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The Subsecond Pulses during the August 10, 2011 Flare by Observations of RATAN-600 and the 4–8 GHz Siberian Solar Spectropolarimeter

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Abstract—We present the results of a study of the subsecond pulses (SSPs) registered in the microwaves during the C2.4 solar flare. The event occurred on August 10, 2011, in the 11236 active region near the western limb and reached a maximum at 0935 UT. Subsecond pulses were registered by RATAN-600 for the first time when this flare reached its maximum. The fact of detection of SSPs was confirmed by simultaneous observations carried out with a spectropolarimeter at the Radio Astrophysical Observatory, Institute of Solar–Terrestrial Physics. A former analysis of the emission nature of the main flare source revealed the presence of a high-temperature ($T > 30$ MK) source that determined both the microwave and X-ray emission parameters of this event. We have compared the temporal variations of the SSPs microwave emission with the variations of the plasma parameters (temperature and emission measure) taken from observations with the FERMI space telescope with a subsecond time resolution. The obtained results suggest that the nature of SSP generation, as well as of the flare itself, was determined by the high-temperature source.

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INTRODUCTION

Studies of the fine time structure of radio emission of flares are already underway for a few decades. Observations and interpretations of this phenomenon make it possible to carry out effective diagnostics of flare plasma. Our work deals with studying subsecond pulses (SSPs) or millisecond radio spikes. These spikes may be described as intense radio radiation pulses with a subsecond duration that are overlaid on a more long time burst (Fleishman and Melnikov, 1988). SSPs are usually observed in the impulsive flare phase and are traditionally associated with the primary energy release processes. SSPs are also usually accompanied by a hard X-ray (HXR) burst (with the energy of photons exceeding 25–30 keV), but an unambiguous correlation between these two types of radiation is generally not observed. The fragmentation of the observed radio emission is particular interest. First, it may be caused by the fragmentation of the primary energy release itself (a single spike is a single energy release or a particle acceleration event in the course of a solar flare). This model was used to explain the observed bursts by Meshalkina et al. (2004, 2012). However, the fragmentation of radio emission may also be a feature of the radiation mechanism itself or may be a result of the secondary fragmentation of the structure of a radio emission source. Two mechanisms are associated with the secondary fragmentation: the electron cyclotron maser and the plasma mechanism. A lot of of different models were developed based on these two mechanisms. The electron cyclotron maser requires high plasma density and high magnetic field strength (Fleishman and Melnikov, 1988; Fleishman, 2004). The plasma radiation mechanism is understood as a two-stage process. At the first stage, natural oscillations that are unable to leave the plasma (for example, Langmuir waves) are generated in the source. At the second stage, they are transformed into fast transverse electromagnetic waves that are then observed in the form of radio radiation (Fleishman and Melnikov, 1988).

The variety of the suggested models that explain the observed SSPs and the application of these models in different observational scenarios allow one to make progress in understanding the processes of energy release and transfer in solar flares. The aim of our study is to analyze the radio emission of SSPs, which were observed in a weak flare near the limb, with the use of additional X-ray data obtained with subsecond time resolution. These additional data allow for the estimating of the variation in the flare plasma parameters on the time scale of observations of bursts.

OBSERVATIONAL RESULTS

The studied SSPs were registered during the C2.4 solar flare. The event occurred on August 10, 2011, in the 11236 active region near the western limb and

