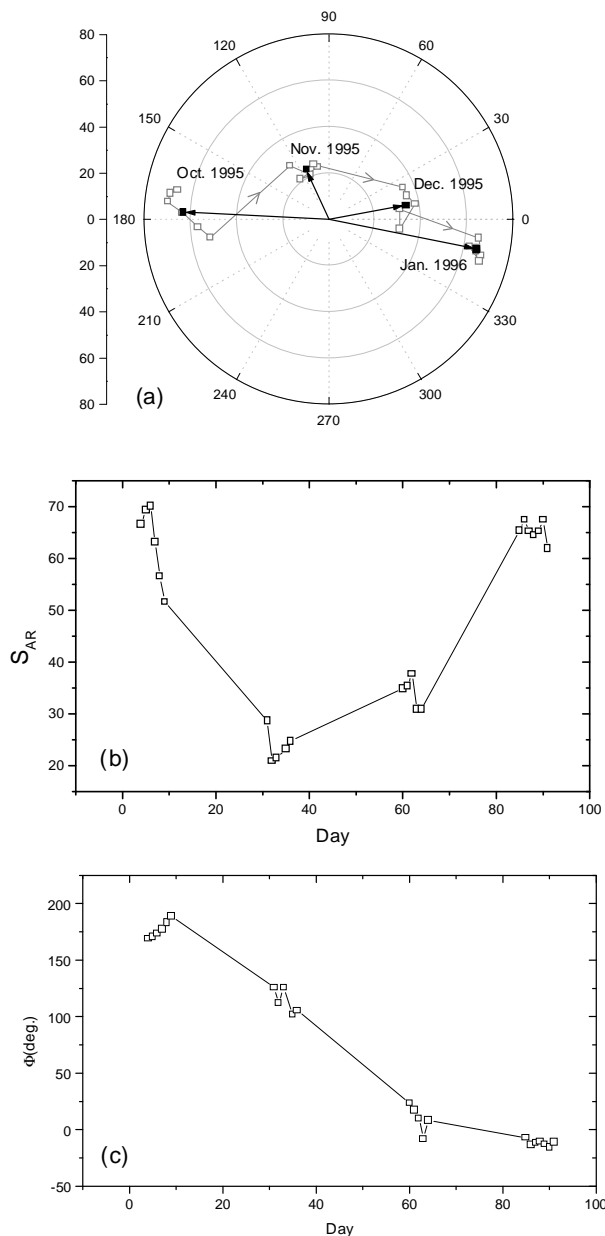


Fig. 3.— Relative evolution of the leading polarity with respect to the following one (only the magnetograms closer than 33 deg. from CMP have been used in order to avoid important projection corrections). (a) Polar plot (see text for an explanation). The arrows on the light grey lines show the way the time proceeds. (b,c) Time evolution of the size  $S_{AR}$  of the active region and of the angle  $\Phi_{AR}$  as defined in the text. The vertical axes in (a) and (b) are expressed in Mm. Day number one corresponds to October 10, 1995 in (b) and (c).

