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Long Duration Events Observed with the Nobeyama Radioheliograph

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Abstract

We give an overview of the observations of long duration events (LDEs) as observed with the Nobeyama Radioheliograph. Images of LDEs at 17 GHz show not only the brightening of arcade loops, which also characterizes soft X-ray images, but also of their footpoints. The observations indicate that the brightening of arcade loops is due to free-free emission from the hot and dense thermal plasma and that the footpoint brightening, highly polarized, is due to gyroresonance emission from thermal plasma in strong magnetic field regions. Except during the initial part of some events, there is no hint of gyrosynchrotron emission, indicative of the absence of high-energy electrons in LDEs. The radio data provide temperature diagnostics of the arcade loops when compared with soft X-ray images, and information on the magnetic field structures through analyses of the polarization maps. These are discussed in this paper.

Key words: Sun: flares — Sun: corona — Sun: radio emission

1. Introduction

Long Duration Events (LDEs) are the flares characterized by the long-enduring arcade development in soft X-rays, which last for several hours. Their longevity suggests that the energy release continues for hours, but hard X-rays from high-energy electrons are not observed except in the early phase of the flare. Therefore, the thermal emission is predominant in LDEs. Although the LDEs are lacking in the non-thermal emission, which efficiently radiates radio emission, the continuous imaging observations of the LDEs in short cm-waves is a unique capability of the Nobeyama Radioheliograph. Therefore, we present here an overview of the observations of LDEs with the Radioheliograph, and would like to answer the questions, "How are the LDEs observed at 17 GHz? How can the Radioheliograph data of the LDEs help the understanding of the LDE flares?" Hanaoka (1994) has already reviewed on the preliminary results of the observations of the LDEs with the Nobeyama Radioheliograph, but a new image processing technique gives more reliable images.

Figure 1 shows an example of LDEs, an X3.9 flare on 1992 June 25–26 near the west limb observed in soft X-rays with the SXT on board *Yohkoh* and at 17 GHz with the Nobeyama Radioheliograph. An arcade structure seen in the soft X-ray image is also seen in the 17 GHz image (figure 1c) and it shows no polarization (figure 1d). The emission from the arcade at 17 GHz is the free-free emission from hot, dense plasma in the arcade loops. In addition to the arcade, there are bright points at the footpoints of the arcade loops in the 17 GHz image. They are strongly polarized, and correspond to the sunspots in figure 1b. The brightness variation of the footpoint brightenings is well correlated with the soft X-ray brightness of the arcade (Hanaoka 1994), and the footpoint brightenings are observed throughout the flare duration. Therefore, its behavior is much different from the footpoint brightenings observed in the early phase of the flares in hard X-rays and radio, and also in soft X-rays (Hudson et al. 1994). We may to conclude that the footpoint brightenings are due to gyroresonance emission from the hot plasma just above the sunspots where the magnetic field is strong enough. Generally, the radio observation is highly sensitive to gyrosynchrotron emission under the strong magnetic field, and this is the reason why the gyrosynchrotron emission is predominant in impulsive flares. However, in the LDEs, there is no sign of gyrosynchrotron emission, except impulsive brightenings observed at the beginning of some LDEs. The fact that the gyroresonance emission is predominant at the footpoints in LDEs means the Presence of very low population of the non-thermal electrons. The lack of gyrosynchrotron emission is an important feature of the observations at 17 GHz as well as the two types of thermal emission – the arcade brightenings and the footpoint brightenings. In the following sections, we review the characteristics of the two types of 17 GHz emission from the LDEs.

