High-beta Disruption in the Solar Atmosphere

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ABSTRACT

The outer layers of X-ray loops in solar flares are known to be more active: they are hotter than the lower loops and above-the-loop-top hard X-ray sources are formed there. These phenomena are interpreted as the result of the reconnection above the loop, which convert magnetic energy into thermal and non-thermal energy of plasma. However, little direct evidence for the reconnection has been presented so far. This paper interprets the activity in the outer layer of flaring loops on a different scenario. Coronal loops filled with hot and dense plasma (high beta) or with fast plasma flow, surrounded by the low-beta corona, are unstable at their outer boundary where the curvature is convex outward and the density gradient is inward. The centrifugal force acting upward on the plasma in the loop can exceed that of gravity. This condition is favorable for localized interchange instability called "ballooning instability" and the plasma in the loop is ejected when the instability has developed into non-linear phase ("high-beta disruption"). This is a natural consequence of the high-beta (and/or the high velocity) plasma confined in a curved coronal loop. The high- beta disruption has many elements common to solar flares. In this paper, importance of the high-beta plasma is stressed, which is a neglected part of the solar activity so far.

Subject headings: instabilities, plasmas, sun: corona, sun: flares

1. Introduction

The solar corona is believed to be generally low beta. In a low-beta plasma, any excess energy is stored in the form of magnetic free energy, above that represented by a potential field. Energy inputs to the corona can be foot-point motions of magnetic fields which are anchored at the photosphere, or the emergence of new magnetic flux from below. Due to the high electric conductivity of the corona, magnetic energy or electric currents cannot easily dissipate. Rather, the magnetic field lines deform or electric currents flow to store the input energy. To transform the stored magnetic energy into thermal or non- thermal energy of plasma, special conditions are needed. Slow magnetic energy dissipation can be realized by enhanced conductivity in the corona. However, sudden energy release or transformation in solar flares requires localized anomalous resistivity or some other special mechanism in a particular magnetic configuration.

Soft X-ray observations of solar flares show that high density and high temperature plasmas are created in solar flares. They are often confined in small volumes (e.g. Acton et al. (1992)). We expect such plasmas to have finite beta. The Nobeyama Radioheliograph (NoRH) often observes flares with a configuration consisting of a small loop and a large loop together (Nishio et al. 1997; Hanaoka 1997). The sizes of small loops are unresolved or barely resolved with the spatial resolution of the instrument (about 10 arcsec.). Recent TRACE observations (Schrijver et al. 1999) of million-degree corona in active regions showed that plasmas are heated and upward flow motions are driven within the height range of 10 - 20 Mm from the base of the corona. Small flaring loops and energetic phenomena at lower heights in active regions suggest that high-density plasmas be confined to small magnetic loops. It is known that high-beta plasma contained in curved magnetic field is unstable at its outer boundary. High-speed plasma flow along curved magnetic loops, which we can see frequently in TRACE movies (Schrijver et al. 1999), is also unstable if the flow speed exceeds certain value. *Yohkoh* (e.g. Klein et al. (1999)) and NoRH (Shibasaki 1996) also frequently observe plasma flows along magnetic loops associated with flares.

The most extensive studies of high-beta plasma are in the field of nuclear fusion experiments. To realize economical fusion, high density and high temperature plasma contained in a weaker magnetic field is favorable. The stability of such plasmas in the Tokamak configuration has been studied both by experiments and by numerical simulations (e.g. Park et al. (1995)). In the fusion experiments, the greatest interest is to know the conditions for stability. Studies of how instability develops into its non-linear phase and eventually disrupts the structure have also been done. However, due to the boundary conditions of the experiments, no experimental studies of the behavior of the disrupted plasma can be done. Difficulties of the confinement of high-beta plasma in a curved magnetic field are based on the diamagnetic nature of plasma.

