SPECTRAL DYNAMICS OF MILDLY RELATIVISTIC ELECTRONS IN EXTENDED FLARING LOOPS

V.F. Melnikov[1], V.E. Reznikova[1], T. Yokoyama[2], K. Shibasaki[2]

[1]Radiophysical Research Institute, B.Pecherskaya St. 25, 603950, Nizhnii Novgorod, Russia
[2]Nobeyama Radio Observatory, NAOJ, Minamimaki, Minamisaku, Nagano 384-1305, Japan

ABSTRACT

The specific task of this work is an analysis of the microwave spectral dynamics of several well-resolved loop-like radio sources with the Nobeyama Radioheliograph (NoRH) at 17 and 34 GHz. The flares were detected as well with the Yohkoh/HXT and the BATSE/CGRO hard X-ray spectrometer. Their hard X-ray spectral index evolution follows to the classical "soft-hard-soft" behavior, typical for most of impulsive flares with simple time profiles. On the contrary, the temporal evolution of the microwave spectral index derived from the emission at 17 and 34 GHz in different portions of the loop-like sources displays "soft-hard-harder" behavior: decrease of its value from the rise phase to the decay phase. These results indicate on the different spectral evolutions of low and high energy electrons in a flaring loop. Some possibilities for such a difference, including processes of acceleration/injection, trapping and scattering, are considered.

1. INTRODUCTION

Spectral features of mildly relativistic electrons accelerated in solar flaring loops can be studied using observations of their optically thin gyrosynchrotron microwave emission. One of the important findings related to this topic is the dynamic flattening of the frequency spectrum during the rise and decay phases of impulsive bursts in the cm-mm wavelengths (Melnikov and Magun, 1998). In the majority of events such the spectral flattening on the decay phase of bursts is accompanied by the simultaneous spectral softening of the corresponding hard X-ray emission (Melnikov and Silva, 2000). These properties were interpreted as the natural consequence of the non-stationary "trap+precipitation" model, which takes into account the energy spectrum hardening of trapped electrons due to Coulomb collisions as well as the difference between the spectral evolutions of injected and trapped electrons. On the other hand, Lee and Gary (2000) have shown that the evolution of the pitch-angle distribution of non-thermal electrons in a flaring loop can play an important role in the interpretation of the microwave spectral flattening.

So far studies of the spectral evolution of optically thin microwave emission of solar flares were carried out for the full Sun observations without any spatial resolution. One has got only the spectral relationships averaged over a whole source. Consequently, the physical models of a radio source were quite simplified. They consider the electron energy spectral evolution in a flare loop as a whole not taking into account possible inhomogeneity of both magnetic field and plasma density along the loop. Evidently, a study of microwave spectral evolution in different parts of a flare loop on the base of observations with a good spatial resolution may provide us by new, additional information. This information may help us to develop a more appropriate physical model of a radio source and to get better understanding of particle acceleration and transport in flare loops.

So the specific task of this work is an analysis of the microwave spectral dynamics of several well-resolved loop-like radio sources with the Nobeyama Radioheliograph (NoRH) at 17 and 34 GHz.

2. DATA ANALYSIS

We have studied five solar flares observed with NoRH with high temporal (0.1 s) and angular (beam size ~ 10" at 17 GHz and ~ 5" at 34 GHz) resolution: 28 Aug 1999, 12 January 2000, 11 and 13 Mar 2000, 23 Oct 2001. For the analysis of these flares we used also hard X-ray data detected with the Yohkoh/HXT and the BATSE/CGRO hard X-ray spectrometers as well as magnetographic data from SOHO/MDI. The radio sources of all the events had large sizes, much over the beam size of the radioheliograph, and well pronounced loop-like structure at both frequencies (see, for example, Fig.1). The frequency spectrum slope in the range 17-34 GHz during the impulsive phase of the bursts was negative throughout the sources extension. In the frame of the gyrosynchrotron emission mechanism, this fact indicates that the radio sources were optically thin at least at 34 GHz. Below we illustrate the common features found for all the events with the examples of the 28 Aug 1999 and 13 Mar 2000 flares.

