ON THE ORIGIN OF PECULIAR ACTIVE REGIONS

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ABSTRACT

We study the long term evolution of a set of bipolar active regions (ARs) in which the main photospheric polari- ties are seen to rotate one around the other during several solar rotations. After showing that differential rotation cannot produce this large change in the tilt angle, we interpret this peculiar evolution as being the result of the emergence of magnetic flux tubes that are distorted with respect to the classical Ω-loop shape. A possible origin of this distortion is the nonlinear development of a kink-instability. Flux tubes deformed by this mechanism must have the same sign of twist and writhe. From the observed evolution of the tilt of the bipoles, we derive the sign of the writhe of the tube forming each AR; while we compute the sign of the twist from transverse field measurements. Comparing the handedness of the magnetic twist and writhe, we find that the presence of kink-unstable flux tubes is coherent with no more than 32% of the studied cases; so, a small fraction of these peculiar ARs can be explained by this process. Then, we discuss the role that other mechanisms may play inducing the inferred deformation, such as the Coriolis force or external rotational motions of the plasma as the tube ascends in the convection zone. These bipolar ARs will, in general, obey the Hale-Nicholson polarity law (Hale & Nicholson 1925) and Joy’s law (see Hale et al. 1919). Nevertheless, there are several observational examples (see López Fuentes et al. 2000 and references therein) of ARs disobeying these laws and/or presenting an evolution which does not follow at all the usual tendency. The evolution of these peculiar ARs has been associated with the emergence of distorted magnetic flux tubes. In particular, there are some examples that are suspected to be formed by the development of a kink instability (Linton et al. 1999). In López Fuentes et al. (2000), we have analyzed the evolution of a bipolar AR that appeared on the southern hemisphere as a non-Hale region and became a Hale region four solar rotations later. This evolution has been interpreted as the emergence of a very distorted tube having the sign of the twist different from that of the writhe (contrary to what is a condition for a tube where the kink instability has developed).

Key words: magnetic fields; photosphere; active regions.

1. INTRODUCTION

It has long been thought that active regions (ARs) are the manifestation of the emergence of buoyant flux tubes formed at the bottom of the convective zone, the so-called Ω loops (Zwaan 1985, and references therein). After ascending through the convection zone (CZ) and emerging, two flux concentrations appear at the photosphere and progressively diverge from each other in an approximate east-west direction. These bipolar ARs will, in general, obey the Hale-Nicholson polarity law (Hale & Nicholson 1925) and Joy’s law (see Hale et al. 1919). Nevertheless, there are several observational examples (see López Fuentes et al. 2000 and references therein) of ARs disobeying these laws and/or presenting an evolution which does not follow at all the usual tendency. The evolution of these peculiar ARs has been associated with the emergence of distorted magnetic flux tubes.

To test the role of the kink instability to originate the flux-tube deformation, in this work we determine the sign of the writhe and twist for a set of 22 bipolar flux concentrations, in which the main polarities are observed to rotate one around the other. In Section 2, we describe the data used, together with the procedure and criteria followed to determine the writhe of the regions and a brief description of the method used to compute the sign of the twist. We present a summary and interpretation of the results in Section 3. We also discuss the relevance of the kink instability as the origin of the flux-tube deformation, and we analyze the role that other mechanisms, such as the Coriolis force and external rotational motions of the plasma in the CZ, may have in the observed evolution.

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2. DETERMINATION OF THE WRTHE AND 
THE TWIST OF FLUX TUBES

The evolution of the photospheric magnetic field 
concentrations can be related to the morphology of the 
flux tubes that give origin to them. Figure 1 shows 
two flux tubes with their axis distorted in a helix-
like curve. The different planes correspond to con-
secutive intersections of the flux tubes with the pho-
tosphere and illustrate how the magnetic polarities 
evolve as the tubes emerge.