Studies of high-beta plasma in space have been done in the field of Earth's magnetosphere as one of the scenario of auroral substorm (Miura et al. 1989; Ohtani et al. 1989; Roux et al. 1991; Ohtani and Tamao 1993). Near the inner edge of the plasma sheet, the plasma density is rather high and magnetic lines of force are in a closed form. A configuration of high-beta plasma contained in a curved magnetic field is realized there. The stability of this plasma has been studied analytically under the condition of small perturbation. Localized interchange instability (ballooning instability) is expected under such conditions and has been proposed as the onset of an auroral substorm (e.g. Kan et al. (1998)).

In the solar corona, Pustilnik (1973) suggested the ballooning instability as a cause of prominence destabilization. The condition that the heavy prominence matter is supported by the magnetic field is favorable for the ballooning instability. Pustilnik and Stasyuk (1974) also suggested the ballooning instability as a trigger mechanism of the fast magnetic reconnection in the current sheet. High-beta loops created by flares have been discussed as the cause of opening up the loop (Zaitsev and Stepanov 1985) so that the high-energy particles, which are produced in solar flares, can escape into the interplanetary space and eventually can reach the Earth. Theoretical studies of the beta-dependent stability of a loop and an arcade in solar coronal conditions were done by Hood (1986).

In the following sections, we discuss the equilibrium and the stability of the closed magnetic loops filled with high-beta plasma and with high-speed plasma flow. The roles of high- beta plasma and that of high-speed plasma flow in magnetic loops will be discussed in the following section in conjunction with a solar flare scenario. Observational evidences for high- beta plasma and high-speed flow in loops will be reported in separate papers.

2. Plasma in Curved Magnetic Loops

Magnetic field in the solar corona has either an open structure or a closed structure. In the case of the closed structure, the magnetic lines of force are curved. Plasma contained in the curved magnetic field causes various effects due to the bounded motion of charged particles along the magnetic lines of force.

In the following sub-sections, we compare the centrifugal force in closed magnetic fields in the solar corona with gravity and with the magnetic tension force. Then we discuss the equilibrium of plasma contained in coronal loops. Gaussian CGS units are used for the derivation of equations. In the application to the coronal conditions, we introduce normalized units by typical order values of the corona for easier estimation.

2.1. Centrifugal Force vs. Surface Gravity

We often see plasma flow in the solar atmosphere. If the plasma flow is restricted by the closed magnetic lines of force, their motion along the curvature generates an apparent centrifugal acceleration (g_k),

$$g_k = V^2/R, \tag{1}$$

where V is the flow speed along the field and R is the local curvature radius.

Even without bulk flows, the thermal motions of gyration centers of electrons and ions are also restricted by the magnetic lines of force. Their motions generate centrifugal acceleration (g_T),

$$g_T = V_{||}^2/R \tag{2}$$

where $V_{||}$ is the velocity component of the thermal motion along the magnetic field. The mean velocity is related to the plasma temperature (T) and the above equation is rewritten as,

$$g_T = k_B T/(mR) \tag{3}$$

where k_B is the Boltzmann constant ($= 1.38 \times 10^{-16}$ erg K^{-1}) and m is the mass of the ion or the electron.

In the following, we study the ratios between the centrifugal forces (F_k and F_T, upward) and the gravity force (F_g, downward) at the loop apex acting on a plasma volume element. Normalized energy densities (kinetic, thermal, and potential) by the magnetic energy density are used to express the ratios:

$$\beta_k = \left(\frac{1}{2}\right)\rho V^2/\left(\frac{B^2}{8\pi}\right), \tag{4}$$

$$\beta_T = P/\left(\frac{B^2}{8\pi}\right), \tag{5}$$

$$\beta_g = \rho g_0 R/\left(\frac{B^2}{8\pi}\right), \tag{6}$$

where ρ is the plasma mass density, P is the gas pressure, and g_o is the surface gravity acceleration ($= 2.74 \times 10^4$ cm s^{-2}). We refer to these as the kinetic, thermal, and potential beta respectively. The plasma beta is named as thermal beta to distinguish from the others. The ratios of forces are expressed using the beta values as follows:

$$F_k/F_g = 2\beta_k/\beta_g, \tag{7}$$

$$F_T/F_g = \beta_T/\beta_g. \tag{8}$$

For easier estimation of beta values and ratios of forces in the solar corona from observed physical parameters, expressions are given using normalized units of the solar corona as follows:

$$\beta_k \sim 2.1 \times N_9 V_7^2/B_G^2, \tag{9}$$

$$\beta_T \sim 6.9 \times N_9 T_6/B_G^2, \tag{10}$$

$$\beta_g \sim 1.1 \times N_9 R_9/B_G^2, \tag{11}$$

$$F_k/F_g \sim 3.8 \times V_7^2/R_9, \tag{12}$$

$$F_T/F_g \sim 6.3 \times T_6/R_9, \tag{13}$$

where N_9 is the plasma number density in units of 10^9 cm^{-3}, V_7 is the velocity in units of 100 km s^{-1}, T_6 is the temperature in units of million Kelvin, R_9 is the curvature radius in units of 10 Mm, and B_G is the magnetic field strength in Gauß. In derivation of the above expressons, we assumed fully ionized hydrogen gas. Hence $\rho = m_p N$ and $P = 2Nk_BT$, where m_p is the proton mass ($= 1.67 \times 10^{-24}$ g) and N is the plasma number density.

In case of 10 Mm radius loop with 100 km s^{-1} bulk flow or million-degree temperature plasma, the centrifugal force exceeds the gravity force. The plasma pushes the magnetic lines of force upward rather than downward. In case of hot plasma and high-speed flow associated with flares, gravity is negligible even in large loops. Trapped hot and/or fast plasma is ready to fall outward. Even at the chromospheric temperature ($T_6 \sim 0.01$), the centrifugal force exceeds the gravity force if the loop curvature is less than 0.6 Mm.

2.2. Centrifugal Force vs. Magnetic Tension

The outward force of the apparent centrifugal acceleration is counterbalanced by the magnetic tension force (F_t). The ratios of centrifugal forces and magnetic tension acting on a small segment of a loop near the apex are as follows:

$$F_k/F_t = 2\beta_k, \tag{14}$$

$$F_T/F_t = \beta_T. \tag{15}$$

The kinetic beta of the high-speed plasma flow of several hundred km s^{-1} at high density ($N_9 \geq 10$) can easily approach unity if the field strength is weak ($B_G \leq 30$) which is expected high in the corona. The thermal beta of hot ($T_6 \geq 10$) and dense ($N_9 \geq 100$) plasma in a flaring loop is non negligible even in a stronger magnetic field region ($B_G \geq 100$). High-beta (both thermal and kinetic) plasmas are ready to erupt. The high-beta condition does not necessarily require high temperature. At the chromosphere, the gas density is large enough to compensate lower temperature.

2.3. MHD Equilibrium

To study equilibrium conditions of plasma at the outer boundary of a loop, we need to take into account other forces such as magnetic and gas pressure gradients. We use the MHD equations to study the equilibrium. A kinetic treatment of the instability was developed by Mikhailovskii (1974) and the results are consistent with the MHD treatment. We follow the method by Ohtani and Tamao (1993) and include plasma flows and the gravity force.

The equation of motion is:

$$\rho d\mathbf{V}/dt = -\nabla P + \mathbf{J}/c \times \mathbf{B} + \rho \mathbf{g_0}, \qquad (16)$$

and the Ampére law is:

$$\mathbf{J} = (c/4\pi)\nabla \times \mathbf{B}. \qquad (17)$$

We use coordinates in the plane of a symmetric loop lying vertically (Fig. 1). The orthogonal unit vectors **e** and **n** at the loop top are along the magnetic field and along the direction of the curvature normal toward the curvature center respectively. We assume the flow to be along the magnetic field and the system to be in steady state. The condition of the equilibrium along the curvature normal direction is:

$$\beta_T \kappa_P + \kappa_B = 2\kappa_c(1 + \beta_g/2 - \beta_k), \qquad (18)$$