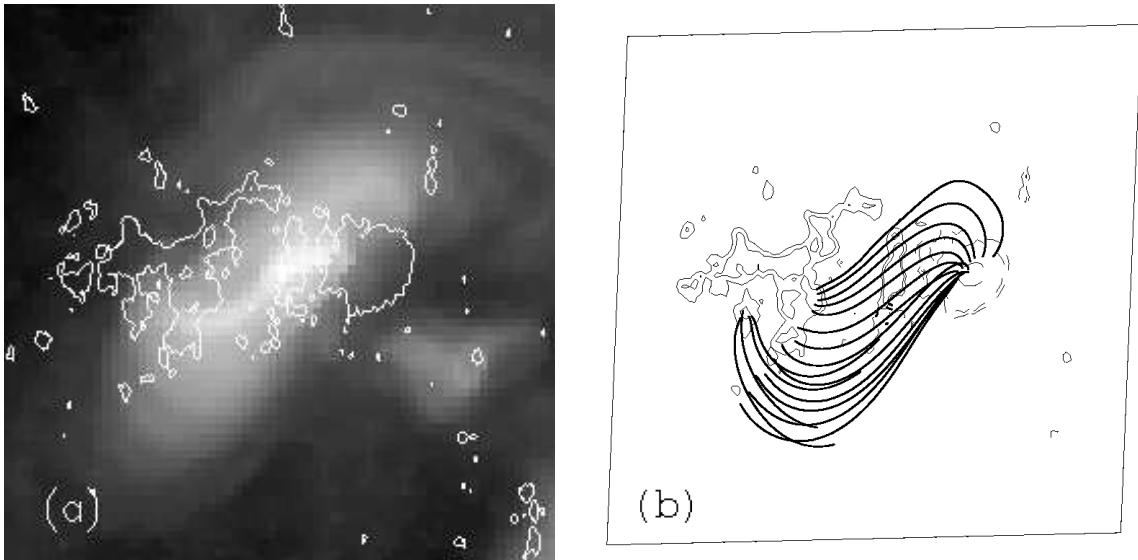


Fig. 4.— Determination of the twist of the coronal portion of the flux tube. (a) Section of a soft X-ray full disk image centered at the location of AR 7912 from Yohkoh/SXT showing an S-shaped sigmoid. The image was obtained on October 16, 1995, at 15:58 UT. An isocontour ( $\pm 100$  G) of the line of sight magnetic field ( $B_l$ ) has been added as a reference. (b) Linear force-free magnetic extrapolation, the best agreement with the SXT observations was found for  $\alpha = 0.03 \text{ Mm}^{-1}$ . The figure is a three dimensional view of the AR in the observer's perspective. Three isocontour levels of  $B_l$  ( $\pm 100, 200, 1000$  G) are shown with positive and negative values drawn with solid and dashed lines, respectively. The size of the region in both figures is  $200 \text{ Mm} \times 200 \text{ Mm}$ . North is up and West is to the right.