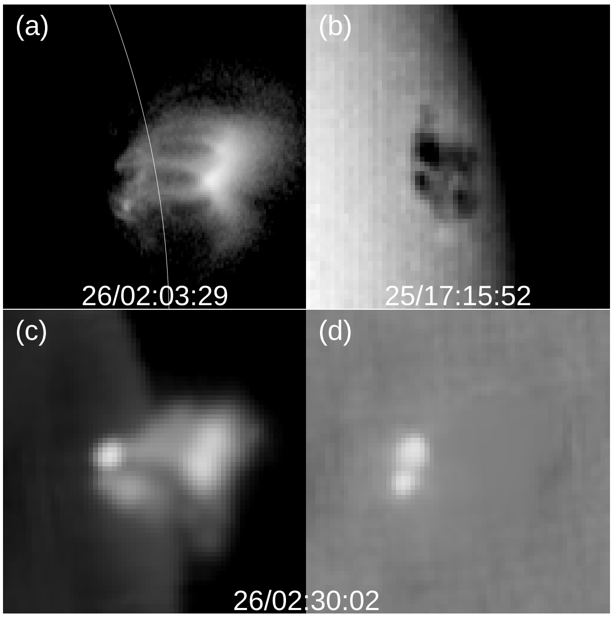

Fig. 1.. Images of the X3.9 flare on 1992 June 25–26 in NOAA 7205. Each image has a field of view of $5.2' \times 5.2'$, and solar north is to the top. (a) Soft X-ray image taken with the SXT on board *Yohkoh.* The solid-line curve shows the solar limb. (b) White-light picture of the active region taken by Big Bear Observatory at half a day before the flare. Images of the intensity (c) and the degree of polarization (d) at 17 GHz taken with the Nobeyama Radioheliograph. In the map of the degree of polarization, the right- and left-handed polarizations are displayed in white and black, respectively.