where

$$\kappa_c = 1/R, \qquad (19)$$

$$\kappa_P = \partial(\ell n P)/\partial n = 1/\ell_P, \qquad (20)$$

$$\kappa_B = \partial(\ell n(B^2/8\pi))/\partial n = 1/\ell_B. \qquad (21)$$

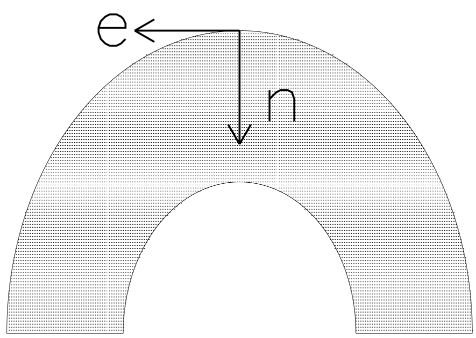

Fig. 1.— The coordinate system.

The pressure scale length (ℓ_P) along the **n** direction is nearly the diameter of the loop. Without the flow and the potential terms, the above equation is the same as the one which Ohtani and Tamao (1993) obtained.

Using the above equation, the interesting nature of the magnetic field and a necessary condition for equilibrium are easily described. In the vacuum, where beta values are zero, the magnetic pressure scale length is exactly half the curvature radius ($\kappa_B = 2\kappa_c$), i.e. the magnetic pressure and the tension are balanced. In the presence of plasma, the kinetic energy density needs to be smaller than the sum of magnetic and potential energy densities ($1 + \beta_g/2 - \beta_k > 0$). In other words, if the kinetic energy density exceeds the sum of magnetic and potential energy densities, no equilibrium can be reached. Such loops start to expand and eventually disrupt. This is one of the high-beta disruptions.

3. Ballooning Instability

The equilibrium of plasma in a coronal loop is established by the balance of outward forces (= pressure gradient + magnetic pressure gradient + centrifugal force) and inward forces (= magnetic tension + gravity force). The magnetic pressure gradient can be directed either outward or inward, depending on the strength of the diamagnetic current. This equilibrium is similar to the condition that heavy liquid is sitting on light liquid supported by the surface tension if the magnetic pressure gradient is negative (magnetic field strength increases with height near the outer boundary of the loop). This situation is unstable against the interchange mode. The global mode of the interchange instability "flute instability" is suppressed in the case of the coronal loops because they are anchored at the photosphere. However, the localized mode of the interchange instability can develop. It is called the "ballooning instability". In the following, we estimate the condition for and the growth rate of this instability. We also summarize the results of the non-linear development of the instability in the nuclear fusion experiments. In the case of the solar atmosphere, plasma flow is an important element that we cannot ignore. Terms representing flow and gravity are thus added as corrections to the existing theory.

3.1. Instability Condition

There are various ways to estimate the condition of the ballooning instability. Here, we use a simple method by using the result of the equilibrium condition obtained in the previous section. As is mentioned already, the condition of the interchange instability is that the heavy plasma is supported by the light plasma with strong magnetic field, i.e. $\kappa_B < 0$. Using the Equation (18),

$$\kappa_B = 2\kappa_c(1 + \beta_g/2 - \beta_k) - \beta_T\kappa_p < 0. \quad (22)$$

The condition for β_T is written as follows:

$$\beta_T > 2(\ell_P/R)(1 + \beta_g/2 - \beta_k). \quad (23)$$

If the thermal beta value exceeds two times of the aspect ratio of the loop (= loop radius / curvature radius), ballooning instability is expected. This is consistent with the result obtained by Mikhailovskii (1974); Ohtani and Tamao (1993). A fat loop is more stable than a slim loop. High-speed flow (large β_k) lowers the critical thermal beta.

