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Thermal and Nonthermal Components in an X-Class Long Duration Flare

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Abstract

We have analyzed the 1992 November 2 GOES X9-class long-duration flare that was accompanied by intense microwave and hard X-ray emission, using data from the Nobeyama Radioheliograph at 17 GHz and the Hard X-Ray and Soft X-Ray Telescopes onboard the Yohkoh. We show that: (1) There are two electron components: one is a quite soft component as inferred from hard X-ray emission, and the other is a quite hard nonthermal component, as inferred from microwave emission. (2) Hard X-ray observations show a bar structure which is located well above the soft X-ray loop. (3) The soft electron component is created in the bar region. It is also suggested that the hard nonthermal electron component is also created in or near the compact bar region and is trapped in the larger region surrounding the soft X-ray source. (4) The bar region has a high temperature of 40 MK, a high density of $5 \times 10^{10}\ cm^{-3}$, and a high thermal energy content of 10^{30} erg.

Key words: Sun: flare — Sun: X-ray — Sun: radio emission — particle acceleration

1. Introduction

Observations with the *Yohkoh* Soft X-ray Telescope (SXT) suggest that energy in some long-duration flares is released by magnetic reconnection in a current sheet above the soft X-ray loop (Tsuneta, et al. 1992; Tsuneta 1996). Masuda (1993) and Masuda et al. (1994) analyzed impulsive hard X-ray flares and found that the hard X-ray source is located above the soft X-ray loop in most of analyzed events. They considered this loop-top hard X-ray source to be evidence that energy release and particle acceleration occur above the soft X-ray loop. Since most of Masuda's events belong to LDE's from a viewpoint of GOES flare classification, the loop-top hard X-ray source is a property of impulsive bursts which occur at the early stage of LDE's.

There are numerous mysteries to be resolved, i.e., whether the loop-top source is nonthermal or thermal, whether the loop-top source is located coincidently with the fast shock where the reconnection outflow collides with the underlying soft X-ray loop, what the relationship between the loop-top hard X-ray source and the loop-footpoint hard X-ray sources is. Clearly, further studies are needed.

In this paper, we report the results of an analysis of the 1992 November 2 GOES X9 flare (S23, W100) which was carried out using data from the Nobeyama Radioheliograph and the *Yohkoh* Hard X-ray Telescope (HXT). This flare has a duration of more than 10 hours in GOES soft X-ray emission, and has a duration of more than 30 minutes in microwave and hard X-ray emission. A preliminary report on the microwave aspects of this flare was made by Nakajima & Metcalf (1995). Since then, the imaging software has been considerably improved by Sato (1997), and as a result, a more detailed analysis of this flare has become possible. This flare has been also extensively analyzed by Feldman et al. (1995) for soft X-ray aspects, and by Altyntsev et al. (1998) for microwave aspects.

2. Observations

Figure 1 shows time profiles of total fluxes of microwave (17 GHz) and hard X-ray (M1: 23-33 keV, M2: 33-53 keV, H: 53-93 keV) emission from the 1992 Nov. 2 flare. Although the hard X-ray observations are only available for the later half of the impulsive phase, the microwave time profile at 17 GHz is similar to those at hard X- rays even in fine structures as seen in Figure 1, especially in the time profiles of the higher energy bands. This suggests

