MAGNETIC ENERGY BUILDUP IN A QUADRUPOLE FIELD BY PHOTOSPERIC SHEAR MOTION

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Abstract. Using a two-dimensional, dissipative magnetohydrodynamic model, this paper presents a numerical simulation of the magnetic energy buildup in a quadrupolar field by photospheric shear motion. When electric current density is larger than a certain critical value, an anomalous resistivity is introduced in order to account for the dissipation caused by instabilities in high current regions. It is shown that like a bipolar field, a quadrupolar field can efficiently store magnetic free energy through photospheric shear motion. Electric current formed by shear concentrates on the separatrix and magnetic loops rooted in areas where the shear velocity gradient is large. The atmosphere is heated by anomalous resistive dissipation during the shear. Both magnetic and thermal energy increases nonlinearly with shearing displacement. When the anomalous resistivity increases or the critical current density decreases, the growth rate reduces for magnetic energy but goes up for thermal energy.

1. Introduction

Previous simulation studies showed that for a bipolar magnetic field photospheric shear motion in active regions serves as an efficient mechanism of magnetic energy storage (Wu and Hu, 1981; Wu et al., 1983, 1984; Hu and Wu, 1984). However, the magnetic field in active regions is multipolar, in general. A multipolar magnetic field has a complicated topology and magnetic separatrices associated with it. These separatrices divide the multipolar field into several adjacent but topologically disconnected bipolar fields. Photospheric shear motion produces not only volume current in these bipolar regions but also strong current in the neighborhood of the separatrices. In the frame of ideal magnetohydrodynamic (MHD) theory, these strong currents appear as current sheets right on the separatrices (Low, 1987; Low and Wolfson, 1988). Such current sheets are subject to instabilities (Zheng and Hu, 1990) and will then collapse by anomalous resistive dissipation and magnetic reconnection. During this process the topology of the sheared magnetic field changes and part of magnetic energy is converted into thermal energy so as to heat the corona (Parker, 1986). Therefore, the energy buildup for a multipolar field must be different from that for a bipolar field. This paper is aimed at studying the evolution and the energy storage of a quadrupolar potential field by photospheric shear motion. An anomalous resistivity is introduced in strong current regions where
electric current density exceeds a certain critical value. The numerical model, simulation results, and conclusions are presented as follows.

2. Numerical Model

2.1. Governing Equations

For simplicity simulation is limited to two-dimensional problems in Cartesian coordinates with the \( y \)-axis perpendicular to the photosphere, and all quantities are independent of \( z \). Defining a magnetic flux function \( A(t, x, y) \), related to the magnetic field by

\[
B = \nabla \times (A \hat{z}) + B_z \hat{z},
\]

and neglecting the gravity, the MHD equations are cast in the non-dimensional form:

\[
\frac{\partial \rho}{\partial t} + v_x \frac{\partial \rho}{\partial x} + v_y \frac{\partial \rho}{\partial y} + \rho \frac{\partial v_x}{\partial x} + \rho \frac{\partial v_y}{\partial y} = 0,
\]

\[
\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + \frac{\partial T}{\partial x} + \frac{T}{\rho} \frac{\partial \rho}{\partial x} + \frac{2}{\rho \beta_0} \frac{\partial A}{\partial x} \Delta A + \frac{2B_z}{\rho \beta_0} \frac{\partial B_z}{\partial x} = 0,
\]

\[
\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + \frac{\partial T}{\partial y} + \frac{T}{\rho} \frac{\partial \rho}{\partial y} + \frac{2}{\rho \beta_0} \frac{\partial A}{\partial y} \Delta A + \frac{2B_z}{\rho \beta_0} \frac{\partial B_z}{\partial y} = 0,
\]

\[
\frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + \frac{2}{\rho \beta_0} \frac{\partial A}{\partial x} \frac{\partial B_z}{\partial y} - \frac{2}{\rho \beta_0} \frac{\partial A}{\partial y} \frac{\partial B_z}{\partial x} = 0,
\]

\[
\frac{\partial A}{\partial t} + v_x \frac{\partial A}{\partial x} + v_y \frac{\partial A}{\partial y} - \frac{1}{R_m} \Delta A = 0,
\]