2.1. Time profiles of the emission from different parts of a loop-like microwave source

In Fig.2a,b we show the flux time profiles from the regions corresponding to different parts of the loop

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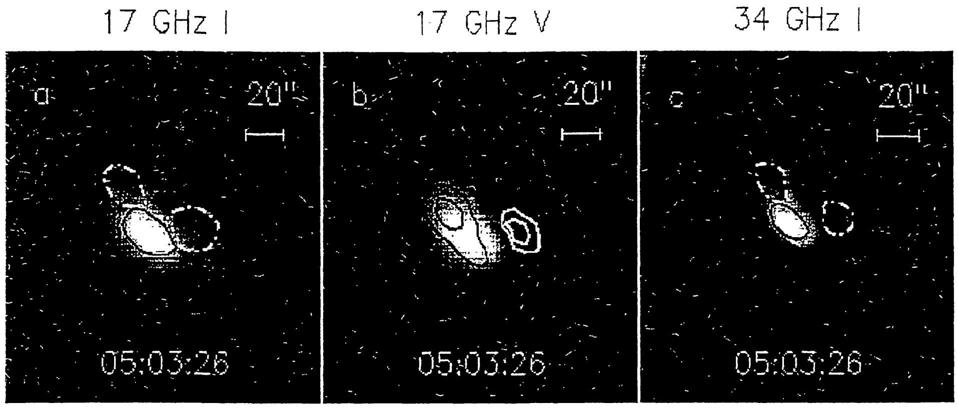

Figure 1. NoRH images at the rise and peak phases of the flare 2000 March 13. Left and right panels: intensity at 17 and 34 GHz with the contours at the level 95% of the maximum at the current time (black solid line) and at the moment 05:02:28 UT (white dashed-dotted line). Middle panel: polarization V with the contours at the levels 40% and 80% of the maximum, black for positive V, and white for negative V.

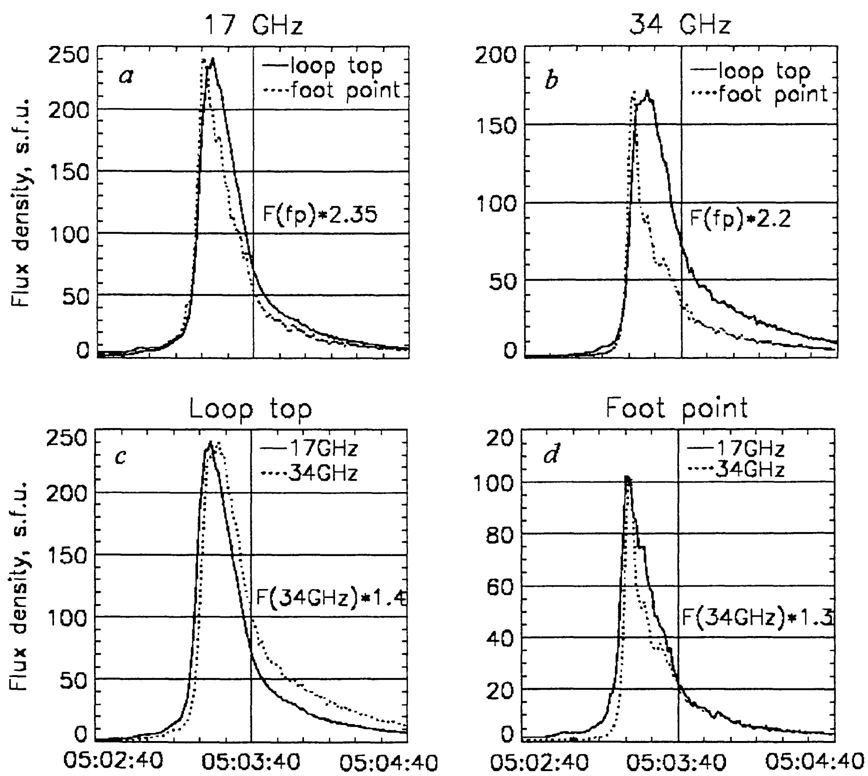

Figure 2. NoRH time profiles of the flux densities from the 10"x10" boxes located at the loop top and the left footpoint (see Fig.1) of the flare 2000 March 13. The flux densities from the footpoint source (a, b) and at 34 GHz (c, d) are multiplied by the coefficients shown on the plots. The delays between the intensity time profiles from the loop-top and a footpoint at both frequencies (a, b), as well as the delay of the emission at higher frequency from the loop top (c) are clearly seen. We did not find any noticeable delay between time profiles at both frequencies from the conjugate footpoints.

