

geofísica  
internacional

Geofísica Internacional

ISSN: 0016-7169

silvia@geofisica.unam.mx

Universidad Nacional Autónoma de México  
México

López Fuentes, M. C.; Mandrini, C. H.; Démoulin, P.; Driel Gesztelyi, L. van  
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Geofísica Internacional, vol. 43, núm. 1, january-march, 2004, pp. 83-88  
Universidad Nacional Autónoma de México  
Distrito Federal, México

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## Inferring the writhe of magnetic flux tubes from the evolution of active solar regions

M. C. López Fuentes<sup>1</sup>, C. H. Mandrini<sup>1</sup>, P. Démoulin<sup>2</sup> and L. Van Driel-Gesztelyi<sup>2,3,4,5</sup>

<sup>1</sup> *Instituto de Astronomía y Física del Espacio, Buenos Aires, Argentina*

<sup>2</sup> *Observatoire de Paris, Meudon, France*

<sup>3</sup> *MSSL, UCL, Holmbury St. Mary, Dorking, Surrey, UK*

<sup>4</sup> *Konkoly Observatory, Budapest, Hungary*

<sup>5</sup> *Center for Plasma Astrophysics, K.U.Leuven, Leuven, Belgium*

Received: March 31, 2001; accepted: October 11, 2002

### RESUMEN

Estudiamos la evolución a largo plazo de regiones activas bipolares en las cuales las polaridades principales rotan una alrededor de la otra por varias rotaciones solares. Proponemos que esta evolución peculiar se debe a la emergencia de flujos magnéticos distorsionados. En este trabajo inferimos el signo de la helicidad de los tubos de flujo a partir de la rotación del eje que une las principales polaridades positivas y negativas. El origen de la deformación se puede explicar por el desarrollo de la inestabilidad kink, pero la otra posibilidad es la interacción con el plasma en movimiento durante el ascenso de los tubos de flujo en la Zona Convectiva. Entre los posibles mecanismos discutimos el papel que la Fuerza de Coriolis, la turbulencia convectiva y otros movimientos de gran escala pueden tener en este proceso.

**PALABRAS CLAVE:** Regiones solares activas, emergencia de flujo magnético, tubos de flujo.

### ABSTRACT:

We study the long-term evolution of bipolar active regions in which the main polarities are observed to rotate one about the other along several solar rotations. We propose that this peculiar evolution is due to the emergence of distorted magnetic flux tubes. We are able to infer the sign of the writhe helicity of the flux tubes from the rotation of the axis joining the main positive and negative polarities. The origin of the deformations may be explained by the development of a kink instability. Another possibility is the interaction with plasma motions during the ascent of the flux tubes in the Convective Zone. We discuss the role of the Coriolis force, convective turbulence and other large-scale motions in this process.

**KEY WORDS:** Solar active regions, emergence of magnetic field, flux tubes.

### 1. INTRODUCTION

Solar active regions (ARs) at the photospheric level may consist of two areas of opposite magnetic polarity. It is believed that they are due to emergence of buoyant magnetic flux tubes shaped as a Greek  $\Omega$  (Zwaan 1987). They are supposed to be formed at the base of the Convective Zone (CZ) (Parker 1993). After ascending through it, they emerge through the photosphere. In general, the bipoles are oriented in the East-West direction, obeying the Hale-Nicholson law (Hale and Nicholson 1925). Although most of the ARs follow this law, there are several observations of non-Hale active regions. These anomalous ARs have often been associated with distorted magnetic flux tubes. Tanaka (1991) studied ARs having a  $\delta$  configuration and explained their origin as due to the emergence of knotted flux tubes. Lites *et al.* (1995) interpreted the evolution of a  $\delta$  configuration as due to the emergence of a nearly-closed flux system. Leka *et al.* (1996) found that the proper motions of several emerging bipoles were consistent with the rise of kink-deformed flux

tubes. Pevtsov and Longcope (1998) analysed two ARs along two solar rotations whose evolution agreed with the emergence of a single flux system resembling a kinked flux-tube.