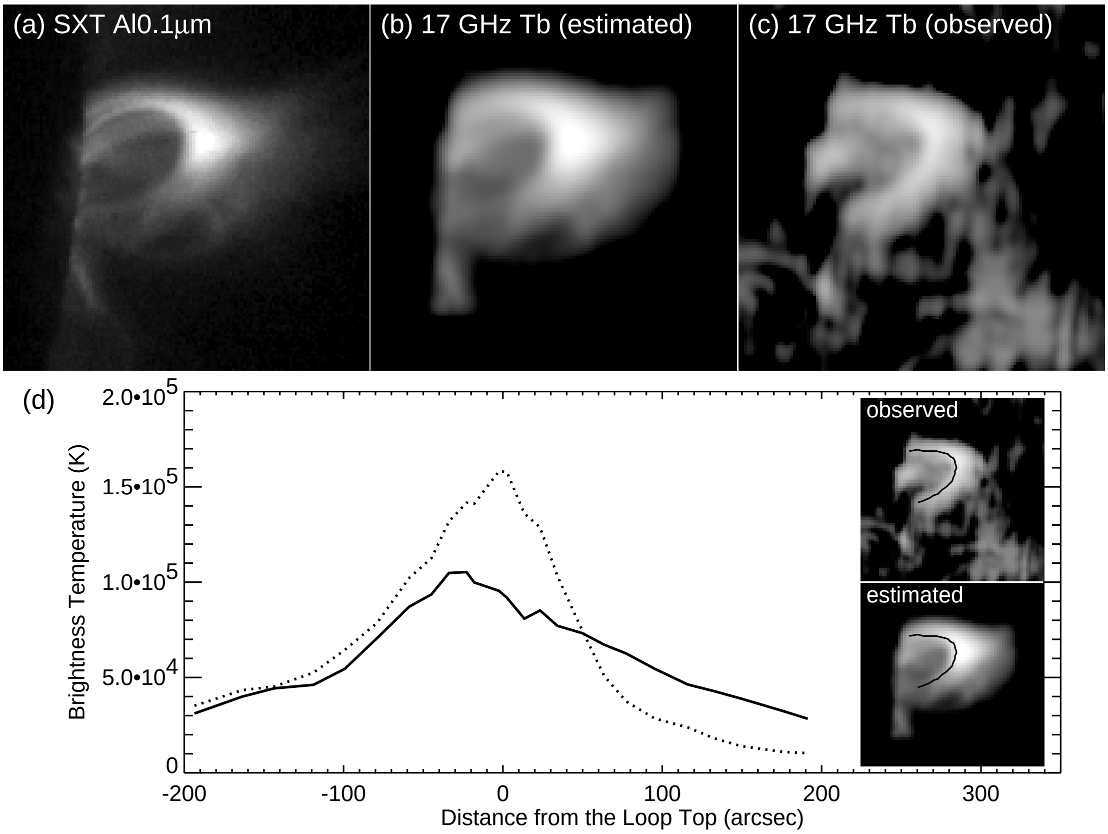

Fig. 2.. Images of the M2.9 flare on 1993 March 15–16 in NOAA 7440. Each image has a field of view of $5.2' \times 5.2'$, and solar north is to the top. (a) Soft X-ray image taken with the SXT on board *Yohkoh.* (b) Brightness temperature at 17 GHz estimated from the soft X-ray observation. (c) 17 GHz image taken with the Nobeyama Radioheliograph. (d) Brightness distribution along the loop axis of the observed image (solid line) and that of the estimated brightness temperature (dotted line). Panels in the right-hand side show the position of the loop axis.

2. Flare Loops

The most remarkable feature of the LDEs is the long-enduring, ascending loop structure. The Skylab observations and the study of the total eclipse data have revealed the fact that the high-lying loops have high-temperature, namely, the temperature hierarchy (e.g., MacCombie, Rust 1979; Hanaoka et al. 1986). The observations with the SXT show that the outermost region of the LDE loops, where the brightness is much lower than the bright core, contains very hot plasma of > 10 MK (Tsuneta 1996). Since the LDE loops include various temperature plasma, a wide-range temperature coverage is required to study them.

Now various instruments which cover a wide temperature range are available. The Yohkoh SXT is sensitive to higher-temperature plasma, and the SOHO EIT, TRACE, and also the Nobeyama Radioheliograph are (mainly) sensitive to lower-temperature plasma. Therefore, we can carry out the temperature diagnostics of the LDE loops with the widest temperature coverage ever. In this paper, we concentrate on the comparison between the SXT data and the images taken with the Nobeyama Radioheliograph. At 17 GHz, free-free emission from coronal plasma ($>$ 1 MK) is always optically thin. The brightness temperature of the optically thin free-free emission is written as

$$T_B \propto T^{-1/2}\mathrm{EM},$$

where T and EM stand for the temperature and emission measure of the plasma. Therefore, the brightness of the coronal plasma at 17 GHz is sensitive to the amount of the low temperature plasma, even if its dependence on the temperature is rather weak.

The Nobeyama Radioheliograph is an interferometer designed to observe flares, namely intense, compact sources. Therefore, the CLEAN procedure works well to reconstruct images of the flares. However, image reconstruction of diffuse sources such as LDE arcades is not easy. The dirty beam has diffuse halo around the central compact core, and this halo makes diffuse background around the LDE arcades (see Hanaoka 1994). This makes it difficult to reconstruct quantitatively reliable images of the LDE arcade. Therefore, in our study of LDEs, we adopt a new imaging technique originally developed by Fujiki (1997). This technique is described below. The low spatial frequency components are dropped to eliminate the diffuse halo. As a result, the images of the solar disk and other active regions are superposed on the image of the LDE, an effect widely known as aliasing. To overcome this effect, we first remove the aliasing sources from the visibility data and then reconstruct images using the high-frequency components alone. This technique causes increase of the background noise, but we can carry out quantitative analyses of the sources which are sufficiently brighter than the background, such as the LDE arcades.