3.2. Growth Time and Size of the Instability

To estimate the linear growth time of the instability (τ), we use the free fall time of the distance of the loop diameter ($\sim \ell_p$) due to g^* (= centrifugal acceleration − gravity acceleration).

$$\tau \sim \sqrt{2\ell_p/g^*} \sim 2\sqrt{\ell_p R}/V_A \cdot (\beta_T + 2\beta_k - \beta_g)^{-1/2}, \quad (24)$$

where V_A is the Aflvén speed. In the case of $\beta_k = \beta_g = 0$,

$$\tau \sim 2\sqrt{\ell_p R}/V_s, \quad (25)$$

where V_s is the sound speed. This is consistent with the results obtained by other methods (Mikhailovskii 1974; Ohtani et al. 1989). The growth time of the instability is roughly the geometrical mean of the sound transit time of the system. Under coronal condition,

$$\tau(sec) \sim 100 \times \sqrt{\ell_{p9} R_9 / T_6}, \quad (26)$$

where lengths are in units of 10 Mm. In the case of 10-Mm radius ($R_9 \sim 1$) loop with the aspect ratio of 1/10 (Bray et al. 1991) and filled with two million-Kelvin plasma, the linear growth time is about 20 seconds. Large kinetic beta shortens the growth time while large potential beta lengthens it.

Ohtani et al. (1989) showed that the ballooning instability is caused by the coupling between the slow magnetosonic wave and the Alfvén wave when the thermal beta is large. Waves grow which have a small wavenumber along the loop and a large wavenumber along the arcade. We expect the size along the loop to be comparable to the loop length and that along the arcade to be comparable to the loop diameter. If there are fine structures in the loop, smaller scale features can grow faster.

The physical mechanism of the interchange instability is illustrated in textbooks (e.g. Chen (1974)). If the drift current flowing around the loop is disturbed by waves along the arcade, space charge is formed at both sides of waves, hence an electric field is created. The induced $\mathbf{E} \times \mathbf{B}$ drift enhances the waves. Space charge and electric field, hence particle acceleration, are necessary elements of the instability.

3.3. Non-linear Development of the Instability

The above theories are for the linear phase (or small amplitude) of the instability. However, the phenomena on the Sun that we can observe from the Earth are at large amplitude after non-linear development. Non-linear analytic treatment of the MHD equations by Cowley et al. (1996); Hurricane et al. (1997) showed that line tied Rayleigh-Taylor-Parker instability grows explosively. They term this "detonation". They concluded that explosive behavior is a natural and generic properties of ballooning instabilities close to the linear stability boundary. Their analyses are limited to up to the explosion.

The most extensive studies of the high-beta ballooning instability in the non-linear phase have been done in the field of nuclear fusion studies. To realize economical fusion, high- density and high-temperature plasma contained in weaker magnetic field is favorable. From the geometrical similarity (loop configuration), we survey the results of the research using Tokamaks. Non-linear studies are based mainly on actual experiments and computer simulations. Besides the spatial and temporal scale differences between the Tokamak experiments and the loops in the solar atmosphere, the flow and gravity terms do not play important roles in Tokamak experiments. As conductors surround the plasma torus in a Tokamak, no studies can be done after the disruption. In the solar atmosphere, we can still observe the plasma after its disruption.

High thermal beta plasma experiments and computer simulations by Fredrickson et al. (1995); Park et al. (1995) using Tokamak Fusion Test Reactor showed interesting phenomena. Under the condition of the critical beta (close to the stability limit), a strong local pressure bulge is formed, and it destroys the flux surfaces. A stochastic magnetic field is suggested in the bulge. Near the time of the disruption, a non-thermal electron population forms.

4. Discussions

In this section, we will discuss possible relations between solar flares and the ballooning instability. Due to the limited knowledge of the ballooning instability in the non-linearly developed phase, and also the little knowledge of the ballooning instability under the actual solar conditions, we need to discuss with inference. If some gradual beta-loading process into the coronal loop from the lower atmosphere continues and the plasma beta reaches the critical value (Equation (23)), the ballooning instability will break out. As is shown in the previous sections, the ballooning instability converts thermal energy and kinetic energy in the loop into turbulent wave energy, non-thermal particle energy, and kinetic energy of ejected plasma. The production of higher temperature plasma is expected from the dissipation of turbulent waves and thermalization of non-thermal particles. The discussion is divided into two: loop type flares and arcade type flares.

