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Observational Evidence of Ballooning Instabilities in a Solar Flare

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Abstract

Radio imaging observation of a solar flare on January 2, 1993, showed the formation isolated radio sources over the loop top of a flaring loop at several times during the flare development. In this paper, it is suggested that these isolated loop-top radio sources are magnetic islands or balloons produced by nonlinear ballooning instabilities due to the high β plasma in the loop. The plasma β is estimated by combining the total flux soft X-ray data, and radio brightness and circular polarization data. The upper boundaries of magnetic loops with high β plasma are unstable against the ballooning instability because of unfavorable curvature (convex outward). A new energy transfer scenario in flares is proposed based on this ballooning instability. It is also pointed out that the centrifugal acceleration caused by thermal motion in the curved magnetic line of force far exceeds the surface gravity and can sustain hot and dense plasma at the top of the elongated loop.

Key words: Sun: flare — Sun: radio radiation — Sun: plasma instability

1. Introduction

Recent observations of flares by the *Yohkoh* satellite found that the area above bright flare loops is energetic. The temperature is higher than that of the bright loop (Tsuneta et al. 1997). Hard X-ray sources are found above the loop top (Masuda et al. 1995). Plasma ejections are found just above the loop (Ohyama and Shibata 1998, Tsuneta 1997). Radio observations also show that the non-thermal radio emission covers a larger area than that of the soft X-ray bright loop (Nakajima and Metcalf 1995). These observational results are interpreted in terms of magnetic reconnection above the bright X-ray loop (e. g. Shibata, 1998). However, key observational evidence is still missing: e.g., no inflow into the reconnection region has been seen (Hara, 1996), no current sheets have been detected, and several other open issues which have been listed by Tsuneta (1996).

In this paper, radio sources which appeared above the loop top are studied. Plasma parameters in the loop are estimated, especially the β value. The capability of measuring the circular polarization of microwaves makes it possible to estimate the magnetic field strength in the corona. The possibility of plasma instabilities at the outer boundary of the loop with high β values are discussed in terms of the appearance of radio source above the flare loop.

2. Radio Imaging Observation of a Limb Event

Microwave imaging observation of the Sun have been made by the Nobeyama Radioheliograph (Nakajima et al. 1994). The Nobeyama Radioheliograph is a radio interferometer dedicated to solar observations. The characteristics of the Nobeyama Radioheliograph made it possible to detect weak and short lived phenomena which we will present in the following sections. Especially, high cadence, wide field of view and high dynamic range imaging capabilities are essential to detect such phenomena. The circular polarization measurement capability makes it possible to measure the magnetic field strength in the corona. The single frequency operation of the heliograph, at the time of this event, limits the interpretation using radio observation only.

The radio event started at 0422 UT on January 2, 1993. It peaked at 0450 UT and the total duration was longer than 2.5 hours. Full disk radio images at 17 GHz were synthesized every 10 seconds. The flare location was on the west limb. The peak brightness temperature reached $10^5 K$ and the integrated total flux reached 11 s.f.u. In the rising phase of the event, various dynamical phenomena were observed (Shibasaki, 1996).

Among them, faint radio sources appeared at several moments above the flare loop. This paper is focused on these sources. The lifetime of these isolated, loop-top radio sources was 2 - 3 minutes. The radio brightness temperature

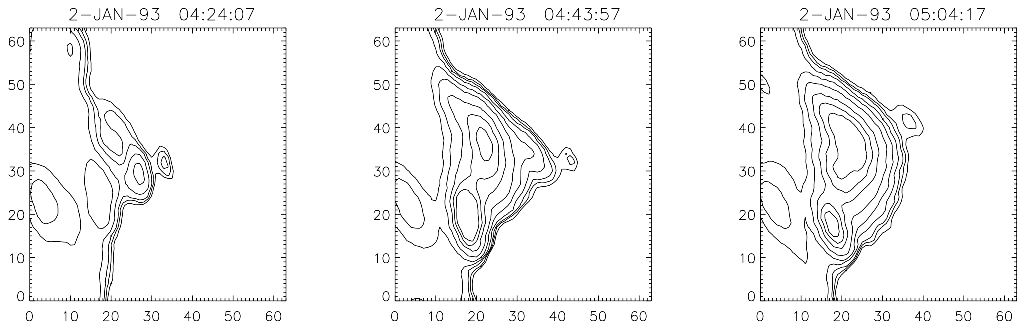

Fig. 1.. Radio Images at the moments when the loop-top sources appeared.