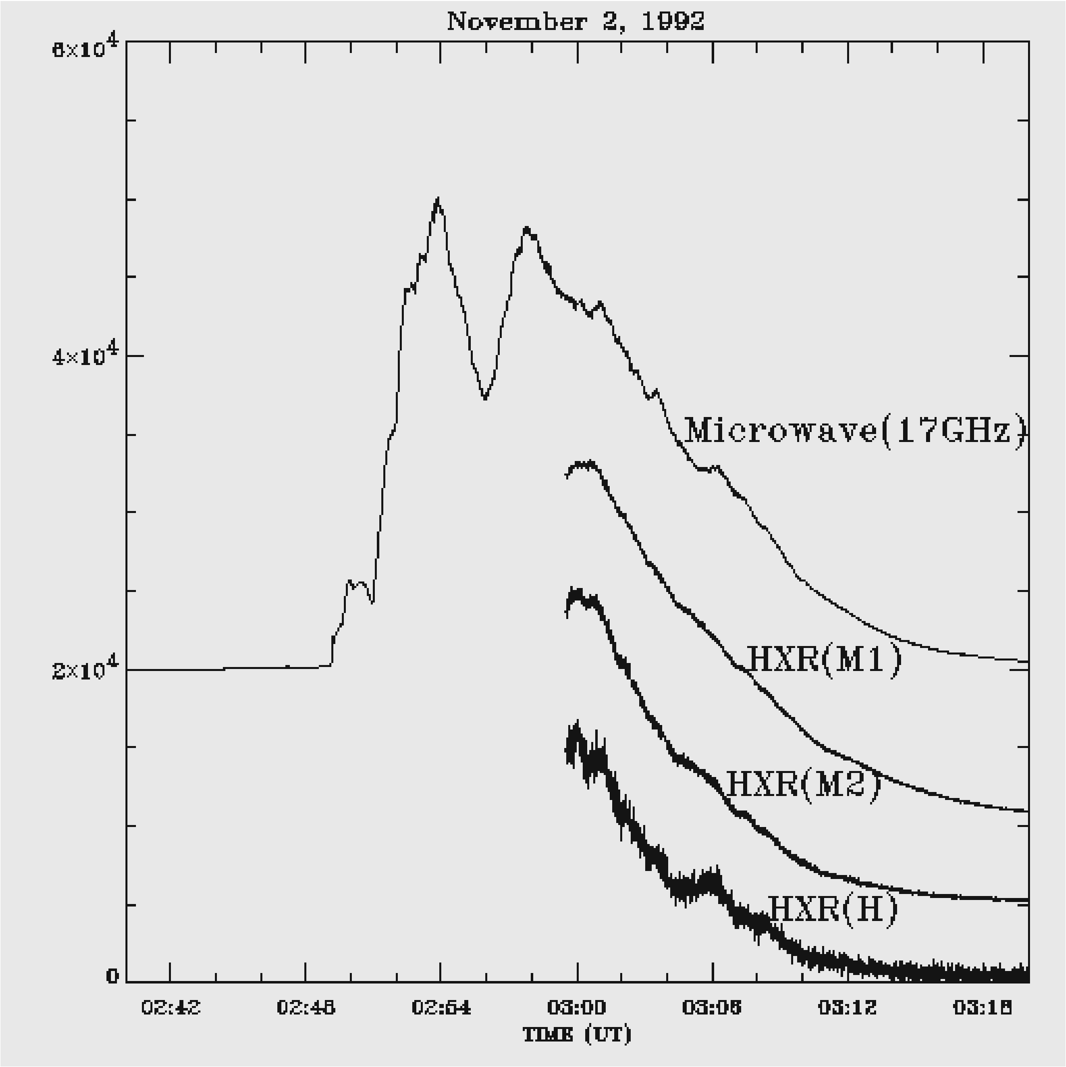

Fig. 1.. Time profiles of microwave (17 GHz) and hard X-ray intensities of the 1992 November 2 flare. The ordinate is an arbitrary unit. The microwave time profile is similar to the hard X-ray time profiles even in fine structures (at 03:01 UT and 03:06 UT), especially at higher energies.

Table 1. Power-law indices and electron temperatures estimated from microwave and hard X-ray total intensity spectra

	γ *1	Te (MK)	δ *2
Microwaves	1.5		3
Hard X-rays:			
M1/L	7.8	35	
M2/M1	7.1	61	
H/M2	5.8	130	

*1: Photon spectral indices. *2: Electron spectral indices.

that both high-energy electrons which contribute to microwave and hard X-ray emission are accelerated or heated by closely related acceleration mechanisms and/or in close proximity to each other.

Table 1 shows effective power-law electron spectrum indices or effective electron temperature which are estimated from microwave and hard X-ray total fluxes. The hard X-ray emission has a very soft spectrum although the indices become somewhat harder at higher energies. The effective electron temperature, which is derived from the M1/L ratio, is 35 MK. The power-law index of nonthermal electrons is estimated to be very hard, about 3, from the optically-thin part of the micro-millimeter wave spectrum. Note that in the case of such a hard micro-millimeter wave spectrum, the micro-millimeter wave emission emanates from nonthermal electrons at energies of more than several hundred keV. These observations show that there are mixed populations of electrons in the flaring region, i.e., a very soft component derived from the hard X-ray spectrum and a very hard spectrum derived from the micro-millimeter wave spectrum.