López Fuentes *et al.* (2000) studied NOAA 7912, a southern hemisphere bipolar AR, in which the main polarities turned one around the other during several solar rotations. AR 7912 appeared as a non-Hale region for the Cycle 22 in October 1995, and became a Hale region four solar rotations later in January 1996, when the main polarities turned one around the other by about 180 degrees. In the next solar rotation (February 1996) the remnant polarities continued rotating, due in part to the influence of the differential rotation. We interpreted the evolution of the AR as due to the emergence of a very distorted magnetic flux tube. One of the physical quantities that characterize magnetic structures is the magnetic helicity; the MHD invariant is defined by

$$H = \int \mathbf{A} \cdot \mathbf{B} \, dV ,$$

where  $\mathbf{B}$  is the magnetic field and  $\mathbf{A}$  is its vector potential (see Sturrock 1994). Because of magnetic helicity conservation, the development of a kink instability was discarded as the possible origin of this peculiar behaviour. In a flux tube deformed by a kink instability the twist (the component of the magnetic helicity associated with the deformation of the field lines around the main axis of the flux tube) and the writhe (the deformation of the axis of the flux tube as a whole) must be the same sign (Linton *et al.* 1999). This was not the case for AR 7912. Instead, López Fuentes *et al.* (2000) proposed that the deformation could be caused by the interaction of the flux tube with the surrounding plasma during emergence through the CZ.

Following López Fuentes *et al.* (2000), we study a set of ARs whose main polarities rotate one around the other during their life time, in a way that suggests the emergence of distorted magnetic flux tubes. Analysing magnetic field observations, we infer the sign of the writhe helicity of the flux tubes that form the ARs. Among the possible interpretations of the peculiar evolution observed, we discuss the role of the kink instability, the Coriolis force and turbulent and large-scale motions in the CZ.

## 2. ANALYSIS OF OBSERVATIONS AND RESULTS

To analyse the long-term evolution of ARs we use magnetic synoptic maps produced from data obtained at the National Solar Observatory at Kitt Peak (NSO/KP). The maps are constructed by integration of full disk magnetic polarimeter observations, and each of them covers a full Carrington rotation. Hence, they allow us to follow the evolution of a particular AR along several solar rotations.

By visual inspection of the maps, we identify bipolar concentrations that appear in two or more successive solar rotations, in which the bipolar axes rotate. To assure that the AR is indeed the same in successive solar rotations, we consider only those cases in which the difference in position of the flux concentrations is less than 15 degrees in longitude and 8 degrees in latitude. As a criterium for the selection, we also consider that the evolution of the flux must be the expected one; that is to say, the AR disperses with time. For each of the reappearance of an AR, we compute:

$$X_{P,N} = \frac{\sum x B_z}{\sum B_z}, \quad Y_{P,N} = \frac{\sum y B_z}{\sum B_z},$$

where  $X_{P,N}$  and  $Y_{P,N}$  are the mean positions of the positive and negative magnetic polarities weighted with the field intensity,  $x$  and  $y$  are the coordinates of the pixels and  $B_z$  is the strength of the magnetic field (supposed to be normal to the photosphere) associated to each pixel. The summation is taken over the pixels where the magnetic field is above a given

value, in all the analysis presented here we use 10 Gauss. Therefore, the mean distance between main polarities and the angle that they form with the equator (tilt angle) are given by

$$S_{AR} = \sqrt{(X_P - X_N)^2 + (Y_P - Y_N)^2}$$

$$\Phi = \arctan\left(\frac{Y_P - Y_N}{X_P - X_N}\right).$$

The tilt angle  $\Phi$  is considered positive (with respect to the east-west direction) in the counterclockwise direction.

We studied a total of 350 maps ranging from 1975 to 2000, and we identified 285 ARs in which the tilt angle changed along several solar rotations. The polar plots in Figures 1 to 4 show the evolution of  $\Phi$  and  $S_{AR}$  for some of the studied cases, the NOAA number corresponding to the first appearance of the AR is indicated in the respective panel. The centers of the plots correspond to the position of the negative polarities, and the arrows and squares indicate the relative position of the positive polarities.

