Nonthermal Electrons Accelerated in Solar Flare Loops

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Abstract

A C9.2 flare occurred on the southeast limb (S20E90) on 1993 November 30. This flare was observed in hard X-rays and microwaves simultaneously, and its spatial structure is well resolved. Three kinds of microwave sources are located at the top and nearly at the both ends of a soft X-ray magnetic loop. The microwave source at the loop top has the following characteristics. Its time profile is basically impulsive, and its brightness temperature is 8e6K at the peak time. The degree of polarization is nearly 0%.

The high brightness temperature of the microwave loop top source cannot be explained by the thermal bremsstrahlung. The most preferable mechanism for the microwave loop top emission is gyrosynchrotron emission from MeV-electrons accelerated in a weak magnetic field (a few tens Gauss). The peak time lags behind those of the other microwave sources at the footpoints of the loop. This time delay is probably caused by the trapping of the MeV-electrons in the magnetic loops. In addition, the time variation of the microwave source is similar to that of the hard X-ray one at the northern end of the magnetic loop, but the time variation of the microwave source is not similar to that of the hard X-ray ones at the southern end. This fact suggests the difference of trapping/ precipitation efficiencies of the accelerated electrons between the both ends of magnetic loops.

Key words: Sun: flare — Sun: Microwaves — Sun: X-rays

1. Introduction

It has been well known that the microwave emissions of the solar flares are sometimes delayed with respect to the hard X-ray emission (e.g., Cornell et al. 1984). Such a time delay is presumed to be caused by the electron trapping in the magnetic loops. Although there have been the studies of the flare events simultaneously observed with the Nobeyama Radioheliograph (Nakajima et al. 1994) and the Hard X-ray Telescope (Kosugi et al. 1991) on board *Yohkoh* (Kundu et al. 1995, Hanaoka 1996, Nishio et al. 1997), there are few studies on the time delay between the hard X-ray and microwave, except that by Bastian and Aschwanden (1999). It is supposed that this time delay may be due to electron trapping in magnetic loops. To clarify the nature of the time delay, we analyzed a C9.2 flare observed both in microwaves and hard X-rays on 1993 Nobember 30 (See. Nishio et al. 1997), which show a clear time delay in microwaves. Since this flare is a limb event and the size of the loop structure is large (about 50,000 km long), the loop-top/footpoint sources in hard X-rays and microwaves are well resolved.

2. Observations

The C9.2 flare occurred at the southeast limb (S20E90) on 1993 November 30 in active region NOAA 7627. In soft X-rays, two loops are clearly seen. The bigger loop is about 50,000 km in length and its height is about 25,000 km. The microwave observation shows three microwave sources in the impulsive phase. At 6:03:33(UT), the three sources were located along the bigger soft X-ray loop. Two of them correspond to the footpoints of the bigger soft X-ray loop. The other one was located nearly at the top of the soft X-ray loop. These microwave sources are labelled M1, M2, and M3 in Figure 1. The microwave source located at the northern end of the loop, M1, reaches the peak brightness 6:03:33(UT), and this peak corresponds to a highly impulsive spike. The peak brightness temperature of M1 is 7e6K, and the degree of polarization is 40% in the precursor phase and about 20% after the peak(see Figure.2-d). The microwave source at the loop top, M2, becomes the peak brightness at 6:03:47(UT), and therefore,the peak time is delayed fourteen seconds behind that of M1. The peak brightness temperature is 8e6K, and its degree of polarization is nearly 0% throughout the flare (Figure. 2-d). The microwave source located at the southern end of the loop, M3, reaches the peak brightness 6:03:40(UT) and is delayed seven seconds behind M1. Its peak brightness temperature is 2e6K, and its degree of polarization is nearly 0% throughout the flare. The time profiles of M2 and M3 are not so impulsive as that of M1.

Hard X-ray time profiles are hard structures extended to the Hi-band (53-93 KeV). The hard X-ray images show a more complicated source structure than that in microwaves, but all the hard X-ray sources are related to the two soft X-ray loops described above. At 6:03:33(UT), the peak in the hard X-ray total flux, the typical double footpoint sources (Sakao, 1993), labeled H1 and H3 in Figure 1, and the loop top one (e.g, Masuda et al. 1994), H2, are conspicuous. These sources are located along the outer and larger soft X-ray loop. Their time profiles show impulsive variations and are similar to each another. In addition, two more hard X-ray sources, labelled H4 and H5 in Figure 1, are also observed. The source H4 is located at one of footpoints of the smaller soft X-ray loop. The source H5 is probably a loop top source of the smaller loop.

