Multi-Wavelength Imaging of Solar Plasma – High-Beta Disruption Model of Solar Flares –

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Solar atmosphere is filled with plasma and magnetic field. Activities in the atmosphere are due to plasma instabilities in the magnetic field. To understand the physical mechanisms of activities / instabilities, it is necessary to know the physical conditions of magnetized plasma, such as temperature, density, magnetic field, and their spatial structures and temporal developments. Multi-wavelength imaging is essential for this purpose. Imaging observations of the Sun at microwave, X-ray, EUV and optical ranges are routinely going on. Due to free exchange of original data among solar physics and related field communities, we can easily combine images covering wide range of spectrum. Even under such circumstances, we still do not understand the cause of activities in the solar atmosphere well. The current standard model of solar activities is based on magnetic reconnection: release of stored magnetic energy by reconnection is the cause of solar activities on the Sun such as solar flares. However, recent X-ray, EUV and microwave observations with high spatial and temporal resolution show that dense plasma is involved in activities from the beginning. Based on these observations, I propose a high-beta model of solar activities, which is very similar to high-beta disruptions in magnetically confined fusion experiments.

Keywords: solar flare, solar activity, solar corona, high-beta plasma, ballooning instability, solar plasma imaging

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1. Inroduction

Solar flares and other energetic phenomena occur in the solar corona. The solar corona is the upper solar atmosphere where the temperature is around 2 million K and the density is around $10^{14}\,\mathrm{m}^{-3}$. In active regions (around sunspot), temperature is several million K and the density is larger than $10^{15}\,\mathrm{m}^{-3}$. Major elements of the corona are Hydrogen and Helium. Due to high temperature, they are in plasma state. The reason why such high temperature atmosphere can extend above 6000 K surface, which is called photosphere, is not yet known. Coronal heating problem is one of the most important problems for solar physics and also for astrophysics. Magnetic field strength of the corona is several to hundred gauss. Hence the plasma beta value (= plasma pressure/magnetic pressure) is very small in normal condition.

Solar flares and other high-energy phenomena are sudden energy release phenomena in the solar corona. Before the release, energy needs to be stored in the corona. In the low beta corona, it is assumed that the energy is stored in the form of magnetic field. Major part of the magnetic field in the corona is potential field. Free magnetic energy is due to electric current flowing in the corona. In the standard model of solar flares (e.g. [1]), it is assumed that the current is in the form of very thin sheet and the current sheet create anti-parallel magnetic field perpendicular to the current. When localized anomalous electric resistivity appears in the current sheet, the current will disrupt and the anti-parallel magnetic field will reconnect. Reconnected field will move along the field due to magnetic tension force and hit the closed magnetic field region and the flow kinetic energy will be converted to thermal energy. The thermal energy is used to heat up lower atmosphere and supply hot and dense plasma into the corona. This reconnection model is supported by observations such as cusp shaped hot plasma loop found by soft X-ray telescope [2] and hard X-ray loop top source found by hard X-ray telescope [3]. However, key elements for this model are not yet clear. There are no direct observations of magnetic reconnection and thin current sheets. How to create thin current sheet and sustain such thin current sheet for a certain moment before disruption is not clear. Cause of anomalous resistivity is not yet known.

In the following section, new observational evidences are presented which show involvement of high-beta plasma from the beginning of solar flares. In section 3, high beta plasma physics is briefly reviewed and is applied to the solar coronal plasma. Then, a new solar flare model is proposed based on these observations and on high beta plasma physics.

2. New Observations

Recent multi-wavelength imaging observations of solar flares with high-cadence and high spatial resolution show that there are many flares without anti-parallel mag-

