Signatures of the Coalescence Instability in Solar Flares

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ABSTRACT

Double sub–peak structures in the quasi–periodic oscillations found in the time profiles of two solar flares on 1980 June 7 and 1982 November 26 are well explained in terms of the coalescence instability of two current loops. This interpretation is supported by the observations of two microwave sources and their interaction for the November 26 flare. The difference of both sub–peak structures and time scales between the two flares are discussed from the viewpoint of different plasma parameters in our computer simulations.

I. INTRODUCTION

Recent observations of X–ray continuum emission, γ–ray line, and continuum emission from solar flares with instruments on the Solar Maximum Mission (SMM) and Hinotori satellites show that energetic ions and relativistic electrons are accelerated almost simultaneously with non –relativistic electrons during the impulsive phase of solar flares. These observational results make it necessary to revise the widely accepted hypothesis of particle acceleration that energetic ions and relativistic electrons are produced in the second phase a few minutes after the impulsive phase (Wild et al. 1963; de Jager 1969; Svestka 1976). Although Bai and Ramaty (1979), Bai (1982), and Bai et al. (1983) revised the hypothesis as the second–step acceleration taking note of a small delay of γ–ray line emission from hard X–ray emission, Kane et al. (1983), and Forrest and Chupp (1983) pointed out that such a small delay can be explained simply by either the injection, propagation, or energy loss processes of particles which are accelerated in a single step.

Tajima et al. (1982, 1983) proposed a simultaneous acceleration mechanism of protons and electrons in solar flares by the nonlinear coalescence instability of two current loops, based on the results of computer simulation. Two adjacent, parallel current loops are unstable against the coalescence instability which involves the rapid (sometimes explosive) conversion of magnetic energy to kinetic energy of particles (Tajima 1982). The results of computer simulation reve-

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aled that the time profiles of the proton and electron temperatures show quasi—periodic oscilla-
tions with double sub–peak structures.

Recently Nakajima et al. (1983) and Kiplinger et al. (1983) reported observations of quasi
–periodic pulses with double sub–peak structure seen in hard X–ray, γ–ray, and microwave emis-
sions in the two intense solar flares of 1980 June 7 and 1980 June 21. We are interested in
the close similarity between the observed time profiles and those obtained with the computer
simulation by Tajima et al.

In this letter, we present the results of our analysis of the 1980 June 7 and 1982 Novem-
ber 26 events, both of which show double sub–peak structures in quasi–periodic oscillations. Since
these two events are widely different from each other in duration, source size, source height, etc.,
they provide a stringent test for examining the validity of our model of particle accelera-
tion in solar flares in terms of the coalescence instability. Our study shows that observational
features of the two events are consistent with the results of our computer simulation.

II. SUMMARY OF OBSERVATIONS

(a) 1980 June 7 Event

The impulsive burst of the 1980 June 7 solar flare (Figure 1) has been investigated by
many authors (Forrest et al. 1981; Kane et al. 1983; Forrest and Chupp 1983; Nakajima et
al. 1983; Kiplinger et al. 1984). We summarize below some essential points from these obser-
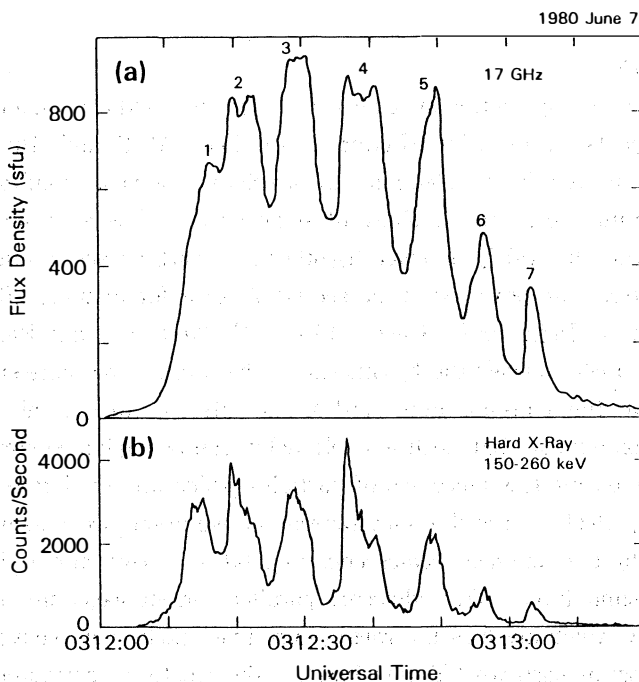vations.

