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Latitudinal distribution of photospheric current helicity and solar activities

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Abstract. In this paper, we analyze the latitudinal distribution of the photospheric current helicity for 422 active regions, including most of the large ones observed in the last ten years. Observations show that most active regions in the northern hemisphere have negative helicities and in the southern hemisphere have positive ones. The negative maximum values of current helicity occurred in 1989 and 1991, while those positive around 1992. It is evident that the observational current helicity of active regions is normally brought up by emerging magnetic flux from the subatmosphere and probably acted by the moving mass. The result observed shows that less than 20 % of active regions have the sign opposite to that of most ones in the same hemisphere. These reversed sign regions of the current helicity are obviously related to abnormal distribution of the vector magnetic field in the active regions, due to emergence of new magnetic flux of opposite polarities.

Key words: Sun: activity – Sun: magnetic fields – Sun: photosphere

1. Introduction

A graph of the range in latitude of sunspots as a function of cycle phase (Butterfly diagram) was discovered many years ago (cf. Wilson 1994). It supplies information on the distribution of strong magnetic field regions on the solar surface within solar cycles. The evolution of the large-scale longitudinal magnetic field in the solar surface was provided by synthetic analysis with a series of full-disk photospheric magnetograms, which contains the information on the origin of large-scale magnetic fields on the solar surface and the reversal of polar magnetic field with solar magnetic cycles. Observations show that strong twisted magnetic fields on the solar surface normally occur in active regions, which relates to properties of the helicity of the magnetic field. Several previous investigations indicate trans-equatorial change in sign of the helicity of active regions in the photosphere (Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1996). If the magnetic field consists of an ensemble of flux tubes, the helicity of the magnetic field depends on the configuration of the flux tubes. By analyzing the twisted magnetic field in the electric current picture, it is found that the formation of the electric current in the active regions obviously relates to the emergence and the evolution of new magnetic flux (Wang et al. 1994; Zhang 1995b, 1997).

The dynamo for the global magnetic field is normally assumed to operate at the base of the convection zone. A possible mechanism is the turbulent alpha effect (Parker 1955), which generates from small-scale velocity fluctuations in electromotive force parallel or anti-parallel to the mean magnetic field. The helicity of the convection motions relates to the generation of poloidal fields from toroidal fields. As the magnetic flux on the solar surface emerges from the deeper layers of the Sun, some information of the alpha effect can be inferred by the photospheric vector magnetic field. The problem is how to link the distribution of the helicity of the magnetic field on the solar surface with solar cycles and the relationship with individual current helicity regions.

In this paper, we pay attention to studying the latitudinal distribution of current helicity of active regions and their relationship with solar activity, especially for some typical active regions.

2. Definition of current helicity

Helicities are topologically a measure of the structural complexity of the corresponding fields (Moffatt 1978; Berger & Field 1984; Seehafer 1990). The helicity of magnetic fields may be characterized by several different parameters. The magnetic helicity density h_m=$\mathbf{A}\cdot\mathbf{B}$, with $\mathbf{A}$ the vector potential for magnetic field $\mathbf{B}$, measures the linkage of magnetic lines of force. The total magnetic helicity is

$$H_m = \int \mathbf{A}\cdot\mathbf{B}d^3x, \tag{1}$$

which may not be conserved when finite resistivity is present (Berger & Field 1984). However, the magnetic helicity is unmeasurable in the solar atmosphere until now. Assuming a linear Ohm's law,

$$\mathbf{E} - \frac{\mathbf{1}}{\mathbf{c}}\mathbf{B}\times\mathbf{v} = \eta\mathbf{J}, \tag{2}$$

the helicity-dissipation rate is

$$\frac{dH_m}{dt} = -2c\int_V \eta\mathbf{J}\cdot\mathbf{B}d^3x. \tag{3}$$

The current helicity density is

$$h_c = \frac{4\pi}{c}\mathbf{B}\cdot\mathbf{J} = \mathbf{B}\cdot\nabla\times\mathbf{B} = \mathbf{B}_\perp\cdot(\nabla\times\mathbf{B})_\perp + \mathbf{B}_\parallel\cdot(\nabla\times\mathbf{B})_\parallel, \quad (4)$$

which describes the linkage of electric current. The simple relationship between h_m and h_c can be inferred in the approximation of the force-free field (Pevtsov et al. 1995), and thus the current helicity density may be written in the form

$$h_c = (B/B_\parallel)^2\mathbf{B}_\parallel\cdot(\nabla\times\mathbf{B})_\parallel. \quad (5)$$

The current helicity, however, is measurable in the solar photosphere. The mean density of current helicity in the local area of the solar surface is

$$\overline{h_c} = \frac{1}{S}\int\int\mathbf{B}\cdot\nabla\times\mathbf{B}ds, \quad (6)$$

e.g. this is an average value of the current helicity density h_c in the observing region S. Because the transverse component of the electric current cannot be inferred by the observational photospheric vector magnetograms, we will only refer to the second term $\mathbf{B}_\parallel\cdot(\nabla\times\mathbf{B})_\parallel$ of the current helicity in Eq. (4) in the following.