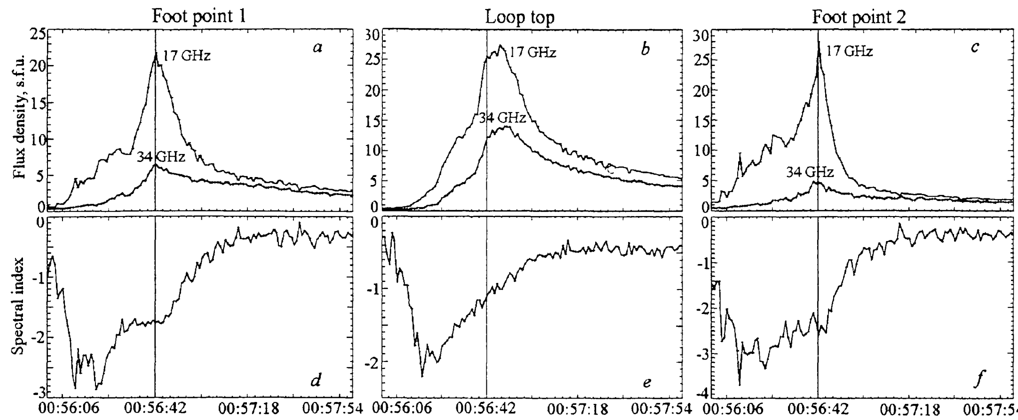

Figure 3. Top panel: NoRH time profiles of the flux densities from the 10"x10" boxes located at the loop top (b) and the footpoint (a,c) of the flare 1999 August 28. Bottom panel: the corresponding time profiles of the spectral index calculated with equation (1). Vertical line indicates the moment of the hard X-ray emission peak, 00:56:42 UT.

source for the event on March 13, 2000: the loop-top (black contour in Fig.1a,c) and the north-east footpoint (white dashed-dotted contour at the same figures). Time profiles of the emission from the second footpoint are not shown here since their behavior is very similar. The size of the regions used for the flux calculations is *10"x10"*. In Fig.2a,b the peak value of the flux from the footpoint source (dashed line) is adjusted to the peak value of the flux from the loop-top (solid line) by multiplying it by the factors shown on the plots.

It is well seen that the burst of emission from the loop top is delayed against the burst from the footpoint source by several seconds. This delay is more pronounced at 34 GHz than at 17 GHz. Furthermore, it is clearly seen that the time profiles of emission from the loop top are wider and their decay is slower than those from the region near the footpoint.

The similar delays and differences in the characteristic decay time are observed for all the events from our sample (see, for instance, Fig.3 for the event of 28 Aug 1999). Note that for all the events the flux peaks from the footpoint sources are coincident in time with the flux peaks of hard X-ray emission (compare Fig.3 and Fig.4 where the vertical line indicates the moment of the hard X-ray emission peak, 00:56:42 UT).

2.2. Time profiles of microwave emission at different frequencies

A comparison of the microwave time profiles of emission at the frequencies 17 and 34 GHz from the same parts of a loop-like radio source is shown on Fig.2c,d and Fig.3a,b,c. One can clearly see that, for the main peak of the bursts, the emission at higher frequency, 34 GHz, is delayed against that at 17 GHz. This is well pronounced for the loop-top part of the sources. However there are no such delays for the footpoin parts (Fig.2d, Fig.3a,c). The footpoint emission at both frequencies peaks almost simultaneously with the peak of the corresponding hard X-ray burst (see Fig.3, 4).

2.3. Microwave spectral evolution

In order to analyze the spectral dynamics of microwave emission quantitatively, we introduce a parameter derived from the data on fluxes at 17 and 34 GHz

$$\alpha = \ln(F_{34}/F_{17})/\ln(34/17). \qquad (1)$$

The fluxes were calculated after the adjustment of images at 17 and 34 GHz to the same antenna beam size. For some extent this parameter can serve as an approximation to the frequency spectral index. This approximation is quite reasonable when the spectral peak of the emission is located at frequencies $f < 17$ GHz, which is the case for the events we analyze here.

