

Fine structure of microwave emission in the August 25, 1999 event and its association with the magnetic field fine structure

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Abstract. A study is made of the initial stage of the August 25, 1999 event, based on using high time resolution microwave observations, as well as the data from the Siberian Solar Radio Telescope and YOHKOH/SXT/HST, and optical data. Microwave emission revealed fine structure of emission with a typical time of about several seconds with the frequency drift of ~ 1 GHz/s, and the structure with a typical time less than 0.1 s with the frequency drift of ~ 10 GHz/s. Emission bands with a slow frequency drift are generated by energetic electrons subject to the cyclotron resonance condition, and the frequency drift is a consequence of a change in plasma density caused by the coalescence of magnetic structures with a typical size on the order of $\sim 10^8$ cm, while the emission with a fast drift is generated by fluxes of energetic electrons generating emission on the Cherenkov resonance. The energetic electron fluxes are produced at the interaction of magnetic structures $\sim 10^6 - 10^7$ cm in size.

1. Introduction

An immense number of publications have been devoted to the observation of solar flares and to development of their scenarios (see, for example, Svestka, 1976; Priest, 1982; Somov, 1992). Observations of this kind are carried out in all ranges of solar emission: from gamma-emission to kilometric radio emission, and each range contains information about the particular aspects of the solar flare process. Fine temporal structure observations of the flare emission are of special interest. As a rule, amplitude oscillations with a characteristic time from a few tens of milliseconds to several seconds are observed in the flare emission (Aschwanden, 2002, 2003). As such oscillations are observed at the time of flares, it would appear natural that they reflect the spatially and temporally intermittent acceleration and injection of electrons from dynamic current sheets operating in a "bursty magnetic reconnection mode" (LeBoeuf et al. 1982; Priest, 1985; Tajima et al. 1987). A great deal of information about these processes is contained in the radio range, especially in the microwave range because it is precisely this range that provides emission originating from the region where most flare energy is released. Besides, this range has the advantage over the other ranges because of its higher temporal resolution (as high as 5 ms) achieved with the spectrographs of the Beijing observatory and the Purple Mountain observatory (China). This provides the means of observing the fine temporal structure of flare emission, which, in turn, is associated with the fine spatial structure of the flaring region (Ledenev et al., 2001a; Ledenev et al., 2001b). However, such a structure of emission is difficult to distinguish at the time of powerful solar flares because of the saturation effects of observing equipment. On the other hand, significantly less intense events can reproduce more distinctly the main processes occurring in flares because there are no saturation effects or their role is of minor nature. This paper is devoted to the description of such a phenomenon at the beginning of the August 25, 1999 flare in the active region NOAA 8674. This flare was investigated in detail by Huang et al., 2003.

2. Observations

This paper is based on the data from the spectrograph at the Purple Mountain observatory operating at 4.5 - 7.5 GHz. The temporal resolution of this instrument varies from 5 to 10 ms, and the frequency resolution is 1-10 MHz. High spatial resolution (as high as 15 arcsec) is provided by the data from the Siberian Solar Radio Telescope (SSRT) operating at 5.75 GHz frequency. Besides, the data from YOHKOH/SXT/HST and optical data were used in this study.

A class M 3.6 X-ray flare of duration about eight minutes began in the small active region NOAA 8674 (S25E35) situated to the south of the larger active region NOAA 8673 (S19E32) at 01:32 UT on August 25, 1999 (Solar-Geophysical Data, 1999). A maximum of the flare occurred at about 01:36 UT. The impulsive phase of the flare began at 01:35:10 UT. It was accompanied by an emission burst throughout the entire radio range. About one minute before the start of the flare's impulsive phase, a precursor with a developed fine structure of emission appeared in the frequency range from 3 to 7 GHz (Figure 1a). Fine structures of duration of up to several seconds drifting mainly upward in frequency with a velocity of about 1 GHz/s are shown in this Figure and Figure 2. The same time there are fine structures of a very short duration in Figure 1a, and it is impossible to determine their frequency drift velocity from this Figure. The region of the spectrum of a one-second duration is shown in Figure 1b, and one can see in the Figure fine structures of a duration of several tens of milliseconds. Some of the fine structures have a frequency drift velocity of about 10 GHz/s.