Here, we compare the time profiles of the microwave sources with those of the hard X-ray sources located close to the microwave sources. The results are shown in Figure 2. The peak time of microwave source, M1 almost coincide to that of the hard X-ray source, H1 and the both time profiles are highly impulsive. The peak time of the microwave source, M2 lags behind hard X-ray source, H2 for fourteen seconds. The microwave time profiles are less impulsive than that of the hard X-rays.

The peak time of microwave source, M3 lags behind the hard X-ray source H2 for seven seconds. The microwave time profile is also less impulsive than that of hard X-rays.

3. Discussion

The analyzed flare shows the microwave loop top source clearly. What is the nature of the microwave loop top source? We discuss several possible emission mechanisms for this microwave source in the following.

The first possibility is that the emission comes from the thermal plasma observed in soft X-rays, because the degree of polarization is quite low. However, the brightness temperature estimated from the temperature and the emission measure of the soft X-ray emitting plasma is about 8e5 K. This value is much lower than the observed value, 8e6 K. It is difficult to account for the microwave loop top source by the emission from thermal plasma.

The second possibility is emission from super-hot plasma of 3-4e7 K in temperature. If such high temperature plasma were present, the count rates of the HXT would be larger than observed.

The third possibility is gyroresonance emission. If so, the magnetic field must be strong at the loop top and the degree of polarization must be high. Therefore, it is difficult to explain the microwave loop top source by the gyroresonance emission.

The forth possibility is the emission from hard X-ray loop top source. However, the time variation of microwave loop top sources is different from that of hard X-ray ones. So, this possibility is also unlikely.

The last possibility is the gyrosynchrotron emission. If the magnetic field strength of the loop-top region is weak (e.g., a few tens of Gauss), the degree of polarization can be very low. The energy of electrons emitting microwaves must be high ($\sim$ 1 MeV) to account for the high brightness temperature of 8e6 K (Kosugi et al. 1988). Such high-energy electrons are effectively trapped in the magnetic loop and therefore, the time delay in microwaves is easily understood.

One more interesting result is the asymmetry of emission in microwaves and hard X-rays between the footpoints of the magnetic loop. At the northern end of the magnetic loop, the time profile of the microwave source, M1, is similar to that of the hard X-ray source, H1, while at the southern end, the time profile of microwave source, M3 is not similar to that of the hard X-ray source, H3.

The footpoints of the magnetic loop are the precipitating region of the accelerated electrons. Accordingly, it is supposed that the hard X-rays originate in the thick target emission and that the microwaves are the gyrosynchrotron emission from the precipitating electrons. This is the reason that the hard X-ray and the microwave profiles are similar to each other at the northern footpoint of the magnetic loop. However in the case of M3 and H3, their time profiles are different from each other. The time profiles of M3 are less impulsive than M1. These observations suggest that the efficiency of the precipitation is higher at the northern end of the magnetic loop and that the efficiency of the trapping is higher at the southern end of the magnetic loop. The strength of magnetic fields are supposed to be different between the both ends of the magnetic loop. The strength of the magnetic field can be estimated from the degree of polarization of the microwave sources.