Table 1. Estimated plasma parameters.

Time (UT)	T_B (10^4 K)	Thickness (10^9 cm)	T_c (10^6 K)	N_e ($10^9 cm^{-3}$)	β
0424	2.5	1.4	14	12	0.9
0444	1.0	1.4	8	6	0.3
0504	8.0	3.5	5.5	10	0.3

and the size of these sources were $10^4 K$ and less than 20 arcsec, respectively. Figure 1 shows the radio images at the moments when the loop-top radio sources appeared.

Unfortunately, *Yohkoh* satellite totally missed this event. No $H\alpha$ or meter-wavelength activity was reported. Total flux measurements in the microwave region (2 - 17 GHz) show a flat spectrum around the peak suggesting optically thin thermal f-f emission. The total flux soft X-ray observation by GOES detected an M1.1 class event.

The size of the flare loop is large. The field of view of each panel in Figure 1 is 5.3 × 5.3 arc min. The overall time scale is rather slow; however, very high speed dynamical phenomena are also seen. For these reasons, combined with a very favorable location (on the limb), this event was well observed by the Nobeyama Radioheliograph.

3. Plasma parameters in the flare loop

In the optically thin thermal free-free emission the plasma temperature cannot be estimated from radio observations alone. We use the GOES data of the integrated soft X-ray fluxes in two energy bands (Thomas et al. 1985) to estimate the plasma temperature. The calculated temperature is the averaged plasma temperature of the heated plasma weighted by the emission measure.

The plasma density distribution can be calculated from the measured radio brightness temperature distribution and the plasma temperature obtained from GOES data. In the calculation, the line of sight thickness is assumed to be equal to the minor size of the projected radio source (FWHM). Also, a uniform plasma is assumed.

Measurements of magnetic field strengths in the corona are very difficult in the optical region due to the broadening of the emission lines by high temperature in the corona. In the microwave region, the opacity difference between right- and left-handed circular polarization in the presence of magnetic field is used to estimate the line of sight component of the magnetic field strength in the corona. There is a simple relation between the longitudinal component of the magnetic field in the radio emitting plasma and the circular polarization degree if the emission is optically thin thermal free-free: $P = 2f_H|cos(\alpha)|/f$. At 17 GHz, the magnetic field strength is $B_{||} \sim 30P(\%)$.

The measured and the derived values of the plasma parameters in the loop are listed in Table 1, at the times that isolated loop-top radio sources appeared.

In the above derivation of plasma parameters from the observations, several sources of error may influence the computation of β. The radio brightness temperature error (about 1,000 K) is less than 10 percent of the measured brightness in the flare loop. The plasma temperature is calculated from the ratio of the total soft X-ray fluxes in two different energy bands. In this calculation, an isothermal plasma is assumed. In the rising phase of the flare, we can see two or three isolated radio sources. We expect these isolated sources have different temperatures. Hence the derived temperature and emission measure during the rising phase may deviate from the actual values. We calculated the radio flux from the derived emission measure and temperature and compared it with the observed value. We found about a factor of two difference in the rising phase of the event and 10 percent difference after the maximum phase. As the radio brightness temperature is less sensitive to the actual plasma temperature ($\sim T_c^{-1/2}$), the error of plasma density derived from the radio brightness due to temperature ambiguity in the loop is smaller than 10 percent. The filling factor of the plasma in the flare loop volume is important for deriving the density from the emission measure. We assumed that the filling factor is close to unity when hot plasma dominates the emission.

The magnetic field strength is the most important parameter in the determination of the β value. The circular polarization measurement accuracy is better than 0.1 percent in the case of bright sources such as the flaring loop. We averaged the circular polarization and the intensity images over 30 minutes assuming that the magnetic field structure did not change during the flare. However, we need to assume the angle between the magnetic field direction and the line of sight. In the Table 2, we assumed 60 degrees to derive the magnetic field strength from the measured line of sight component. The measured circular polarization degree is 0.6 percent and the magnetic field strength obtained in the flaring loop is therefore 36 Gauss. The large scale photospheric magnetic field configuration of the active region observed near the disk center (KPNO) supports this orientation.