Thus fine structure elements with duration and drift velocities differing at least by one order of magnitude are observed. The high spatial resolution observations of the flare in the microwave emission (Figure 3) and in X-rays (Figure 4) show that the sites of the higher radio emission (designated as "burst") and the X-ray flare coincide, and energy release occurred in a small region of the size of about 30" which shows up as an arch in X-rays (Figure 5).

X-ray data (Figure 5) show that at the beginning of the flare the main release of energy in hard X-rays occurred in the same region but at a different footpoint of the loop. Unfortunately, we have no SSRT data for the time of the flare; however, as it follows from the observations (Figure 3), the high microwave brightness temperature remains for some time after the flare, and with high probability we can consider this place as the source of the radio burst.

3. Discussion

We suggest that the fine structure of radio emission, observed at the initial stage of the flare, is generated as a result of the development of a beam instability excited by energetic electron fluxes (plasma mechanism). These fluxes are generated as the result of the release of energy at the interaction of magnetic flux tubes (magnetic loops) emerging into the corona. As follows from observations, the release of energy has an impulsive character with a duration of about one second. This process, in turn, is overlaid by a still smaller-scale process on a typical time scale of several tens of milliseconds. As is known (Martin, 1989), coronal arcades (loops) support two main types of mass motion: energetic electron fluxes (fast motions with velocities approaching the velocity of light), and mass flows as a single whole (slow motions with velocities of about the velocity of sound). In the case under consideration, i.e. the interval 01:34:10-01:35:10 UT, an enhanced X-ray flux is observed in the energy range 25-50 keV (Huang et al., 2003). This means that the energy of particles generating this emission lies in the range 50-100 keV, and their velocity is of the order of 10^{10} cm/s.

As one can see from Figure 5 the X-ray emission is observed this time as a loop of the length of $\sim 3 \cdot 10^9$ cm. The maximum of the hard X-ray emission is shifted at the beginning stage of the flare from the one loop base to another one. The loop position is coincident with the one of

the heightened radio emission source in Figure 3 and bright X-ray source at the flare's impulsive phase (Figure 4). Energetic electron transit time through the loop is about 0.1 s, i.e. agrees with fast drift element duration in Figure 1b. One can suppose with enough high probability that the radio bursts, which are shown in Figures 1, 2, are generated in this magnetic structure also because as heightened radio emission is observed from this region even after the flare.

Obviously, the fine structure elements of microwave emission, observed on dynamic spectra with a frequency drift of about 10 GHz/s (Figure 1b), are generated by energetic electrons during the development of a beam instability (Mikhailovskii, 1974), i.e. the Cherenkov resonance condition $\omega = kv\cos\alpha$ is satisfied, where ω is the frequency of plasma waves excited as a result of the development of the instability, k is the wave number of plasma waves, and α is the angle between the wave vector of plasma waves and the electron velocity vector. The plasma waves then transform to electromagnetic waves (radio emission) (Zheleznyakov, 1970).