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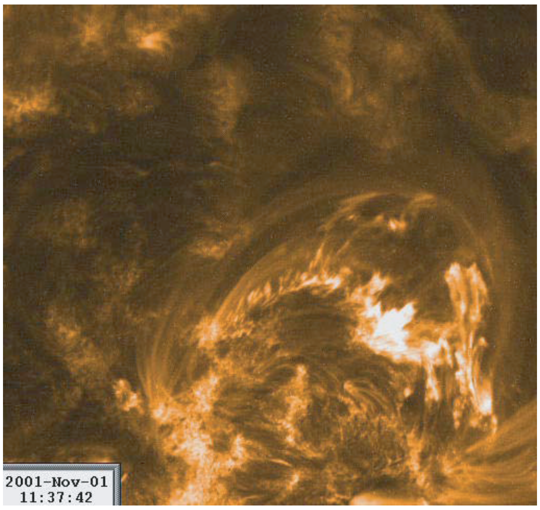
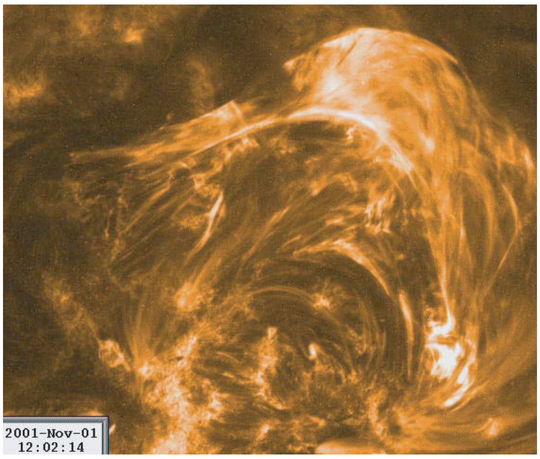
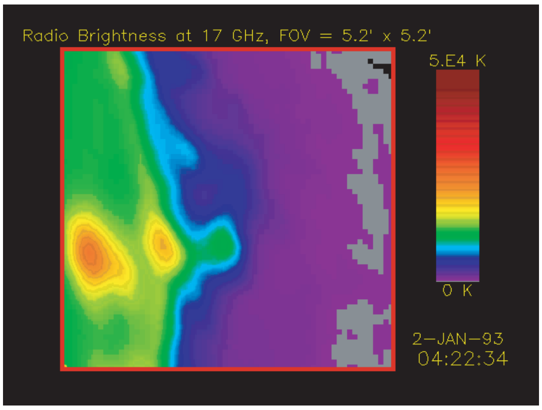


(a)

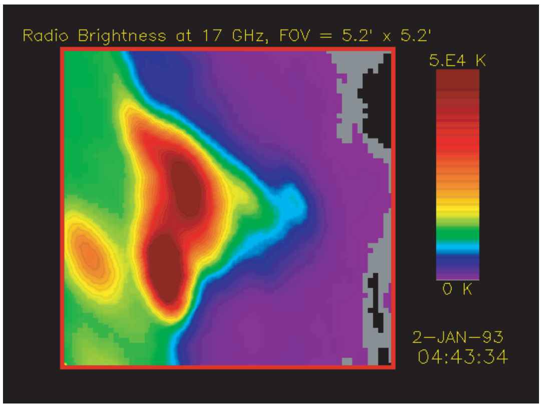


(b)

Fig. 1 EUV images of a solar flare observed by TRACE satellite on Nov. 1, 2001. The top panel (a) is in the very early phase of the development when many plasma fingers are seen along a long filament. The bottom panel (b) is in the developed phase when whole loops are occupied by heated plasma.



(a)



(b)

Fig. 2 Microwave images of a solar flare observed by Nobeyama Radioheliograph on Jan. 2, 1993. The top panel (a) is in the very early phase of the development when small plasma cloud is injected into a large loop. The bottom panel (b) is in the developed phase when the whole loop is occupied by heated plasma.

netic configuration and also show involvement of high density plasma from lower atmosphere in the very beginning of flares. Other observations also show many evidences of involvement of high-density plasma in the beginning (e.g. [4]).

Figure 1 shows images taken by Transition Region and Coronal Explorer (TRACE) satellite in EUV range. TRACE is a solar dedicated satellite operating in EUV, UV, and optical range and has been taking solar images since 1998 [5]. The top panel (a) is in the very early phase of the development when many plasma fingers directed upwards are seen along a long filament. The bottom panel (b) is in the well developed phase when the whole loops are occupied by heated plasma injected as fingers.

Figure 2 shows images of another flare taken by Nobeyama Radioheliograph (NoRH) in microwave range. NoRH is a solar dedicated radio interferometer with 84 element antennas and has been taking solar images at 17 GHz since 1992 and 34 GHz since 1995 [6]. The top panel (a) is the very early phase of the development when a small plasma cloud is injected into a large loop from one of the loop footpoints. The bottom panel (b) is the well developed phase when the whole loops are occupied by heated plasma.

These observational evidences suggest involvement of high beta plasma in solar flares not only as the result of energy release, but also as the cause of energy release. Dense plasma is lifted in the very early phase of solar flares before hot plasma appears.