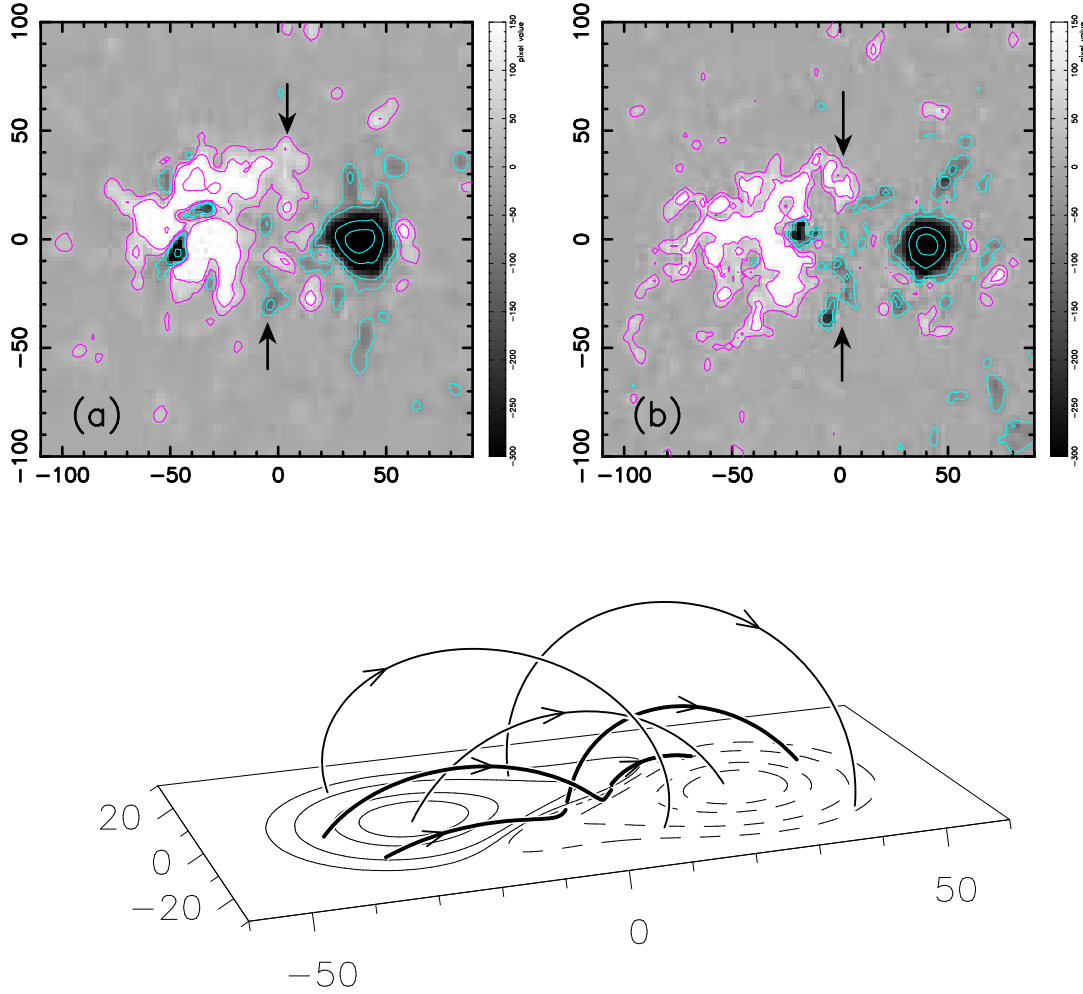


Fig. 5.— Evolution of the photospheric vertical field during the first rotation: (a) on October 13, (b) on October 15 (white/black corresponds to the positive/negative polarities, respectively). During few days (see Fig. 3) the rotation was in the positive direction. This is explained by the contribution of the azimuthal field component ( $B_\theta$ ) to the vertical magnetic component, during the initial emergence of the flux tube with positive twist as sketched in (c). The presence of twist in the  $\Omega$ -loop implies the presence of “tongues” (pointed with arrows in (a) and (b)) in the vertical field when the upper part of the tube is emerging at the photosphere. All axes are in Mm.

