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Sunspot Magnetic Structure and Interspot Radio Source Formation

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Abstract—The magnetic structure of a typical sunspot is represented as a set of three interacting magnetic fluxes. The first one, F1, escapes upward from the sunspot umbra and closes through the corona on the sunspot of opposite polarity. The second, F2, forms the sunspot penumbra. It includes Evershed flows emerging from the sunspot, the heavy photospheric plasma of which cannot be pulled up to the corona. For this reason, the F2 flux at the outer edge of the penumbra should close on the photosphere adjacent to the sunspot, i.e., here the F2 field changes sign. The third flux, F3, is the external magnetic field flux and has the same polarity as F1. Thus, magnetic fields of different signs occur near the outer boundary of the sunspot penumbra. Magnetic reconnections will inevitably take place there. Small- and multiscale current sheets in which particles are accelerated are formed. The latter fill short and low magnetic loops that connect sunspots of different polarity in the bipolar group and form interspot radio sources at the tops of these loops.

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1. INTRODUCTION

In order to simulate sunspots, analyze their energy, and calculate their optical and radio emission, it is necessary to have an idea of the typical structure of the magnetic field as both a single circular sunspot (Solov'ev and Kirichek, 2014) and a bipolar sunspot group. In this paper, the model of three magnetic field fluxes in a round sunspot is considered, which makes it possible to describe the main features of the sunspot magnetic structure and to understand the nature and mechanism of interspot radio source (ISRS) formation (Bacunina et al., 2015).

2. MODEL DESCRIPTION

2.1. A Single Round Sunspot

First, let us consider a single unipolar round sunspot with a well-developed penumbra. Its typical magnetic structure (vertical central section) is shown in Fig. 1. The magnetic field flux emerging from the sunspot is divided into two parts. The first part, F1, is the field flux that escapes upward from the sunspot in the corona and closes in the distance through upper layers of the solar corona on the sunspot (or few sunspots and pores) of the opposite polarity. The second part, F2, is the magnetic flux, which forms a relatively thin layer of the sunspot penumbra where there are Evershed flows that radially emerge from the sunspot and carry a sufficiently dense photospheric plasma that cannot be pulled up into the corona. For this reason, the magnetic force lines of the F2 flux are strongly pressed against the surface of the Sun, and they close on the photosphere in the close vicinity of the sunspot at the outer penumbra boundary, such that the vertical component of the field F2 changes its sign. Furthermore, in the active region in the sunspot vicinity there is always a magnetic field F3 external to the sunspot, which has the same polarity as the field in the sunspot, but its intensity is significantly weaker (about 300–500 G). At points near the outer penumbra boundary, where the field flux that emerges from the sunspot is divided into directed upward F1 and directed downward F2, there is a special line (in the projection on the vertical plane in Fig. 1 it is marked by a circle) that forms the upper boundary of the separatrix surface between magnetic fluxes F2 and F3, which are have opposite polarities on different sides of this surface (Fig. 1). Magnetic reconnections inevitably occur on this separatrix surface, and multiple small-scale current sheets are formed in which the plasma is heated by the emission of magnetic energy (hence, there are many bright points around the sunspot, the known belt of increased brightness), but the heat is minimal, since the plasma density here is relatively high (the Alfven velocity is small). In these magnetic reconnections, however small and weak they were, Dreiser and sub-Dreiser electric fields, as well as accelerated particles (mostly electrons) emerge, respectively. There are not many of them, relatively, but they are always present in the mentioned separatrix region. It is important to emphasize that magnetic reconnections at outer boundary of sunspot are random and stochastic because of the dynamic nature of the sunspot penumbra, i.e., the magnetic field in the penumbra is extremely nonuniform and sharply fragmented with Evershed flows emerging radially from the sunspot with velocities of several km/s along thin magnetic fibers. As is shown by modern space observations, these multiple magnetoplasma jets in the sunspot penumbra constantly change their shape, mix, and over-

