Decametric Radiations from a Large Scale Magnetic Loop in the Solar Corona

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Rising tone bursts whose frequencies are drifting in decametric wavelength range (20–40 MHz) are sometimes observed associated with strong flares; the studies on these bursts have been made for the case of flare event on February 6, 1986 by analyzing dynamic spectra obtained at the Tsukidate observatory, in relation to the configuration of coronal magnetic field. The present analyses for the frequency drift of decametric radiation suggest the motion of energetic particles along the special form of the magnetic loop and its origin and evolution. That is, a large scale isolatedly closed magnetic loop is formed by magnetic reconnection and is pushed out with a speed of 400–500 km/s toward outer coronal region.

1. Introduction

The origin of the flare is generally thought to be in the process of the release of the magnetic field energy through the magnetic reconnection in the lower coronal regions (SVESTKA, 1976; STURROCK, 1980; MCLEAN and LABRUM, 1985; SOMOV, 1991; and see references in these articles). Therefore, it is naturally inferred that the configuration of magnetic fields is changed drastically in the solar coronal region before and after a flare. Highly active variations of the magneto-plasma in the region of the solar flare origin propagate into the outer coronal region; the characteristic features of the magneto-plasma conditions associated with the solar flare events are also transferred into the outer corona. The behaviors of the magnetic field variation and associated energetic particle motions in the distance range from middle to outer coronal regions are, therefore, very important both for understanding of the origin of the solar flare and for understanding the mass, momentum and energy transportation into interplanetary space. If the temporal and spatial change of the magnetic field configuration can be monitored even in the middle and outer coronal regions, we are able to obtain important information of the magnetic field variation relating to the flare mechanism. In the middle to outer coronal region, the mass ejection and magnetic field transportation are not simple outward flowing processes; but plasma processes in these regions are dominated with acceleration of energetic particles or deceleration with heating of the plasma being associated with large scale change of the magnetic field structure. By the detailed analyses of the decametric radio bursts from the outer solar coronal regions, we can clarify the processes of the variations of the magneto-plasma. Relating to this context, the observation of solar radio bursts in wide frequency range covering the decameter wavelength range is one of the most effectual methods. Under this motivation, an observation station for the decametric (20–40 MHz) solar radio bursts has been developed at Miyagi Polytechnic College (see AOYAMA and OYA, 1987). The observation started from July, 1982. Since then, many flare events have been observed at the station providing the data which contain the information of the magnetic field configurations in the outer coronal regions.

The purpose of the present paper is to show the results of a case study for the configuration of the magnetic field and its time dependent deformation, in the outer coronal region, associated with an intense flare. The studies have been made based on data of dynamic spectra observed on February 6, 1986 at the Tsukidate station; the data show the rising tone bursts suggesting the existence of magnetic field loops and the related motion of source agency of the decametric radiations.
2. Sequential Occurrence of Rising, Falling and Rising (SOC-RIFAR) of the Decametric Radiation

2.1 Fast type SOC-RIFAR

From February 4 to February 6, 1986 (UT), very intense and continuous radio bursts relating to a group of strong flares were observed. Especially, a white light flare with very intense decametric radio bursts occurred at about 06:19 UT (15:19 JST) on February 6, 1986. During course of the evolution of this flare event, a series of bursts in the decametric frequency range with a special characteristics of spectrum pattern took place in a period about 06:00 to 24:00 UT on February 6 (15:00 on February 6 to 09:00 on February 7, JST), 1986.

The total feature of bursts observed on February 6, 1986 are shown in Fig. 1 where two types of bursts are indicated; one is a burst group with fast frequency drift rate indicated by (A) and (B), the other is a burst group with relatively slow drift rate labeled (C), (D), (E) and (F). Though, there is a long data gap between bursts (C) and (D) because of local nighttime period (08:00–21:00 UT; no intense flare was reported in this period) at the observation station, it is considered that the burst group from (A) to (F) is a chain of bursts directly related to the white light flare from common nature of sequential occurrence of rising, falling and rising tones.

