A STUDY ON ELECTRIC CURRENTS IN A SOLAR ACTIVE REGION - A DYNAMO PROCESS AT A PLACE OF REPEATED FLARING

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Abstract. We present a study of electric current systems in a solar active region and their relationship to the features of magnetic field and chromospheric activities. We found current cells dominated by azimuthal currents flowing around strongly inclined flux bundles (footpoints of a loop prominence) as well as current cells dominated by field aligned currents flowing along chromospheric fibrils.

The strongest vertical current cell was observed at an area where subflares and brightenings occurred nearly continuously during the whole day. This site of preferred flaring and strong vertical current was located just at the place where two bipolar regions met each other. The morphological structure of velocity and longitudinal field (perpendicular inversion lines) indicates a cyclonic flow across the magnetic field. So we presume the presence of a subphotospheric dynamo process continuously generating the current and the associated energy which is sequently released by the small flares and brightenings observed in the different flux loops rooting in this area.

1. Introduction

In the solar atmosphere electric currents ensure the stability of solar phenomena, such as sunspots and prominences, on the other hand, current driven instabilities belong to the intensively discussed triggering mechanisms in dynamical processes such as flares and filament eruptions.

In the photosphere and lower chromosphere due to the high plasma density the plasma energy dominates over the magnetic energy and the pressure gradient between

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structures of highly concentrated flux and the surrounding undisturbed atmosphere is balanced by Lorentz forces generated by currents flowing across the magnetic field. A simple framework to detect and analyse azimuthal currents was given by Hofmann (1991) using measurements of photospheric vector magnetic fields.

In the upper chromosphere and lower corona the magnetic energy density dominates over the plasma energy and the magnetic field is force free, i.e. the electric currents flow parallel to the magnetic fields. The superpotential energy released in solar flares is stored by these currents. In various trigger mechanisms of solar flares, field aligned currents play fundamental roles, too (cf. Table 2 by Spicer and Brown, 1981). Therefore studies concerning the observational evidence of chromospheric and coronal currents and their photospheric sources are of high importance in investigating dynamic phenomena of solar activity.

Using the first available photospheric vector magnetographic measurements Moreton and Severny (1968) found a coincidence of the brightest parts of solar flares with locations of high values of vertical current density. Levine (1976) concludes on upward and downward currents flowing in active regions when comparing results of linear (constant alpha) force free field extrapolations to EUV and soft X-ray emission features. A first determination of the large-scale current systems flowing in an active region and their relationship to flare activity was performed by Ding et al. (1987) based on photospheric vector magnetograms and the derived current densities, high resolution heliograms and Hα filtergrams. They found oppositely directed current systems in the area of a magnetic delta-configuration being the site of flaring.

Hagyard (1988) separated from vector magnetographic observations the source field, i.e. that part of the field which is produced by currents above the photosphere and their mirror currents below, and compared the source field with the field produced by arcades of current-carrying loops across the neutral line. Lin and Gaizauskas (1987) compared high resolution Hα observations of a flare with the currents derived from a vectormagnetogram taken simultaneously at the MSFC. They also found a coincidence between the sites of strong Hα emission and the long-lived peaks of longitudinal current density.

Hofmann and Kalman (1991) investigated the structure of the magnetic field and currents at the site of an umbral/penumbral flare ribbon. They found a strongly twisted field and a current flowing opposite to the magnetic field in the flaring loops. They used two models to describe the current and energy build-up and compared the calculated currents with the observed ones. Recently Canfield et al. (1991) found that the sites of energetic electron precipitation are located close to the neutral line inbetween the edges of the vertical current maxima.
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In this paper an investigation of the vector magnetic field, the derived current densities and Hα observations is carried out with the goal to find the current systems flowing in this region and their relationship to chromospheric features especially at a site of repeated flaring.

2. Observational Results

2.1. The Active Region and Hα Flares

The active region NOAA 4201 was of high magnetic complexity, when it rotated over the disc. It consisted of 4 bipolar magnetic subsystems (henceforth BMS) and the inner structure of the AR-complex changed in dependence on the evolutionary state of each BMS at a certain time. The structure of the AR on June 03, 1983 is shown in Figure 1a. On this day the BMS 1 consisting of the spots P1 and F1 was the dominating group. The BMS 2 is a large scale emerging flux region evolving very rapidly with respect to the other BMSs. BMS 3 and 4 are two small groups located in the southeast and southwest of F1 or P2, respectively. During the day under study, significant developments were observed in the spot F1, leading to a further splitting of the umbra and a reduction of the spot area.