3. Magnetic Properties of Plasma

Properties of magnetized plasma are well described by magneto-hydrodynamic (MHD) equations. However, the MHD treatment cannot explicitly describe non-linear and diamagnetic nature of plasma. In this section, plasma is treated as electromagnetic media.

3.1 Magnetic moment of plasma

Moving charged particles in magnetic field gyrate around magnetic field due to Lorenz force, which is perpendicular to both magnetic field and velocity. In normal solar active regions, gyration radius (or Larmor radius) of protons and electrons are about 2 m and 4 cm respectively. As the Coulomb mean free paths of electrons and protons are about 400 km, both electrons and protons are well magnetized. Gyration of charged particles creates ring currents and they are equivalent to magnetic moment. As the direction of the charged particles depends on the sign of electric charge, the direction of the ring current is the same for both electrons and protons. In case the plasma is in thermal equilibrium state with temperature T, magnetic moment per unit volume is:

$$\vec{M} = -\left(\frac{2Nk_BT}{B}\right)\left(\frac{\vec{B}}{B}\right), \quad (1)$$

where $\vec{B}$ is magnetic flux density, N is plasma density and k_B is the Boltzmann constant. For simplicity, it is assumed that solar coronal plasma consists of electrons and protons. This expression clearly shows the non-linear and diamagnetic nature of plasma. Magnetic flux density is related to magnetic field ($\vec{H}$) and magnetic moment as follows:

$$\vec{B} = \mu_0(\vec{H} + \vec{M}). \quad (2)$$

The ratio between the magnetic moment (2nd term on the right hand side) and magnetic flux density (left hand side) is the plasma beta. This means that magnetic moment term is ignored in the low beta treatment. The vector rotation of the left hand side gives the total current and that of the first term of the right hand side gives the true current. The rotation of the second term gives the magnetization current which flows perpendicular to $\vec{B}$. The magnetization current is the result of the gyration of charged particles due to thermal motion and Lorenz force. Hence, Joule dissipation of the magnetization current is not expected. This current is also neglected in the low beta treatment. The scalar relation of equation (2) along $\vec{B}$ is:

$$B^2/2\mu_0 - HB + 2Nk_BT = 0. \quad (3)$$

The condition that B has real values which satisfy Equation (3) is,

$$\beta_0 \equiv \frac{2Nk_BT}{B_0^2/2\mu_0} \leq 1/2 \text{ or } \beta \equiv \frac{2Nk_BT}{B^2/2\mu_0} \leq 2, \quad (4)$$

where $B_0 = \mu_0 H$ (μ_0 is the magnetic permeability of the vaccum). When plasma beta exceeds this limitation, plasma needs to be separated into two parts; one satisfies Equation (4) and the other, which has no magnetic field.

3.2 Magnetic energy and magnetic force

Calculation of magnetic energy of non-linear magnetic media is different from that of linear magnetic media. Magnetic energy increment is calculated as follows [7]:

$$\delta U = \vec{H}\cdot\delta\vec{B} = \delta\left(B^2/2\mu_0\right) + 2Nk_BT\,(\delta B/B). \quad (5)$$

The second term is due to the interaction between plasma and magnetic field. Magnetic force can be calculated as the energy decrease against displacement as follows:

$$F = -\frac{\delta U}{\delta s} = -\frac{\delta\left(B^2/2\mu_0\right)}{\delta s} - \frac{2Nk_BT}{B}\frac{\delta B}{\delta s}. \quad (6)$$

The second term is the magnetic force acting on plasma. In the particle view, this is the mirror force. This force does not depend on magnetic field strength but depends on magnetic field structure or magnetic scale length. Due to this force, plasmas are pushed toward weak magnetic field region. In the solar corona, magnetic field decreases outwards; hence we expect ubiquitous plasma up-flows against the strong gravity force. The condition that magnetic force exceeds gravity force is:

$$L_B < H_T \quad (7)$$

where

$$\frac{1}{L_B} \equiv \frac{1}{B}\frac{dB}{ds}, \text{ and } H_T = \frac{2k_BT}{mg_0}, \quad (8)$$

m is the proton mass and g_0 is the surface gravity acceleration. L_B and H_T are the magnetic and the hydrostatic scale lengths respectively. In the open radial magnetic field region, upward force is:

$$F = 4Nk_BT/r, \quad (9)$$

where r is the distance from the center of the Sun. This force is the same as the driving force of solar wind [8]. In the closed magnetic field, plasmas are compressed around the top of the loop where magnetic field is the weakest. As the result, localized high-beta region is created spontaneously around the loop top. In a highly asymmetric closed magnetic field, plasma flows from strong magnetic field region toward weak magnetic field region. Localized high beta region created around the top of the curved magnetic field, and plasma flow along curved magnetic field, are unstable against interchange mode of instabilities due to outward centrifugal force. Because both ends of magnetic loops are anchored at the lower atmosphere, localized interchange mode, called ballooning instability, is expected. In the above process, magnetic field plays as a converter of thermal random motion into coherent flow motion and instability, not as an energy source because the Lorenz force is perpendicular to the velocity.

