Chapter 4

Electric Current Helicity of Active Regions [1]

4.1 Introduction

It is widely accepted that the energy of non-stationary processes in solar corona is the magnetic field energy stored in the form of electric currents. Flares in active regions are typical phenomenon on the Sun. That is why the energy build up mechanism have to be easy accessible for all solar active regions.

The well known conception for the generation of large-scale current systems in active regions is shearing motions in the photosphere on the scale at least of sunspot size (e.g. Hagyard et al. 1984; Abramenko, Gopasyuk & Ogir 1991). New conceptions of the magnetic energy build-up based on the helical nature of solar magnetic fields were proposed recently. Rust and Kumar (1994) have shown that such non-stationary processes as 'filament eruptions, coronal mass ejections and active region loop expansions follow from the build-up of magnetic helicity in emerged flux ropes'. Seehafer (1994) showed that the current helicity is of particular importance in the magnetic energy build-up. If we suggest that coronal fields evolve through the sequence of force-free states, the energy of small-scale fluctuations of magnetic field and velocity, propagating upward from the photosphere along the field, can be transferred to the equilibrium magnetic field energy (Seehafer 1994). This is equivalent to the generation of an electromotive force parallel to the equilibrium field (the α-effect). As follows from Equation (23) of Seehafer (1994), if the α-effect acts in some volume V, then there is a predominant (over the volume V) sign of the current helicity,

$$H_c = \mathbf{B} \cdot (\nabla \times \mathbf{B}). \tag{4.1}$$

The main purpose of our study is to check whether there is a predominant sign of the current helicity at the photosphere of various active regions.

If a spot has the well-pronounced vortex structure, it is possible to determine the sign of current helicity, because it coincides with the sign of α in the equation for the force-free field: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$ (Seehafer 1990). Comparing the configuration of force-free field lines with vortex-like Hα-filament configuration, one can choose an α (at least the sign of α) that corresponds to the best fit. So the sign of current helicity in a vortical magnetic structure may be determined. Seehafer (1990) studied 16 active regions and made a conclusion that the α is predominantly negative (positive) in the northern (southern) hemisphere. Negative (positive) current helicity corresponds to a counter-clockwise (clockwise) vortex. Similarly, determining α by minimizing the differences between the computed constant-α force-free and observed transverse magnetic fields, Pevtsov et al. (1995) studied the average helicity of 69 active regions and obtained that 76% of active regions in the northern hemisphere have negative helicity, and 69% in the southern hemisphere, positive helicity.

[1] *in Solar Phys. 168, 75 (1996)*

These result are in a good accordance with the Hale's sign rule (Hale 1927): 'about 80% of the high level hydrogen whirls, in all sunspot cycles, are counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere'. This inference, confirmed later by many authors (Richardson 1941; McIntosh 1979; Ding, Hong & Wang 1987) allows to suggest that the regular vortex structure of sunspots more frequently is caused by forces of rotation of the Sun (Coriolis force and/or differential rotation).

However, a considerable number of active regions have a very complex magnetic and Hα structures, so that it becomes impossible to reveal the predominant twisting by visual inspection. Nakagawa (1971) investigated the shape of Hα fibrils and filaments in ARs and could find no predominance of clockwise to counter-clockwise curvature of fibrils or filaments. Such an ambiguity may be caused by a projection effect or by real fragments of vortices with opposite direction in a spot. So it is desirable to estimate the sign of predominant current helicity over an AR without necessity for comparing modelled and observed vortex structures.

It is worthwhile to obtain a quantitative estimation of the imbalance of current helicity over an AR's area using the vector magnetic field measurements in the photosphere. The value of such an imbalance could tell us if there is in the AR the possibility of large scale currents build up due to the α-effect. And the sign of the current helicity imbalance will show the direction of the predominant twisting.