\[
\frac{\partial B_z}{\partial t} + v_x \frac{\partial B_z}{\partial x} + v_y \frac{\partial B_z}{\partial y} + B_z \frac{\partial v_x}{\partial x} + B_z \frac{\partial v_y}{\partial y} - \frac{\partial v_x}{\partial x} \frac{\partial A}{\partial y} + \frac{\partial v_y}{\partial y} \frac{\partial A}{\partial x} = \frac{\partial}{\partial x} \left( \frac{1}{R_m} \frac{\partial B_z}{\partial x} \right) - \frac{\partial}{\partial y} \left( \frac{1}{R_m} \frac{\partial B_z}{\partial y} \right) = 0,
\]

\[
\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + (\gamma - 1)T \frac{\partial v_x}{\partial x} + (\gamma - 1)T \frac{\partial v_y}{\partial y} - \frac{2(\gamma - 1)}{\rho \beta_0 R_m} \left[ (\Delta A)^2 + \left( \frac{\partial B_z}{\partial x} \right)^2 + \left( \frac{\partial B_z}{\partial y} \right)^2 \right] = 0,
\]
where $\rho$, $T$, and $v(x, y, z)$ are density, temperature, and flow velocity, normalized by $\rho_0$, $T_0$, and $v_0 = (RT_0)^{1/2}$, respectively; $x$, $t$, $A$, and $B_z$ are normalized by $L_0$, $t_0 = L_0/v_0$, $A_0$, and $B_0 = A_0/L_0$, respectively; $\gamma$ is the adiabatic index; $\beta_0$ and $R_m$ are the ratio of gas pressure to magnetic pressure and the magnetic Reynolds number respectively, expressed by

$$\beta_0 = \frac{2\mu_0\rho_0 RT_0}{B_0^2}, \quad R_m = \frac{\mu_0 v_0 L_0}{\eta},$$ (9)

where $\mu_0$ is the vacuum permeability, and $\eta$ is the anomalous resistivity.

2.2. INITIAL CONDITIONS

The initial magnetic field is assumed to be a potential one produced by four parallel line magnetic charges, located at $x = \pm a$, $\pm b$ on $y = -d$, with line charge density equal in magnitude and opposite in sign for adjacent line charges (Hu, 1985), and the non-dimensional form of the corresponding magnetic flux function is

$$A = \arctan \left[ \frac{2b(y + d)}{x^2 + (y + d^2) - b^2} \right] - \arctan \left[ \frac{2a(y + d)}{x^2 + (y + d^2) - a^2} \right].$$ (10)

There is a neutral point at $y_N = \sqrt{ab} - d$, where $B = 0$, and the separatrix passes it. For $a = 1$, $b = 2$, $d = 0.6$, and $y_N = 0.81$, the magnetic field configuration is shown in Figure 1(a) where the numbers are values of $A$ on each field line, the arrows show the orientation of typical field lines in each bipolar region, and the separatrix is drawn by a dashed line. The separatrix passes through the neutral point and falls into two branches there, which stretch to the flank and intersect the $x$-axis at $x = \pm 2.35$ and $x = \pm 0.53$, respectively. The quadrupolar field is divided by the separatrix into four topologically disconnected bipolar fields: a local bipolar field across the origin below the lower branch of the separatrix, a large-scale bipolar field above the upper branch of the separatrix, and two local bipolar fields on the two sides between the two branches. The magnetic neutral lines of the latter two local bipolar fields are situated at $x = \pm 1.5$ on the $x$-axis, where $B_y = 0$.