The frequency drift of about 1 GHz/s corresponds to the emission source velocity about 10^9 cm/s. Such a high mass velocity is not observed in solar flares (Martin, 1989). On the one hand, this velocity is too small to generate emission by a plasma mechanism, as this requires a velocity of electrons far exceeding the thermal velocity of background plasma electrons. On the other hand, it is unlikely that the same process would generate particles differing in energies by two orders of magnitude. Hence it is natural to anticipate that the generation mechanism for slowly drifting elements of the emission fine structure differs from the generation mechanism for rapidly drifting bands. We suggest that slowly drifting bands are also generated by energetic electron fluxes but subject to the cyclotron resonance condition on a normal Doppler effect $\omega - k_{\parallel} v_{\parallel} - s\omega_{He} = 0$, where k_{\parallel} is the longitudinal (with respect to the magnetic field) wave number component, v_{\parallel} is the longitudinal electron velocity component, ω_{He} is the electron cyclotron frequency, and s is the cyclotron harmonic number. An instability due to a normal Doppler effect develops if the distribution function of energetic electrons is anisotropic, namely, if the transverse (with respect to the magnetic field) thermal spread is larger than the longitudinal one (Mikhailovskii, 1974). This condition is readily realized for energetic electrons travelling toward an increasing magnetic field due to conservation of adiabatic invariance. Furthermore, plasma waves are generated predominantly across the magnetic field, and their frequency is close to the upper hybrid resonance frequency, i.e. $\omega = (\omega_{pe}^2 + \omega_{He}^2)^{1/2}$. The drift of the emission source in this case is caused by a change of density and magnetic field strength in the place of magnetic field reconnection. Analogous mechanism of solar radio emission generation was used by Zheleznyakov and Zlotnik (1975) and Kuijpers (1975) for interpretation of the metre wave band "zebra"-pattern and by Ledenev et al. (2001a, 2001b) for interpretation of slowly drifting bands in microwave emission.

If we suppose that energetic electron beams are formed as a result of magnetic field lines of force reconnection, two characteristic durations observed in the event correspond to two characteristic times T of magnetic field reconnection. If we estimate the reconnection time as the ratio of the magnetic structure dimension L to the Alfvén velocity v_a , then for $v_a \sim 10^8$ cm/s we have $L \sim 10^8$ cm for $T \sim 1$ s, and $L \sim 10^6 - 10^7$ cm for $T \sim 0.1 - 0.01$ s. Magnetic loops of the cross-section of $\sim 10^8$ cm are observed in EUV flare's emission (Schrijver et al., 2001; Aschwanden & Alexander, 2001). It is natural to suppose that magnetic loops of such dimension are in regions emitting X-ray and microwave radiation. During the flare these loops coalesce each other (Tajima et al., 1987). This process is followed by plasma heating and particle acceleration which are developed as heightened emission in different ranges. Besides that a local short time increase in plasma density occurs (Tajima et al., 1987). In microwave range it is developed as emission bands of about one second duration with frequency drift about 1 GHz/s (Wang et al., 2001).

In our case the flare occurred in the region of the dimension of $\sim 3 \cdot 10^9$ cm and developed in X-ray emission as a loop of the cross-section of $\sim 5 \cdot 10^8$ cm (Figure 5). The space resolution of the used instruments is not sufficient to reveal the magnetic field fine structure in the flare region. However based on observed (Figures 1, 2) radio emission's fine structure (the bursts of duration of ~ 1 s) we can suppose the magnetic field in our case also is an assembly of loops of the cross-section of $\sim 10^8$ cm. Besides that, observations of flare's beginning stage before its maximum is enable to give an opportunity to reveal the emission finer structure with characteristic duration of a few tens of milliseconds (Figure 1b). Apparently this fine structure's origin is analogous to the one of narrow band bursts of small duration (~ 100 ms) at the metre and decimetre ranges, so named "spikes" (Benz, 1986, 1996). However in our case relative emission band can achieve 20% (Figure 1b) whereas for "spikes" it is $\sim 1\%$. This is caused by high density gradients in the regions of microwave radiation generation and more stronger energetic electron streams which generate this radiation.

One possible process scenario is the formation of a current sheet with magnetic islands (Altyntsev et al., 1986; Karpen et al., 1998). One can suppose the flare takes place during magnetic field reconnection in current sheets of the size of 10^8 cm. The reconnection process is accompanied by the formation and subsequent dissipation of magnetic islands of the size of $10^6 - 10^7$ cm. Such a situation can be realized if the magnetic field is a set of magnetic loops of 10^8 cm cross-section. Another possible scenario is a creation of local current sheets of a dimension of $10^6 - 10^7$ cm by magnetic field lines of force winding and interweaving within the loops (Parker, 1987). Magnetic lines of force reconnection and energy release in such sheets develops as microwave radiation fine structure with characteristic time a few tens of milliseconds.