In the last ten years, many of vector magnetograms for active regions were observed at Huairou Solar Observing Station of Beijing Astronomical Observatory, which allows us to compute the distribution and the evolution of the current helicity. The data reduction of vector magnetograms, calculating the longitudinal electric current and the corresponding current helicity, was described by Wang et al. (1994) and Bao & Zhang (1998). For analyzing the distribution of the electric current helicity in the solar latitude, we consider 422 active regions in the last ten years. Most of the active regions belong to solar cycle 22 and a few of them belong to solar cycle 23.

3. Latitudinal variation of current helicity

The latitudinal distribution of current helicity in active regions is shown in Fig. 1. We can see that most current helicities in sunspot groups in the northern hemisphere show negative sign, while positive in the southern hemisphere, which is consistent with Seehafer's result (Seehafer 1990). The distribution of current helicity in active regions also shows the Butterfly pattern if comparing the distribution of current helicity through the solar cycle. This means that the positions of high electric current helicities are firstly in the middle latitudes at the beginning of a new solar cycle, then shift to high latitudes towards the equator with time, giving rise to the characteristic Butterfly pattern. We see that less than 20% of the active regions do not follow the general trend, but have a positive sign of the current helicity in the northern hemisphere and negative in the southern hemisphere.

The regions of high negative current helicity occurred in 1989 and 1991 which includes active regions NOAA 5395, 6659 (two super-active regions) and 6619 in the northern hemisphere, and NOAA 6615 in the southern hemisphere. The high helicity regions of positive sign occurred between the end of 1991 and the beginning of 1993. They included active regions NOAA 6891, 7321 and 7440 in the southern hemisphere. That the maximum values of current helicity in the northern hemisphere occurred in 1989 and 1991 and that in the southern hemisphere around 1992 are consistent with the configuration of two peaks of the solar activity in the solar cycle 22, which is well-known.

The imbalance of electric current helicity in an active region is defined by

$$\rho_h = \frac{\int\int h_c ds}{\int\int |h_c| ds}. \quad (7)$$

The sign of the electric current helicity may not be the same at each position in an active region. In other words, a given active region probably contains mixed signs of current helicity. The imbalance ρ_h of current helicity in an active region does not immediately relate to the amplitude of current helicity, because the total helicity of a solar active region sums the local helicities (sometimes with mixed signs) over the whole region in Eq. (7). The latitudinal distribution of imbalance ρ_h of current helicity in active regions is shown in Fig. 2.

By comparing between Figs. 1 and 2, we can find that some sunspot groups, which show low current helicity, have relatively strong imbalance of current helicity between the positive and negative signs in an active region, i.e. these regions have a predominate twisting direction of the magnetic field.

In addition, the average values of the intensity and imbalance of current helicity in active regions calculated by us are shown in Fig. 1 after data smoothing. Their distributions are a little different from one other, but show the same tendency. This means that the statistical average of the current helicity regions normally corresponds to that of the imbalance of the helicity. The average values of current helicity in 1989 occurred in the northern hemisphere, while that in 1992 in the southern hemisphere. Because most large active regions in the last ten years are included, these probably reflect the real tendency of current helicity in active regions in both hemispheres.

4. Current helicity and magnetic shear in active regions

According to the second term of Eq. (4) and Eq. (5), we can see that the density of current helicity depends on the twist of the transverse magnetic field and the intensity of the longitudinal magnetic field. The observational results of the photospheric magnetic field demonstrate that the formation of the twisting magnetic field (electric current) obviously relates to the arrangement of the magnetic field in the active regions (Zhang 1995b, 1997).

To analyze the global properties of current helicity of active regions, we define the normal current helicity which follows the global sign rule of the current helicity (i.e. in the northern (southern) hemisphere the sign of helicity is negative (positive)) and the reversal current helicity which shows the sign oppositely to the global rule. We present some examples of current helicity in the following.