Figure 2 shows a beautiful example of the LDEs observed on 1993 March 15-16 in NOAA 7440. The active region is behind the west limb at the time of the flare occurrence. Figures 2a and 2c show the soft X-ray and radio images. They are much different from each other. Particularly, the observed 17 GHz image does not show the bright blob at the loop-top in the soft X-ray picture, which is the remarkable common feature in LDEs observed with the SXT. To compare them quantitatively, we calculated the expected brightness temperature at 17 GHz from the hot plasma observed with the SXT. Based on the temperature and the emission measure derived from the soft X-ray images, we can estimate the brightness temperature at 17 GHz. Figure 2b shows the convolved image of the calculated brightness temperature distribution with the beam of the Radioheliograph to match its spatial resolution to that of the radio images. The loop-top bright blob is still remarkable in figure 2b, and the difference between the observed brightness and the estimated brightness is obvious. Figure 2d shows the brightness distributions of the observed loop at 17 GHz and the estimated 17 GHz brightness along the axis of the flare loop shown in the right-hand side of figure 2d. The excess of the estimated brightness at the loop top is clearly shown, and on the other hand, the observed brightness exceeds the estimated one in the southern part of the loop (right-hand side in the plot). The excess of the observed brightness is easily understood if there is cool plasma (about 1 MK, for instance) which cannot be observed with the SXT. The concentration of the cool plasma in low altitude is well-known from old observations. However, the excess of the estimated brightness is quite puzzling. This fact means that the existing plasma observed with the SXT cannot be seen at 17 GHz. We cannot show other examples here because of the limitation of space, but the lack of the loop-top bright blob of the LDE arcades in the 17 GHz images is a common feature of many events. Furthermore, the cusp extending above the loop in soft X-ray images cannot be seen in the 17 GHz images. The difference between the soft X-ray images and the 17 GHz images is a structural one. Such a difference cannot be explained by an error in the absolute calibration. One possible explanation of this discrepancy is that the bright blob is much hotter than the temperature derived from the SXT images, and it emits 17 GHz radiation only weakly. However, we cannot arrive at any definite conclusion in the current stage. Since the loop-top region is close to the presumed energy release site, to obtain the correct temperature/emission measure of the loop-top region is extremely

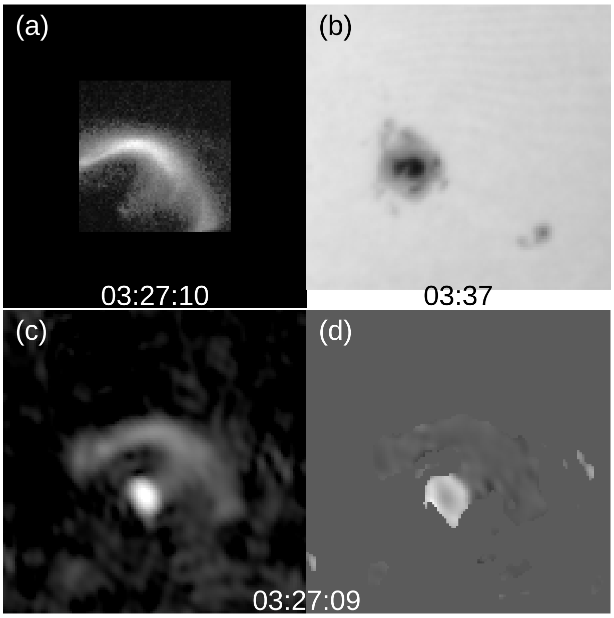

Fig. 3.. Images of the C6.3 flare on 1993 March 11 in NOAA 7440. Each image has a field of view of $5.2' \times 5.2'$, and solar north is to the top. Images are not co-aligned. (a) Soft X-ray image taken with the SXT on board *Yohkoh*. (b) White-light picture of the active region taken by the Flare Telescope of NAOJ, Mitaka. (c)-(d) Images of the intensity and the degree of polarization at 17 GHz taken with the Nobeyama Radioheliograph. In the polarization map, the right- and left-handed polarizations are displayed in white and black, respectively.

important. To solve this discrepancy, further comparison among the data obtained with the SXT / EIT / TRACE / Radioheliograph, and also the HXT, with which we can observe super-hot plasma, is strongly needed.

As shown in figure 1d, the arcade loops show no polarization. However, on the basis of the integration of many images, Shibasaki (1999) shows that actually the loops are very weakly polarized. The polarization of the free-free emission is caused by the magnetic field. Therefore, it is possible to estimate the magnetic field strength of the arcade loops on the basis of the precise measurement of the polarization.