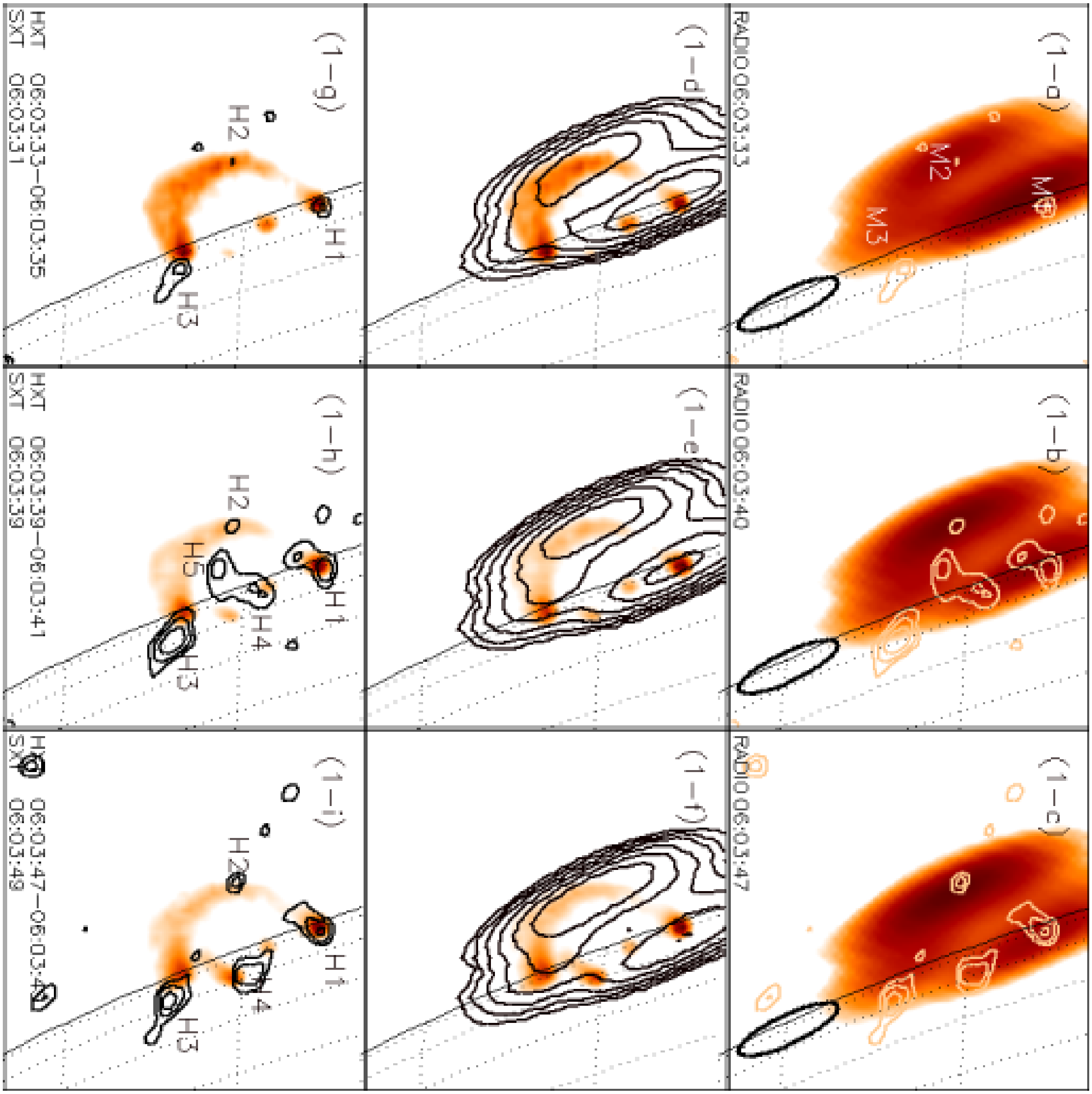

Fig. 1.. The evolution of the microwave, HXR and SXR sources for the 1993 Nobember 30 event. The upper figures are overlays of microwave images (gray scale) and HXT M1 band images (contours). The middle figures are overlays of SXT images (gray scale) and microwave images (contours). The lower figures are overlays of SXT images (gray scale) and HXT M1 band images (contours).

