STUDIES ON POST-FLARE LOOP PROMINENCE OF 1981 APRIL 27

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Abstract. By use of the Hz observations of the Astrophysical Observatory in Catania, Italy and the Purple Mountain Observatory in Nanking, China as well as hard X-ray and gamma-ray burst data from the Solar Maximum Mission (SMM) Gamma-Ray Spectrometer (GRS), a major eruptive loop prominence was studied during the limb solar flare event of 1981 April 27.

Our preliminary analysis shows that there seems to exist a second abrupt energy release for this event, almost 20 min after the end of the impulsive phase of the flare. This energy release is probably associated with the rapidity in upward motion or activation of the loop prominence.

A possible candidate for such a process could be the reconnection of the old magnetic field with a newly emerging magnetic field.

A theoretical gross estimate for the energy release and particle acceleration has also been made in this work. It appears that the proposed model for charged particle acceleration is very efficient.

1. Introduction

It is well known that the loop-like prominences are closely related to two-ribbon flares. A loop prominence usually appears above the active region, where a large flare having a two-ribbon shape has just happened and where its footpoints are located in the flare. During the solar maximum years, 1980–1984, the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite has provided observations on over 150 large solar gamma-ray bursts. Some of these are associated with two-ribbon type flares. Use of this rich data will enable us to further understand post-flare loop prominence phenomena.

In this work we choose the large solar flare of 1981 April 27 as an example, because it was the only large flare, so far, that we know to have a large loop prominence that has occurred on the limb (≈ 90°) during the current solar maximum. This will give us some information on the post-flare loop prominence along the direction perpendicular to the surface of the Sun. The Astrophysical Observatory in Italy and the Purple Mountain Observatory and the Yunnan Observatory in the People’s Republic of China have observed this flare, which is located on the active region of a sunspot group (SESE

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Following the flare, a giant eruptive loop prominence formed. The SMM GRS recorded hard X-ray and gamma-ray bursts during the flare.

Some simple morphological analyses, on this limb event, have been presented in several other papers in the past years (Hu and Cao, 1982; Cao et al., 1985). However, these authors have not used space data for their method of analysis. There is no doubt that a comparison between hard X-ray bursts, gamma-ray bursts, and Hα flare events is necessary, and will reveal some new information about solar flares or present some new restrictions on existing flare models.

2. The Impulsive Burst and Growth of the Post-Flare Loop

The flare started before 08:00 UT. Due to the fact that the flare is located on the limb of the Sun, it has not been possible to determine the exact flare onset. Most observational astronomers in China suggest that the main part of the flare brightening may probably be located behind the limb. From the rising of the X-ray count-rate in the lower energy channels, recorded by SMM GRS and SMM HXRBS, the onset of the limb flare of 1981 April 27 probably occurred between 07:41-07:55 UT. At 07:59 UT, optically, a bright patch of a flare-like area was observed, on the west limb. At 08:10 UT a loop-like structure was formed and rose upward quickly; the base of this structure seem to be connected with the flare-like bright patches. The brightest part of the post-flare loop is on the top, which is in agreement with the work of Nolte et al. (1979).

In Figure 1 are shown, schematically, several images of the Hα post-flare loop prominence during the process of its development. It was found from the Hα observations that in the period of 08:16-08:26, 08:37, and 08:39-09:08 UT, the northern leg of the loop was wider than the southern leg, while during 08:28-08:30 and 08:37-08:38 UT the southern leg was wider than the northern one. As the legs increased gradually in height, the footpoints of the loop separated from each other with a velocity of several kilometers per second.

Figure 2 shows the location of the hard X-ray double sources at 07:56 UT with unbalanced intensities of this event over the limb of the Sun. This data was obtained from the Solar X-ray Telescope (SXT) on board the HINOTORI satellite (Tsuneta et al., 1982). We can see from Figure 2 that the positions of the hard X-ray sources basically coincide with the post-flare loop footpoints, implying that two X-ray sources are connected through the same magnetic tube. But the separation between the two X-ray sources seems to be a little larger than that between the two Hα flare loop footpoints within the accuracy of the measurement. We would like to point out that this may be in good agreement with the model of the Hα post-flare loop which lies below the X-ray loop (Cliver, 1983).