In Figure 5 we show the histogram of the distribution of the angle of rotation ( $\Delta\Phi$ ) for the full set. For the data plotted in the histogram the rotation angles of ARs in the South hemisphere has been reversed, so that it is symmetric

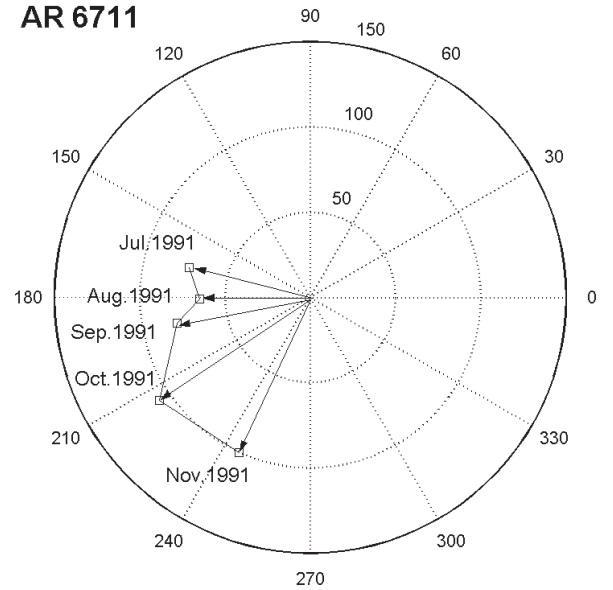


Fig. 1. Polar plot showing the long-term evolution of  $S_{AR}$  (Mm) and  $\Phi$  (degrees) for AR 6711, observed from July to November 1991 in the North hemisphere. The origin of the plot corresponds to the position of the negative polarity, and the arrows and squares indicate the relative position of the positive polarity in this and similar figures. This AR rotates in the counterclockwise direction.

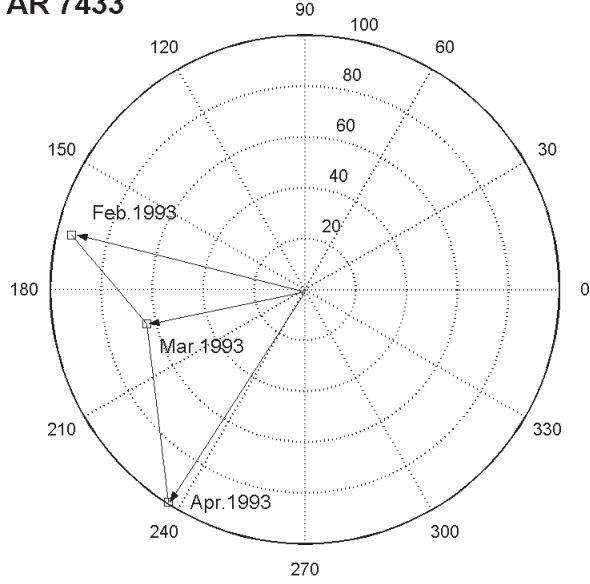
**AR 7433**

Fig. 2. Idem Figure 1 for AR 7433, a northern hemisphere AR observed from February to April 1993. The polarities rotate in the counterclockwise direction, which we associate to a flux tube with positive writhe (see discussion in Section 3).

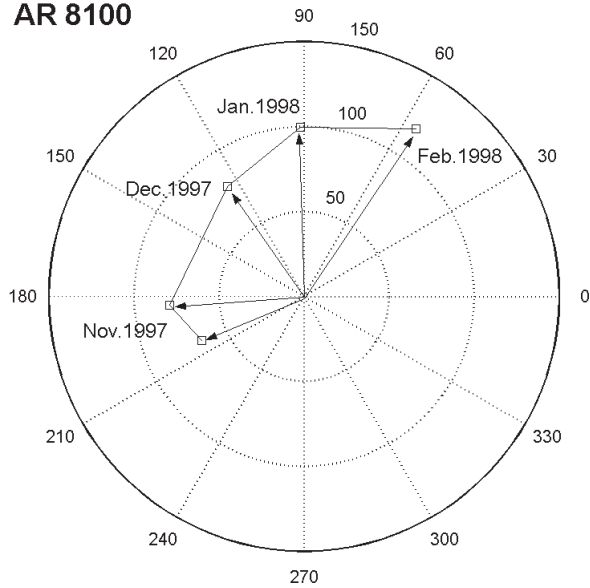
**AR 8100**

Fig. 3. Idem Figure 1 for AR 8100, observed in the South hemisphere from November 1997 to February 1998. This AR rotates in the clockwise direction; then we infer that the flux tube forming it has a negative writhe. Since the AR has a high tilt angle after the first two rotations, its later evolution is mainly due to the effect of the differential rotation.

in both hemispheres. This symmetrization means that the rotation angle in the South hemisphere is considered positive in the clockwise direction.

