Distribution of electric current in solar plasma loops

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Abstract

The distributing profile of electric current in solar plasma loop is a key factor for the MHD instabilities of the loops. However, it is very difficult to measure such profile in single loop. In this paper, we assume that, in spite of the complexity of the structure in most of the sunspots, the distribution of the electric current in some small simple sunspots may reflect the main feature of the distribution in solar plasma loops. We utilize the high-cadence, high-resolution vector magnetograms observed by Big Bear Solar Observatory (BBSO) to derive the longitudinal electric current and analyze the distribution of the longitudinal electric current in the region of sunspots, and simulate the distributing features of the solar plasma loops. From these analysis, we find that the electric current in some small simple sunspots, or to say in plasma loops, are concentrated to their center. Such distribution feature is consistent with the theory of pinch effect in current-carrying plasma loops.

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1. Introduction

It is well known that the electric current may play an important role for the solar plasma heating (Goodman, 2004; Socas-Navarro, 2005b) and eruptive events triggering, especially for the latter, that the electric current may play a key role in the process of the MHD instabilities and the energy dissipation in the magnetized plasma loops by affecting their evolution behaviors and triggering the loops eruptive processes. From the experiments of Tokamak plasma, we know that the total current and its distributing profiles in the section of the tokamak plasma loop will dominate the process of the MHD instability (e.g., the tearing mode instability, etc.) and the magnetic reconnection (Alfvén and Carlqvist, 1967; Furth et al., 1973; Boozer, 2004). As we know that most of the solar plasma loops are current-carrying magnetized plasma loops, they are similar to the regime of Tokamak plasma loop. So, it is very important to explore the distributing profile of the electric currents associated with solar current-carrying plasma loops for understanding the evolution behaviors of the loops. And the results of the current distribution is the precondition for analysis the tearing mode instability and magnetic reconnection in the plasma loops. It will provide us a new mechanism of energy release and solar eruptive events.

Then, how does the current distribute in the solar plasma loops? In 1992, Beaufume, Coppi, and Golub supposed that skin effect will dominate the distributing profile of electric current in current-carrying plasma loops, and the current will stay localized at the periphery of the loop in an annular-shaped current sheath of radius close to $a$, extended along the loop length $2L$, and having a width $d$. In the mean time, according to the theory of pinch effect (Bennett, 1934), the current will concentrate to the axis of the current-carrying plasma loops (see Fig. 1). Then, which regime is more close to the fact?

At present, it is very difficult to determine the distributing profile in the solar plasma loops. The main reason is that we can’t distinguish the loop boundary clearly from observations. In 1998, Zaitsev et al provided a LRC-circuit...
analog of current-carrying magnetic loop model to diagnose the electric current in the solar plasma loops. In their expression, the total current in the solar plasma loop is about:

\[ I_0 \sim 10^{12} \times P^{-1} \, (A). \]  

Here \( P \) is the period of the eigen oscillation of the LRC-circuit with the unit of second. They use the spectral analysis of the Metsahovi millimeter wave solar data of 16 solar flares and revealed the modulation period is 0.7–1.7 s, and this gives the currents is about \( I_0 = 6 \times 10^{10} \cdot 1.4 \times 10^{12} \, A \).

With this method, we may estimate the total currents flowing in the solar plasma loops. However, it cannot provide the distributing profiles in the sections of the loop.

In this paper, the author assumes that the current distribution in some simple sunspots may reveal or simulate the general features in the solar plasma loops, and then derives the total current and its distributing profile in the loop section by calculating the current density along the diameter of the sunspots from the photospheric vector magnetograms in simple sunspot regions. However, it is well known that almost all the sunspots have intricate structures within their umbra and penumbra (Socas-Navarro, 2005a; Thomas and Weiss, 2004, etc.). We must be cautious when we introduce the above assumption. Generally, it may be more reasonable to select the small simple sunspot to trace the characteristic profiles of the electric current and magnetic field in solar plasma loops. As we know that the difference between the sunspots and the solar plasma loops is very obvious, the above approach is only a provisional way to trace the current profile in the section of the solar plasma loops before we find the other more accurate way.