3. Footpoint Brightenings

As described in section 1, the footpoint brightenings is the most remarkable difference between the soft X-ray and the 17 GHz images. They always correspond to sunspots. Their brightness temperature sometimes exceeds 1 MK, and they are always highly polarized. Such brightenings are due to gyroresonance emission from the third or the fourth harmonic layer. Within the usual ranges of the coronal temperature and electron density, the second harmonic layer is always optically thick for X-mode. Emission from the third and fourth harmonic layers strongly depends on the coronal parameters. The fifth and higher harmonic layers are virtually invisible. The magnetic field strengths of the third and the fourth harmonic layer for 17 GHz are 2000 G and 1500 G, respectively. If one of the footpoint of the flare loops of LDEs is located at a sunspot, the optical thickness of gyroresonance emission show remarkable increase during the LDEs due to the increase of hot and dense plasma, and the footpoint brightenings are produced.

In some cases, the footpoint brightenings show an interesting feature — a ring-like structure of the degree of polarization. Figure 3 shows an LDE on 1993 March 11 in NOAA 7440, which is an example of the ring-like polarization. The soft X-ray and the 17 GHz images show a flare loop (figures 3a and 3c). Since the location of the active region is not far from the disk center (W30), they are roughly the 'top-view' of the flare loop. In addition to the flare loop, the 17 GHz image show a bright point at one of the footpoints of the flare loop. The polarization map (figure 3d) shows a ring-like structure at the footpoint brightening. As seen in figure 3d, the ring-like structure is due to the depression of the degree of polarization at the center of the footpoint brightening. The footpoint brightening corresponds to a sunspot shown in figure 3b.

The ring-like structure appears in the main phase of the flare. Figure 4 shows the enlarged views and the east-west cross sections of the footpoint brightening in the preflare phase, the main phase of the flare, and the post-flare