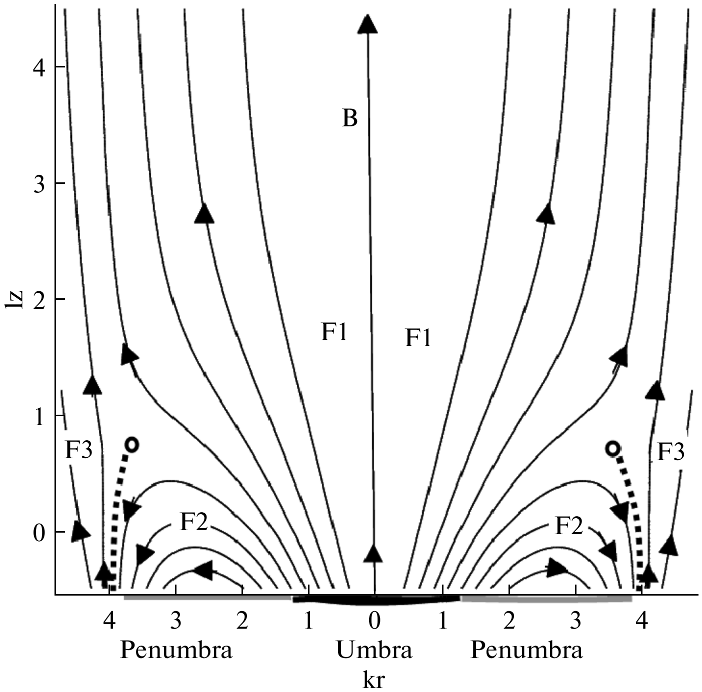

Fig. 1. Example of the calculation of the magnetic structure of the round sunspot with the developed penumbra obtained from the condition: $A = A_1 + A_2 + A_3 =$ const. Thick dotted lines indicate the position of the separatrix surface that separates fluxes F2 and F3.

lap. All of this leads to the fact that small- and multiscale current sheets are continuously formed in the region of the specified separatrix. The lifetime of each of them is short, i.e., a few minutes. They appear and disappear rapidly, but it is important that a certain number of such current-sheets exists permanently, because magnetic fields of opposite polarity collide due to the general large-scale geometry of the system at the outer penumbra boundary, where heavy Evershed flows close on the photosphere. Multiple current sheets generate a certain background of accelerated particles around the sunspot. These particles propagate along magnetic field lines and should be accumulated in traps, in magnetic loop tops with footpoints near magnetic reconnection regions. It is natural to assume here that the lower accelerated particles fall in the loops, the greater their energy should be, because the magnetic field is more noticeable at the low magnetic loop footpoints that emerge from the reconnection region (Fig. 2) and thus stronger electric fields are generated here with magnetic reconnections. Following this logic, one can expect that low-lying loops in the vicinity of the sunspots can be heated by the thermalization of accelerated particles caught in them to higher temperatures than higher loops with a smaller magnetic field filled with fewer energetic particles. It should be noted that the total number of particles used for the thermalization of nonthermal electrons is approximately the same as in high loops as in low even thought the plasma density is higher in lower loops,

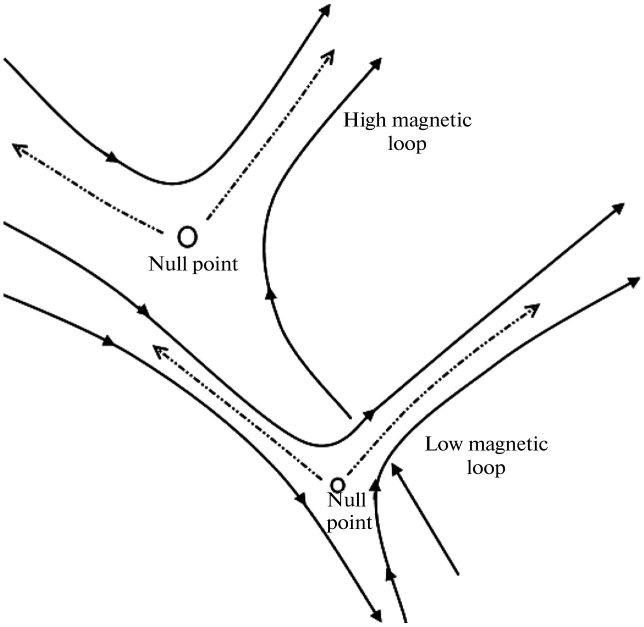

Fig. 2. Diagram of magnetic reconnections increasing with depth that occur in the magnetic field. Circles indicate positions of null points, in the vicinity of which the main acceleration of particles occurs. Thin dashed lines show the motion direction of particles that fill magnetic loops which have footpoints on the separatrix surface. The magnetic field intensity is higher in lower photospheric layers, and it can be expected that the particles that fill the lower loop have greater energy on average.