During the 1981 April 27 flare, SMM GRS successfully observed solar bursts, in the energy range from 10 keV to 10 MeV, lasting for six orbits (270 min) in lower energy range. Figures 3 and 4 show the time development of the hard X-ray bursts and the gamma-ray bursts, respectively. The first burst started during the time period of 07:56-08:02 UT (depending on the energy channel) and reached the maximum near

3049, MW 22216).
Fig. 1. Hα images of 1981 April 27 post-flare loop during the process of its development.

Fig. 2. The location of hard X-ray double sources.
08:09 UT. At least three peaks can be seen clearly, in various energy channels of GRS, during this burst, except in Channel 1 (14–28 keV) and Channel 2 (21–56 keV), which seem to start about 20 min earlier. The earlier occurrence of the lower energy X-ray emission of the SMM GRS X-ray detector and the hard X-ray image observed on the HINOTORI SMT lead us to the conclusion that the footpoint emission had started before the beginning of the gamma-ray burst. It is clear that the charged particles producing the lower energy X-ray emission were energized at a time much earlier than when the charged particles producing the higher energy X-ray and gamma-ray emission were accelerated. This implies that the properties of emission in the lower energies are mainly thermal. De Jager and Švestka (1985) have reported similar occurrences for the 1980 May 21 flare.

The second burst with less intense peak takes place at 08:32 UT, about 40 min after the flare onset, almost 20 min after the end of the impulsive phase.

It is important to note that the main peaks labelled a, b, and c in Figure 4, in different energy ranges, occurred at different times. The hard X-ray emission (56–199 keV)
reached the maximum, at first, both for the first burst and for the second burst. Approximately $\frac{1}{2}$ to 1 min later soft gamma-ray emission (0.298–1.0 MeV) reached the maximum. The hard gamma-ray emission (1.102–1.994 MeV) seems to reach a maximum last.

In order to check any relationship between the hard X-ray and gamma-ray bursts and flare loop motion, we measure the position of the front of the Hα post-flare loop, using the amplified image obtained from a special precision optical system at the Purple Mountain Observatory. Thus the positional variation of the front of the flare loop and its average expanding velocity with time can be determined. All the results of these measurements are given in Figures 5 and 6. One can see from these figures that the motion of the flare loop does not appear to be uniform. At about 08:28 UT the loop seems to stay at a height of 32,000 km for a while, and after 08:32 UT it rises abruptly with a velocity of 18 km s$^{-1}$. We will call this type of behaviour of a flare loop activation or jump, which also has been observed in the major flare of 1980 May 21 (De Jager and Švestka, 1985; Lemmens and De Jager, 1986). For the purpose of comparison, the
Fig. 5. The positional variation of the front of the flare loop with time.

time-variation of hard X-ray and gamma-ray intensity also are shown in Figure 6. It is worthwhile to point out that such an activation or jump seen in Hα might be related to X-rays and gamma-rays increase in flux, because of the simultaneity of their occurrence. We have to emphasize here that in the case of the 1980 May 21 flare, only the connection between the Hα jump in height and the lower energy X-ray increase in flux can be seen. In the present example, the Hα jump was associated not only with an abrupt rise in X-rays, but also with a hard gamma-ray increase, which requires a new injection process of high-energy charged particles with energies as high as several MeV, at least. To our surprise, optically we could not find any apparent variation in brightness and shape of the structure on the limb except for the Hα flare loop itself during the second jump, implying no energy transport from the lower solar atmosphere. It is not clear where the energy supply for the second increase comes from. The only possible origin of so large an amount of energy, for this event, appears to be coming from a very high region above the limb, probably higher than 32,000 km. A likely candidate for such a process could be the reconnection of magnetic field lines. This is in apparent agreement with the Kopp and Pneuman (1976) model of the formation of post-flare loops. Theoretically, it is possible that any activation, or re-excitation, or jump, or new formation of the loop may
result from reconnection of magnetic field lines at different altitudes above a two-ribbon flare which can lead to new energy release and particle acceleration or perturbation of stored particles. Thus the second hard X-ray and gamma-ray burst, which occurred 20 min after the end of the impulsive phase, and represents a late-energy release, may represent non-thermal high-energy particle acceleration in the post-maximum phase of the flare. This is direct evidence that in a two-ribbon flare, energy release lasts for a long time or sometimes quickens, suddenly after the end of the impulsive phase.