Figure 2 shows overlays of microwave (17 GHz), hard X-ray, soft X-ray flare images around 03:00 UT. We can clearly see that a hard X-ray source with a bar structure, 1.1×10^4 km in length and 4.3×10^3 km in width, is located about 1.5×10^4 km above the brightest apex of the soft X-ray loop. This hard X-ray bar structure is more evident in the M2 band image. We call this hard X-ray bar source bar-1. At lower energy bands (L- and M1-bands), a larger, diffuse source surrounds the compact M2-band hard X-ray source. On the other hand, the microwave source at 17 GHz, which represents the nonthermal component, is large and covers the soft X-ray and hard X-ray sources. The centroids of the microwave and hard X-ray sources are not located exactly above the soft X-ray source but are slightly displaced from exactly above the soft X-ray source toward the south. There is also a weak indication of another weaker bar source (bar-2) which is located below and parallel to bar-1, at almost the same height as the top of the soft X-ray loop.

The microwave and hard X-ray sources show temporal change during ten minutes after 03:00 UT as shown for two typical times in Figure 3. The bar-1 source at M2-band consists of symmetrical double-sources (we designate the southern and northern one as ds-1 and ds-2, respectively) at 03:00 UT. As time elapses, ds-1 decreases more rapidly than ds-2 and simultaneously, bar-2 becomes visible. As a result, the weighted centroid of the double source shifts to the north. This change of the hard X-ray source structure at M2-band can be traced in the lower-band (M1-band) image. Correspondingly, the microwave source at 17 GHz shifts toward the same direction as the hard X-ray sources move. These observations suggest that nonthermal electrons which emit microwave emission at 17 GHz are accelerated in or near the same region as the hard X-ray bar regions and propagate along magnetic field lines, resulting in formation of the larger region which covers the hard X-ray bar source.

Table 2 shows physical parameters at 03:00 UT for the compact bar (bar-1) region and the halo region which are estimated from hard X-ray data. The bar-1 region has effective temperature of about 40 MK. On the other hand, electron temperature of about 30 MK can be derived for the hard X-ray bar region from the soft X-ray images using the filter ratio method. This suggests that the bar-1 region is actually filled with electrons of about 40 MK. The halo component has slightly lower temperature of about 30 MK and is distributed, surrounding the bar-1 region, which suggests that high-temperature thermal plasma is created in the bar-1 region and diffuses away from it.

3. Summary and Discussion

The present observations are summarized as follows. (1) There are two kinds of electron components: One is a quite soft component derived from hard X-ray emission. The other is a hard nonthermal component derived from microwave emission. (2) Hard X-ray observations show a bar structure which is located above the soft X-ray loop.