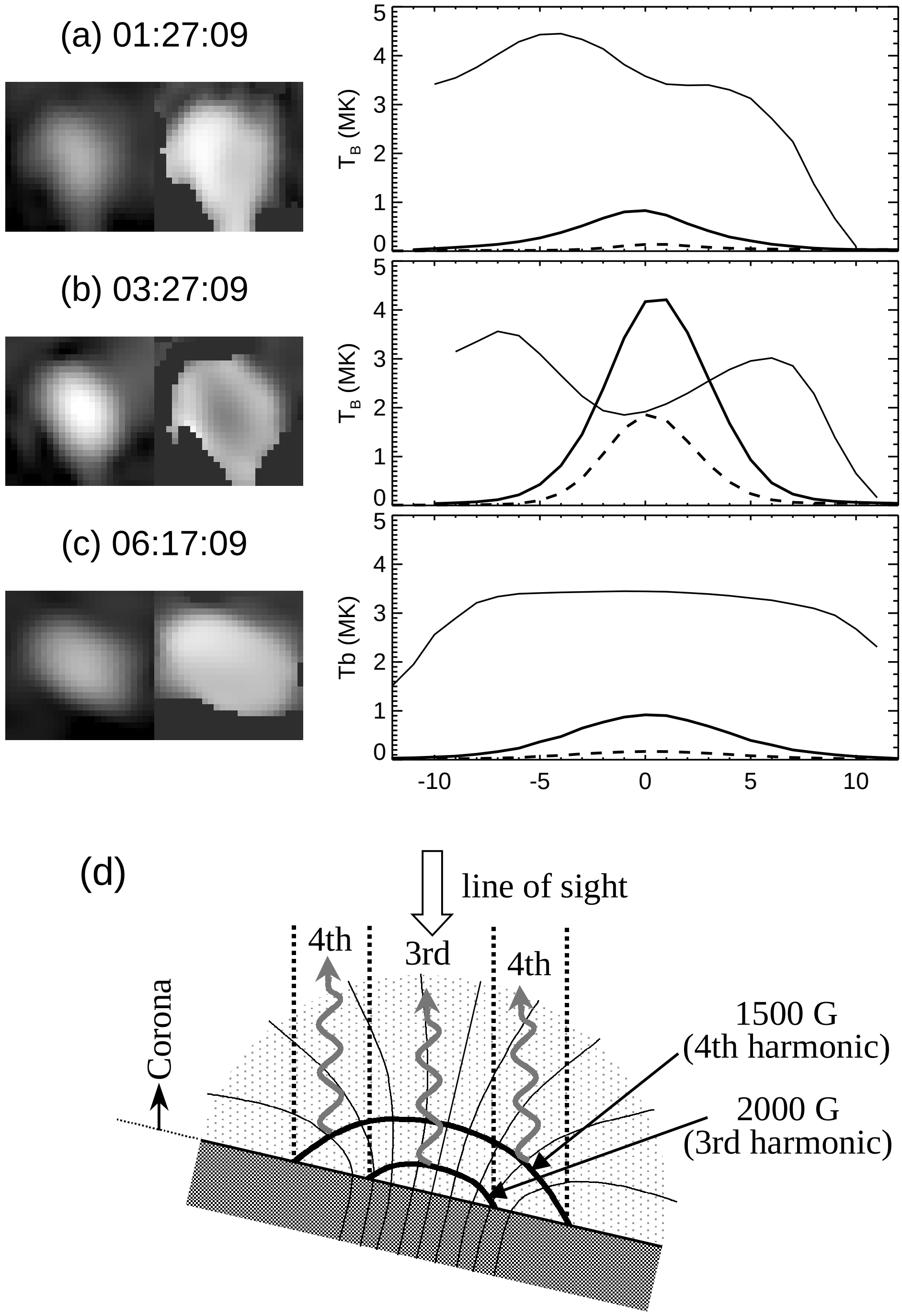

Fig. 4.. (a)-(c) Enlarged view of the maps of the brightness temperature and the degree of polarization of the footpoint brightening of the 1993 March 11 flare, and E-W cross sections of the RCP intensity (thick solid line), LCP intensity (thick dashed line), and degree of polarization (thin solid line) at (a) the preflare phase, (b) the peak of the flare, and (c) the later phase of the flare. The unit of the x-axis is pixel (1 pixel = 2.46″). (d) Schematic view of the magnetic field structure of the footpoint brightening.

phase. The schematic picture of the footpoint brightening is also shown. It is presumed that the third and fourth harmonic layers exist in the corona above the sunspot. The changes of the brightness temperature and the degree of polarization during the flare can be explained as follows. In the preflare phase, the x-mode (RCP in this case) of the third harmonic has substantial optical thickness, even if it is not optically thick. The optical thickness of the o-mode (LCP in this case) of the third harmonic is low, and therefore, the degree of polarization is high. During the main phase of the flare, the corona above the sunspot is filled with hot and dense plasma. The x-mode of the third harmonic becomes optically thick, and the brightness temperature of the RCP is saturated. The brightness temperature corresponds to the coronal plasma temperature (of course, the beam effect is to be considered). The optical thickness of the o-mode of the third harmonic has substantial optical thickness, but it is still optically thin. Since the o-mode (LCP) is not saturated, the degree of polarization decreases. It decreases to about 60 % at the flare maximum from about 80 % in the preflare phase. During the main phase of the flare, the x-mode emission of the fourth harmonic layer becomes observable, while the o-mode is still negligible. Since the optical thickness of the fourth harmonic is three–four orders of magnitude smaller than that of the third harmonic, it does not affect of the brightness temperature of the central region. However, in the outskirts of the footpoint brightening where there is no third harmonic layer along the line-of-sight, the highly polarized emission from the fourth harmonic layer is observed. This emission creates the high-polarization ring of the footpoint brightening, even if the brightness temperature of the fourth harmonic emission is not high (it is several tens of thousands K). In the later phase of the flare, the corona above the sunspot becomes cool and low-density. Therefore, the x-mode of the third harmonic is only substantial emission source, and the ring-like structure disappears. The degree of polarization becomes high again.

On the basis of this observation, we can conclude that the 2000 G magnetic field of the third harmonic layer exists in the corona above the sunspot, and such lowermost corona filled with flare plasma during the main phase of the flare.

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