3. Emerging Magnetic Flux and Particle Acceleration

On the basis of analysis of the Hα data, morphological tracings, positional measurements, and hard X-ray and gamma-ray solar burst data from the SMM GRS, we have
inferred in previous sections that the second energy release may be related to the reconnection of magnetic fields. On the other hand, such a concept must be reconciled with the mechanism of post-flare loop formation.

In the past ten years, solar physicists have tried to interpret the origin of some prominences through coronal condensation. Their model, however, cannot explain formation of a post-flare loop prominence, because it involves an amount of matter, considerably larger than that of the coronal condensation. It is also unlikely that the total matter of the flare loop comes from the lower chromosphere or even photosphere, because the measurements of the velocity field for the 1981 April 27 limb event show that the matter in the flare loop falls down at any time (Gu et al., 1984). So far, the Kopp and Pneuman (1976) model, revised by Švestka et al. (1982), and modified by Gu et al. (1984) is relatively better for the post-flare loop. According to the model of these authors, when the open magnetic field lines become closed, the solar wind plasma and coronal matter captured by the closed magnetic loops provide the source for the loop prominence. However, in the Švestka model it is assumed that before the flare, a preflare loop-like field exists. In fact, in our case, Švestka’s model seems to be difficult to adopt, due to the facts that:

(i) We could not find any Hα filaments or any filament-like structure parallel to \( H_\| = 0 \) line before the flare.

(ii) The magnetic structure of the active region where the 1981 April 27 flare occurred is not favourable for forming a magnetic system of sheared loops which bridges the \( H_\| = 0 \) line.

The other difficulty in using Švestka’s model, in our case, is that it cannot explain the long duration hard X-ray emission (\( \sim 30 \) keV), lasting almost for 6 hours, with no continuous energy release.

Thus for this limb-flare event, it seems likely, we believe, that it is a result of the coupling of the emerging magnetic flux (EMF) with the old magnetic field (Heyvaerts et al., 1976). If the reconnection of a newly emerging magnetic field, with the old magnetic field, continues to proceed after the eruption of a flare, this would lead to the occurrence of a post-flare loop prominence, and during the magnetic reconnection, the neutral point and current sheet would rise continuously, as can be seen in Figure 7. The rising velocity depends on how quickly the newly emerging flux emerges and how fast the annihilation process of a magnetic field is. The upward motion of the flare loop we see in Hα is only the result from such a process. At the same time the particles are accelerated in the neutral current sheet.

Now let us make an estimate of how much energy can be released during this limb event. The distribution of magnetic fields of sunspots in the direction perpendicular to the surface is taken as

\[
B(h) = B_0 \left(1 + \frac{h}{d} \right)^{-3},
\]

where \( d \) denotes the depth of the magnetic dipole. By use of the observations of large
spots by Beckers and Tallant (1969), we can make a gross estimate for the value of $d$, and obtain the average depth of magnetic dipole

$$\bar{d} \approx 2.6 \times 10^4 \text{ km}.$$  

If we assume that the magnetic field of a sunspot in the photosphere is $B_0 = 2000 \text{ G}$, the dimensions of the solar flare $L = 2 \times 10^4 \text{ km}$, and the average speed of current sheet shift $dD/dt$ is approximately the same order as the average expanding speed of the Hα-flare loop, then the energy released per second during the reconnection can be estimated approximately by

$$\frac{dw(h)}{dt} \approx \frac{B^2(h)}{8\pi L^2} \frac{dD}{dt}.$$  

The results are given in Figure 8. The total energy released during the first burst is approximately $2 \times 10^{31} \text{ erg}$ and about $3 \times 10^{29} \text{ erg}$ during the second burst, two orders less than the first. This amount of energy is enough to accelerate the charged particles, the question is how the particles are accelerated.

According to the EMF model, Tang and Xu (1983) have proposed that the charged particles can be accelerated through the impulsive electric field, formed during the current sheet expansion. In their model, the width of the current sheet is taken as $l \approx 10^{-6} L$, the characteristic time for the impulsive phase $t \approx 240 \text{ s}$, and the average
electron energy gained from the impulsive electric field is approximately $W_e \approx 10$ keV. Such a value, however, is too small in our case for explaining gamma-ray events.