4.1. Loop Type Flares and the Ballooning Instability

Solar flares have wide range of variety in size, shape, duration, involved energy, etc. However, there are also many common characteristics. Among them, the following items are also found in ballooning instability: activity above the loop, turbulence, plasma concentration, plasma ejection, impulsive nature, and particle acceleration.

By gradual supply of plasma with/without high speed flow into the loop from one of the footpoints, the loop gets unstable at the outer boundary. In the process of development of the instability, enhanced turbulent waves (Alfvén and magnetosonic modes) are expected there. Non-thermal line broadening, detected by BCS/YOHKOH (Bentley 1996) and other observations just before or during the impulsive phase of flares, can be interpreted as the enhanced turbulent waves. Line widths and wave amplitudes can be directly linked. The temporal development of line width (hopefully spatially resolved in the future) will tell us how the instability develops. Due to the coupling of the Alfvén mode (transverse) and the slow magnetosonic mode (longitudinal), we cannot expect a clear directivity of line broadening relative to the magnetic field orientation.

In the Tokamak experiments, it is shown that non-linearly developed instability causes concentration of plasma at regions of bad curvature and eventually it pushes the magnetic field outward and ejects the plasma contained within (Park et al. 1995). The cause of plasmoid ejection from the tops of loops associated with solar flares (Ohyama and Shibata 1998) could thus be attributed to the non-linear development of the ballooning instability. High-density plasma concentrations at the loop top (Acton et al. 1992; Feldman et al. 1994, 1995; Doschek et al. 1995; Jakimiec et al. 1998) could also result from the instability because of the development of a stochastic magnetic field (Park et al. 1995; Fredrickson et al. 1995; Jakimiec et al. 1998).

After the ejection of the plasma from the loop top, the ejected plasma will follow the surrounding magnetic field structure. If the magnetic field above the loop has larger curvature, then the ejected plasma will be thrown out into higher corona. Or, if the magnetic field above the loop has closed structure with similar curvature with the loop, and the ejected plasma cannot continue ballooning, then the plasma will stay there. Structures observed above flare loops could be the plasma cloud stopped above the loop. However, as no researches have ever been done on the behavior of the plasma after ejection by experiments, by computer simulations, nor by theories, we need to develop researches in this field and to compare the results with observations.

In the process of disruption, electric field caused by charge separation plays an important role to enhance waves or instability. Moreover, discharge processes of the separated charges will occur along the magnetic lines of force. Both upward and downward particle accelerations are expected (Roux et al. 1991). These accelerations will be synchronized with excited waves. Quasi-periodic fluctuations of microwave and hard X-ray intensities may be related with the instability. Studies of the relation between the fluctuation periods, loop sizes, and wave velocities, will tell us about the waves in non- linearly developed phase. Loop-top and foot-point hard X-ray and microwave sources are expected due to the bi-directional accelerations caused by the alternate potential drop and increase. Simultaneity of the brightening of hard X-ray sources at both foot points (Sakao 1994) are expected due to the downward electron acceleration by the potential drop at the loop top. Upward-accelerated electrons and/or trapped electrons in the loop by magnetic mirror effects could be trapped in the stochastic magnetic field around the loop top and eventually disrupt. This could be the loop-top hard X-ray source (Masuda et al. 1995). In the Tokamak experiments, non-thermal electron production are recorded in association with the disruption (Park et al. 1995; Fredrickson et al. 1995).