The initial atmosphere is assumed to be in isothermal static equilibrium with $\rho = 1$, $T = 1$, and $v = 0$. There are several simplifications made in the solar atmosphere, and let us now list two of them and briefly explain why they are basically plausible. First, the solar atmosphere is highly structured and far from isothermal; its temperature varies remarkably with height, from about $6 \times 10^3$ K in the photosphere to more than $10^6$ K in the corona. It is certainly an extreme simplification to take an isothermal equilibrium as the initial state with an intermediate temperature $T_0 = 10^5$ K. Next, we have omitted other energy terms in Equation (8), such as heat conduction, heating and radiative cooling. These terms are presumably kept in a dynamical balance, maintaining the highly structured atmosphere in equilibrium. If one attempts to examine the structure of a realistic
Fig. 1. (a) The initial potential magnetic field configuration with the dashed line representing the separatrix, and (b) the shear velocity profiles at the base given by Equation (13) (solid line) and Equation (14) (dotted line).
solar atmosphere and the mechanism for its formation, one has to incorporate all these physical factors mentioned above. However, the interest of this paper lies in the magnetic energy buildup in the solar atmosphere. As observations show, the magnetic field in solar active regions is very strong, with a ratio of gas pressure to magnetic pressure much less than unity. Therefore, the solar atmosphere as a whole has very little influence on the behavior of the magnetic field but simply serves as a highly conductive medium, carrying the electric current, freezeing the magnetic field in it, and in addition, generating anomalous resistivity in local high current regions as presumed by the present model. From this point of view, the above-mentioned simplifications have no significant bearing on the problem of magnetic energy buildup in the solar atmosphere.

2.3. ANOMALOUS RESISTIVITY

Following Hayashi and Sato (1978), the resistivity is taken to be a function of electric current density \( j \), given by

\[
\eta = \begin{cases} 
\eta_0 (j/j_c - 1)^2 & (j > j_c), \\
0 & (j < j_c).
\end{cases}
\]  

(11)

The associated Reynolds number is

\[
R_m = \begin{cases} 
R_{m0} (j/j_c - 1)^{-2} & (j > j_c), \\
\infty & (j < j_c)
\end{cases}
\]  

(12)

where \( R_{m0} = \mu_0 \nu_0 L_0 / \eta_0 \) and \( j_c \) is the critical current density below which the resistivity vanishes. Both \( j \) and \( j_c \) are normalized by \( j_0 = B_0 / (\mu_0 L_0) \).

The anomalous resistivity plays a crucial role during the magnetic energy buildup process. The resistive dissipation and magnetic reconnection associated with it serves as a prerequisite of conversion of magnetic energy to thermal energy in regions of centralized current with \( j > j_c \). In other regions with \( j < j_c \), the magnetic field evolves in an ideal MHD manner so as to efficiently store magnetic free energy in the solar atmosphere. Physically, the anomalous resistivity reflects dissipations caused by microscopic instabilities associated with electric current. Careful study is needed concerning its origin and appropriate mathematical description but beyond of the scope of this study. For lack of a unanimous conclusion on the representation of the anomalous resistivity, we take Equation (11) with a more or less artificially selected value of \( j_c \) as an expedient.

2.4. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The computational domain is taken to be \( 0 \leq x \leq 3, 0 \leq y \leq 3 \); and discretized into a \( 61 \times 61 \) uniform mesh. A symmetrical boundary condition is applied to the
left boundary \((x = 0)\) and a non-reflecting boundary condition to the right \((x = 3)\) and top \((y = 3)\) boundaries. A shear motion is introduced at the base \((y = 0)\) exactly along the \(z\)-direction so that \(v_x(t, x, 0) = 0\) and \(A(t, x, 0) = A(0, x, 0)\). In addition, it is limited in between the magnetic neutral lines of the two local bipolar fields in the flank \((|x| < 1.5)\), i.e., within the magnetic region of N–S polarity across the center. As one knows, volume current in a bipolar field region comes from a gradient of the shear speed at the base instead of the magnitude of the shear speed. Meanwhile, the deformation of the magnetic field in two adjacent bipolar field regions by shear will bring about a pinch on the separatrix between them, leading to the occurrence of either a current sheet if the magnetic field evolves in an ideal MHD manner, or a high-current layer in the presence of anomalous resistivity right on the separatrix. To exclude the direct contribution of shear velocity gradient to electric current formation on the lower branch of the separatrix, we intentionally let the shear velocity take a maximum at the footpoints of that branch \((x = \pm0.53)\), where the shear velocity gradient vanishes. To this end, we take

\[
v_z(t, x, 0) = \begin{cases} 
v_m(t) \text{sign}(x) \left[ 1 - \left( \frac{|x|}{0.53} - 1 \right)^2 \right], & |x| < 0.53, \\
v_m(t) \text{sign}(x) \left[ 1 - \left( \frac{|x| - 0.53}{0.91} \right)^2 \right], & 0.53 \leq |x| < 1.44, \\
0, & |x| \geq 1.44,
\end{cases}
\]