In our opinion, the gamma radiation-producing charged particles cannot be produced through any macroscopic electric field, set up during the reconnection, as done by Tang and Xu (1983) and other workers. This is so because the reconnection region is so high ($\sim 40,000$ km) for the second burst and the magnetic field is so weak there, that any impulsive electric field, induced by a magnetic field is rather limited. Instead, we explore the possibility of charged particle acceleration through the coupling of a plasma turbulence field with charged particles.

As is well known, during the reconnection of the magnetic fields, a plasma turbulence field (such as a Langmuir wave field, etc.) can be set up near the annihilation region of
the magnetic field, which would be immediately coupled with fast electrons or protons in the Maxwellian high-energy tail. Then the relativistic electrons and high-energy protons are produced within a short time interval.

Let \( U_L \) denote the energy density of plasma turbulence, \( R \) the ratio of \( U_L \) to the magnetic energy density, then the average energy density of plasma turbulence with wave number \( k = 2\pi/\lambda \) can be written as

\[
\bar{U}_k \approx \frac{3R_D^3}{4\pi} U_L \approx \frac{3R_D^3}{4\pi} R \frac{B^2}{8\pi},
\]

where \( R_D \) is the Debye radius. The average number density for Langmuir waves with \( k \) can be expressed as

\[
\bar{N}_{kl} \approx \frac{6\pi^2}{h\omega_L} R \left( \frac{B^2}{8\pi} \right) \left( \frac{k_BT_e}{4\pi Ne^2} \right) \approx 3.6 \times 10^{16} \text{ cm}^{-3},
\]

in which we took \( R = 10^{-2} \), electron temperature \( T_e = 10^5 \text{ K} \), magnetic field \( B = 100 \text{ G} \), electron density \( N = 10^9 \text{ cm}^{-3} \). It is evident that in the lower corona, the plasma Langmuir wave field still is intensive enough for accelerating particles.

The statistically increasing rate of energy gain for charged particles in such a plasma turbulence field may be calculated (cf. Tsytovich, 1970) from the equation

\[
\dot{\epsilon}(p) = \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D'(p) \frac{\partial \epsilon(p)}{\partial p} \right),
\]

where \( p = mv/\sqrt{1 - \beta^2}, \beta = v/c \), \( D'(p) \) is the longitudinal diffusion coefficient. In the wave vector space this may be expressed as

\[
D'(p) = \hbar^2 p^{-2} \int \int N_{kl}(k \cdot p) \frac{e^2}{h\pi} \frac{1}{\partial \omega_l} \delta(\omega_l - k \cdot v) \sin \theta \; d\theta \; d\phi.
\]

In the case of Langmuir turbulence Equation (4) can be simplified as

\[
D'(p) \approx 2\hbar e^2 \int_{\omega_L/v}^{\omega_{max}} \frac{N_{kl}}{kv^2} \frac{\partial}{\partial \omega_l} \epsilon'(\omega_l, k) \omega_l^2 \; dk
\]

or

\[
D'(p) \approx 2\hbar e^2 \int_{v^2}^{v_f} \frac{1}{v^3 v_f} \frac{N_{kl}}{\partial \omega_l} \epsilon'(\omega_l, k) \omega_l^2 \; dv_f,
\]
where $\omega_L$ is the Langmuir frequency, $\varepsilon'(\omega_L, k)$ is the longitudinal Fourier component of dielectric constant, which is usually taken as

$$
\varepsilon'(\omega_L, k) \approx 1 - \frac{\omega_L^2}{\omega_0^2} \left( 1 + \frac{k^2}{\omega_0^2} \frac{k_B T_e}{m} \right);
$$

$k_B$ being the Boltzmann constant and $v_f$, the phase velocity of the Langmuir wave.

From Equations (2), (3), (5), and (6), the statistically increasing rate of energy gain for a charged particle can be estimated. The final result is given (cf. Zhang, 1979) by

$$
\dot{E}(p) \approx e^2 \omega_L^3 \sqrt{m} \frac{h \phi_{kl}}{\left( \frac{e^2}{mc^2} - \frac{\varepsilon_0}{mc^2} \right)^{3/2}}.
$$