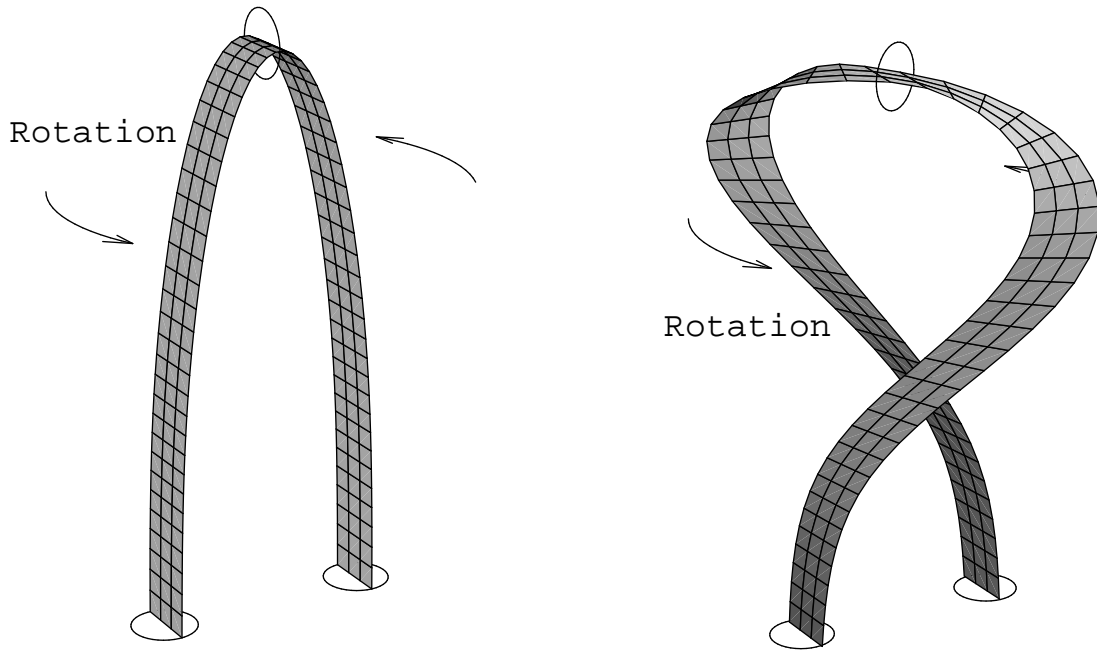


Fig. 6.— Sketch for the evolution of a buoyant flux-tube in the convective zone. (a) Shape of the flux tube after the Parker instability grows, but before the effect of rotational motions. Only a ribbon of field lines is drawn (circles outline the shape of the tube) and the flux tube is represented with no twist to simplify the drawing. (b) Evolution of the flux tube in the convective zone with no twisting motions at its “ends”, but with a deformation of its axis by external rotational motions, giving a negative writhe to the flux tube axis. This induces a positive twist inside the flux tube.



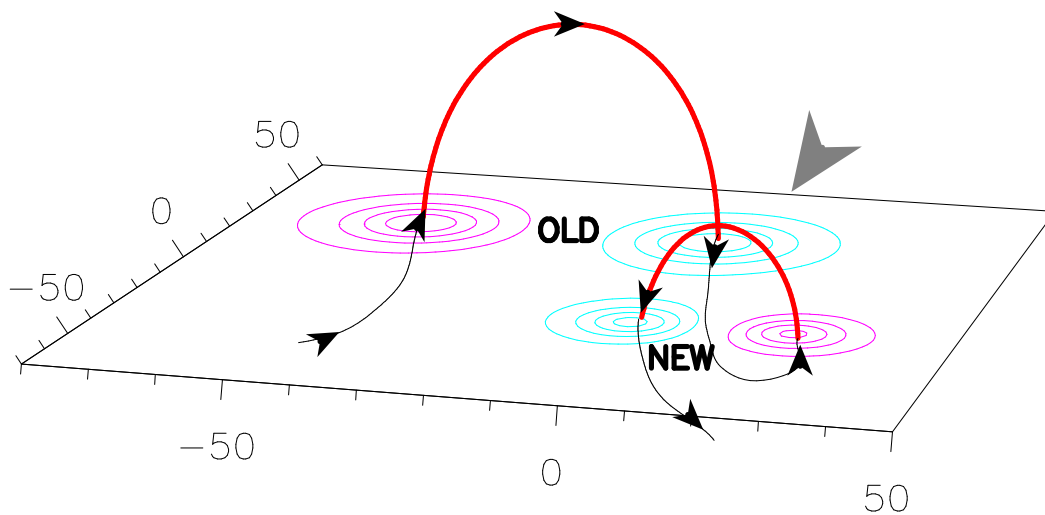


Fig. 7.— Possible magnetic configuration for the two cases analyzed by Pevtsov & Longcope (1998). Their first case is represented with the labels “old” for AR 7918 and “new” for AR 7926 to indicate which active region emerged first (see their Fig. 2). It is enough to inverse the position of “new” and “old” and the sign of the polarities, since they are on different hemispheres, to get the basic configuration of their second example (i.e. “old” for AR 7091 and “new” for AR 7123, see their Fig. 9). We suggest that this configuration was formed in the same way we propose in Fig. 6 for the region called “new” or, alternatively, by a deformed  $\Omega$ -loop pushed down close its central portion as indicated by the largest grey arrow (see text). The portion of the flux-tube axis above (below) the photosphere is shown with a thick (thin) continuous line. Dark (light) grey isocontours correspond to the positive (negative) polarities.