Figure 1: Time profiles of the 17 GHz microwave emission and the 150–260 keV X–ray
emissions (from HXRBS) for the 1980 June 7 event.

(1) The burst is composed of seven successive pulses with a quasi-periodicity of about 8 seconds. Each of the pulses in hard X-rays, prompt γ-ray lines, and microwaves is almost synchronous and similar in shape.

(2) The microwave pulses consist of double sub-peaks as seen especially in the second and fourth pulses in Figure 1(a). The double sub-peak structure is also evident in the hard X-ray time profiles (Figure 1(b)).

(3) The starting times of hard X-rays, prompt γ-ray lines, and microwaves coincide within ± 2.2 seconds.

(4) The time scales of accelerations for both electrons (up to energies above 1 MeV) and ions (above 10 MeV/nucleon) are less than 5 seconds. And the accelerations must occur almost simultaneously.

(5) The height of the microwave source is estimated to be within 10 arc sec above the photosphere (Hα flare; N12°, W74°). The source has a small size of less than 5 arc sec in the east-west direction and shows no motion.

The Hα photographs from the Peking Observatory (H. Chow, private communication) add a new finding. The flaring region has two structures that appear to be in contact with each other, one stretching in the east-west direction and the other in the north-south.

(b) 1982 November 26 Event

We briefly outline the characteristics of the 1982 November 26 flare (Figure 2). This event is of much longer duration than the event on 1980 June 7, about 20 min compared to about 1 min.
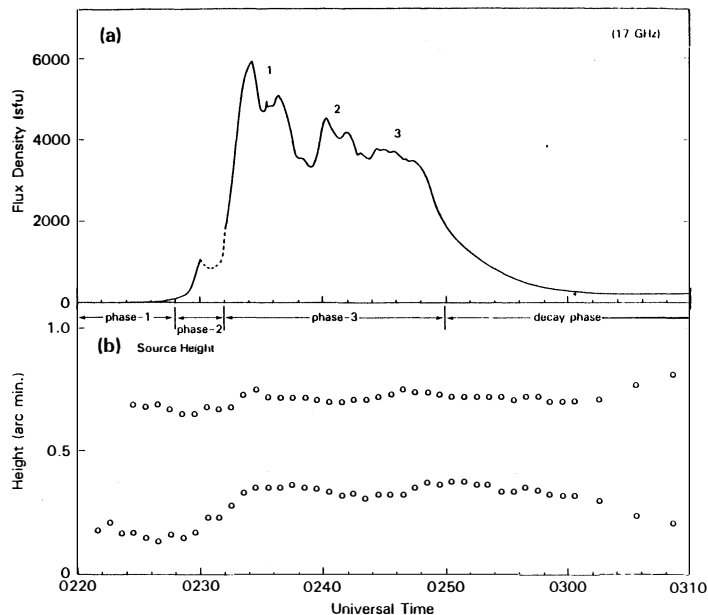

Figure 2: (a) The time profile of the 17 GHz microwave emission and (b) the time variation of the heights of two microwave (17 GHz) sources for the 1982 November 26 flare.

The microwave observations were made with the 17 −GHz interferometer at Nobeyama, Japan, and the hard X−ray observation with the Hard X−Ray Burst Spectrometer (HXRBS) on SMM. More details will be reported in a separate paper ((Nakajima et al. 1984).

(1) The microwave burst is composed of three successive peaks with a quasi−periodicity of about 6 min as indicated by number 1−3 in Figute 2(a).

(2) Each of the microwave peaks further consists of two sub−peaks. The hard X−ray time profiles seems to coincide with the microwave sub−peaks. The SMM hard X−ray data are available only for the first peak.

(3) The microwave and hard X−ray emissions start almost simultaneously within 10 seconds.

(4) The microwave source is composed of two sources, one at a height of $\sim 10^4$ km above the photosphere and the other at $\sim 3 \times 10^4$ km. These values are derived on the assumption that the sources are located directly above the Hα flare (S10°, W88°).