To measure the change in the tilt angle, we have 
used synoptic magnetograms produced from data ob-
tained with the National Solar Observatory Vacuum 
Telescope at Kitt Peak. These maps cover a total of 
337 Carrington rotations, from March, 1975, to De-
cember, 2000. The maps are constructed through a 
weighted integration in longitude of the line of sight 
magnetic field measured in daily full disk images of 
the Sun. We have developed a routine that allows us 
to compare successive synoptic maps and to select 
from them ARs that survive more than one solar ro-
tation by visual inspection. In particular, we have 
chosen ARs where a systematic evolution of the tilt 
angle is observed along several solar rotations. Once 
a flux concentration is selected, we compute from 
the data in the corresponding submatrix: the flux 
weighted mean longitude ($\phi$) and latitude ($\lambda$) of 
the positive and negative magnetic polarities, the mean 
longitude and latitude of the AR, its dipolar size, its 
tilt angle, the dispersion of the polarities measuring 
their flux weighted mean size and the total magnetic 
flux. The computations are done taking the pixels 
where $|B|$ is above a given value $B_{\text{min}} = 10$ G, and 
the results are kept in a set of files that cover 2.5 
solar cycles.

To test that the supposed reappearances of a flux 
concentration correspond to the same AR seen in 
successive solar rotations, we have applied the fol-
lowing criteria: 1) the longitude and latitude of an 
AR cannot differ by more than 8 and 5 heliograph-
ic degrees, respectively, when differential rotation is 
taken into account, 2) we require that the magnetic 
flux presents only one maximum during its evolution 
and that neither the dipolar size nor the radius of 
the polarities decrease form one solar rotation to the 
next. To compute the effect of differential rotation, 
which can be important depending on the latitude of 
the ARs, we have used its classical expression tak-
ing the values of the constants form Komm et al. 
(1993). The previous criteria have been implemen-
ted in a code that we ran using as input the data 
base built by visual inspection. After applying these 
criteria to the original data set, we identify $\approx 300$ ro-
tating ARs, from June 1975 to December 2000. This 
study is limited to a set of 22 ARs for which we can 
derive both the sign of the writhe and the twist. The 
main results are summarized in Tables 1 and 2.

It is not possible to obtain a direct measurement of 
the twist of the magnetic flux tubes that form ARs. 
Nevertheless, computations of the global value of 
the force-free field parameter, $\alpha$, provide a proxy for 
the sign of the magnetic twist in the tubes. Excep-
t for two regions, for which we have data from the
magnetograph of the Marshall Space Flight Center (MSFC), we have used vector magnetograms from the Haleakala Stokes Polarimeter at Moes Solar Observatory to determine $\alpha$. In force-free magnetic field configurations the current density and the magnetic field are related by: $\mathbf{\nabla} \times \mathbf{B} = \alpha \mathbf{B}$. Using the expression for the projection of the force-free equation in the $z$ direction ($z$ normal to the photosphere), we can create maps of $\alpha$ from vector magnetograms. To obtain the single value of $\alpha$ for a linear force-free field that best fits the AR magnetic field, we apply a least-square method as discussed in Pevtsov et al. (1995). When more than one magnetogram is used for a particular AR, we compute the standard deviation which is shown in the third column in Tables 1 and 2. There are 4 cases where the sign of $\alpha$ changes along the evolution of the AR. For AR 6855 and AR 8243 the change in the sign of $\alpha$ is significant, so we will not use these ARs in our analysis. For AR 7518, the change occurs only in the last appearance and its error is much larger than its mean value; then, we consider that this measurement is irrelevant. Finally, the evolution of AR 8100 along five solar rotations has been studied in detail by us (Green et al. 2002); we have found that, except in the first rotation, the twist was always positive, therefore, we keep the positive sign.

3. DISCUSSION AND CONCLUSIONS

We first discuss the influence of differential rotation of the variation of the tilt angle. The results summarized in Tables 1 and 2 show that for most of the ARs $\Delta \varphi$ and $\Delta \varphi_{\text{cor}}$ have comparable values. In three cases (ARs 4711, 8100 and 8113) differential rotation has a large effect, but a significant rotation of the polarities remains even after correcting it. Then, we conclude that differential rotation is not the main mechanism responsible for the rotation of the bipoles. In all cases, the correction of the tilt angle for differential rotation does not change its sign (which is equivalent to keep the inferred sign of the writhe unchanged) and, therefore, it does not alter our conclusions.