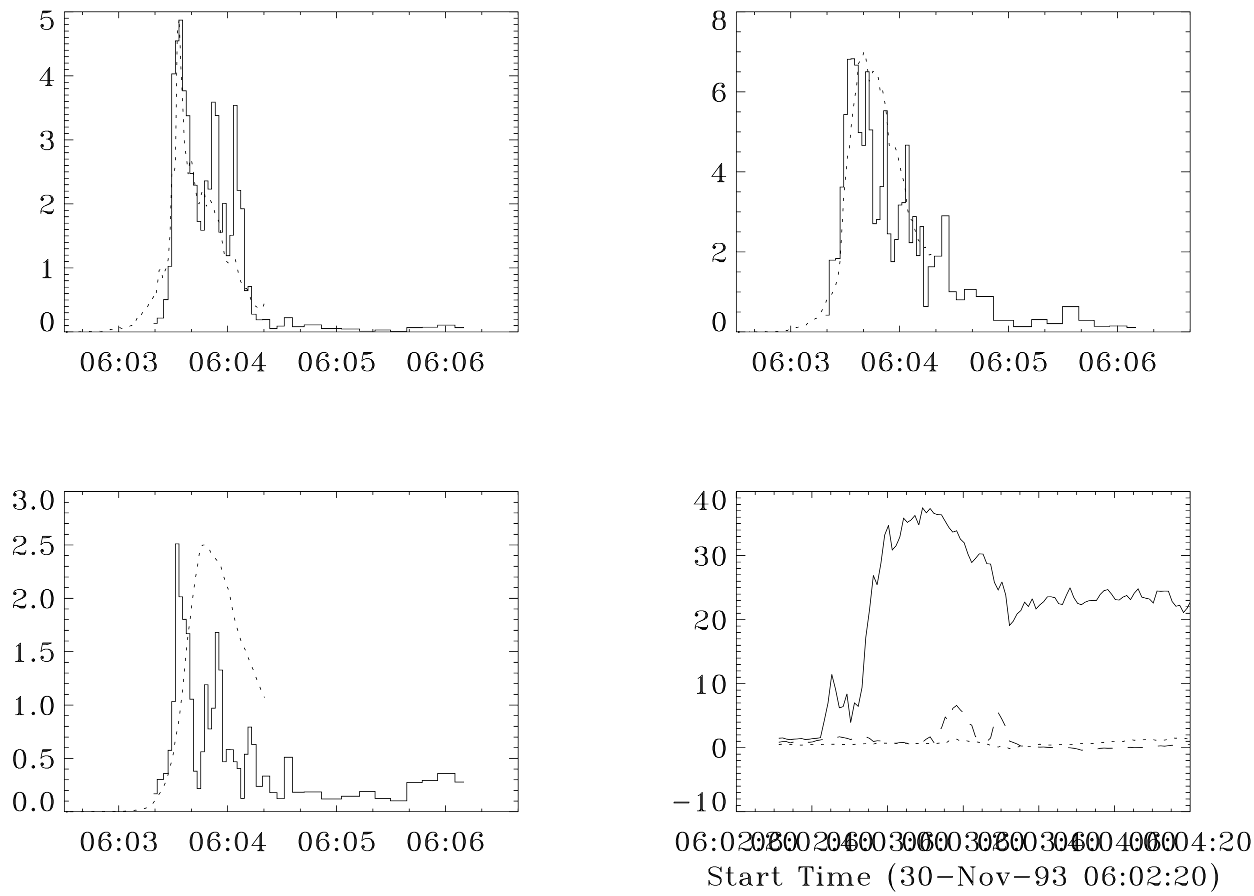

Fig. 2.. Light curves of microwave source and hard X-ray sources, M1 and H1 (2-a), M2 and H2 (2-b),M3 and H3 (2-c). (2-d) shows the light curves of the degree of polarization. Solid lines, dotted lines and dashed lines show the degree of polarization of M1, M2, and M3, respectively.

4. Conclusions

The C9.2 flare on 1993 November 30 occurred at the southeast limb and its spatial structure is deduced from the simultaneous observations in microwaves and X-rays. It is found that one of the microwave source is located nearly at the loop top of the soft X-ray magnetic loop. The peak time of the microwave source lags behind the peak of the total hard X-ray flux and also behind the peak of one of the microwave sources at the footpoints of the magnetic loop. Its brightness temperature is about 8e6 K at the maximum, and its degree of polarization is nearly 0%. The microwave loop top source likely originates in gyrosynchrotron emission from MeV-electrons. Probably, the accelerated electrons are reflected by the magnetic mirror at the footpoints and are trapped in the magnetic loop. The findings of this microwave loop top source is evidence that high energy electrons are trapped in flaring magnetic loop.

In addition, the microwave and hard X-ray observations show the efficiencies of the precipitation/trapping at the ends of the magnetic loop are different from each other. This fact reflects the difference of magnetic field strengths at ends of the magnetic loop.

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