In both scenarios the density in the reconnection region increases with the time corresponding to the reconnection time of larger structures, i.e. ~ 1 s. Since a slow drift is directed toward higher frequencies, in the region of emission, as follows from the cyclotron resonance condition, the density increases when the emission is observed, because it is assumed that $\omega_{pe} > \omega_{He}$ in the emission region. Since the energy release process has an impulsive character, the growth of density at maximum energy release is superseded by its decrease. The decrease in density is sometimes observed on dynamic spectra as a change of sign of the frequency drift (U-burst) (Figure 2). The observed total spectral width of the fine structure of emission reaches 50%. This means that the density in the emission region can change by a factor of two on a time scale of about a few seconds.

Thus the overall picture of the phenomenon at the initial stage is as follows. The emerging magnetic flux consisted of many flux tubes and is seen as an X-ray loop in Figures 4, 5 become unstable (Somov et al., 1998). The flare, i.e. the coalescence process of magnetic flux tubes takes place in small region of about 30" dimension and gives rise to energetic electron fluxes and density in the coalescence region. The coalescence process has an impulsive character on a typical time scale of about one second. On dynamic spectra, this is distinguished as emission bands with the frequency drift of about 1 GHz/s. This large-scale process is overlaid by a process with a typical time of less than 0.1 s, resulting in the formation of energetic electron fluxes that generate narrow-band or rapidly drifting emission bands. These electron fluxes generate also slowly drifting emission bands on a cyclotron resonance.

4. Conclusion

We have investigated the phenomenon at the initial stage of the flare that occurred on August 25, 1999 at 01:36 UT (maximum) in the active region NOAA 8674. This phenomenon was characterized by an increase of the microwave emission flux two minutes before the maximum of the flare and had a clearly pronounced fine structure observed in the range from 4 to 7 GHz. Concurrently with the phenomenon there was an enhancement of the X-ray flux in

the energy range 25-50 keV. On the basis of the data from the spectrographs at the Purple Mountain observatory, as well as the data from the SSRT and Yohkoh, and optical data it has been shown that the flare occurred in the region of the dimension of $\sim 30''$ in the group of small spots and pores. At the beginning stage the flare has an impulsive character in microwave emission with typical times of about one second and several tens of milliseconds. Such typical times seem to be a reflection of the fine structure of the magnetic field in the flare region, i.e. the magnetic field consist of an assembly of magnetic loops of cross-section of $\sim 10^8$ cm and energy release time of about one second corresponds to coalescence of these loops, and a small-scale structure of dimension of $\sim 10^6 - 10^7$ cm develops within such loops, to which a microwave emission typical time of several tens of milliseconds corresponds. The interaction of the magnetic loops gives rise to the plasma density in the interaction regions of about one second duration. They are distinguished on dynamic spectra as slowly drifting emission bands. The interaction of small-scale structures produces subrelativistic electron fluxes that show up as short-duration (several tens of milliseconds) narrow-band bursts or rapidly drifting emission bands.

Thus observations of the microwave emission fine structure allow us to draw conclusions about magnetic field fine structure in the flare's region and about processes occurred there.

We are grateful to Dr. Grechnev for his assistance in preparation of Figures for this paper. The work was supported by the Russian Foundation for Basic Research (grants 03-02-16229, 477.2003.2), grants NSFC 10225313 and MOST G2000078403 and FAPESP (2003/06665-2).

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Figure captions

Fig.1. Dynamic spectrum of the emission at the initial stage of the August 25, 1999 flare (a), and portion of the dynamic spectrum that represents short duration and rapidly drifting spectral elements (b).