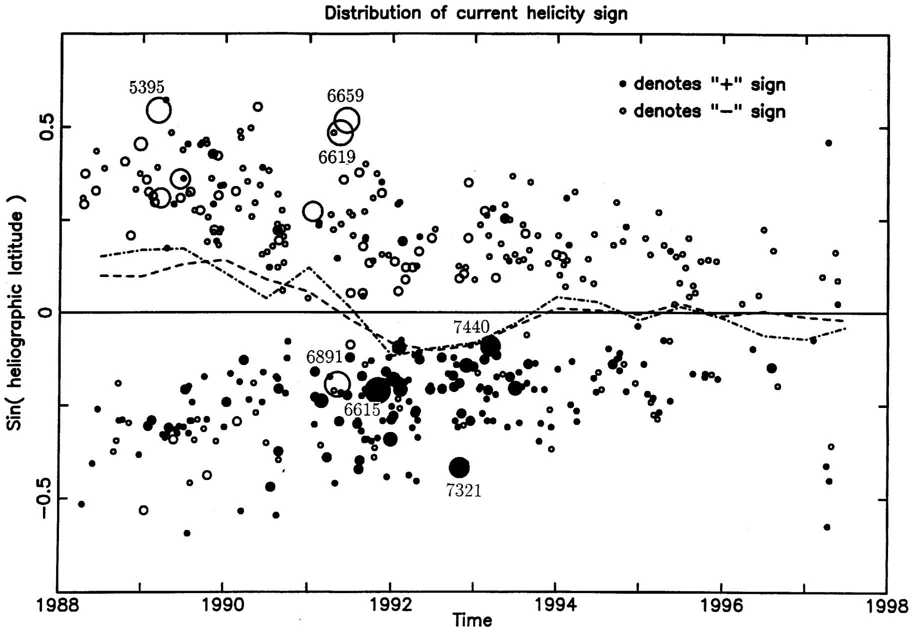


Fig. 1. Butterfly diagram of the electric current helicity. The mean density of the current helicity of active regions is marked by size of the circles for grades: 0, 1, 3, 5, 7 ($\times 10^{-3} G^2 m^{-1}$). The dashed-dotted line marks the average value of current helicity and the dashed line marks the average value of the imbalance of current helicity after the data smooth.

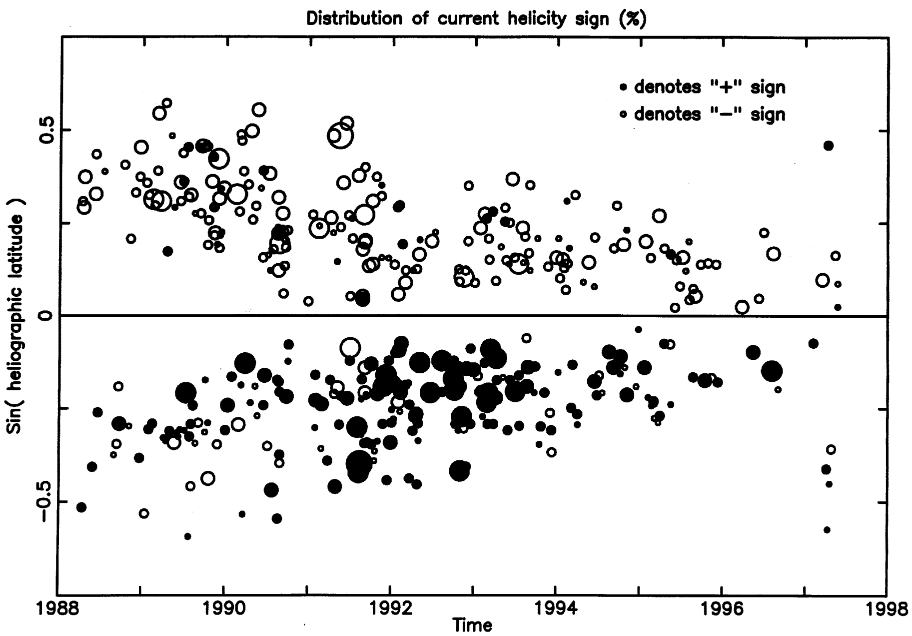
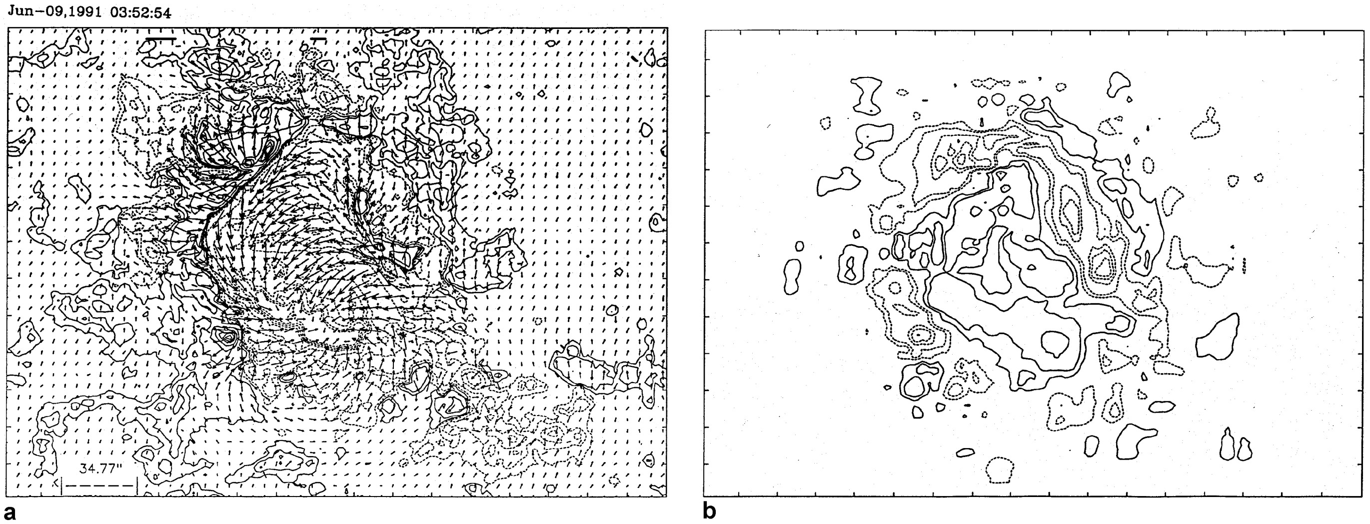