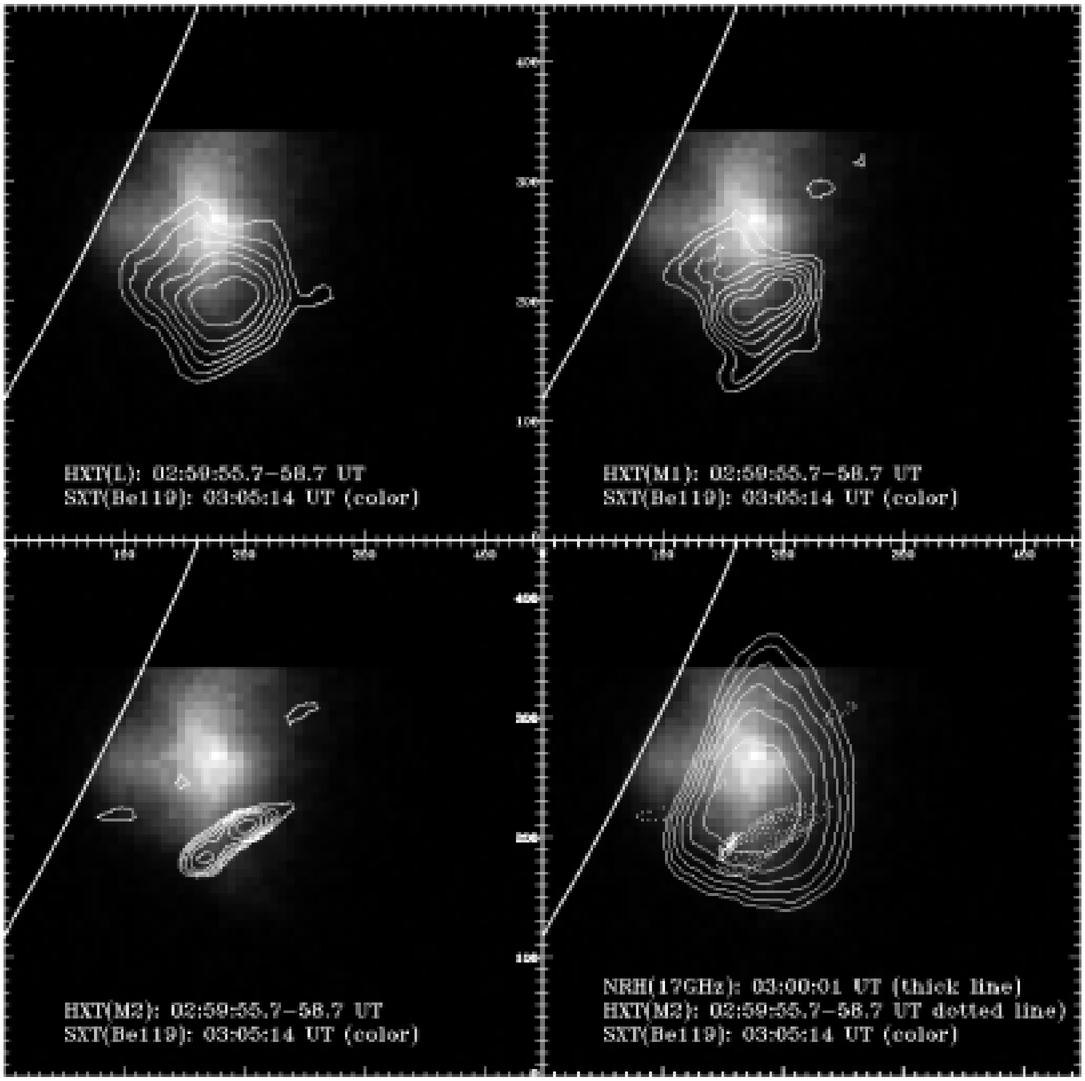

Fig. 2.. Overlays of hard X-ray (dotted contours), soft X-ray (greyscale), and microwave (thick contours) flare images around 03:00 UT. All contour levels are in steps of $\sqrt{2}$ starting from 12.5% of the peak intensity in each panel. The field of view is 2.5 arcmin. The solar north is up. The location of the west solar limb is shown in each panel.

Table 2. Physical parameters of hard X-ray compact and halo components in the case of thermal fitting.

	Te (MK)	EM (cm^{-3})	Ne (cm^{-3})	Etotal (erg)
Compact component				
M1/L	37	1×10^{49}	5×10^{10}	1×10^{30}
M2/M1	54			
Halo component				
M1/L	33	5×10^{49}	4×10^{10}	5×10^{30}