Reliable magnetic field measurements are restricted to the photosphere level, hence we can calculate only a part of current helicity: $B_z \cdot (\nabla \times \mathbf{B})_z$ in the photosphere, but just this part is the most important in the processes of energy transport from the photosphere to the corona.

4.2. Observational Data

We analyzed the data of magnetic field vector obtained with SMFT (Ai, 1987), with a field of view about $5.23' \times 3.63'$ (512×512 pixels of CCD). The data were averaged over 3×4 pixels. We have used the photospheric vector magnetograms recorded in FeI5324.19Å spectral line (Ai, Li and Zhang 1982). It is a broad line with a width of about 0.33Å and Landé factor 1.5. For such a strong and broad line the Zeeman saturation and Doppler shift are not important. The magnetic field vector in the photosphere was obtained on the basis of measurements of four Stokes parameters I, V, Q, U. Parameter V was measured in the wing of the line FeI5324.19Å at the distance -0.075Å from the line center, and Q and U parameters were measured at the line center. Passband of the birefringent filter is 0.15Å. After 256-frame integration, the noise level of the measurements of the line-of-sight magnetograms is less then 20G; for the transverse magnetograms with the same integration time it is about 100 G (Wang et al. 1996). The 180 degree ambiguity of the transverse field was resolved according the potential field approximation method (Wang, Xu, & Zhang 1994) with taking into account the evolution of an AR and the orientation of chromospheric fibrils.

We chose 40 active regions located near the central meridian, and recorded with good seeing conditions. For high-latitude active regions the projection effect was removed according to the formulae of Gary and Hagyard (1990). Different kinds of magnetic configurations are presented among these 40 ARs: unipolar spots, δ-configurations, bipolar groups at different stages of evolution. They are presented in Table 4-1.

4.3. Method

According to the definition (4.1) of current helicity, to calculate its value in some point one must have $\nabla \times \mathbf{B}$. If $\mathbf{B}$ is available only in the photosphere, and

$$j_z = \frac{c}{4\pi}(\nabla \times \mathbf{B})_z \ ,$$

we can calculate a part of the current helicity h_c, in the photosphere:

$$h_c = B_z \frac{4\pi}{c} j_z. \tag{4.2}$$

The vertical electric current density was calculated on the basis the following expression:

$$j_z = \frac{c}{4\pi s} \oint_L \mathbf{B}_\perp \cdot d\mathbf{r} \ ,$$

where $\mathbf{B}_\perp$ is the vector of transverse magnetic field, and s is the surface enclosed by contour L. In our calculations the contour L enclosed an area 5×5 pixels around the central point where the current density j_z was determined. Integration along each side of the L was performed by Simpson's formula. Electric currents, obtained by this way and by differential formula with subsequent smoothing (Wang, Xu, & Zhang 1994), are in a good agreement.

To test our currents calculation scheme we determined the electric currents in NOAA AR 6233 and compared them with current structures obtained for the same AR by Wang et al. (1996) using the FFT method with subsequent smoothing. In both approach the main current structures are quite similar but in our routine peaks are more sharp and structures are more jagged. The noise level in our calculations was about $0.004\mathrm{Am}^{-2}$, whereas the maximal values of the current density was about 0.04–0.06 Am^{-2}.

Our main aim was to reveal whether there exist a predominant sign of current helicity h_c calculated by (4.2) over an active region. The most appropriate parameter for this should be the imbalance of the current helicity over an active region determined as:

$$\rho_h = \frac{\sum_{S_+} |h_c(i,j)| - \sum_{S_-} |h_c(i,j)|}{\sum_{S_+} |h_c(i,j)| + \sum_{S_-} |h_c(i,j)|} \times 100\%, \tag{4.3}$$

where $h_c(i,j)$ is the value of current helicity in a given pixel (i,j), S_+ is a set of pixels with $h_c(i,j) > 0$ and S_- is the set of pixels with $h_c(i,j) < 0$. The values ρ_h are shown in column 4 of Table 4-1. Also in columns 5 and 6 of Table 4-1 the imbalance, ρ_c, of vertical electric currents and the imbalance, ρ_B, of vertical magnetic field component are shown. ρ_c and ρ_B were calculated by the formulae similar to (4.3).