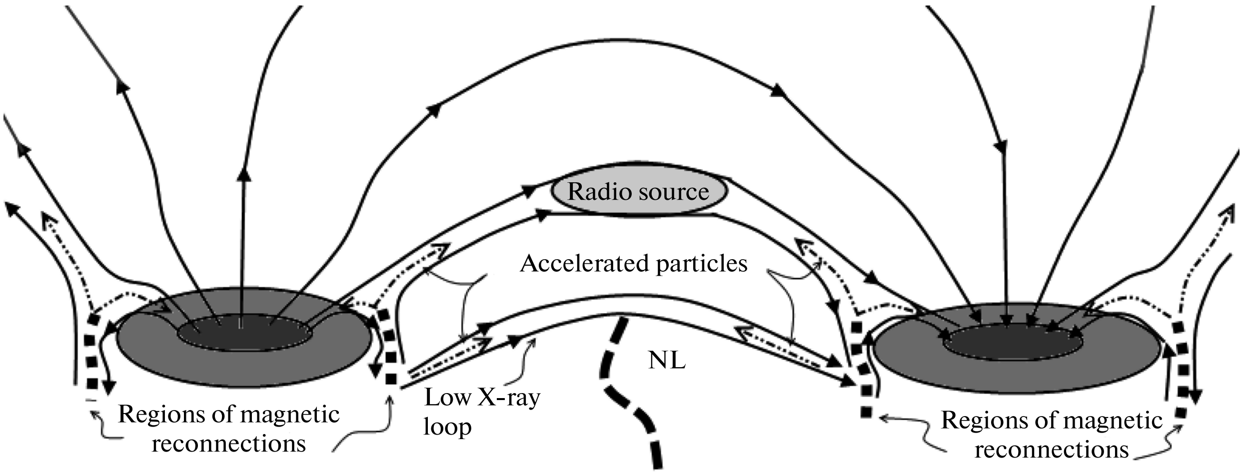

Fig. 3. Diagram of ISRS formation in the symmetrical bipolar sunspot group. At the tops of short, closed magnetic loops located between the sunspots above the photospheric neutral line, NL, particles accelerated in current sheets near their footpoints are accumulated. On lateral and external sides of sunspots, accelerated particles are not accumulated in high loops that extend far from sunspots and ISRSs are not formed. Thick dashed lines refer to projections on the vertical plane passing through the sunspot centers and the separatrix surface that separates magnetic fluxes of opposite polarity, F2 and F3. Thin dashed lines show the motion of accelerated particles from the magnetic reconnection region to the loop tops and sunspot center. Flows directed toward the center provide the opposite Evershed effect observed in the sunspot chromosphere, which has never been theoretically explained. Radio sources are arranged at the tops of relatively high magnetic loops. In lower loops, which have stronger magnetic fields at their footpoints, the plasma can be heated by the thermalization of accelerated particles up to X-ray temperatures (Tun et al., 2011).

because their length is significantly smaller. Thus, the energy and number of accelerated particles trapped in a particular loop become the decisive factor for plasma heating. This simple assumption is confirmed by data from the *HINODE* space observatory (Tun et al., 2011, see, Fig. 18), which show that thin magnetic loops observed near the sunspot in X-rays are located systematically lower than loops that generate heat and gyrosynchrotron microwave emission. Apparently, in the case of the complete thermalization of accelerated particles, thermal radio radiation occurs in the loop, while the gyrosynchrotron emission emerges in the case of the partial thermalization. The data from the cited paper seem to us an important observational confirmation of general qualitative considerations about the structure of the sunspot magnetic field in general and the mechanism of the occurrence of magnetic loops that stand out against the background due to their increased radiation, not only in the radio region but also in the X-ray region.

Thus, in the case of a simple unipolar sunspot, the radio sources associated with it should preferably have a circular shape, though in reality the electrons that fill magnetic loops and are thermalized in them can provide geometric figures of more complex shapes.

2.2. Analytical Representation of the Triple-Flux Magnetic Structure of the Unipolar Sunspot

The magnetic field of an axially symmetric sunspot is described in cylindrical coordinates r, φ, and z by the function of the magnetic flux $A(r, z) = \int_0^r B_z(r, z) r dr$, such that

$$B_z(r, z) = \frac{1}{r}\frac{\partial A(r, z)}{\partial r}; \quad B_r(r, z) = -\frac{1}{r}\frac{\partial A(r, z)}{\partial z}; \qquad (1)$$

and the magnetic field solenoidity condition, $\mathrm{div}\mathbf{B} = 0$, holds automatically.

Let us represent the sunspot magnetic field as a set of three magnetic fluxes.