Fig. 2. Imbalance ρ_h of the current helicity. The imbalance of the current helicity is marked by sizes of the circles for grades: 0, 10, 30, 50, 70 (%).

4.1. Normal current helicity

Fig. 3a shows a vector magnetogram in the active region (NOAA 6659) on 9 June 1991. This active region was a super-active region and occurred in high latitude (N32) in the solar cycle 22. The relationship between the flares and the configuration of the magnetic field was analyzed by Zirin & Wang (1992) and Zhang (1995a, 1996) etc. The transverse magnetic field rotates counter-clockwisely towards the center of the active region and a series of highly sheared magnetic flux successively emerges near the magnetic neutral line. As comparing with the vertical electric current map (Fig. 3b), we may guess that the electric current flows up from the center of the active region towards the surrounding areas. The large-scale current helicity shows negative sign, even though a positive area is located at the north of the active region. This is a good evidence of the current helicity due to the twist of the transverse magnetic field in the northern hemisphere, which coincides with the normal sign rule of the distribution of current helicity (Seehafer 1990). By analyzing the evolution, we find that it was a mature active region and gradually drawn away by the different rotations (Schmieder et al. 1994), even though a series of highly-sheared magnetic flux emerged near the magnetic neutral line to trigger flares.

Fig. 4 shows a vector magnetogram in active region (NOAA 6772) on 12 August 1991. This active region was located at the southern hemisphere (S24) and consisted of an unipolar spot. The transverse magnetic field shows counter-clockwise vortex. The vertical electric current flows up from the center of the



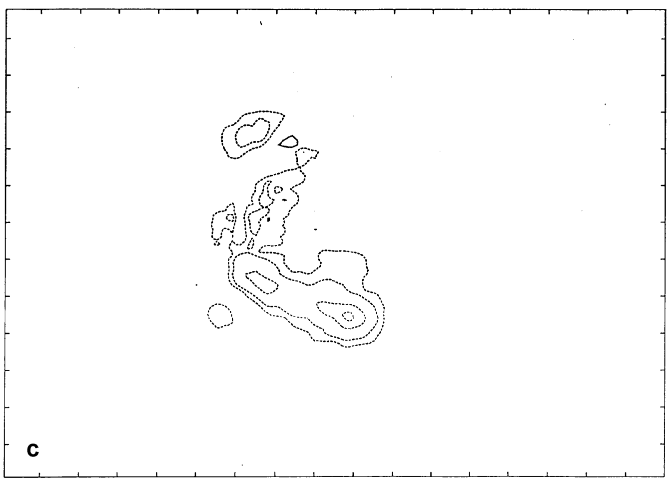


Fig. 3. **a** A vector magnetogram of active region (NOAA 6659) on 9 June 1991. The solid (dashed) contours indicate the positive (negative) longitudinal magnetic field distribution of ±20, 160, 640, 1280, 1920, 2240, 2560 and 2880 Gauss. **b** The corresponding vertical electric current distribution of ±0.2, 0.4, 0.8, 1.0, 1.2, 1.4, 1.6 and 2.0$(\times 10^{-2}) Am^{-2}$ and **c** the electric current helicity distribution of ±0.5, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 $(\times 10^{-1}) G^2 m^{-1}$. The north is top and the east is at left.

sunspot and returns to the surrounding areas. A similar case can be found in the active region (NOAA 6767) in Fig. 5, which was also located in the southern hemisphere (S26.5) on 9 August 1991. They are decaying active regions and show obvious single sign of current helicity, which coincide with the general rule of global helicity. These are not significant trails of newly-emerging magnetic flux in these active regions. The rotation of the photospheric transverse magnetic field probably reflects the original properties of the sunspot magnetic field, which pattern may be partly distorted in some complex active regions.