Provided that the rotation of the bipole axis can be influenced by the differential rotation, we correct the tilt angle data to remove its contribution. To do that we have used the differential rotation profile given in Komm *et al.* (1993). The distribution is close to a normal one, with a mean of 1.2 degrees and a standard deviation of 29 degrees. Without correcting for differential rotation, the distribution is still close to normal, but the mean value changes to 6.2 degrees, what is expected since the differential rotation contributes with positive rotation to ARs located in the northern hemisphere.

**3. DISCUSSION**

Assuming that the evolution of the main polarities of the ARs at photospheric level reflects the emergence of deformed flux tubes, we can infer the handedness of the deformation of the flux tube axis from the change in the tilt angle  $\Phi$ . The component of the magnetic helicity associated to that kind of deformation is the so called writhe (Berger and Field 1984).

The other component of the helicity or twist, corresponds to the turning of the magnetic field lines of the flux tube around the main axis. The drawings in Figure 6 show how the evolution of the tilt angle and the sign of the writhe can be related. The sense of rotation of the polarities in the clockwise direction indicates a negative (left handed) writhe and a counterclockwise rotation a positive (right-handed)

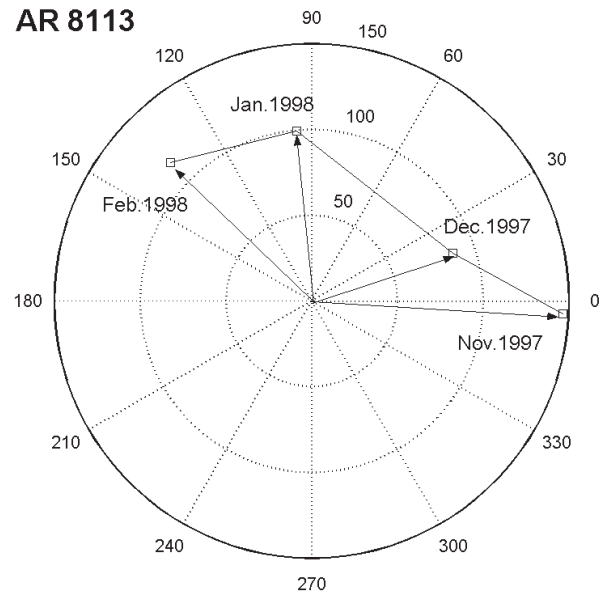
**AR 8113**

Fig. 4. Idem Figure 1 for AR 8113, observed from November 1997 to February 1998, in the North hemisphere. This AR rotates in the counterclockwise direction; then, the inferred sign of the writhe is positive. As in the case of AR 8100, the evolution observed in the last two solar rotations is mainly due to differential rotation.

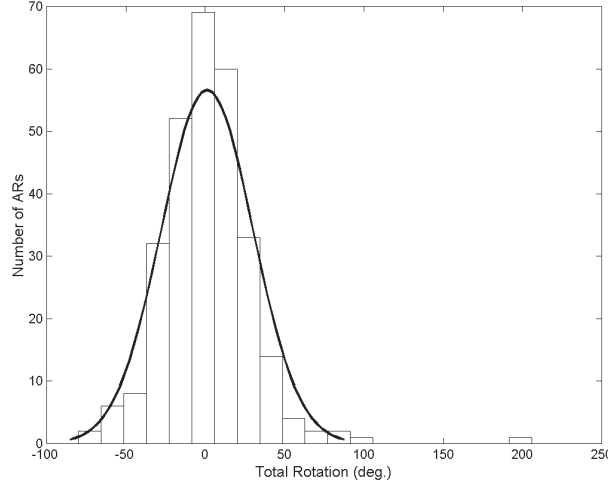


Fig. 5. Histogram showing the distribution of the angles of rotation for a total of 285 ARs identified from 1975 to 2000. The distribution is nearly gaussian, the mean value is 1.2 degrees and the standard deviation is 29 degrees.

writhe. We now discuss the probable origins of the proposed deformation.