As a result, the ambiguity of the derived β values will be a factor of two. The main cause of the ambiguity is the assumption of the orientation of the magnetic line of force.

4. Ballooning Instability

In the previous section, it was found that the plasma β in the flaring loop during times the isolated loop-top radio sources appeared were non-negligible (0.3, 0.9). The high β plasma confined in the magnetic field is unstable when the magnetic field curvature is convex outward like a flaring loop. A large scale magnetohydrodynmic (MHD) instability such as a flute instability is suppressed by photospheric anchoring. However, a locally developed instability called a ballooning mode is expected. In the following, we will interpret the presence of isolated loop-top radio sources as the result of a nonlinear ballooning instability in the flaring loop.

Thermal motions of ions between collisions are bound along the magnetic field. Due to the curvature of the magnetic line of force in the loop, the thermal motion causes the centrifugal force. The direction is outward. The centrifugal acceleration is proportional to the square of the velocity component parallel to the magnetic field ($v_{||}$) and is inversely proportional to the curvature (R). Hence, it is proportional to the plasma temperature. A simple calculation shows that the centrifugal force is about 10 times larger than the surface gravity of the plasma when the temperature is 10^7 K and the loop size is 10^{10} cm. The concentration of hot plasma at the tops of flaring loops often observed by the *Yohkoh* Soft X-ray Telescope (Doschek et al. 1995, Feldman et al. 1995) can be explained by the strong centrifugal force due to the small curvature at the loop top and due to the high temperature. It is also expected that higher temperature plasma (higher than million degrees) and lower temperature plasma behave differently in the corona: the former can be sustained in large loops while the latter can be sustained only in low-lying small loops. This may be one of the reason why large coronal loops need to be hotter than a million degree.

Under this condition, plasma in the flaring loop is pushed outward and is confined by magnetic tension. If the magnetic field could move freely, we expect an interchange instability at the outer boundary of the loop. It is called a flute instability. The linear growth rate of the flute instability is: $\gamma_f = \sqrt{(|g/\ell|)}$ (Mikhailovskii 1974), where, g is the effective acceleration due to the centrifugal forces acting on the plasma, and ℓ is the scale size of the plasma density gradient.

However, the coronal magnetic fields are anchored at the photosphere. They cannot move freely (line-tying). Hence, the flute instability is suppressed in the solar corona. Magnetic shear also suppresses the flute instability if it exists. Its effect is similar to that of the line-tying which causes magnetic tension.

When the centrifugal force is strong enough to overcome the magnetic tension, a ballooning instability is expected. The linear growth rate of the ballooning instability is : $\gamma_b = \sqrt{(\gamma_f^2 - k_{||}^2 V_A^2)}$, where, $k_{||}$ is π n/L (n = 1, 2, 3, .. :line-tying condition), V_A is the Alfven velocity and L is the loop length (Mikhailovskii 1974) . Hence the necessary condition of the ballooning instability is: $\gamma_f^2 > k_{||}^2 V_A^2$. This relation can be expressed in terms of the plasma β. $\beta > \beta_{cr}$, where, $\beta_{cr} = 2 \times (\pi n/L)^2 \ell R$.

If we assume a simple loop geometry of semicircular shape ($L = \pi R$) and the lowest harmonics (n = 1), the critical β can be expressed in a simple form: $\beta_{cr} = 2 \times \ell/R$. Namely, the critical β is two times the ratio between the scale size of the density gradient (ℓ) and the radius of the loop (R). In the real situation, the ratio between the loop length

(L) and the curvature (R) near the loop top will be larger than π, hence the critical β value will be much smaller. The observed ratio (ℓ/R) is about 0.1 - 0.2, which satisfies the ballooning instability condition for n = 1.

Most of the dynamical phenomena on the Sun which can be observed from the earth are after they have developed nonlinearly. The analysis shown above is based on the linear theory. It is necessary to know how the ballooning instability develops nonlinearly to be applicable to the observed phenomena. Analytical studies of nonlinear phenomena are very limited, hence we need the help of numerical simulations to understand nonlinearly developed phenomena.