4.2. Reversal current helicity

Fig. 6 shows the active region (NOAA 7070) on 25 Feb. 1992. This active region was located in the northern hemisphere (N5.6). From daily vector magnetograms, we find that the magnetic field in this active region consists of two main parts. One is magnetic poles (N_1 and S_1), another is (N_2 and S_2). The magnetic shear occurs near the magnetic neutral line between the magnetic poles (N_1 and S_1) of opposite polarity. Newly emerging magnetic flux occurs near the magnetic neutral line between magnetic poles (N_2 and S_2) of opposite polarity and pushs them apart. Thus, this active region relates to two electric current systems and contains opposite signs of the helicity, which does not completely coincide with the normal rule of the current helicity due to the emergence of magnetic flux. The development of the magnetic field in this active region is provided in a subsequent paper.

Fig. 7 shows a vector magnetogram in the active region (NOAA 6615) on 7 May 1991 and the corresponding electric current and helicity maps. This active region located in the southern hemisphere (S11.2) shows opposite sign of current helicity to the sign rule of most of the active regions in the southern hemisphere. We analyze the distribution of the vector magnetic field in the active region and its evolution, and we can find that it was a newly-growing active region. From a series of daily magnetograms, we find that two magnetic bipoles (N_3, S_3) and (N_4, S_4) emerge in the active region, and their transverse component of the magnetic field rotates clockwisely. The distribution of the vertical component of the electric current provides the information that the electric current flows towards the center of the active region from the surrounding areas.

From the results in active regions (NOAA 6615 and 7070), we find that the emergence of the magnetic flux of opposite

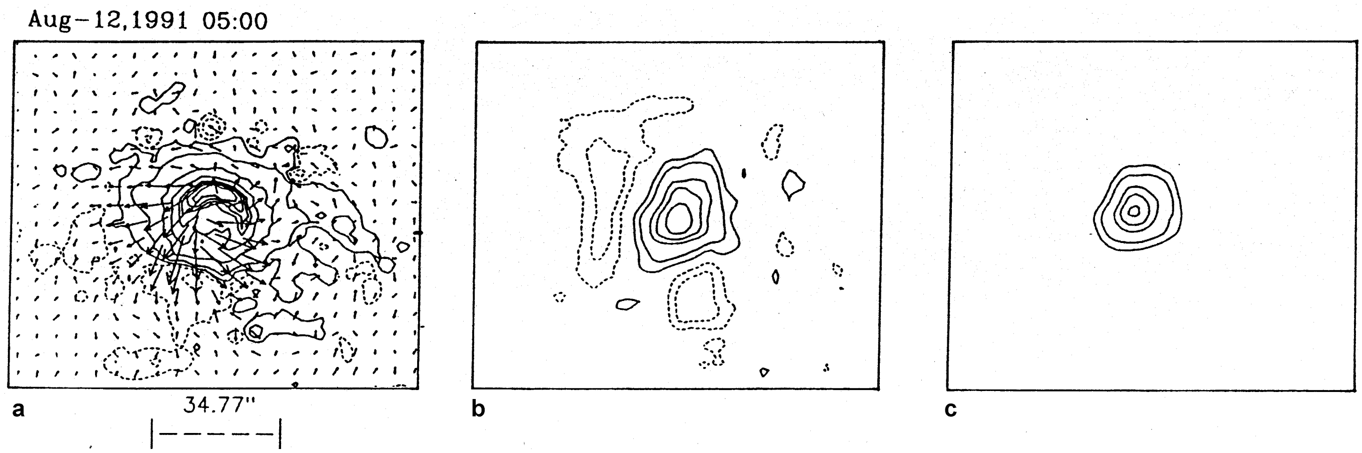


Fig. 4. a A vector magnetogram of active region (NOAA 6772) on 12 August 1991. The solid (*dashed*) contours indicate the positive (*negative*) longitudinal magnetic field distribution of ±20, 160, 640, 1280, 1920, 2240, 2560 and 2880 Gauss. **b** The corresponding vertical electric current distribution of ±0.2, 0.4, 0.8, 1.0, 1.2, 1.4, 1.6 and 2.0$(\times 10^{-2}) Am^{-2}$ and **c** the electric current helicity distribution of ±0.5, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 $(\times 10^{-1}) G^2 m^{-1}$. The north is top and the east is at left.