Differential rotation produces relative displacements parallel to the equator; then, its effect will be relevant only in ARs having high tilt angles, close to 90 degrees. On the other hand, the differential rotation would force all ARs in a given hemisphere to rotate in the same sense. From the histogram shown in Figure 5, this is clearly not the case for the set of ARs analysed here. We discard vortex motions of the plasma at the photospheric or close by subphotospheric level, because they are not expected to be sustained during the long-term evolution of the ARs (several solar rotations). Moreover, motions having these length scales and durations are not observed in other photospheric features.

A possible origin of the deformation is the development of a kink instability (Linton *et al.* 1999, Fan *et al.* 1999). This instability occurs in a flux tube when the twist helicity reaches a threshold given by the flux tube properties. The excess of twist in the most unstable modes provokes the transformation of twist helicity into writhe helicity, making the flux tube reach a new state of equilibrium consisting in the appearance of a kink in the flux tube as a whole. Then, the signs of the twist and the consequent writhe must be the same. A comparison between the signs of the twist and the writhe for a reduced number of ARs in the set studied here (22 ARs), show that the conditions required in kink unstable flux tubes are not met (López Fuentes *et al.*, 2002, in press).

Other possible mechanism is the interaction of the flux tube with plasma motions while ascending in the CZ. Among

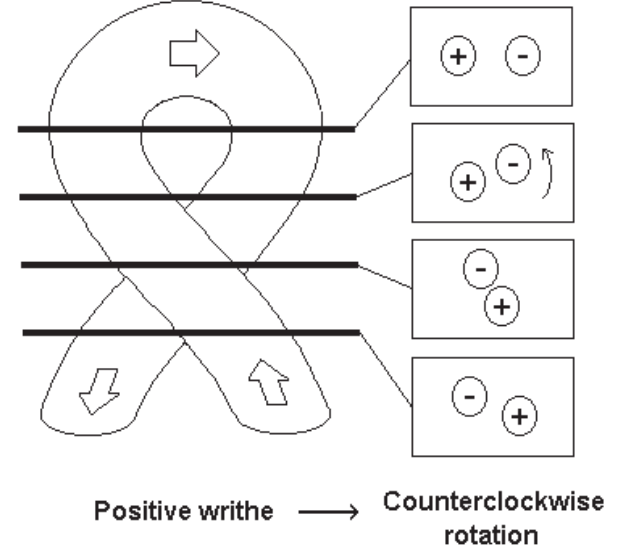


Fig. 6. The sketch shows how the emergence of a distorted flux tube with positive writhe can be inferred from the rotation of the main polarities in the counterclockwise (positive) sense. A flux tube with negative writhe is the mirror image of the one shown in the figure; in this case, the rotation of the polarities will be in the opposite sense. The segments cutting the tube correspond to the relative position of the photosphere at different stages during the emergence. The drawings show the corresponding appearance of the photospheric magnetic field of the AR, according to the sense of the magnetic field given in the tube (see arrows). The sketched flux tube corresponds to the extreme case in which the deformation is such that the AR rotates by 180 degrees during its full emergence.

these processes we can mention the action of the Coriolis force. In this particular case, the deformation has to be consistent with the sense of rotation given by Coriolis acting on ascending tubes. In the North hemisphere, for instance, the Coriolis force would produce a clockwise rotation; then, the flux tube would be deformed in a right handed way acquiring positive writhe (see Figure 6). On the other hand, in the South hemisphere, ascending tubes would be rotated counterclockwise; then, they would acquire negative writhe. Moreover, according to what is shown in Figure 6, flux tubes hypothetically deformed by Coriolis force will give raise to ARs that rotate in the positive direction (counterclockwise) in the North hemisphere and in the negative (clockwise) in the South hemisphere. In the case of AR 7912, studied in López Fuentes (2000), the proposed deformation was coherent with the sense of the rotation given by the Coriolis force on an ascending tube located in the southern hemisphere. It is easy to note that this argument also applies to the ARs shown in Figures 1 to 4. Nevertheless, when analysing the data for the full set of ARs (see histogram in Figure 5), after the tilt angle measured for the South hemisphere ARs has been transformed using the same convention as for the angle measured in the North hemisphere ARs, the distribution shows no preferred sense of rotation.