The burst group labeled (A) and (B) in Fig. 1 is reproduced in the top panel of Fig. 2 with high time resolution where color levels expressing bursts intensity are changed from the case of Fig. 1, to show more detailed time dependent features of the burst spectra. The bursts (B) in Fig. 1 are divided into three typical portions labeled (B1), (B2) and (B3) in Fig. 2 where the higher time resolution spectra of bursts labeled (B1), (B2) and (B3) in the top panel are given in lower three corresponding panels. Though burst group (A) seems continuous bursts, a detailed analysis shows that the burst group (A) consists of succeeding emissions of type III bursts with very high wave intensity corresponding to the white light flare; and bursts (B1), (B2) and (B3) consist of the series of rising tone bursts (B1) which are succeedingly changed to falling tone bursts (B2) and are again changed to rising tone bursts (B3). All these rising and falling tone bursts show the fast frequency drift rate. That is, a sequential occurrence of falling, rising, falling and rising tones is indicated, corresponding to (A), (B1), late half of (B2) and (B3), respectively. From the characteristic feature of the repetition of sequence of rising and falling nature of the emission with fast drift rate, we call here the phenomena the fast type SOC-RIFAR (Sequential Occurrence of Rising, Falling and Rising) decametric emission.

2.2 Slow type SOC-RIFAR

After the fast drifting bursts labeled (A) and (B) in Fig. 1, a series of slowly drifting bursts with unusual spectrum pattern which shows the sequential variation of the falling, rising and falling tone was observed in the period about 07:00 to 24:00 UT on February 6. We call here the phenomena slow type SOC-RIFAR considering the similarity with the fast type SOC-RIFAR. These bursts were observed continuously in this period, except for the data gap period from 09:00 to 21:00 UT due to local nighttime. Corresponding to the burst groups labeled (C), (D), (E) and (F) in Fig. 1, slow type SOC-RIFAR is shown in Fig. 3 being separated into four corresponding panels, i.e., sequential change of falling (C), rising (D), falling (E) and rising (F) tones of SOC-RIFAR are given with slower frequency drift rate, compared with the case of bursts (B1), (B2) and (B3). We separate other types of bursts such as type III bursts being distinguished from the slow type SOC-RIFAR phenomena in these dynamic spectra from (C) to (F) given in Fig. 3.

3. Large Scale Magnetic Loop Activity

Based on the sequence of the occurrence of the fast type and the slow type SOC-RIFAR phenomena, a large scale magnetic loop activity which shows formation and disconnection of the magnetic loops in the solar corona, ranging from 2 to 3 solar radii (measured from the center of the sun), has been investigated.
Fig. 1. Sequence of rising and falling tone bursts observed on February 6, 1986 (UT). A series of fast drifting radio bursts (fast type SOC-RIFAR) labeled (A) and (B), and slowly drifting bursts (slow type SOC-RIFAR) labeled (C), (D), (E) and (F) are given in the form of dynamic spectra for 20-40 MHz range. Bursts labeled (C) and (E) are characterized by falling tone; and bursts labeled (D) and (F) are characterized by rising tone nature. The observing times (UT) are indicated in the top portion of each panel.
Fig. 2. Reproductions of the burst spectra with higher time resolution corresponding to the parts labeled (A) and (B) shown in Fig. 1. Bursts labeled (B) in Fig. 1 are expanded in time being divided into three parts labeled (B1), (B2) and (B3) which are further expanded in time as given in corresponding three lower panels indicating more detailed feature; the panels (B1), (B2) and (B3) correspond to respective bursts (B1), (B2) and (B3) in the top panel. Bursts (A) and (B2) consist of mainly falling tone bursts while bursts (B1) and (B3) consist of rising tone bursts with fast frequency drift rate.
Fig. 3. Reproductions of burst spectra with higher time resolution corresponding to the bursts labeled (C), (D), (E) and (F) in Fig. 1 in corresponding panels. Bursts labeled (C) and (E) consist of falling tone emissions while (D) and (F) consist of slowly drifting rising tone bursts. The time scale for 30 minutes is given in the bottom commonly for all panels.
with a principle that the intense decametric radiations are taking place with the beam-plasma interaction processes at the local plasma frequency. The observed falling tone bursts are therefore corresponding to the outgoing electron beams and the rising tone bursts are corresponding to the inward motion of the electron beams. The sequential repetition of rising and falling tones of bursts is therefore strictly related to the beams which are guided by the magnetic loop where the trapped electron beams show clear change of the moving direction from outgoing to inward motion or vice versa. Considering the difference of drift rates, which correspond to the beam speeds, we have here divided the period into two cases of the phase; i.e., i) early phase corresponding to the fast type SOC-RIFAR and ii) late phase corresponding to the slow type SOC-RIFAR. In this paper, we concentrate on the burst group in early phase, and the generation mechanisms of the bursts in late phase will be given in another paper.