The first one, F1, we describe as the potential field of a magnetic monopole with direct force lines radially emerging from a center located below the photosphere

$$A_1(r, z) = B_{0.1}\frac{w}{k^2}\left[1 - \left(1 + \frac{(kr)^2}{w}\right)^{-\frac{1}{2}}\right], \qquad (2)$$

where $w(z) = (1 + z/z_0)^2$, $k = r_0^{-1} = \mathrm{const}$ is the inverse transverse scale of the sunspot and $(-z_0)$ is the monopole penetration coordinate (below in numerical calculations we will take $z_0 = 1Mm$). $B_0(z)$ is the magnetic field intensity on the sunspot axis. The magnetic flux along the axis in the form $B_0 w(z) = \mathrm{const}$ should be preserved with height. The use of this potential distribution makes it possible to pull up sufficiently strong magnetic fields high in the corona.

It is convenient to set the second flow such that is limited by height and describes not only the umbra but also the sunspot penumbra, for example, in the form of

$$A_2(r, z) = \frac{B_{0.2}}{k} r J_1(kr)\left[\exp(-kz) - \frac{k^2}{l^2}\exp(-lz)\right], \quad (3)$$

where $J_1(kr)$ is the first order Bessel function of the first kind, $B_{0.2}$ is field the measurement unit in the flux A_2, and l is the inverse vertical height scale in the sunspot, which is several times larger than k. This field becomes potential at $lz \gg 1$. If this condition is not fulfilled, field (3) is not a potential one, and the magnetic force inside the sunspot is not zero, which leads to differences in its temperature and density characteristics from the photospheric ones. The calculation of equilibrium states of plasma sunspots corresponding to the magnetic field described above, i.e., in fact, the calculation of the model of observed sunspot layers for a given magnetic structure is beyond the scope of this paper. A separate study will be devoted to this difficult problem. Finally, the third flux, F3, which describes the external potential field, can be represented by the formula

$$A_3 = aB_0\frac{1}{2}(kr)^2, \quad (4)$$

where a is a positive constant less than unity. In Fig. 1 the structure of the magnetic field (central vertical cross-section) described by the sum of the above three fluxes at $a = 0.15$ and $l = 10k$ in formula (3) for A_2 is calculated as an example.

2.3. ISRS Formation in the Bipolar Sunspot Group

Now let us consider a bipolar magnetic structure, i.e., a case closer to the real one. It may well be not a bipolar sunspot group but a single sunspot with a preferred direction of the main magnetic flux closure on some nearby photospheric region.

For simplicity, let us consider a symmetrical bipolar group (Fig. 3). The basic idea of our model is that electrons are accelerated near separatrix surfaces of each of the sunspots moving to loop tops in relatively short magnetic loops, which connect sunspots of opposite polarity with each other, are accumulated there, are partially or fully thermalized, and generate interspot radio sources (ISRS) with a whole set of inherent properties. Accelerated electrons go far from each of the sunspots along magnetic force lines (loops) that occur on side and external parts of sunspots. In such long and high magnetic loops, they do not accumulate in significant amounts, and therefore ISRS do not emerge on the sides and external sides of sunspots.

In the region between sunspots, lower loops, at the footpoints of which magnetic fields are stronger (as can be seen from formula (3), the F2 field, which is pressed against the photosphere, increases rapidly with depth), can be filled with sufficiently energetic particles that occur in reconnections on the separatrix in stronger magnetic fields (Fig. 2). As was mentioned above, such energetic particles can heat plasma in magnetic loops extending from the sunspot boundary to the very large X-ray temperatures (Tun et al., 2011), while a relatively small amount of the electrons accelerated in multiple current sheets are captured in the higher loops with a weaker magnetic field, and they give only heat (in the case of complete thermalization) or weak gyrosynchrotron radio emission in the case of the partial thermalization of accelerated particles captured in the loop.

It should be added that it is possible within the presented concept to understand the origin of not only long-living ISRSs but also of flares and flare phenomena of different types. When fairly large magnetic tubes of different polarity meet on the separatrix surface between F2 and F3, there can be a powerful burst of radio emission and even a small chromospheric flare. In our opinion, the small-scale, flickering, white-light kernels in weak solar flares near sunspots described in (Kowalski et al., 2015) can be considered as this kind of phenomena.

3. CONCLUSIONS

The sunspot magnetic structure model and ISRS formation scheme in the bipolar sunspot group presented in this paper are of a phenomenological nature and require further development, but it is important that they make it possible to consider the mechanism of the occurrence of interspot radio- and X-ray sources near sunspots in active regions on the Sun and to establish a direct connection between this kind of formation and features of the typical sunspot magnetic structure from unified positions based on the general theoretical representation.

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