4.2. Filament Eruptions and Arcade Type Flares

The recent discoveries of counter-streaming flows in dark filaments by Hα observations (Zirker et al. 1998) and flows by TRACE observations (Schrijver et al. 1999) have made it possible to apply high-beta (kinetic) scenarios to filament activation. When the kinetic energy density of the flow exceeds a certain value, the filament will start to rise and can eventually reach interplanetary space. If some part of the rising filament collides with the magnetic arcade that overlies the filament, another effective upward acceleration will be generated in the filament plasma. The ballooning instability is expected all along the arcade simultaneously or successively due to this acceleration. Some of the filament plasma can get through the overlying loop due to the non-linearly developed ballooning instability and pull the magnetic field upwards. Fans of rays found by YOHKOH/SXT (Švestka et al. 1998; McKenzie and Hudson 1999) above flare arcades in the post flare phase might be the magnetic field pulled up by this process. Particle acceleration is also expected along each loop in the process of the ballooning instability. A large-scale two-ribbon flare with a bright arcade is expected as the result of the ballooning instability all along the arcade triggered by the collision of the lifting filament with the overlying magnetic arcade. Projected view of the post flare loops along the direction perpendicular to the planes of the loops is the superposition of bright loops, plasma concentrations around the loop top, and the elongated magnetic field above the loops. This mimics the cusp structure above flare loops (Tsuneta et al. 1992). More complicated features are expected when the overlying magnetic field have nested structures.

5. Conclusions and Further Studies

In the previous sections, we showed that high-beta (both kinetic and thermal) plasma confined in magnetic loops can play important roles in solar activity. The centrifugal or curvature force can exceed the surface gravity force. If the kinetic beta exceeds a critical value, magnetic tension cannot restrain the centrifugal force, so no equilibrium can be reached. High-kinetic-beta plasma will lift a loop and could eventually disrupt it. Even if equilibrium were established, a localized instability can develop and develop non-linearly causing disruption. We call these phenomena high-beta disruptions by extension (the original term of high-beta disruption is limited to high-thermal-beta disruption). Magnetic loops filled with high-beta plasma are exciters of solar activity.

High-beta disruption is a promising candidate for a solar flare scenario. It contains various elements associated with solar flares: turbulence, plasma ejection, high-energy particle acceleration both upward and downward, plasma blobs at loop top, over-the-loop (outer layer of the loop) activity, impulsive nature, quasi-periodicity of high energy phenomena and others.

The origin of magnetic activity in the solar atmosphere has long been thought of as magnetic reconnection at low beta. If we start with the low-beta atmosphere, magnetic reconnection may indeed be a natural cause of energy release or activity. Recent observational evidence however suggests that high-beta plasmas must also be playing an important role. Closed magnetic loops act as catalysts to convert thermal and kinetic energies of plasma into other forms.

The high-beta scenario of solar flares presented here needs to be tested by observations quantitatively. First, we need to check the energetics, whether the thermal and kinetic energy estimated from observations is large enough to explain the total flare energy. For the quantitative studies of the instability conditions, the most important physical parameter is the magnetic field strength in loops. Direct measurement of magnetic field strength in loops using circular polarization degree at microwave region (Bogod and Gelfreikh 1980) should be a very powerful technique for these studies. Estimation of coronal magnetic field from the measured photospheric magnetic field with potential (Sakurai 1982) or force-free (Sakurai 1981) assumptions can also be used. For the estimation of thermal energy in loops, multi-wavelength diagnostics of the plasma (temperature and density) in loops are needed. For the estimation of kinetic energy, Doppler shift measurements of lines are needed together with the estimation of plasma densities.

To see the dynamical development of the ballooning process discussed in the previous section, we need high-cadence (a few seconds or better) and high-resolution (better than 1 Mm) observations at the right position and time with all the available diagnostic tools of the plasma, magnetic field and high-energy particles. To realize these conditions, many trials of coordinated observing campaigns of active regions and filaments using many instruments are needed.

As the observed phenomena are mostly at the non-linear phase, it is necessary to do numerical simulations under the condition of the solar atmosphere to understand how the actual disruption proceeds and to compare with actual observations.

In this work, we have not mentioned about beta-loading mechanisms, i.e. how the high-kinetic and high-thermal beta plasmas are supplied from below. This problem seems to be a key to the coronal heating. The ballooning instability in small loops in the dense lower atmosphere can be a candidate, but we need further studies to identify the beta-loading mechanisms.

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