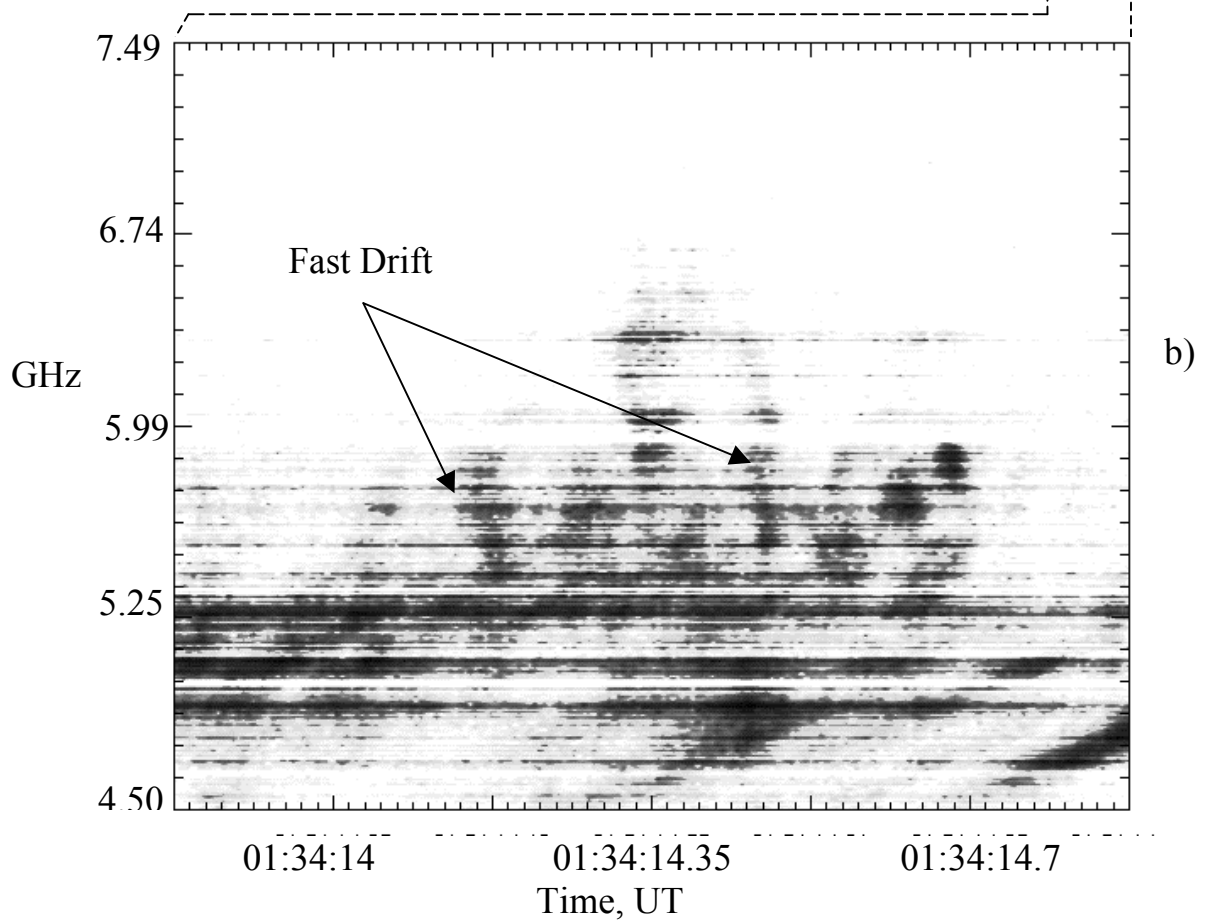
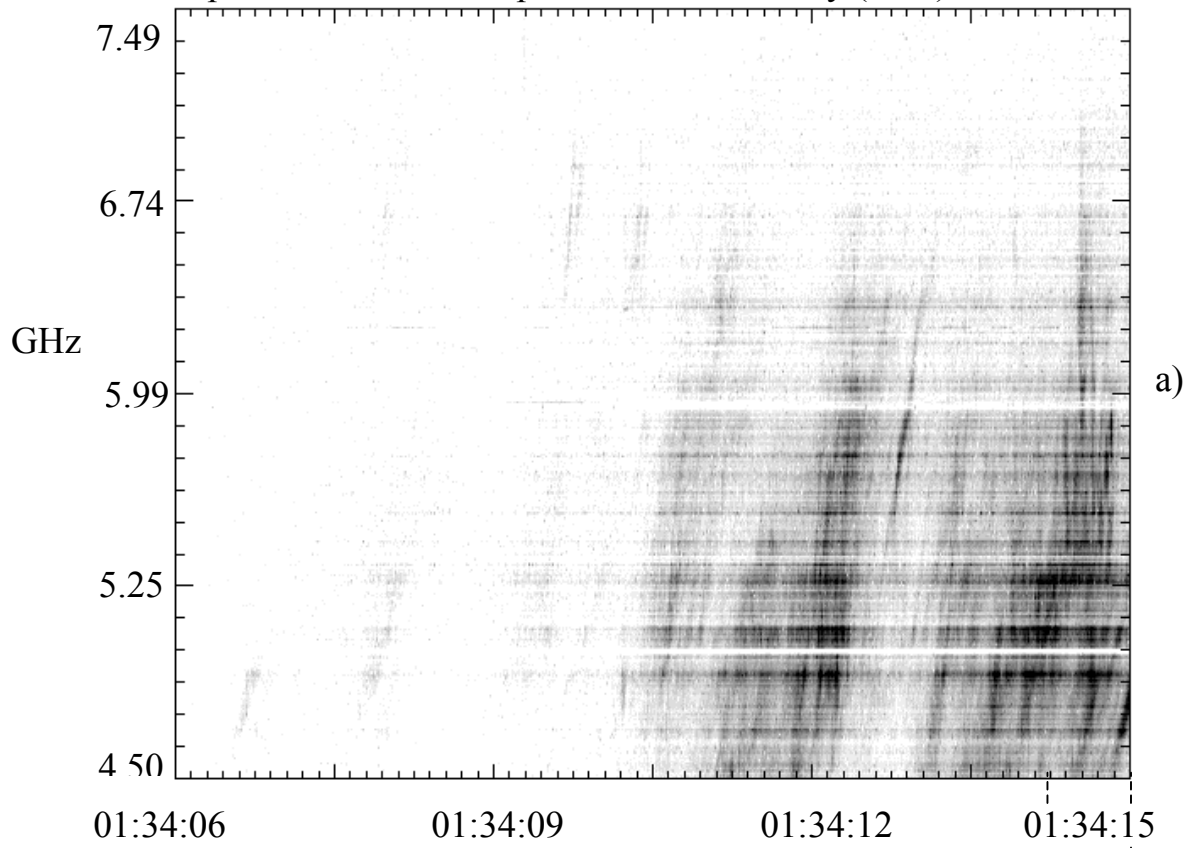
Fig.2. Dynamic spectrum that represents slowly drifting spectral elements.