Numerical simulations of high β plasma in the solar atmosphere have not yet been done. In fusion plasma studies, a lot of effort has been expended on the studies of high β plasma and the ballooning instability due to the necessity of confining high β plasma in order to realize high efficiency fusion. Park et al. (1995) did three-dimensional MHD simulations of high β plasmas in Tokamaks and compared their results with experiments. In the following, their results are summarized.

Park et al. used a nonlinear 3D resistive MHD code to study high β plasma in Tokamaks. They showed that, first, a low-n mode destabilized; this caused a local pressure steepening in the region of favorable magnetic curvature. The high-n ballooning modes became even more localized and produced a strong local pressure bulge that destroyed the flux surface resulting in a thermal quench. During the pressure steepening phase, ballooning oscillations were observed. After the recovery, large magnetic islands were formed. Under the Tokamak condition, plasma which escape from the broken flux surface, hit the wall.

Based on the previous result, we expect similar phenomena can happen also in the flare loop on the Sun. The isolated loop-top radio sources which we detected can be interpreted as the plasma clouds which escaped through the flux surface destroyed by the nonlinearly developed ballooning instability. To confirm this scenario, it is necessary to do numerical simulations under the coronal conditions.

5. Discussion

In the previous section, the ballooning instability is introduced to explain the radio sources appeared over the flaring loop detected by the Nobeyama Radioheliograph in the event of January 2, 1993. However, the discussions above are general and can be applicable to other flares and related phenomena as well.

It became clear, in the previous section, that the outer or upper layer of the hot and dense flare loop is unstable against the ballooning instability if the plasma β is non-negligible. Plasma in the loop can escape by destroying the flux surface by a nonlinearly developed strong local pressure bulge.

Recent results from *Yohkoh* observations of flares by the Soft X-ray Telescope and the Hard X-ray Telescope show that: 1) the outer regions of flare loops are hotter than the flare loops themselves (Tsuneta et al. 1997), 2) localized hard X-ray sources are found above flare loops (Masuda et al. 1995), and 3) plasma cloud ejections are sometimes found from the preheated loops (Ohyama and Shibata 1998). All these phenomena are interpreted in terms of the magnetic opening-up and re-closing (or magnetic reconnection) scenario of flares (Shibata 1998). They are supported by the similarity between observed features and results of numerical simulations (e.g. Yokoyama 1995).

However, in the case of the event of January 2, 1993, the isolated loop-top radio sources appeared after the high pressure regions appeared in the loop below. It is difficult to interpret these radio sources as the result of reconnection which occurred above the loop. Energy flow is not from the top but from the bottom.

Some of the *Yohkoh* results listed above can be explained in terms of the ballooning instability. Plasma heating and particle acceleration can be expected at the time of localized flux surface destruction. It is necessary to further study this phenomenon to show whether the ballooning instability also plays an important role in high energy phenomena. The energy source of the ballooning instability is the thermal energy contained in the flare loop. We need to assume some mechanism which injects thermal energy into the loop. Discussion in this work is limited to the phenomena after the hot and dense flare loop has formed.

6. Summary and Conclusion

In this paper, the origin of isolated loop-top radio sources is investigated above a flaring loop. Plasma parameters in the loop are estimated by combining the radio image data and the total flux of the soft X-ray emission in two energy bands. Circular polarization measurements at 17 GHz made it possible to estimate the magnetic field strength in the corona. The calculated values of the plasma β were 0.9 and 0.3 at different times.

The high β plasma contained by the magnetic field is unstable against exchange type instabilities when the magnetic line of force has a curvature that is favorable to the instability (convex outward). Hence, the flare loops filled with high β plasma are unstable at the upper boundary. Magnetic anchoring at the photosphere and shearing suppress the flute instability. However, a localized ballooning mode can develop when the β value is large enough. Numerical simulations and the experiments by Park et al. (1995) showed that once a low-n mode (n=1) ballooning instability starts, it develops nonlinearly into a localized density enhancement and eventually breaks the flux surface. The isolated loop-top radio sources can be interpreted as the result of a nonlinear ballooning instability. Further studies are needed of the ballooning instability under the coronal condition and also its relation to high energy phenomena in flares.

In this study, it is also found that the centrifugal acceleration is playing important role in the corona. It is caused by thermal motions along the curved magnetic line of force. Its effect far exceeds surface gravity. High density hot plasma can be sustained high in the loop top.

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