The results of our analysis are as follows. The temporal evolution of α for different parts of a loop-like source, where it is optically thin (negative α), shows the very common behavior: a gradual increase of its value in the rise and decay phases of the bursts (Fig.3). This "soft-hard-harder" behavior of the microwave emission is associated with the "soft-hard-soft" behavior of the corresponding hard X-ray emission. The opposite evolution of the spectral slopes of the microwave and hard X-ray emissions on the decay phase is well seen on the plots Fig.3d,e,f and Fig.4c. Such kind of spectral evolution is similar to the spectral evolutions of microwave and hard X-ray emissions integrated over a whole source (Melnikov and Silva, 2000).

Along with this we have found that the temporal increasing of α (flattening of the microwave spectrum) during the decay phase goes remarkably faster in the regions close to the footpoints than to the loop top (compare Fig.3d,f and 3e). We also confirmed the result by Yokoyama et al (2002) that the microwave spectrum near footpoints is considerably softer (by $\Delta\alpha \sim 0.5$-1) than near the loop top during the main peak of the bursts under our study.

3. DISCUSSION AND CONCLUSION

The temporal flattening of the microwave spectrum in its optically thin part throughout the loop-like source (from the loop top to the footpoints) together with simultaneous softening of hard X-ray spectrum during the decay phase of bursts, as well as the time delays at higher frequencies, indicate on a different spectral behavior of low energy electrons generating hard X-ray emission and mildly relativistic electrons trapped in a flaring loops and generating the microwave emission. This may be caused by acceleration mechanism itself or some transport effects. One of the transport effects is the Coulomb collisions that cause a shorter life time for lower energy electrons trapped in a magnetic loop (Melnikov and Silva, 2000).

The other interesting microwave spectral features are the differences in the flux dynamics and spectral slope of emissions coming from the loop top and footpoint parts of a flaring loop. They include: 1) slower intensity decay and time delays of microwave emission from the loop top part compared to the footpoint part; 2) steeper frequency spectrum near footpoints; 3) faster spectral flattening of emission from the footpoint part. Our model simulations show that these three features can be adjusted with each other if one takes into account the magnetic field inhomogeneity in a flaring loop. The physical reason for that is the following. The gyrosynchrotron emission at a given frequency from the loop top is generated at higher harmonics of gyrofrequency due to the lower magnetic field compared to the footpoint region. In its turn the emission at higher harmonics is generated by more energetic electrons that have a remarkably longer life time in the trap. The longer lifetime of these electrons explains naturally a) the slower intensity decay, b) the delays of emission and more gradual spectral flattening of emission from the loop top compared to the footpoints. Note, however, that this reason does not always explain the whole set of observed emission characteristics, for example, radio brightness distribution along a flaring loop (Melnikov et al., 2002). An important role in creating the observed spectral properties of microwave emission can be played by an anisotropy of accelerated/injected electrons as well as by different kinds of wave-particle interactions that are able to redistribute the contributions into the emission from precipitated and trapped electrons.

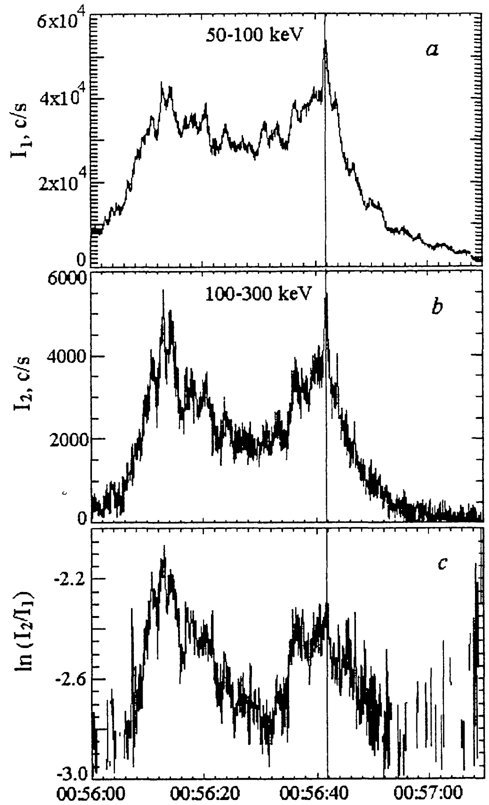

Figure 4. Time profiles of the hard X-ray intensities detected with CGRO/BATSE (a, b), and the corresponding ratio (c) for the flare August 28, 1999.

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