The AR was monitored at the Hvar Observatory with a Solar double telescope which consists of a chromospheric 130/1950 mm telescope equipped with a Hα filter, bandwith 0.7 Å, and a photospheric 217/2450 mm telescope. A detailed description of the instrument is given by Ambroz et al. (1977). Images of the active region were recorded on film with a time resolution ranging from 2 minutes to 30 seconds, depending on the state of activity in the region.

For our analysis there are several relevant chromospheric structures in the complex which we denote as:

LP - loop shaped prominence connecting P1 and the western part of the splitted umbra of F1
AFS- arch filament system between the leader and follower polarity of the growing EFR (BMS 2)
F - eastward directed fibrils starting in P3
FS - filament system connecting the eastern and western parts of BMS 1

According to Solar Geophysical Data, Comprehensive Reports, 24 flares occured in AR NOAA 4201 on June 3, 1983 and ten of them had a X-ray importance ranging between C1.7 and C8.2. The observations with high resolution carried out at Hvar from 0600 UT to 1600 UT reveal that the majority of the flares occured in and near the southern penumbra of the spot F1. Exclusively subflares occured that day. This was
Fig. 1. (a) Sketch of the active region. BMS = bipolar magnetic system. P or F denotes the preceding or following spot/pore of the corresponding BMS.

(b) Hα filtergram of the active region taken at Hvar Observatory. LP-loop prominence, AFS-arc filament system, F-short intense fibrils, FS-filament system.

(c) Continuum map of the magnetographic field of view and locations of dark Hα structures (hatched) and flares. The same symbol means that flares at separate locations brightened simultaneously. The numbers inside a symbol indicate how often flares occurred at the same location from 06 00 UT to 16 00 UT.
also a general property of AR NOAA 4201 which produced more than 200 flares during its passage over the disc, and less than 5% were flares of Importance 1. No flare with Importance 2 or larger was observed (Ruzdjak et al., 1986).

The locations of flares observed at Hvar on June 3 are shown in Figure 1c. One can see that the flares occurring at the preferred place south of the spot F1 were partly homologous, and there was a westward shift of the flaring sites during the day. Few of the flares in this region showed a single point structure, while in the majority a multi-element structure could be detected by an image processing procedure. We would like to stress that flare patches at different locations brightened simultaneously with most of the flares in the preferred area. Such synchronous flares (Gaizauskas, 1983), not implying necessarily that one event triggers the other one are denoted by the same symbol in Figure 1c, where the number inside the symbol denotes how often flares occurred at the same location. A part of synchronism certainly can be considered as being accidental, but the flares located along the filament system FS and the two umbral flares in P1, where the prominence LP terminated, might be physically connected with the flares in the preferred area. Inspecting also the locations of the flares which occurred outside our observing interval as given in Solar Geophysical Data, it appears that the flare activity showed a similar trend during the whole day, i.e. that most flares were located at the same preferred site south of F1.

2.2. Vector Magnetic Field and Current Density

The vector magnetograms were taken with the code impulse vector magnetograph at the Solar Observatory "Einsteinturm" in Potsdam. Details of observation and reduction techniques are described by Hofmann et al. (1989) and Hofmann and Kalman (1991).

In Figure 2a the direction of the transverse magnetic field is shown by segments superposed on the isolines of relative brightness (Stokes-intensity) which outline the contours of sunspots. Figure 2b shows the contour plot of the longitudinal magnetic field. It very clearly reflects a relative 'regular' field of the preceding spot P1 and the high complexity of the following part located in the eastern half of the magnetogram. The line shifter (Doppler compensator) used to center the line onto the photometer slits enabled to measure the line-of-sight velocities, shown in Figure 2c. The transverse component of the magnetic field has been used to derive the vertical current density $j_z$ shown in Figure 2d. Based on signals of 'field free' solar regions, the standard deviation of the current levels was determined to be $0.8 \times 10^3 \text{ Am}^{-2}$. 

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Fig. 2. (a) Azimuth plot of the transverse field (segments) superposed on the relative brightness (isolines). The dash-dot line indicates the inversion line of the longitudinal field.

(b) Contours of the longitudinal (line-of-sight) component of the magnetic field. The inner frame marks the cutting shown in Figure 3.

(c) Contours of vertical current densities, derived from the curl of the transverse field.

(d) Contours of Doppler velocities. The inner frame marks the cutting shown in Fig. 3.