4.4 Results

As it follow from the Table 4-1 in 90% of cases the imbalance ρ_h of current helicity h_c over an active region was quite significant: only in 4 cases from 40 ones the values ρ_h was close to zero. This means that in most of cases there was the condition for the growth of magnetic field energy due to the α-effect on the scale of a whole active region.

Further, in 82.5% of cases the predominant current helicity was negative ($\rho_h < 0$) in the northern hemisphere and positive ($\rho_h > 0$) in the southern hemisphere. This inference is in accordance with the Hale's sign rule and allows to suspect that such a regular sense of twisting of magnetic structures is caused by the forces of the rotation of the Sun (Coriolis force and/or differential rotation).

The distribution of active regions at the diagram: the imbalance of current helicity in an AR versus the latitude of an AR, is shown in Figure 4.1. The points are located predominantly in the 2nd and 4th quadrants. Unipolar spots (denoted by open circles) tend to have the more strong imbalance of current helicity than another magnetic structures at the same latitude; the three of the four δ-configurations (denoted by star) have extremal location on the diagram showing high value of ρ_h at high latitudes. Three δ -configurations obey to the Hale's sign rule, but one (AR5747) do not. In the northern hemisphere two ARs do not obey to the Hale's sign rule.

The possible reasons how such situations should be realized in an active region, seem to be clear up by inspection of maps of the vector magnetic field along with the maps of current helicity values $h_c(i,j)$ (see Figures 4.2-4.8).

Often in large bipolar sunspot groups the Hale's vortices may be observed in both leading and following parts, as in the AR6757 (Figure 4.2). In agreement with Hale's rule the vortices are counter-clockwise. In this AR we found the negative predominant current helicity in both leading and following parts. The total over the entire AR imbalance of the current helicity was about -23%. But sometimes the structure of magnetic field is quite complex and small-scale one, and to reveal the predominant twisting by transverse field orientation or by Hα-fibrils is rather difficult. Whereas the map of $h_c(i,j)$ shows the predominance of current helicity of some sign. For example, in AR6805 (Figure 4.3) only the main spot in the following part of the AR shows the well-pronounced counter-clockwise vortex. The leading spots without obvious vortices are rather weak. At the same time the map of the current helicity h_c shows that in the leading pattern of the AR negative current helicity also dominated.

A more interesting situation was met in the AR7496 (Figure 4.4). It was impossible to reveal any predominant vortex in any spot by visual inspection of transverse field. The map of current helicity showed the predominance of negative current helicity in the leading spot (in accordance with the Hale's sign rule) and large excess of positive helicity in the following spot (this spot grew rapidly on that day). So the imbalance ρ_h of current helicity over the entire active region turned out to be positive – against to the Hale's rule. The similar situation, when leading spot of an active region has an excess of current helicity in accordance with the Hale's rule and the following spot has an opposite excess of current helicity, was met also in the AR6860 and in the AR6001. In such ARs the leading magnetic structure seems to be twisted by the forces of solar rotation, whereas in the following part most probably local subphotospheric motions suppress the forces of solar rotation creating their own predominant twisting. But in any case both in the leading and in the following magnetic systems significant imbalance of current helicity took place, thus there was the condition for the growth of magnetic field energy due to the α-effect.