In the early phase, the complicated feature of fast SOC-RIFAR given in Fig. 2 can be understood by having a model of large scale isolatedly closed magnetic loop which is moving outwards in the solar corona. The model is schematically depicted in Fig. 4 where three succeeding features of the moving

![Figure 4](image-url)
magnetic loops (labeled (I) and (II)) are shown with the indication of trapped electron beams by arrows. The shaded area in each panel corresponds to the region of plasma frequencies which coincide with observing frequency range of the decameter wavelength (20–40 MHz). Associated with start of the white light flare at around 06:19 UT on February 6, it is inferred that the reconnection of the magnetic field has taken place corresponding to the portion R in panel (a) of Fig. 4. From the recent achievement of Yohkoh satellite observations of the soft-X ray images, we can use the representative distance of about 0.1–0.3 Rs (Rs: solar radius) (Ogawa et al., private communication, 1991), for the height of the portion R. Due to this reconnection, the magnetic loop (II) is isolated from loop (I) which is connected to the solar surface. Being associated with the flare eruption, the electrons were accelerated in the deep lower coronal region forming localized electron beams; a part of localized electron beams were trapped in the magnetic loops (I) and (II). It is probable that the electron beams circulate along the isolatedly closed magnetic loop (II), generating the decametric radio emissions at the corresponding local plasma frequency. The localized electron beam circulating along the isolatedly closed magnetic loop entered the range of observable frequency (shaded areas) repeatedly producing the sequential occurrence of falling, rising, falling and rising tone bursts (SOC-RIFAR), corresponding to the panels (a) and (b) (top and middle panels) in Fig. 4. In the period of case (c) (bottom panel) in Fig. 4, when the closed magnetic loop already passed away from the region observable at the decametric frequency range (shaded area), the radiation from the beams trapped by the magnetic loop (II) was shifted to lower frequency range than observable range, though flowing electron beams currently generated radio bursts moving along the magnetic loop (II) after the period of bursts (B) before the start of the bursts (C) given in Fig. 1.

Using the observed spectra, we can roughly estimate the speed of the electron beam and the speed of the outward movement of the isolatedly closed magnetic loop. From the frequency drift rates given in the spectra in Fig. 2, relative speeds of the electron beams with respect to the case (A) in Fig. 2 are obtained for (B1), (B2) and (B3) bursts, respectively to be 0.22, 0.37 and 0.28. The beam speed for the case (A) estimated for various electron density models (see Malitson and Erickson, 1966) is in a wide range from 0.075C to 1.0C (C: light velocity). When we adopt the $V_b$ value (beam velocity) for case (A) as 0.1C as a possible assumption of the typical type III bursts (see McLean and Labrum, 1985), the representative electron beam velocities $V_b$ in the case of bursts (B1)–(B3) are decided in a range from 7000–11000 km/s, for the assumed electron beam speed component in the direction of the plasma density gradient. The remarkable difference of the $V_b$ values between bursts (A) and (B) gives conclusion that the electron beam speed was decisively decelerated between two stages of isolatedly closed magnetic loop corresponding to the bursts (A) and (B) (see panel (a) and (b) in Fig. 4). It can be considered that the slow down of the electron beam is caused by the energy dissipation due to deformation and turbulent states of the moving magnetic field in the outer corona, while the beams are moving along the magnetic loop.

The higher speed of the electron beam corresponding to bursts (B2), than that of bursts (B1) and (B3), may partly be caused by Fermi acceleration process; i.e., an interaction between the outward moving magnetic loop and the electron beam along the magnetic loop flowing outwards.

The height of the 20-MHz level (see Fig. 4) is decided to be about one solar radius from the photosphere (Newkirk, 1961; Malitson and Erickson, 1966; etc.). Using this value for 20-MHz level and the distance from the photosphere to portion R which is assumed here to be 1–2 $\times 10^5$ km, we can obtain the characteristic distance from the portion R to 20-MHz level to be in a range from 5 $\times 10^3$ km to 6 $\times 10^5$ km. Because the duration period of the fast type SOC-RIFAR is about 20 minutes, the speed of the bottom part of the isolatedly closed magnetic loop (II) movement is estimated to be in a range from 400 km/s to 500 km/s; that is, the estimated speed of the magnetic loop is nearly equal to local Alfven speed in the corona.