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3. Interpretation and Discussion

3.1. Currents Dominated by Azimuthal Components

The $j_r$-contours derived from the transverse magnetic field mark regions of currents flowing up or down through the photosphere. Presently, sufficiently accurate measurements of the transverse component are more or less restricted to sunspots and their vicinity. There the field is not force-free and we have to take into account that not only current components flowing parallel to the field, but also those flowing perpendicular can contribute to the observed contours. We found such a configuration at the location of cells 6 and 7. This pair of up- and downflowing currents is situated symmetrically to the axis of the footpoint bundle of the loop prominence rooting deep in the penumbral photosphere. In an earlier paper (Hofmann et al., 1989) we studied in more detail the specifics of the magnetic field, currents and Hα observations at that location and concluded that this pair indicated an azimuthal current flowing around the nearly horizontal flux bundle and generating the Lorentz forces causing its concentration.

We find a configuration with similar characteristics at the other end of the loop prominence rooting inbetween the cells 2a and 3 in an umbral region, too. So we interpret also this pair as an azimuthal current flowing from area 2a to area 3 around the eastern root-bundle of the loop prominence.

3.2. Current Cell 1

The current cell 1 is located in the leading polarity of the emergent flux region BMS2 just at the south-west end of the arch filament system AFS. At this location we can not find such a counterpart (a comparable current strength situated in the same polarity) so that we do not conclude in the same way as for the pairs in section 3.1. Rather we assume that this current cell is dominated by field aligned currents flowing concentrated in the arch filament system. From the Hα observations and the longitudinal field map it is evident that the magnetic loops of this system reenter the photosphere eastward of current cell 1 distinctly less concentrated. The transverse component is there lower or close to the noise level and the upflowing counterpart of cell 1 cannot be inferred.

3.3. Current Systems Near the Flaring Site

The region between P4 and F1 was the preferred site of flaring and we intend to investigate the structure of currents in the vicinity of this region. The cells 7 and 8 are situated tightly together on different sides of the neutral line. The field between the areas is directed perpendicular to the neutral line. Furthermore, two short fibrils visible
in Hα (Figure 1b) connect the centre of negative cell 5 with the maxima of the upflowing currents observed in cell 4. Following the conception of Ding et al. (1985) we assume that the fibrils trace horizontal chromospheric and field aligned current systems. Summarizing all facts we conclude on the existence of relatively small scale, but concentrated, current systems flowing from the maxima of cell 4 into the chromosphere and from there parallel to the field along the fibrils toward cell 5.

The cell 2b is located northwest of cell 5, being the most intense source of vertical currents in the AR. A comparison with Figure 1c shows that the cell 2b coincides with the centre of flare activity. Most of the flares occurred one after another at this location nearly during the whole day. The energy released by these flares cannot be stored in a long build up process before the individual flares and one has to find a mechanism which permits the energy generation a short time before or/and during each flare.

This site of homologous flaring is located at the BMS position where the two developing bipolar systems BMS1 and 3 met and interact. That should be the site of powerful motions and velocity shear.

In Figure 3 we show cuttings of the maps of the longitudinal field and of Doppler velocity taken just from the location of the current cell 2. In the Doppler velocity we find an inversion line oriented nearly parallel to the radius vector of the disk. The region is about 26° outside disc center, so the direction of the inversion line is influenced by the perspective. Radially diverging motions (Evershed type) will lead to an inversion line perpendicular to the radius vector, whereas the observed ones should be caused by a more cyclonic motion. This region of cyclonic motion is crossed by an inversion line of the magnetic field. Such configurations are very often observed as preferred sites of flaring (Martres et al., 1971; Martres and Soru-Escaut, 1977). The reversal of the flow in a region of inversion of the magnetic polarity creates electromotive forces and a current is driven into the corona. Such dynamo models were developed supposing similarities between the solar photosphere and the ionosphere of the Earth (Sen and White, 1972; Kan et al., 1983). Henoux and Somov (1987, 1990 and 1991) studied very intensively the problem of current generation by motions across the line of force. Hofmann and Kalman (1991) reported on an observation in which the inferred current flowed opposite to those given in an photospheric dynamo model by Henoux and Somov (1987). In that observation the vortex motion was located inside a sunspot. The region studied in this paper is located in the photosphere where we have a higher temperature (and ionization) compared to the sunspot. This is possibly a better condition for a dynamo action. So we assume that the current and energy being dissipated in the sequence of small flares and brightenings is continuously generated by a dynamo effect in the sub-photospheric level in between the two bipolar regions. The single flares are triggered by current interruption in single flux systems rooting in this site of cyclonic motion.
Fig. 3. Cuttings of the longitudinal field (left) and the Doppler velocity (right). The thick segment in the Doppler map marks the direction of the inversion line of the longitudinal magnetic field component, and the thick segment in the magnetic map marks the inversion line of the Doppler velocity field.