Fig.3. Magnetogram of the active region NOAA 8674 with superimposed contours (solid lines) of microwave emission observed with the SSRT in the decreasing phase of the flare. The microwave burst site is indicated by the arrow. The other contours represent microwave emission above the active region spots. Dashed lines represent neutral lines of the magnetic field.

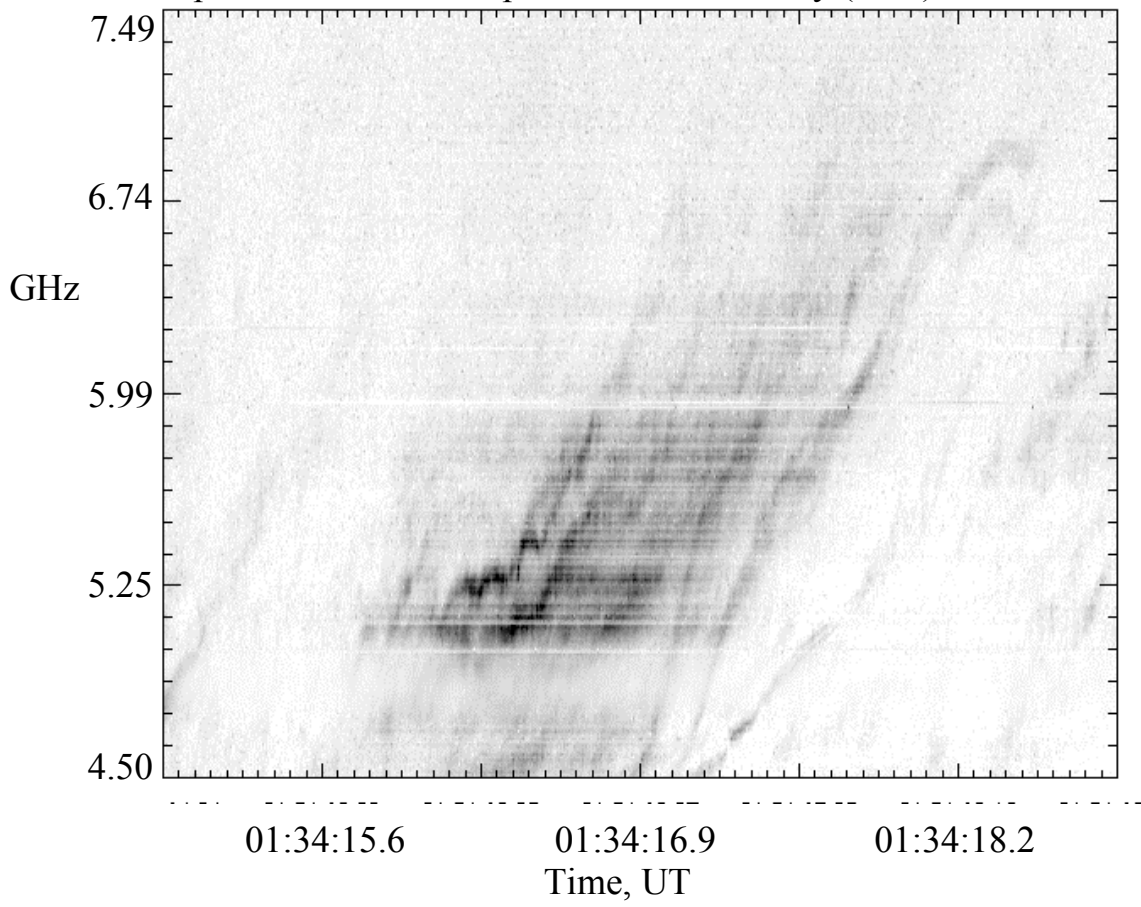
Fig.4. Yohkoh soft X-ray image of the active region at the time of the flare before its maximum phase (August 25, 01:34:48 UT). The flare region in the Figure center is partly suppressed and shown enlarged and background-subtracted in Figure 5. The distance from the solar disc center is plotted on the axis in seconds of arc.

Fig.5. Yohkoh soft X-ray flare images with superimposed hard X-ray contours (energy band 23-33 keV). It is seen that prior to the flare (01:31:55.9 UT) the maximum of hard X-ray emission lies near the lower base of the arch, whereas at the time of the flare (01:35:13.9 UT) the maximum of emission has shifted toward the upper base. The distance from the solar disc center is plotted on the axis in seconds of arc.

Purple Mountain Obs. Spectrometer: Intensity (R+L) 4.5-7.5 GHz



Purple Mountain Obs. Spectrometer: Intensity (R+L) 4.5-7.5 GHz



August 25 1999/SSRT 01:43/MDI 01:39 UT