2. Observational data analysis and results

2.1. Observational data

Here, we choose the vector magnetograms observed by BBSO during 18:30–23:10 UT on July 26, 2002 in the active region NOAA10044 and NOAA10039 to derive electric current. The Cal line at 6103 Å is used to observe vector magnetograms with about 1 min cadence. The hardware and other details of Digital Vector Magnetograph (DVMG) have been described by Spirook et al. (2002). The DVMG/BBSO data consists of four images: a 6103 Å filtergram (Stokes \( I \)), a line-of-sight magnetogram (Stokes \( V \)), and transverse magnetograms (Stokes \( U \) and \( Q \)). After rebinning the camera to the 512 \( \times \) 512 mode, the pixel resolution is about 0.6\( ' \). The line-of-sight magnetic sensitivity is about 2 G, while the transverse sensitivity is about 20 G. The cadence for a complete set of Stokes images is typically one minute. The accurate position information of BBSO images is determined by aligning with MDI continuum images, taking sunspots as reference. The accuracy of the alignment is about 1\( ' \). We use the algorithm developed by BBSO group to derive the vector magnetic field components (\( B_x, B_y, B_z \)) from the Stokes parameters (\( I, Q, U, V \)), where \( B_l \) is the longitudinal component, \( B_x \) and \( B_y \) are the two transverse components in the image coordinates. The calibration of the data was done with a standard procedure from BBSO. We use the Uniform Shear Method (USM) developed by Moon et al. (2003) to resolve the 180\( ^\circ \) azimuth ambiguity of the transverse magnetic fields, in the meantime, we use the minimum energy method developed by Metcalf (1994) to check them.

2.2. Analysis method

It is well known that only one electric current component (longitudinal or vertical component) can be derived from the photospheric vector magnetogram. When the view field is not in the center of solar disk, it is necessary to rotate the view field to the solar disk for deriving the vertical electric current. And we know that any rotation will enlarge the uncertainty of all the magnetic components and the electric current density. In this investigation, since the center of the view field is located at S18E18, which is near the center of solar disk, it is reasonable to apply the longitudinal current component, which is derived from original observations, to study the current distributing profiles in the section of the loops. The longitudinal electric current density can be derived by the following formula:

\[ j_l = \frac{1}{\mu_0} (\nabla \times \mathbf{B})_l = \frac{1}{\mu_0} \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right). \]  

Errors in computing the electric current density are mainly from two sources: one is the measurement of the transverse magnetic field while the other is from resolving the 180\( ^\circ \) ambiguity. As mentioned above, the sensitivity of DVMG/BBSO for transverse magnetic field is 20 G. Taking the 2.4\( ' \) spatial resolution, the uncertainty of electric current density in this study corresponds to \( \sim 0.91 \times 10^{-3} \, \text{A m}^{-2} \). However, it is difficult to determine the uncertainty caused by the 180\( ^\circ \) ambiguity. We estimate the error by computing the standard deviation \( \sigma \) in the whole field of view. A current is considered to be significant.
only if its absolute value exceeds $3\sigma$ over the average value of the whole field of view. The value of $\sigma$ ranges from $2.6 \times 10^{-3}$–$5.1 \times 10^{-3}\text{ A m}^{-2}$ during the period of 18:30–23:10 UT.

In order to obtain the longitudinal electric current in the loop and the distributing profiles in the loop sections, it is important to determine the circumferences of the projection of the solar plasma loops on the photospheric surface. In this paper, we may select the half maximum values of the longitudinal magnetogram at every sunspots to determine the circumferences of the loops. Fig. 2 shows these circumferences. In each circumferences we can calculate the total longitudinal electric current, and plot the density distributing profile along the diameter of each circumference, which simulates the section of plasma loop.

2.3. Results

In the two active regions, there are two M-class flares occurred, one is an M8.7 flare, and the other is an M1.0 flare. Wang et al. (2004) provided the behaviors of the emerging magnetic flux associated with the M8.7 flare, Ji (2006) found the emerging satellite sunspots associated with the M1.0 flare. Tan et al. (2006) investigated the temporal behaviors of the longitudinal electric current associated with the two flares. Fig. 3 shows the spatial distributions of the averaging longitudinal electric current density in the time rage of 18:30–23:10 UT. From this we may find that the maximum current density is not always occurred in the flaring regions.

The calculating results of the longitudinal electric current and the magnetic flux in the sunspot regions are shown in Table 1. Fig. 4 shows the distributing profiles of the longitudinal electric current density along two different lings across the magnetic neutral lines (we may name these lines as crossing lines). Fig. 5 shows the distributing profiles of the longitudinal electric current and all the components of the magnetic field ($B_x$, $B_y$, $B_z$) along diameters of arbitrary two circumferences, and they may reflect the main feature of current distribution on the section of plasma loops. The abcissa indicates the diameter from one end to the other, the erecting dashed line may represent the position of the axis of the loop, i.e., the position of the center in the loop section.