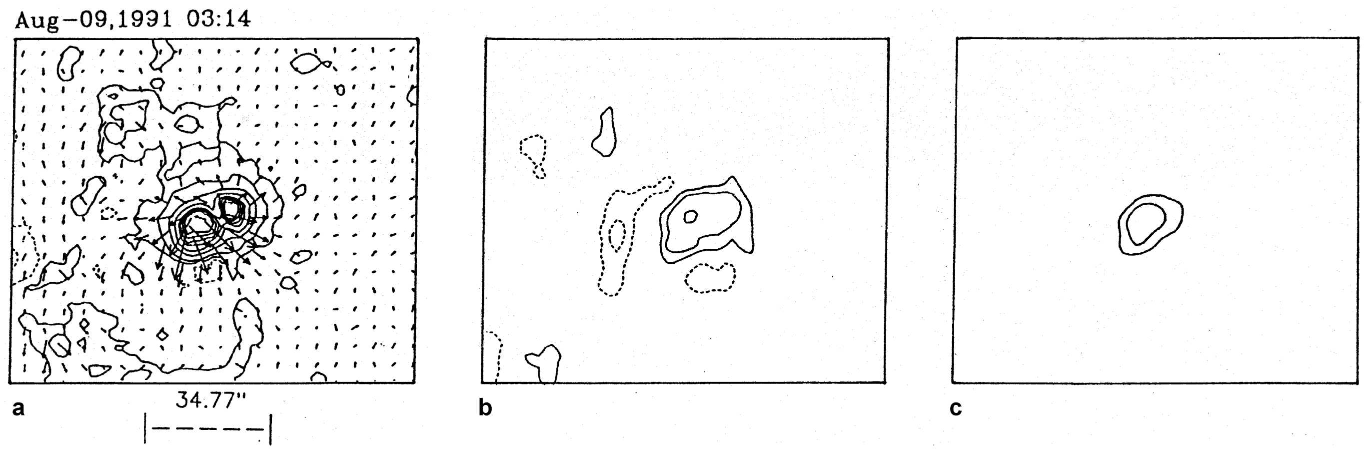


Fig. 5. a A vector magnetogram of active region (NOAA 6767) on 9 August 1991. The solid (*dashed*) contours indicate the positive (*negative*) longitudinal magnetic field distribution of ±20, 160, 640, 1280, 1920, 2240, 2560 and 2880 Gauss. **b** The corresponding vertical electric current distribution of ±0.2, 0.4, 0.8, 1.0, 1.2, 1.4, 1.6 and 2.0$(\times 10^{-2}) Am^{-2}$ and **c** the electric current helicity distribution of ±0.5, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 $(\times 10^{-1}) G^2 m^{-1}$. The north is top and the east is at left.

polarity influences the distribution of the electric current in the photosphere (Zhang 1995b, 1996). The current helicity in these emerging flux regions trend towards the opposite sign relative to the general ones.

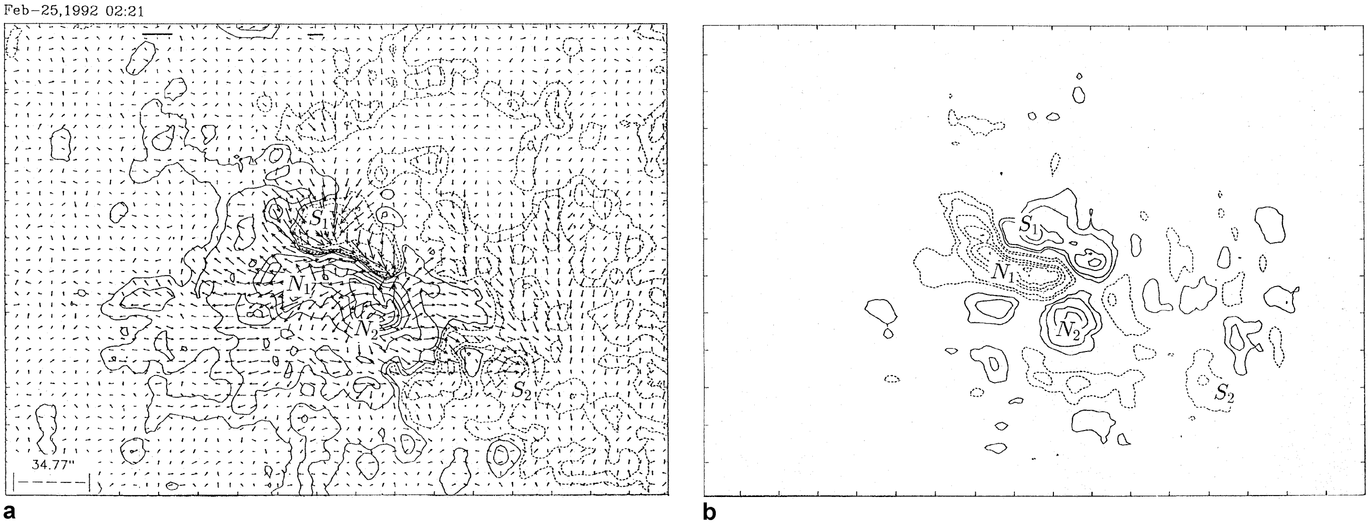
5. Discussion and results

The study on distribution of the current helicity and its relationship with the solar cycle is an important topic, because it provides information on the transportation of the twisted magnetic field (electric current) from the subatmosphere, which is different from that of the sunspot groups and the large-scale pattern of the longitudinal magnetic field.