By substitution of the value of $N_{kl}$ obtained from Equation (2) in (7), it was easy to see that the particle acceleration mechanism we suggested here was quite efficient, and that a charged particle can be accelerated to relativistic velocity within a very short time interval. For example, in the nonrelativistic case, Equation (7) becomes

$$
(2E_e)^{3/2} \frac{dE_e}{dt} \approx e^2 \omega_L^3 \sqrt{m} h \phi_{kl},
$$

where $E_e$ is the kinetic energy of electrons. Let $E_e^0$ denote the initial kinetic energy of electrons, $E_e^t$ the kinetic energy of electrons at time $t$, then we have

$$
t = 2^{5/2} \left[ \frac{(E_e^t)^{5/2} - (E_e^0)^{5/2}}{5e^2 \omega_L^3 \sqrt{m} h \phi_{kl}} \right].
$$

From (9) we can estimate the time required to accelerate a charged particle with initial energy $E_e^0$ to the high energy $E_e^t$. For an electron with initial energy 0.1 keV, the plasma turbulence acceleration mechanism only requires $10^{-4}$ s to energize the electron to 100 keV.

In the relativistic case, the governing Equation (7) for increasing rate of electron energy, takes the form

$$
(mc^2)^{5/2} (\gamma^2 - 1) \sqrt{\gamma^2 - 1} \frac{d\gamma}{dt} = e^2 \omega_L^3 \sqrt{m} h \phi_{kl},
$$

where $\gamma = 1 / \sqrt{1 - v^2/c^2}$. Integrating Equation (10), we find that the solution can be expressed as

$$
e^2 \omega_L^3 \sqrt{m} h \phi_{kl} t = \left[ (mc^2)^{5/2} \left\{ \frac{7}{8} (2\gamma^2 - 1) \sqrt{\gamma^2 - 1} + \frac{3}{8} \ln | \gamma + \sqrt{\gamma^2 - 1} | - (mc^2)^{5/2} \left\{ \frac{7}{8} \sqrt{\gamma^2 - 1} \right\} \right] \right]_{\gamma_0}^{\gamma(t)}.
$$
in which $\gamma_0$ is the initial energy of the electron, $\gamma(t)$ the electron energy at time $t$. As an example, suppose the initial kinetic energy is 0.01 keV, then the time-scale needed to energize an electron to 1 MeV is approximately

$$t \approx \frac{(mc^2)^{5/2} \gamma(t) \sqrt{\gamma^2(t) - 1} \left(\frac{3}{2} \gamma^2(t) - \frac{5}{2}\right)}{2e^2 \alpha_L^3 \sqrt{\mu \hbar N_{kl}}} \approx 10 \text{ s}.$$  \hspace{1cm} (12)

It can be seen from Equation (7) that the rate of energy gain of a charged particle is proportional to $e^{-3}$ in the extreme relativistic case. Thus for higher energy charged particle acceleration, the mechanism usually requires much more time to energize the particles. For example, in order to accelerate an electron with initial energy 0.1 keV to 5 MeV, about 1 min is needed.

Of course, in the real case the problems involved are more complicated; because the plasma turbulence exists in a very narrow region. Where the plasma instability has occurred, the actual effective time of particle acceleration is very short and different for different particles, depending on their motion in the magnetic field. In addition, particle acceleration also depends on how strong a plasma turbulence field can be produced and how long it can last. In this respect, much work remains to be done to obtain an explicit model. We only put forward a preliminary suggestion for particle acceleration to be considered here and do not want to make a detailed theoretical calculation.

4. Summary

The limb event of 1981 April 27 provides us with an excellent chance to study the structure of a post-flare loop and its evolution in the radial direction.

Our analyses show that impulsive solar gamma-ray burst phenomena associated with high-energy particles or even with a relativistic particle acceleration process, can take place even after the end of the initial impulsive phase, and during usual the decay phase of a flare, although the gradual energy release during the decay phase of a two-ribbon flare has been observed by many solar physicists (Sturrock, 1985).

Such a solar gamma-ray burst or high-energy particle acceleration or injection process seems to be tied up with a post-flare loop activation process or jump.

For the two-ribbon flare, the energy source supporting the post-flare loop or re-excitation of a formed flare loop probably comes from the lower coronal region. A possible mechanism for a second energy release may be the reconnection of new emerging magnetic field lines with old existing magnetic field lines. If this is true, the reconnection process occurring at so high an altitude is an interesting question for solar physics.

On the basis of the EMF model, a simple approach regarding particle acceleration in a plasma turbulence field is proposed. This preliminary model is very efficient to explain energizing of lower energy particles to very high energies within a short time-scale.
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