3.3 Ballooning instability

To realize nuclear fusion in magnetically confined plasma such as Tokamaks, it is necessary to increase plasma density and temperature. To be economic, weak magnetic field for confinement is preferable. These conditions result in high beta plasma. It is well known that high-beta plasma of more than several percent are unstable. This value depends on the magnetic field and plasma configuration and mainly depends on the ratio between the minor radius to the major radius of the plasma torus. When the plasma beta exceeds the limit, the confined plasma will disrupt and this is called high-beta disruption. The actual mode of plasma disruption is mainly the ballooning instability (e.g. [9, 10]). A lot of efforts are going on to suppress the instability with higher beta value. This means that if the plasma beta increases in the solar corona, it will easily disrupt. From the Earth, we can only observe well-developed non-linear phase of the instability, which is not observed in laboratory experiments due to conductors surrounding plasma. In the solar corona, plasma flows play important roles. Strong plasma flow along curved magnetic field lines will result in the similar results as high-beta disruption [11].

4. A New Solar Flare Model

In the previous section, we learned that plasma flows in the solar atmosphere are ubiquitous and that high-beta regions are spontaneously created due to diamagnetic and non-linear nature of plasma. We apply this nature of solar plasma to explain activities in the solar atmosphere, mainly solar flares [11]. High-beta plasma around the top of curved magnetic loops and plasma flows along curved magnetic loops are unstable against localized interchange mode, called ballooning instability. With the particle view of plasma, outward centrifugal force is generated by thermal random motion and/or coherent flow motion along curved magnetic field. Plasma particles drift perpendicular to both magnetic field and the centrifugal force and create drift current along the arcade ridge. Small ripples of plasma boundary along the ridge create space charge and hence electric field. The ripples are enhanced due to force and eventually disrupt. This is the particle view of high-beta disruption. Particle acceleration is expected due to electric field (caused by space charge) along magnetic field lines [12]. The disruption creates turbulent region above the arcade of loops. Turbulent energy and particle beam energy will eventually converted to thermal energy of plasma. Energy source of these phenomena is flow kinetic energy and thermal free energy due to confinement. This high-beta disruption model of solar flares can explain dynamical behavior of plasma in very early phases of solar flares shown by recent high-resolution and high-cadence images at various wavelengths. In this model, it is assumed that each plasma particles in the solar atmosphere have enough energy in the form of thermal and/or flow. How to supply enough energy to particles is the question of coronal heating mechanisms. This problem is not touched here.

5. Summary and Future Directions

Recent imaging and non-imaging observations of solar flares show many evidences of involvement of high-density plasma in the very beginning of the events, not as the result of energy release process in solar flares. These observations suggest that high-beta plasma plays important roles in solar flaring mechanism. Based on studies of diamagnetic and non-linear nature of plasma, it is found that plasma flow is ubiquitous in solar atmosphere and that high-beta regions are spontaneously created in the solar atmosphere. These behaviors of plasma in the atmosphere suggest a new model of solar flares: high-beta disruption model [11].

To prove the high-beta disruption model of solar flares, it is necessary to know physical parameters (density, temperature, flow speed, magnetic field) of pre-erupting plasma in magnetic loops. Also, high-cadence and high-spatial resolution imaging of eruption itself is very important to identify the instability mode during the eruption. Imaging of non-thermal particles by microwave and hard X-ray imager is necessary to identify particle acceleration mechanisms associated with eruptions. For these purposes, multi-wavelength imaging is inevitable. Fortunately, we have many solar dedicated telescopes onboard satellites and on the ground. Especially, recently launched HINODE satellite has optical, EUV and soft X-ray imagers with high-spatial resolution and high-cadence and can diagnose plasma parameters including magnetic field. I hope, this new set of telescopes and existing telescopes will provide datasets to prove the high-beta model of solar flares and other activities.

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