Mechanisms by which the turbulence can introduce helicity in an ascending tube have been proposed by Longcope *et al.* (1998) to explain the distribution of tilt angles of ARs (the so called Joy's law). Stochastic processes, if able to produce such distortions, would not discriminate the sense of the deformation as it is done by the Coriolis force or the kink instability (which implies an internal redistribution of helicity). Then, provided that the distribution of rotation angles is approximately a normal or gaussian one centered in 0, turbulent processes are the likely mechanisms that may lay at the origin of the deformation of flux tubes. The main problem with these processes is that theoretical studies predict that turbulence is relevant only in the upper layers of the CZ (Longcope and Choudhuri, 2002). The presence of large-scale vortex motions in the CZ, interacting with the ascending flux tubes should also be considered as a possible origin of the deformation, as discussed in López Fuentes *et al.* (2000). This interaction comes from the coupling of the flux tubes with the plasma via the drag force, which is coherent with the high  $\beta$  conditions of the plasma in the CZ.

#### 4. CONCLUSION

In this paper we study set of bipolar ARs, identified in Kitt Peak synoptic maps, in which the main polarities are observed to rotate one around the other for several solar rotations. We interpret this evolution as due to the emergence of deformed flux tubes. We measure the tilt angle and we relate its evolution to the writhe helicity sign of the flux tubes to discuss the plausibility of different mechanisms that are able to produce deformations in them. Among the possible mechanisms we propose: the development of a kink instability, the action of the Coriolis force, the influence of turbulence and the presence of large-scale vortex motions in the plasma surrounding the flux tube during its ascent in the CZ. The relevance of the kink instability will be analysed in a future paper, preliminary results show that only a minor number of the ARs fulfill the sufficient but not necessary conditions to be related to this kind of process. Concerning the Coriolis force, the distribution of the rotation angles does not support this hypothesis. Although turbulence would be a good candidate according to the characteristics of the distribution found for the tilt angle of the analysed ARs, it is not expected to produce major deformations provided that its influence is not relevant along most of the CZ (Longcope and Choudhuri 2002). Nevertheless, vortex motions of the scale size of the emerging flux tubes, which are able to produce such deformations, may be present in the CZ.

Deformations due to the interaction of the emerging flux tubes with the surrounding plasma, including large scale vortex motions, cannot be completely discarded. A deeper analysis is needed. Future work should include the study of the relation of the rotation angle with other measured quantities, such as the magnetic flux and the size of the ARs (de-

finied here as  $S_{AR}$ ) in order to obtain clues on the processes involved in the formation and evolution of magnetic flux tubes. This kind of studies should contribute to our knowledge of the mechanisms at work in the solar interior.

#### ACKNOWLEDGEMENTS

M.L.F. acknowledges LESIA, Observatoire de Paris, Meudon for the grant of an ESA fellowship. C.H.M. and P.D. acknowledge financial support from ECOS (France) and SeCyT (Argentina) through their cooperative science program (A01U04). LvDG was supported by the Hungarian Government Grants OTKA T-032846, T-038013 and by the Research Fellowship F/01/004 of the K.U. Leuven. P.D. and L.v.D.G. acknowledge the Hungarian-French S&T cooperative program. The NSO/Kitt Peak data used here are produced cooperatively by NSF/NAO, NASA/GSFC, and NOAA/SEL.

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M. C. López Fuentes<sup>1</sup>, C.H. Mandrini<sup>1</sup>, P. Démoulin<sup>2</sup> and L. van Driel-Gesztelyi<sup>2,3,4,5</sup>

<sup>1</sup> Instituto de Astronomía y Física del Espacio, CC. 67, suc. 28, 1428 Buenos Aires, Argentina

Email: [lopezf@iafe.uba.ar](mailto:lopezf@iafe.uba.ar)

<sup>2</sup> Observatoire de Paris, DASOP, F-92195, Meudon, France

<sup>3</sup> MSSL, UCL, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK

<sup>4</sup> Konkoly Observatory, Budapest, Pf. 67, H-1525, Hungary

<sup>5</sup> Center for Plasma Astrophysics, K.U.Leuven, Celestijnenlaan200B, 3001Leuven, Belgium