From the dynamic spectra shown in Fig. 2 which indicate clear SOC-RIFAR phenomena, we can also estimate the scale of the closed magnetic loop flowing outward. The repeating period of bursts (B1), (B2) and (B3) is about 3–5 minutes and the typical speed of electron beams is estimated above to be in a range from 7000 km/s to 11000 km/s. These results lead a reasonable value of the loop scale, that is from $1.3 \times 10^6$ to $3.3 \times 10^6$ km. The interval between start of (B1) bursts and that of (B2) bursts is 3–4 minutes.
This can be interpreted by the present model where the returned beams corresponding to (B) bursts are reflected back inside the region of the loop that is isolated from the portion R. Because of relatively slow movement of the loop, the distance from the inside end of the loop to the source region of 20–40 MHz waves is estimated to be about $5 \times 10^5$ km. Slight difference from the estimated time delay of 1.5–3.5 minutes and observed interval 3–4 minutes can be attributed to the deceleration of the beam due to the possible electric field along the inside end region of the loop.

4. Discussion

In the dynamic spectra given in Fig. 1, there is the interval of about 20 minutes between bursts (B) and (C) when no radio burst is observed in a frequency range of the present observation. This evidence can be considered as an important support of our model for the formation of the isolatedly closed magnetic loop. That is, if the loop is connected to the lower level of the solar plasma atmosphere, there should be constant supply of the energetic particles or beams which become the origin of the decametric radio bursts when the energetic particles or beams move across the visible height level corresponding to the present decametric radio wave frequency range. The existing blackout in the given frequency range shows the period of blank of the source agencies in the corresponding height level; this can be only understood for the case of very limited group of the beams which are confined in a loop that is isolated from the supplying source region of the energetic particles or the beams. That is, even the source agency of the radio waves is currently emitting radio waves, the radiations cannot be detected in the present frequency range when a group of beams moves out from the corresponding visible height level for 20 to 40 MHz.

Another remarkable feature of this event of SOC-RIFAR is the significant difference of the typical frequency drift rates between the fast type SOC-RIFAR corresponding to the phenomena (A) and (B) and the slow type SOC-RIFAR corresponding to (C), (D), (E) and (F). This difference of the drift rate apparently indicates the difference of source conditions in acceleration regions of source agencies, and trapping states of source agencies, as have been already considered by a model given in Fig. 4.

The evidence of the change from the fast type SOC-RIFAR to the slow type SOC-RIFAR with a blackout period between these two, give us a clue to have a conclusion that the outward movement of the isolatedly closed magnetic loop (II) took place after the reconnection. The white light flare occurred on February 6, 1986 (UT) was, therefore, possibly associated with the X-type reconnection at the very initial phase of the flare onset. Considering the sequence of the event of the present results, we can find an interesting analogue in the case of the magnetic substorm, in the earth, where the reconnection of the tail magnetic field starts the injection of the plasma into the polar region while the isolatedly closed magnetic loop moves back towards the distant magnetotail forming plasmoid (HONES, 1977; and see references in this articles).

5. Conclusion

The observations of the decametric radio bursts give us important information for the configuration of the middle to outer coronal magnetic field and the behavior of the associated electron beams. To analyze these features, an event on February 6, 1986 (UT) which was associated with a strong white light flare has been studied.

After the strong flare bursts, a series of fast drifting rising, falling and rising tone bursts (fast type SOC-RIFAR) has been observed. The results of analyses of the dynamic spectra give us a scenario that groups of electron beams with speed in a range from 7000 km/s to 11000 km/s were circulating along the large scale isolatedly closed magnetic loop which moves outward in the solar corona with speed of 400–500 km/s containing the beams which become the source agencies of the decametric radio bursts. The moving velocity of the isolatedly closed magnetic loop approximately coincides with the local Alfven velocity. The scale size of the moving magnetic loop is also estimated to be in a range from $1.3 \times 10^6$ to $3.3 \times 10^6$ km. The most plausible processes to be the origin of this event is inferred to be caused by the
coronal magnetic loop that is associated with X-type magnetic reconnection at the initial moment of the flare.

Following a series of decameter radio bursts with fast drift rate (fast type SOC-RIFAR), another series of slowly drifting falling and rising tone bursts (slow type SOC-RIFAR) have been received. The detailed discussion on the generation mechanism for these bursts with characteristic spectral patterns will be given in another paper.

The present results of data analyses for February 6, 1986 event indicate, so far, the usefulness of the observation of solar decametric radio bursts for searching the magnetic field processes in middle and outer corona with associated energetic particle behavior.

REFERENCES