(13)

where \(v_m(t)\) is the peak shear velocity at \(t\), and it increases with time from zero to 20 km s\(^{-1}\) within a period of \(\tau\) and keeps constant hereafter. Figure 1(b) shows the profile of \(v_z\) at the base for \(t \geq \tau\) by solid line. For comparison, an alternative for Equation (13),

\[
v_z(t, x, 0) = \begin{cases} 
v_m(t) \text{sign}(x) \left[ 1 - \left( \frac{|x|}{0.265} - 1 \right)^2 \right], & |x| < 0.53, \\
0, & |x| \geq 0.53,
\end{cases}
\]

(14)
as shown in Figure 1(b) by a dotted line, is also considered. It confines the shear within the base of the central local bipolar field. Incidentally, other quantities such as \(\rho, T, v_y,\) and \(B_z\) are all calculated through equi-value extrapolation at the base.
2.5. Parameters

The related characteristic parameters are taken to be

\[ \rho_0 = 1.67 \times 10^{-9} \text{ kg m}^{-3}, \quad T_0 = 10^5 \text{ K}, \quad v_0 = 41 \text{ km s}^{-1}, \]
\[ L_0 = 10^4 \text{ km}, \quad A_0 = 5 \times 10^5 \text{ Wb m}^{-1}, \quad B_0 = 5 \times 10^{-2} \text{ T}, \]
\[ j_0 = 4 \times 10^{-3} \text{ A m}^{-2}, \quad v_{m0} = 0.49, \quad j_c = 2, \quad \gamma = \frac{5}{3}, \quad \tau = 20 \tau_A, \]
\[ \beta_0 = 2.8 \times 10^{-5}, \quad R_{m0} = 6000, \]

where \( j_c \) stands for a critical current density of \( 8 \times 10^{-3} \text{ A m}^{-2} \), equivalent to a field strength gradient of \( 0.1 \text{ G km}^{-1} \), \( v_{m0} \) stands for a maximum shear velocity of \( 20 \text{ km s}^{-1} \) and \( \tau_s = L_0 / v_{A0} = L_0 (\beta / 2)^{1/2} / v_0 = 9.2 \text{ s} \) is the Alfvénic transit time and will be used later on as the time unit instead of \( t_0 \). The shear motion in the photosphere has a typical velocity ranging from 0.1 to 1 \text{ km s}^{-1}; taking a larger shear velocity here is aimed at saving computer time. Equations (2)–(8) are solved using the multistep implicit scheme developed by Hu (1989).

3. Results

In what follows, discussion is aimed at the shear pattern given by Equation (13), and the alternative given by Equation (14) is considered only for comparison. As we will see later, the magnetic field is nearly force-free during its evolution, and thus the electric current is almost along the field lines everywhere and in the same direction as the magnetic field. If either the shear speed or the magnetic field changes in direction, then the electric current will become antiparallel to the magnetic field instead. The distribution of the magnitude of the electric current density is shown in Figure 2 at several separate times. As Figure 2 shows, a loop-like high current density structure appears in each of the three local bipolar regions, with its roots located in the vicinity of the maxima of the shear velocity gradient. Besides, strong current is also found on the separatrix. As Equation (13) shows, the shear velocity takes its maximum at the base of the lower branch of the separatrix, but its gradient vanishes there; no shear exists at the base of the upper branch of the separatrix. Therefore, the occurrence of strong current on the separatrix is not directly owing to the shear motion. Actually, it originates from a pinch on the separatrix provided by the three local bipolar fields, which expand upwards due to the shear motion. In particular, the current density in the vicinity of the neutral point is first to become larger than \( j_c \) so as to switch on anomalous resistive dissipation. The resistive dissipation and the expansion of the heated plasma reduce the current density there, but the pinch provided by the sheared magnetic field enhances it. At the beginning when the separatrix is low in position, the pinch effect dominates, and the current density near the neutral point remains larger than \( j_c \). During the upward
Fig. 2. The electric current density distribution at $t = 20, 40, 60,$ and $80 \tau_A$. 
movement of the separatrix the pinch of the sheared magnetic field weakens, and the current density decreases with time. Eventually the current density becomes less than $j_c$ and the related anomalous resistive dissipation stops. Within the central high current loop and near the base of the lower branch of the separatrix, current density may also exceed $j_c$. In these regions the shear effect takes a leading role so as to keep the current density higher than $j_c$; the associated resistive dissipation there constitutes the main contribution to atmospheric heating. In places other than the two high current regions, current density has been less than $j_c$, and thus no anomalous resistivity dissipation and atmospheric heating take place.