The observational helicity of active regions provides a chance to analyze the twist of the strong magnetic field in the solar surface. We find that the areas of strong current helicity of opposite sign first occur in the middle latitudes of the both hemispheres at the beginning of a new solar cycle and gradually migrate from high latitude to low latitude. The signs of most current helicity in active regions coincide with the normal rule (i.e. in the northern (southern) hemisphere the sign of helicity is negative (positive)). If the atmospheric currents are generated in the (subphotospheric) region of dynamo operation before the flux ropes from which active regions result have broken away from the toroidal field belt, these currents should be generated by the alpha effect (Seehafer 1990).

The statistical results demonstrate that the distribution of current helicity in both hemispheres also connects with the solar activity, e.g. most of the powerful flare producing regions show strong current helicity, such as the active regions 5395 and 6659. This means that the helicity is an important index of the reserved magnetic energy in active regions.

We also find that the imbalance of the current helicity in the unipolar active regions (decaying active regions) is obvious,



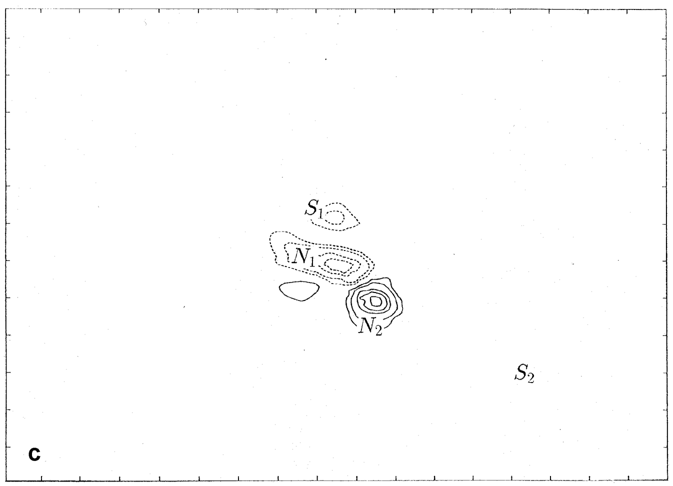


Fig. 6. **a** A vector magnetogram of active region (NOAA 7070) on 25 February 1992. The solid (*dashed*) contours indicate the positive (*negative*) longitudinal magnetic field distribution of $\pm$20, 160, 640, 1280, 1920, 2240, 2560 and 2880 Gauss. **b** The corresponding vertical electric current distribution of $\pm$0.2, 0.4, 0.8, 1.0,1.2, 1.4, 1.6 and 2.0$(\times 10^{-2}) Am^{-2}$ and **c** the electric current helicity distribution of $\pm$0.5, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 $(\times 10^{-1}) G^2 m^{-1}$. The north is top and the east is at left.

while the values of current helicity normally are not large. Evershed flow in the sunspots is probably an important reason of the twisted transverse magnetic field proposed by Seehafer (1990), due to the action of Coriolis force on the magnetic field lines. The decaying process of the magnetic main pole, which is due to the outward movement of the broken magnetic fragments, and the relationship with Evershed flow in a similar active region were demonstrated by Wang et al. (1989) and Zhang et al. (1992).

It is noticed that the signs of current helicity in some active regions reverse to the normal rule. The observational results demonstrate that the intrinsic twisting character of newly-emerging magnetic flux tubes is probably insignificant in some active regions (Zhang & Song 1992; Zhang 1995b), or hard to detect in the unresolved size. The magnetic shear in active regions is obviously caused by the emergence of magnetic flux of opposite polarities, such as in the active active regions NOAA 6615 and 7070. This means that the emerging magnetic flux of opposite polarity not only carries up the new current helicity from the subatmosphere, but also interacts with the pre-existing magnetic field and breaks up the distribution of former current helicity in active regions in the photosphere, although the current helicities brought by newly-emerging magnetic flux for most of the active regions coincide with the sign rule in both hemispheres.

From the above discussion, we find that the configuration of the current helicity of active regions and its change in the photosphere comes from two possibilities. One is caused by the emergence of new magnetic flux, which brings the new helicity into the photosphere from the subatmosphere. Another comes from the mass motion, such as the Evershed flow in sunspots near the photosphere, which changes the arrangement of the magnetic field in the action of the Coriolis force. These progressively change the distribution of the global helicity. Moreover, the twisted magnetic fields are probably ejected as CMEs and magnetic clouds, which transport the current helicity from the solar atmosphere into interplanetary space. On the other hand, even though the current helicity in active regions is interperted by us, many questions on the understanding of global properties of the helicity remain to be answered, such as we do not clarify the relationship between the helicity in active regions and that of the large-scale global field on the solar surface.