4. Conclusion

The plasma of an active region can be described either in the frame of the currents or the magnetic field picture. A number of coronal and chromospheric processes - for instance the high rate of energy dissipation can be explained easier using the currents than in the magnetic field description.

Electric currents cannot be measured directly in the solar atmosphere. Some limited information ($j$) can be derived only indirectly from measurements of the vector magnetic field $B$. In Table 1 we present the summary of the estimated values of net electric current densities ($j$) and total electric currents ($I$) in the inferred current cells. So, one aim of this paper is to study the morphological relationship between magnetic fields and currents. Different features observed in Hα are of great help to identify currents which are connected.
**Table 1** Sizes, net current densities \((j)\) and current strengths \((I)\) of strongest \(j_e\)-areas

<table>
<thead>
<tr>
<th>Area</th>
<th>Size ((10^2 m^2))</th>
<th>(j) ((10^2 Am^{-2}))</th>
<th>(I) ((10^{11} A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95</td>
<td>-5.5±3.6</td>
<td>-6.5±4.3</td>
</tr>
<tr>
<td>2a</td>
<td>35</td>
<td>2.2±1.1</td>
<td>2.6±1.3</td>
</tr>
<tr>
<td>2b</td>
<td>202</td>
<td>12.1±6.0</td>
<td>14.3±7.1</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>-2.8±2.1</td>
<td>-3.3±2.5</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>6.3±3.2</td>
<td>7.5±3.8</td>
</tr>
<tr>
<td>5</td>
<td>107</td>
<td>-6.9±3.4</td>
<td>-8.2±4.0</td>
</tr>
<tr>
<td>6</td>
<td>107</td>
<td>6.4±2.6</td>
<td>7.6±3.1</td>
</tr>
<tr>
<td>7</td>
<td>83</td>
<td>-4.7±2.0</td>
<td>-5.5±2.4</td>
</tr>
</tbody>
</table>

- We found pairs of up- and downflowing currents of the same magnitude at two places. Both cells of each pair were located more or less symmetrically to the axes of the concentrated flux bundle of a loop prominence. We conclude that these cells are dominated by currents which flow azimuthal around the concentrated flux bundle running very flat into the photosphere. The intensity of the currents amounts to about \(3 \times 10^{11}\) A or \(6 \times 10^{11}\) A, respectively.

- At one place we found neighbourly current contours located in different polarities. The centres of the contours are connected by chromospheric fibrils, so that we presume the existence of field aligned currents closed in the chromosphere and corona.

- We found the most intense current cell with a current intensity of about \(1,4 \times 10^{2}\) A at a place of repeated flaring. The directions of the inversion lines of velocity and magnetic field indicate there a cyclonic flow in a region of polarity inversion.

We infer a subphotospheric dynamo process creating a current and a more or less continuously energy input into the corona. Single flux systems become unstable and triggered by current interruption, non-potential energy is released in the flux systems by small flares and brightenings. This scenario is suitable to explain the very often observed sequences of small homologous flares.

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ISTRAŽIVANJE ELEKTRIČNIH STRUJA U JEDNOM AKTIVNOM PODRUČJU NA SUNCU - PROCES DINAMA NA MJESTU UČESTALE POJAVE BLJESKOVA

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Sažetak. Prikazuju se istraživanja sustava električnih struja u jednom aktivnom području i njihova veza sa svojstvima magnetskih polja i kromosferskih aktivnosti. Ustanovili smo postojanje čelija pretežito azimutalnih struja koje teku oko vrlo nagnutih cijevi magnetskog toka (nožista petljaste prominencije), kao i čelija struja koje teku pretežno uzduž magnetskog polja kromosferskih fibrila.

Najsnažnija čelija vertikalne struje ustanovljena je u području gdje su tijekom čitavog dana, skoro neprekidno, opažani bljeskovi i pojačanja sjaj kromosfere. To područje, u kojem se pojavio velik broj bljeskova i nalazila snažna vertikalna struja, bilo je na mjestu sastajanja dva bipolarna područja. Morfološko ustrojstvo polja brzina i uzdužnog magnetskog polja upućuju na ciklonsko kolanje poprečo magnetskog polja. Stoga pretpostavljamo postojanje subfotosferskog procesa dinama koji neprekidno generira struju, a s njom povezana energija se postupno oslobađa u malim bljeskovima i slabijim procesima koji dovode do povremenih povećanja sjaja kromosfere, opaženim u različitim petljama magnetskog toka usidrenih u tom području.

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