Figure 3 shows the magnetic configuration and distributions of the temperature, excessive magnetic energy density and $B_z$ at $t = 80 \tau_A$. It can be seen through comparing Figure 3(a) with Figure 1(a) that each labeled field line moves upwards during the shear, leading to a pinch on the separatrix (dashed line in both panels). Under the action of the pinch, the separatrix ascends and the two branches combine partly into a segment of a transverse one across the neutral point. The value of $A$ on the separatrix changes from 0.68 at $t = 0$ to 0.66 at $t = 80 \tau_A$, which means that magnetic reconnection has occurred at the neutral point. Incidentally, if the shear motion is limited to the base of the central local bipolar region, as given by Equation (14), the related transverse separatrix ascends faster and becomes wider. Moreover, the current density on the upper branch of the separatrix decreases substantially, and no high current loops appear in the local bipolar fields on the two sides. As Figure 3(b) shows, the anomalous resistivity dissipation causes an increase of temperature in regions on the newly formed transverse separatrix and the lower branch of the separatrix, whereas adiabatic cooling leads to a slight decrease of temperature elsewhere.

Wu et al. (1984) obtained a distribution of excessive magnetic energy density for a sheared bipolar field, and related the concentration of the excessive energy with flare occurrence. Figure 3(c) shows the distribution of excessive magnetic energy density for the sheared quadrupolar field. In comparison with Figure 2, no one-to-one correspondence exists between high densities of excessive energy and electric current. As a matter of fact, a high current density region appears to coincide with a large gradient region of the magnetic energy density. In regions with a comparatively low excessive magnetic energy density, say, on the separatrix or in the highly stressed loops inside the local bipolar regions, current density may be very large. An incomplete coincidence between a high current density region and a high excessive magnetic energy density region indicates that the two regions play different roles in solar flares. Anomalous resistive dissipation in high current regions may serve as a trigger for solar flares, whereas high excessive magnetic energy regions may provide a sufficient amount of magnetic free energy to them. In general, the coexistence of the two sorts of regions in an active region is a necessary condition for flare occurrence.

The sheared magnetic field is nearly force free since the ratio of gas pressure to magnetic pressure is small, $10^{-3}$ in order of magnitude. Therefore, $B_z$ is almost
Fig. 3. (a) The magnetic field configuration, (b) the temperature contours ($\times 10^5$ K), (c) the excessive magnetic energy density contours ($\times 10^{17}$ erg km$^{-3}$), and (d) the $B_z$ contours ($\times 500$ G) at $t = 80 T_\nu$. 
constant along each magnetic field line, as seen from Figures 3(a) and 3(d). In the vicinity of the newly formed transverse separatrix and the base of the lower branch of the separatrix, however, $B_z$ contours deviate slightly from field lines, because the variation of $B_z$ caused by resistive dissipation in these locations propagates outward along field lines with a finite speed.

Now let us discuss the growth of magnetic and thermal energy due to the shear. Figure 4 shows the magnetic energy ($E_m$) and the thermal energy ($E_t$) in the computational domain ($|x| \leq 3$, $0 \leq y \leq 3$, $0 \leq z \leq 3$) as a function of the maximum shearing displacement ($s$) for different sets of parameters $R_{m0}$ and $j_c$. Taking the shear pattern given by Equation (13) as an example, a larger $R_{m0}$ or $j_c$ results in a larger growth rate of $E_m$ but a smaller one of $E_t$ (Figures 4(a–d)). In other words, the magnitude of the anomalous resistivity and the time when the anomalous resistive dissipation sets in are closely related to the magnetic energy buildup and the associated atmospheric heating. However, such a relation exists only for sufficiently large shearing displacement. As for a small shearing displacement, the growth of $E_m$ and $E_t$ has nothing to do with values of $R_{m0}$ and $j_c$. The reason is obvious: a slightly sheared magnetic field has its current density less than $j_c$ everywhere, and hence no resistive dissipation takes place. For the shear pattern given by Equation (14) (see dotted line in Figures 4(e) and 4(f)), the growth rate of $E_m$ decreases remarkably, but the growth rate of $E_t$ turns out to be slightly higher compared with those for the shear pattern given by Equation (13) (see solid lines in Figures 4(e) and 4(f)).