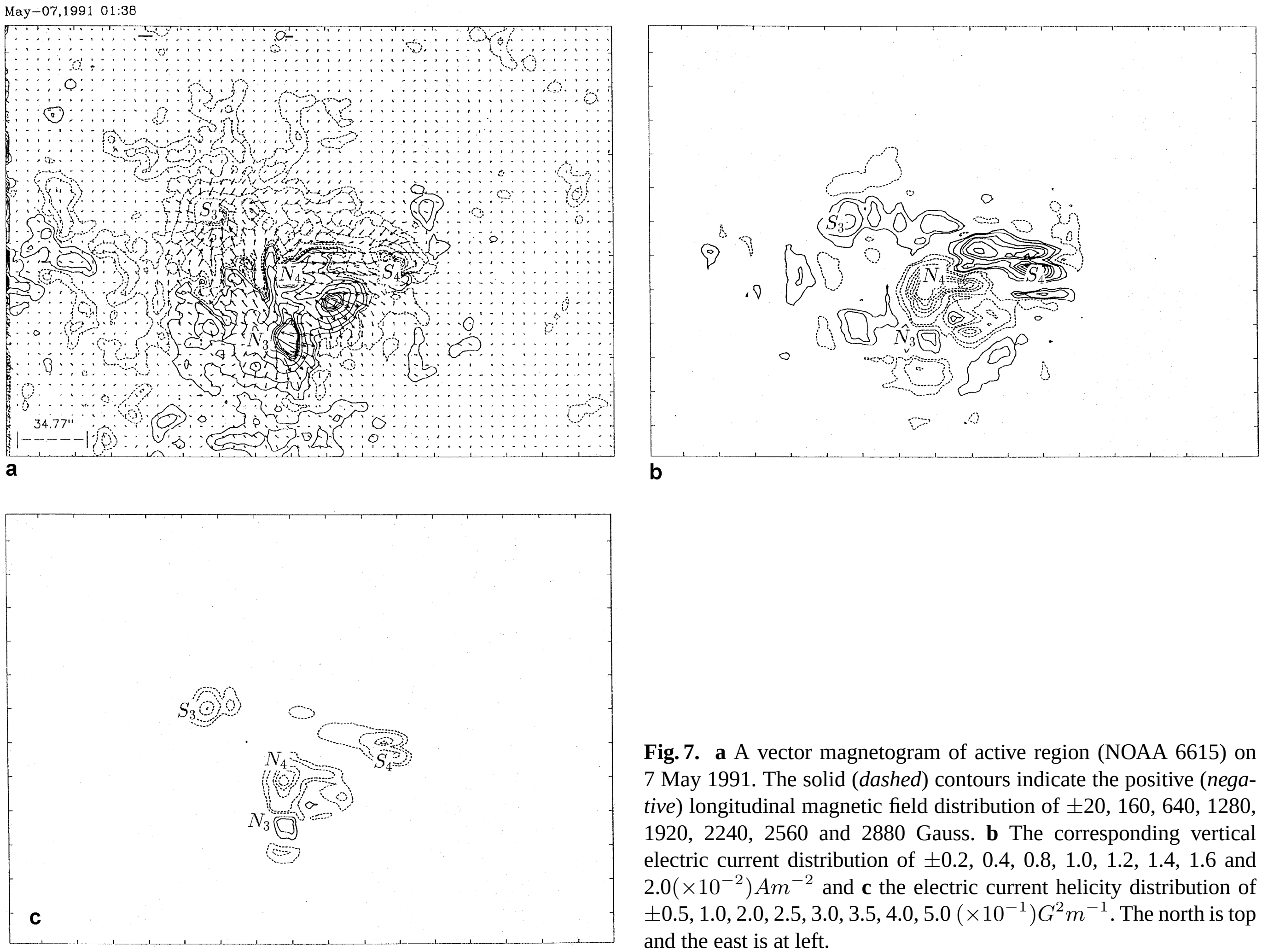


Fig. 7. **a** A vector magnetogram of active region (NOAA 6615) on 7 May 1991. The solid (*dashed*) contours indicate the positive (*negative*) longitudinal magnetic field distribution of ±20, 160, 640, 1280, 1920, 2240, 2560 and 2880 Gauss. **b** The corresponding vertical electric current distribution of ±0.2, 0.4, 0.8, 1.0, 1.2, 1.4, 1.6 and $2.0(\times 10^{-2}) Am^{-2}$ and **c** the electric current helicity distribution of ±0.5, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 $(\times 10^{-1}) G^2 m^{-1}$. The north is top and the east is at left.

After the analysis, the main results are as follows:

1. The average current helicity of active regions normally shows opposite signs in the two hemispheres. The maximum negative values occurred in the northern hemisphere in 1989 and 1991, while the positive ones in the southern hemisphere in about 1992 in the solar cycle 22.
2. The reverse signs of the current helicity of active regions to the normal rule in the same hemispheres are related to abnormal distribution of the vector magnetic field of active regions, due to the emerging magnetic flux of opposite polarities, which probably brings new helicity of opposite sign from the subatmosphere or breaks the sign distribution of current in both hemispheres.

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