Figure 2(b) shows the height of the two microwave sources as a function of time. In the pre−burst phase (phase 1: 0220−0228 UT), the upper source appears at a height of $\sim 2.9 \times 10^4$ km above the photosphere and the lower one at $\sim 0.7 \times 10^4$ km. In phase 2, the lower source rises at a velocity of ~ 30 km s^{-1}. The main phase (phase 3) started when the lower source reaches a height of $\sim 1.5 \times 10^4$ km. It is suggested that the two sources collide with each other at this time. In fact. a small up−and−down motion of the lower source is observed in the main phase. The oscillation period and peak−to−peak amplitude of the up−and−down motion are ~ 14 min and $\sim 2 \times 10^3$ km(significantly larger than the fluctuation level due to the signal to noise ratio), respectively. After the main phase, the lower source begins to go down towards its previous position. On the other hand, the upper source rises gradually, though it remains at almost the same height until the decay phase starts.

The observational facts summarized above, especially the collision of the two microwave sources and the small up−and −down motion of the lower source in the 1982 November 26 event, suggest that the current−loop coalescence takes place. The existence of two Hα bright components in the 1980 June 7 event also supports this interpretation.

Ⅲ. INTERPRETATION BY SIMULATIONS

Two parallel current loops are unstable against the coalescence instability (Pritchett and Wu 1979). They are attracted by and collide with each other and finally coalesce into one loop. Its nonlinear development can release a large amount of poloidal magnetic energy associated with the current loops into particle energies (Tajima et al. 1982; Leboeuf et al. 1982). We investigated this process, i.e., the global plasma dynamics, heating and acceleration of particles, and so on, through computer simulations. Here, we made two different types of simulations in order to experiment with a wide variety of plasma parameters: one is an MHD particle simulation (Brunel et al. 1981), and the other a collisionless full−electromagnetic particle simulation (Tajima 1982), both of which are two−dimensional in space across the plane perpendicular to the current loops and three−dimenstinal in velocity space.

(a) Fast Coalescence−−−1980 June 7 Flare

The case that two parallel loops have sufficient electric currents so that they attract each

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other fast enough (in about one Alfvén transit time) was simulated using the collisionless full–electromagnetic particle code.

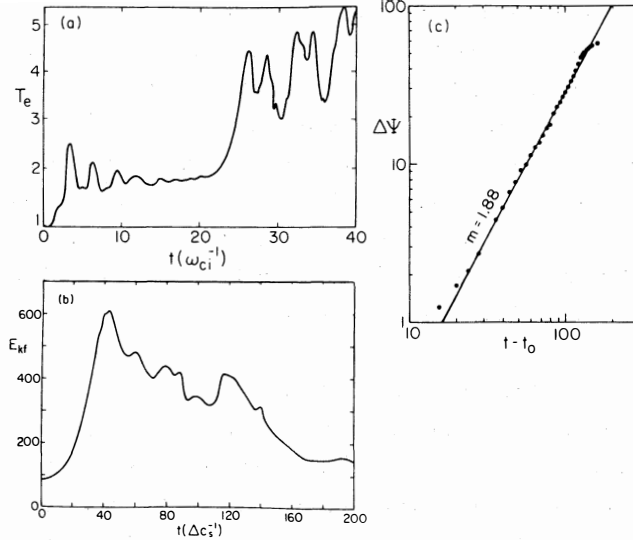The resultant time history of the electron temperature is shown in Figure 3(a).

Figure 3: (a) The time history of the electron temperature T_e in case of fast coalescence (the oscillation period is about one Alfvén time) from the EM particle simulation. $\omega_{ci} = eB/Mc$ the ion cyclotron frequency and here one Alfvén time is about $8\,\omega_{ci}^{-1}$. T_e is normalized with the initial value.

(b), (c): Time histories of (b) the electron kinetic energy E_{kf} and (c) the integrated reconnected flux $\triangle\varPsi$ through the X–points, in case of slower coalescence (the oscillation period is about five Alfvén times), from the MHD particle simulation. The time unit

is $\triangle c_s^{-1}$ with $\triangle$ and c_s being the grid spacing and the sound speed, respectively. The initial separation of loops is $\sim 60\triangle$. m is the slope ($\triangle\psi \propto (t-t_0)^m$).

We can clearly see a quasi–periodic oscillation, the period of which is about one Alfvén transit time ($8\ \omega_{ci}^{-1}$). The cause of this oscillation is as follows: after fast reconnection of poloidal magnetic fields takes place at the X–point between two approaching current loops, the two plasma blobs pass through each other and overshoot, resulting in the repetition of this process.