The situation when the regular forces of the solar rotation compete with local processes in twisting of magnetic structure becomes more pronounced in δ –configurations and unipolar spots. If the regular forces of solar rotation and local processes act at the same direction in a δ-configuration, then magnetic structures with strong imbalance of current helicity can occur (in our study: ARs 7321, 6891, 6659; see Table 4-1 and Figure 4.1). The well-pronounced counter-clockwise vortex of transverse magnetic field in this AR one can see in Figure 4.2 in Zhang and Wang (1994). But occasionally a regular vortex seems to be significantly distorted by local processes, and large patterns of opposite rotation appear, as in the AR5747 (Figure 4.5) and in the AR5612 (Figure 4.6). The imbalance of current helicity may be close to zero (AR5612) or even of opposite sign (AR5747).

All unipolar symmetric spots in our analysis obeyed to the Hale's sign rule, thus one

can suggest that local motions either are negligible or act at the same direction as the regular forces of the solar rotation in twisting of such a magnetic structure. This kind of magnetic configurations showed in our analysis the highest value of current helicity imbalance – up to 74.6% in AR7294 (Figure 4.7).

We have met with one active region (AR6064, Figure 4.8) which was large enough, bipolar one, and its main spots showed no vortices so as its transverse field structure was potential-like. Calculation of (total over the AR) imbalance of current helicity gave the value about zero. Apparently, in such a bipolar quasi-potential active region there were no conditions for growth of magnetic field energy due to the α-effect on the scale of the whole active region.

4.5 Conclusions

The way how magnetic energy of the electric current form builds up in the corona above an active region is not completely clear. Seehafer (1994), under assumption that the magnetic field evolves through the sequence of force-free states, theoretically obtained some condition under which the energy of small-scale fluctuations of magnetic and velocity fields can be transferred into the energy of large-scale currents in an AR. This condition is the presence of predominant sign of current helicity over some volume, in particular, over the whole active region. Here we attempted to reveal how frequently such a condition may take place in active regions on the scale of the whole ARs.

Using the data of measurements of magnetic field vector in the photosphere we calculated the current helicity (more precisely, the part of helicity: $B_z(\nabla \times \mathbf{B})_z$) over the whole AR area for 40 active regions of 22 solar activity cycle. Among them there were sunspot groups of various kinds: unipolar spots, δ- configurations, bipolar active regions at different stages of evolution.

Analyzing the distribution of current helicity over the area of every active regions we have come to the following:

1) Very frequently, in 90% of cases, there existed significant excess of current helicity of some sign over the active region area. This means that in 90% of cases the condition for the growth of magnetic field energy due to α-effect on the scale of the whole active region was performed. This result permits to suggest that the build up of large-scale currents in an active region due to small-scale fluctuations may be rather typical phenomenon in ARs, if the magnetic field evolves through the sequence of force-free states.

2) The negative (positive) excess of current helicity over some area means that magnetic structure in the area has a predominant counter-clockwise (clockwise) twisting. So, the Hale's sign rule (the predominance of counter-clockwise (clockwise) vortices in the northern (southern) hemisphere) was satisfied in 82.5% of cases in our analysis. Such a result allows to suggest that Hale's sign rule is valid not only for unipolar spots with obvious vortex structure (Hale 1927; Richardson 1941; McIntosh 1979; Ding, Hong, & Wang 1987; Seehafer 1990), but also for ARs of different types. The force of rotation of the Sun (Coriolis force and/or differential rotation seem to take effect in the twisting of various magnetic structures.

3) Regular forces of solar rotation seems to be superposed by local processes in formation of a resulting vortex around a spot.

4) The imbalance of current helicity do not depend from both the imbalance of magnetic flux and the imbalance of vertical currents. The imbalance ρ_B of magnetic flux varies in large limits (from -41% to 58%, see Table 4-1), whereas the imbalance ρ_c of vertical

currents is rather small value: less then 3.5%.

It is worth while to note that results obtained here by the proposed method are in a good agreement with qualitative inferences based on the traditional method of visual inspection of the field lines curvature.

Our method allows to study both the imbalance and the distribution of current helicity over the AR's area. The method can be applied to those ARs where the determination of predominant sign of current helicity by traditional visual inspection of Hα-patterns are not reliable.