The magnetic helicity of a flux tube that originates at the base of the CZ is preserved with a good approximation as it emerges (see Berger 1984). However, an internal transfer between twist and writhe helicity can occur. In particular, any helicoidal-like distortion of the flux tube axis will introduce writhe helicity. Because of helicity conservation, this induces a change in the twist helicity. There are various mechanisms that can provide this transformation. These can be: an internal instability of the tube (such as the kink mode), or the Coriolis force acting on the ascending tube, or the drag action of external convective vortexes. The kink instability is then a possible mechanism for the origin of the rotating ARs. However, one characteristic of this instability is that writhe and twist should have the same handedness (i.e. same sign). The results of Tables 1 and 2 show that only 7/22 ARs have the same twist and writhe sign, but 13 ARs have opposite signs. That is to say, at most only $\approx 32\%$ of the ARs in our sample can be associated to the formation of kinked flux tubes (in the sense given by the kink instability), while $59\%$ cannot. It is worth mentioning that the fact that the signs of twist and writhe are the same does not imply that the deformation of the flux tube is due to the kink instability. Having the same sign is a necessary but not a sufficient condition to confirm the kink instability as responsible for the deformation.

Looking at our results in Tables 1 and 2, we find that from the 13 ARs that cannot be associated with the kink instability, 12 have the right sense of rotation that could be induced by the Coriolis force. Besides, from the 7 ARs that could be related to a deformation of flux tubes due to a kink instability, 3 can alternatively be originated by the Coriolis force (they satisfy the Joy’s law and rotate towards the East-West direction). Broadly speaking, 15 out of 22 ARs rotate in the direction consistent with a flux tube deformed by the Coriolis force, i.e. counter-clockwise on the North and clockwise on the South hemisphere. However, we find only 7 of these cases that relax to the East-West direction within $10^6$. Moreover, only 2 ARs relax towards this direction without reaching it. When considering the full set of ARs, we find that an important fraction of the ARs ($8/22$) rotates toward the East-West direction, but after reaching this direction, they continue to rotate and overpass it significantly (with a mean value of $30^\circ$). We found also a smaller fraction of ARs ($5/22$) that rotate away from the East-West direction. The number of cases in each of the above categories is the same if we do not correct for differential rotation. We conclude that, under our assumptions, the rotation of the polarities for most of the studied ARs is not consistent with the effect of the Coriolis force on the ascending flux tube.

Large scale vortex motions are presently difficult to infer from the data. Nevertheless, Ambroz (2001 and references therein) claimed to have detected large scale vortexes with a spatial size of the order of 200 Mm and with a time scale of 4 Carrington rotations. On the theoretical side, Longcope et al. (1998) propose that the turbulent velocities in the CZ can, via the drag force, deform the axis of an ascending magnetic flux tube. This effect (called $\Sigma$-effect) modifies the writhe in the flux tube. The mean tilt angle and its dispersion compare favorably with the corresponding observations. Although the same mechanism can originate the variation of the tilt angle found in the 22 ARs, our selection criteria restricts us to use a too small sample, and does not let us arrive to any conclusion about a mechanism which is by nature of statistical origin. It will be the objective of the next paper to study the kinetic properties of a much larger set of ARs to determine the relevance of this mechanism.

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<th>NOAA</th>
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<th>Δφ</th>
<th>Δφ cor.</th>
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<td>-2.0±1.1</td>
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<td>7205</td>
<td>20/06/92</td>
<td>4.2±1.1</td>
<td>19±2.0</td>
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<td>8269</td>
<td>16/07/98</td>
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Table 1. List of ARs from the North hemisphere. The first column gives the NOAA number of each appearance for which α is available. NOAA numbers that do not belong to the same flux tube are separated by a blank line. The second column gives the date of the central meridian passage (CMP) of the corresponding region. The following columns show, respectively, the value of the force free parameter α (in units of 10⁻⁸m⁻¹), the total rotation angle of the AR not corrected (Δφ) and corrected (Δφ cor.) for differential rotation in degrees.

Table 2. Idem Table 1 for the South hemisphere

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