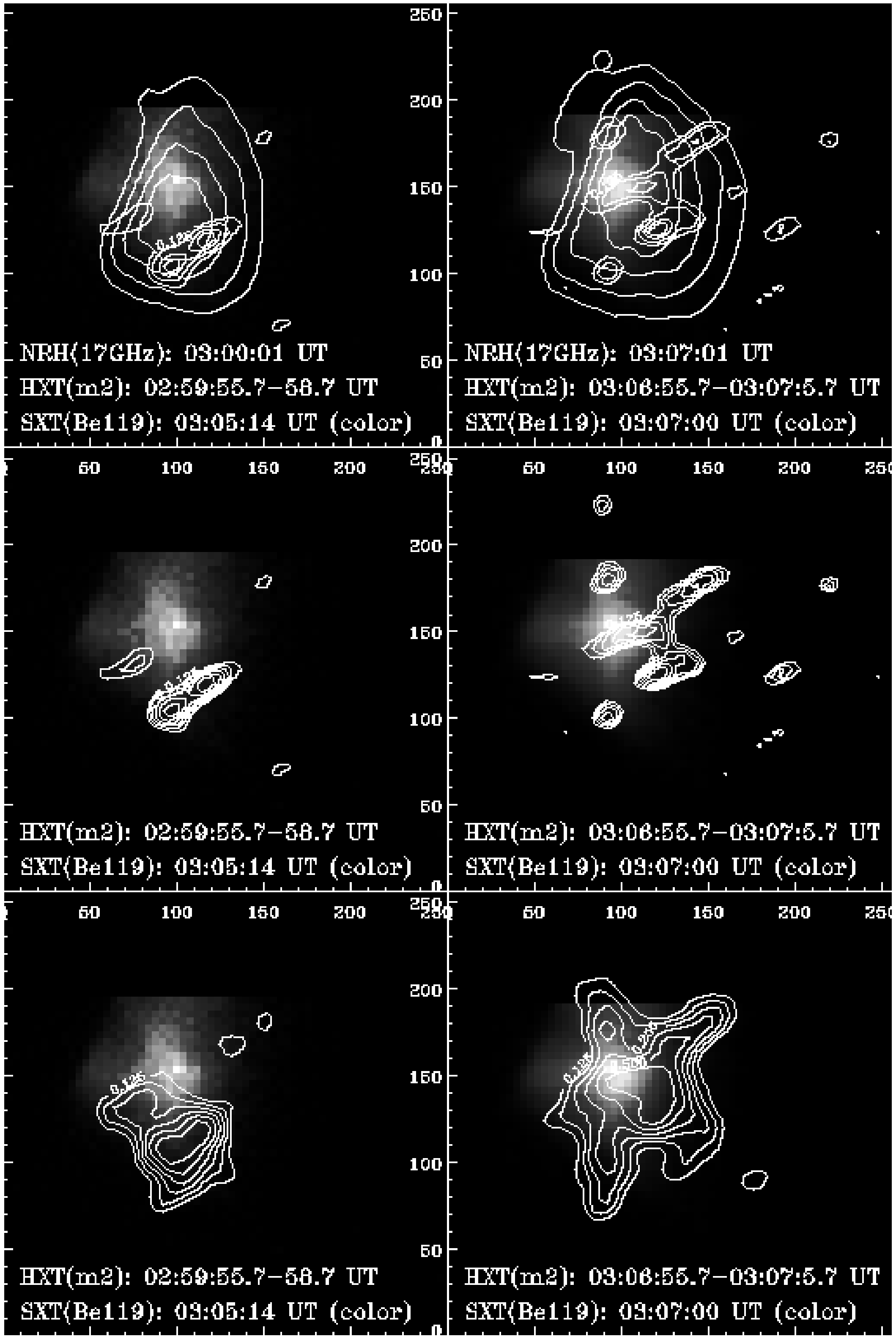

Fig. 3.. Coaligned microwave (contours), hard X-ray (contours), and soft X-ray images (greyscale) at two typical times (03:00 UT and 03:07 UT). All contour levels are 10, 25, 50, and 75 % of peak intensities. The field of view is 2.5 arcmin.

The other, much weaker bar structure (bar-2) is also observed at roughly the same height as the soft X-ray loop top. (3) The soft electron component with the temperature of 40 MK is created in the bar region. It is also suggested that the hard nonthermal electron component is also created in or near the compact bar region and is trapped in the larger region surrounding the soft X-ray and hard X-ray sources. (4) The bar region has a high temperature of 40 MK, a high density of 5×10^{10} cm^{-3}, and a high thermal energy content of 10^{30} erg.

Masuda et al. estimated for the loop-top hard X-ray source of the 1992 January 13 GOES M2-class flare that the effective electron temperature is 2×10^{8} K, the density is 2×10^{10} cm^{-3}, and the thermal energy content is 3×10^{28} erg. As compared with these properties, the 1992 November 2 event shows a lower temperature but a much higher thermal energy content.

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