Figure 4 also shows that $E_m$ increases nonlinearly with $s$: the larger $s$ is, the higher the growth rate of $E_m$ will be. In interpretation of numerical results it is improper to take an average growth rate of magnetic energy over a certain range of shearing displacement as that throughout the whole range of the shearing process. A correct estimation should be achieved based on a synthetic analysis of the shear of the initial magnetic field and the subsequent process of shear as a whole. The increase of $E_t$ is also nonlinear. It stems from an adiabatic compression for small displacement ($s < 5 \times 10^3$ km) and mainly from anomalous resistivity dissipation for large displacement ($s > 10^4$ km). For a moderate shearing displacement, the two effects mentioned above coexist but are both weak, and the thermal energy increases rather slowly with $s$ (see Figures 4(b), 4(d), and 4(f)).

For $\beta_0 = 2.8 \times 10^{-3}$, $j_c = 2$, and $R_{m0} = 6000$, the net gains of $E_m$ and $E_t$ reach $1.65 \times 10^{31}$ ergs and $3.6 \times 10^{30}$ ergs, respectively, and the ratio $E_t/E_m = 22\%$. The shear takes nearly 42 hr if the shear velocity is set to be 0.1 km s$^{-1}$. More magnetic energy storage is attained taking a smaller value of $\beta_0$, i.e., a stronger initial magnetic field. Moreover, the ratio of the thermal energy gain to the magnetic energy gain increases when $R_{m0}$ or $j_c$ decreases. For instance, this ratio becomes 37\% for $R_{m0} = 50$ and $j_c = 2$ (cf., Figures 4(a) and 4(b)). In general, the gain of thermal energy holds a considerable share in the energy budget during the shear of a multipolar field.
Fig. 4. The magnetic energy ($E_m$) and the thermal energy ($E_t$) vs the displacement ($s$) for several values of $R_{e,0}$ and $j_c$ (a–d), as well as for two patterns of shear motions (e, f) given by Equation (13) (solid line) and Equation (14) (dashed line). $R_{e,0}$ = 6000 and $j_c = 2$ for all curves unless specified otherwise.
4. Conclusions

We have made a numerical study of the magnetic energy buildup and atmospheric heating in a quadrupolar field by photospheric shear motion in terms of a two-dimensional dissipative MHD model. The initial magnetic field is assumed to be a quadrupolar potential one embedded in an isothermal atmosphere with the gravity neglected. A distinct feature of the present simulation lies in the fact that the initial field is a quadrupolar one instead of a dipole, and anomalous resistive dissipation is incorporated in the model. Several main conclusions are summarized as follows.

(1) Like a bipolar field, a quadrupolar field can efficiently store magnetic free energy through photospheric shear motion. The growth rate of the magnetic energy becomes higher and higher with increasing shearing displacement.

(2) Electric current formed by shear concentrates in magnetic loops rooted in areas where the shear velocity gradient is large. Strong current also appears on the separatrix because of a pinch on it provided by the neighboring sheared magnetic fields.

(3) The anomalous resistivity dissipation in high current density regions hinders the growth of current density there and converts part of the magnetic energy into thermal energy. The growth of thermal energy comes from an adiabatic compression for small shearing displacement and is attributed mainly to anomalous resistive dissipation otherwise. In general, the gain of the thermal energy holds a considerable share and it amounts to $\frac{1}{5} \sim \frac{1}{3}$ of the gain of the magnetic energy.

(4) When the anomalous resistivity increases or the critical current density decreases, the growth rate of the magnetic energy reduces and the growth rate of the thermal energy goes up.

(5) The region of high excessive magnetic energy density does not completely coincide with the region of high current density; the coexistence of the two regions in an active region seems to be a necessary condition for flare occurrence.

References