3. Summary and discussion

From the above analysis and results of the calculations, we may obtain the following conclusions:

(1) From Table 1, we may find that the typical value of the electric current in small simple sunspots is about $10^{10}$–$10^{11}\text{ A}$. According to our assumption of approximating the solar plasma loop with small simple sunspots, the typical value of the current flowing in single plasma loops is also obtained the same value. However, there is an exception in the region

<table>
<thead>
<tr>
<th>Loop number</th>
<th>Electric current(A)</th>
<th>Magnetic flux (Mx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>$+3.288 \times 10^{11}$</td>
<td>$-6.859 \times 10^{20}$</td>
</tr>
<tr>
<td>f2</td>
<td>$+2.870 \times 10^{10}$</td>
<td>$-1.399 \times 10^{21}$</td>
</tr>
<tr>
<td>f3</td>
<td>$+4.851 \times 10^{11}$</td>
<td>$-5.672 \times 10^{20}$</td>
</tr>
<tr>
<td>f4</td>
<td>$-8.314 \times 10^{11}$</td>
<td>$+1.815 \times 10^{21}$</td>
</tr>
<tr>
<td>f5</td>
<td>$-9.120 \times 10^{11}$</td>
<td>$+1.139 \times 10^{21}$</td>
</tr>
<tr>
<td>f6</td>
<td>$-3.462 \times 10^{12}$</td>
<td>$+1.035 \times 10^{22}$</td>
</tr>
<tr>
<td>f7</td>
<td>$-4.933 \times 10^{11}$</td>
<td>$+1.160 \times 10^{21}$</td>
</tr>
<tr>
<td>f8</td>
<td>$-3.521 \times 10^{11}$</td>
<td>$-1.175 \times 10^{21}$</td>
</tr>
<tr>
<td>f9</td>
<td>$+2.860 \times 10^{11}$</td>
<td>$-5.850 \times 10^{20}$</td>
</tr>
</tbody>
</table>

And the loop numbers are shown in Fig. 2.
of $f_6$ which the current reached up to $3.462 \times 10^{12}$ A. From Fig. 2 we can speculate easily that the $f_6$ sunspot has a very complex structure. It is possibly composed of several small sunspots localized in the same region, i.e., here it is not a single loop-foot, but a multiplex of many loop-foots.

(2) From Fig. 4, we may find that the relation between electric current and the longitudinal magnetic field is very complex along the lines across the magnetic neutral lines. Generally, their signs are opposite, but, not all of their reversed points localize at the same position, they always have an excursion.

(3) From Fig. 5, we may find that, near the center of the sunspots, the absolute value of the longitudinal magnetic field ($B_z$) reached its maxima as well as the longitudinal electric current density. From the center to the boundary, all of them are degressive. From the same figure, we may find that the transverse magnetic components ($B_x$, $B_y$) are reversed, and get the maximum variational rate near the position of the sunspot center, and this may reconfirm the fact that the electric current reached its maxima at the center of the sunspots. These results support the regime of pinch effect in the current-carrying plasma loops (shown in Fig. 1). With these results, we may extrapolate that the solar current-carrying plasma loop may have the similar distributing profiles in their section. Tan and Huang (2006) adopted such kind of distributing profile in the study of neoclassical effect in the solar plasma loops, and obtained some reasonable conclusions.

(4) From Table 1, Figs. 4 and 5, we may find that, in most cases of the loops, the sign of the electric current and that of the magnetic flux are opposite. There is only one exception in the above mentioned cases (include 9 sunspots, 2 crossing linges, and almost all of the diameters of the loops), which is the $f_8$ sunspot. These results are consistent with the theory of electric current helicity (Seehafer, 1990; Bao and Zhang, 1998; Choudhuri et al., 2004).

As sunspots always have complex structures (Parker, 1979; Socas-Navarro, 2005a; Thomas and Weiss, 2004), the above method of determining the distributing profile of the electric current in the solar plasma loops by measuring the longitudinal current density along the diameter in simple small sunspot regions is only an approximative approach. However, since we have no more rigorous techniques, the above method may be a reasonable approach (or a provisional approach) to trace the feature of the electric current in the solar plasma loops at present. And the results of the above work will be helpful to the study of MHD instability of the solar plasma loops. Maybe, when
the Solar-B begins to work, we can get a more accurate way for the topic of this paper.

Based on the distributing profiles of the current density in the section of the solar plasma loop, we can analysis the tearing mode instability and the magnetic reconnection of the inner of the loop. Maybe such analysis can help us to quest for a more reasonable mechanism for the heating of the solar atmosphere and the eruptions of solar plasma.

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References