Figure 3(a) also shows that the electron temperature oscillation is characterized by prominent double sub–peak structure. The double sub–peaks occur just before and after each peak in the magnetic field intensity. Just before a peak, the magnetic acceleration of the plasma by $jx\,B$ becomes strongest so that the magnetic flux behind the colliding plasma blobs as well as the plasma blobs themselves are strongly compressed. This plasma compression causes the first sub–peak of the electron temperature. Then, the plasma particles acquire velocities close to the Alfvén speed along the colliding direction, so that they detach from the magnetic flux against which they have been compressed, resulting in an expansion and hence in an adiabatic cooling of the plasma as the magnetic fields obtain peak values. After the peak in the magnetic fields, the process reverses giving rise to the second sub–peak of the electron temperature.

A similar time history is obtained for the kinetic energy of high-energy tail electrons and protons as well as for the proton temperature. The acceleration of the high energy-tail particles is due to a combination of localized electrostatic field acceleration across the poloidal magnetic field and magnetic acceleration in the poloidal to toroidal directions (Tajima et al. 1983). Since these processes accompany the local plasma compression/ decompression just before and after coalescence, it is not surprising that the time profile of the microwave emissions caused by high-energy tail electrons (Figure 1(a)) resembles that of figure 3(a).

The results of this simulation can also explain the observed period of the quasi-periodic oscillation of the 1980 June 7 event. The observed period ($\sim$ 8 seconds) of the June 7 flare is close to one Alfvén transit time ($\sim$ 4 sec) which is estimated with source size ($\sim$ 5 arc sec), magnetic field ($\sim$ 200 Gauss: Kiplinger et al. 1983) and emission measure ($\sim 10^{49}$ cm^{-3}) from the GOES soft X-ray data (Solar Geophysical Data).

(b) Slow Coalescence--- 1982 November 26 Flare.

When two parallel loops have insufficient electric currents or are well separated and hence the attracting force of them is weaker than that of the previous case, reconnection of poloidal magnetic fields during loop coalsecence becomes slower. (However, this reconnection rate is still faster than what would be predicted by a classical tearing theory (Furth et al. 1963)). This case was also simulated using the MHD particle code. Figure 3(b) shows the temporal development of plasma kinetic energy (the electron pressure energy) during the coalescence. Also shown in Figure 3(c) is the time history of the integrated reconnected magnetic flux through the X-point (case shown in Figure 5(a) in Bhattacharjee, et al. 1983). Note that a slight amount of oscillations of reconnected flux can be seen around the straight line. Again we can see the oscillatory behaviour with double sub-peak structure in both time histories, though it is less prominent compared with that of the fast coalescence case presented in the previous subsection. The period of oscillation is about 5 times the Alfvén transit time.

The obtained time history resulting from the simulation is explained as follows. In the case of slower reconnection, the two plasma blobs do not pass through each other but are qushed back by the magnetic field compressed between the two loops. This motion is repeated resulting in the damping oscillation shown in Figure 3(b). The amplitude of the oscillation in this case is less prominent compared with the previous case (Figure 3(a)).

The observed plasma kinetic energy oscillations exhibit a structure quite similar to the microwave time profile of the 1982 November 26 flare as shown in Figure 2(a). The source size of the November 26 flare is about 10 times larger than that of the June 7 flare. We therefore estimate the calculated period of the oscillation to be 5x4x10 = 200 sec, assuming that the Alfvén velocity is about the same for both cases. This period is close to the observed period of about 6 min. Note also that in this case the flow velocity is much below the Alfvén velocity in agreement with the observational fact that the 30 km/s colliding velocity of the lower loop is much smaller than the Alfvén velocity of $\sim 10^3$ km/s.

IV. SUMMARY AND CONCLUSIONS

The results obtained from computer simulations of the coalescence instability of two current

loops are in good agreement with observations of two widely differing flares.

The key characteristics which are well explained are the simultaneous accelerations of both electrons and ions, and the double sub—peak structure in quasi—periodic pulses. The double sub— peak structure is more pronounced when the currents in the two loops are sufficient for the fast coalescence to occcur. This case corresponds to the 1980 June 7 flare. When the currents are insufficient for the fast coalescence, the double sub—peak structure is less pronounced. This case corresponds to the 1982 November 26 flare. In addition, we have the observation sugges- ting the collision of the two microwave sources for the 1982 November 26 event.

Therefore, we consider that this mechanism is a plausible process for the particle accelera- tion mechanism in solar flares.

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