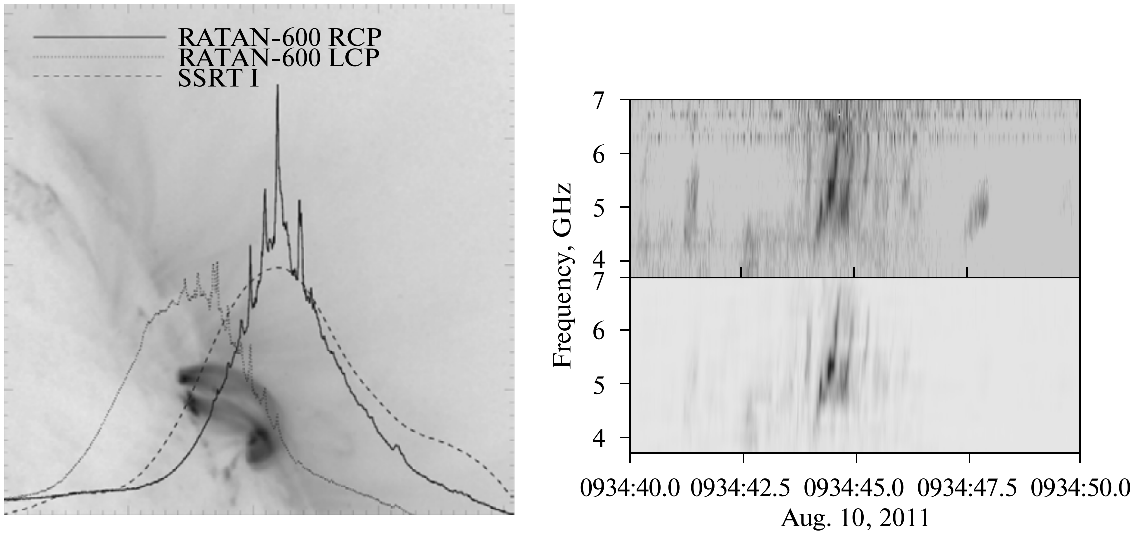

Fig. 1. Left panel: the image of the flare loop (EUV 94 A AIA/SDO) is overlaid by the simultaneous one dimensional profiles of RHP (solid line) and LHP (dotted line) subsecond pulses obtained with RATAN-600 at 0934:37–0934:51 UT at a frequency of 5.7 GHz. The dashed line traces the one-dimensional intensity distribution that was reconstructed using Siberian Solar radiotelescope data obtained at the same frequency and during the same period of time. Right panel: a comparison of the dynamic spectra (left-hand polarization) obtained using a 4–8 GHz spectropolarimeter (upper panel) and RATAN-600 (lower panel).

reached a maximum at 0935 UT (see Fig. 1, left panel). The images obtained by the Atmospheric Imaging Assembly (AIA) on board of the Solar Dynamics Observatory (SDO) in extreme ultraviolet (EUV) wavelength channels that characterize the flare plasma show that the flare loop had a simple shape, which was close to the potential one (Boerner et al., 2012). This event was registered simultaneously with RATAN-600 (Bogod et al., 2011) and with Siberian Solar spectropolarimeters (in the ranges 2–24 and 4–8 GHz) at the Radio Astrophysical Observatory, Institute of Solar–Terrestrial Physics (Zhdanov and Zandanov, 2011). X-ray observations of this event were carried out simultaneously by the RHESSI spacecraft (with a time resolution of four seconds) (see (Lin et al., 2002)) and the Fermi Gamma-ray Space Telescope (with second and subsecond time resolutions) (see (Megan et al., 2009)). The peculiarity of this event is to detection of the X-ray flux at energies above 25 keV that is not typical of such weak flares. A comparison of the time profiles of microwave (MW) and X-ray radiation revealed that they were closely correlated (Kashapova et al., 2013). This correlation indicates that the radiation in both ranges was generated by the same electron population. The other feature of this event was revealed in the course of a study that was carried out using plasma parameters determined from the X-ray spectra and gyrosynchrotron radiation modeling. The results of the study show that both the observed microwave and X-ray emission was generated by a high-temperature source with $T > 30$ MK (Kashapova et al., 2013).

The solar radio radiation was registered with RATAN-600 using right- (RCP) and left-hand circularly polarized (LCP) antenna feeds shifted by the same distance from focus. Thereafter, the RCP and LCP diagrams were spaced apart. The Sun passed through them at different times with a 2.52-s delay (Bogod et al., 2011). The simultaneous spatial one-dimensional RCP and LCP profiles of SSPs obtained with RATAN-600 at a frequency of 5.7 GHz are shown in Fig. 1 (left panel).

When the flare reached its maximum, SSPs were detected simultaneously by RATAN-600 and the 4–8 GHz spectropolarimeter (see Fig. 1, right panel). The detected pulsed emission reached maximum intensity when the maximum of the primary source passed through the center of the RATAN-600 pattern. Since the intensity was lower before and after this point in time, one might suggest that the pulse source was compact and was located near the primary flaring source.

The data from the 4–8 GHz spectropolarimeter demonstrate that the SSP radiation was not polarized. At the same time a comparison of the time profiles of the SSP bursts recorded for the RH and LH polarizations with RATAN-600 shows that some of the pulses have significant degree of circular polarization and the polarization sign might change from one single pulse to the other. We compared the time profiles of intensity of the MW and hard X-ray emission and found a correlation of MW emission with X-ray radiation in the 11.4–26.3 keV energy band (see Fig. 2). This fact indicates to relations of a MW emission production with

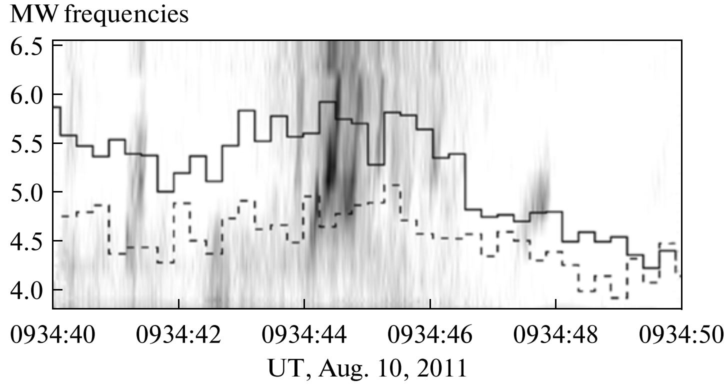

Fig. 2. Dynamic spectrum obtained using a 4–8 GHz spectropolarimeter (background) and the time profiles of X-ray radiation in the energy bands 11.4–26.3 (solid line) and 26.3–49.9 keV (dashed line) obtained using the Fermi Gamma-Ray Space Telescope.

electrons which energy is about 50 keV. However, such a correlation is absent in the case of X-ray photons with higher energies, although a certain signal level was registered up to 50 keV. This may be explained in two ways. The first likely cause is the low signal level and the high level of noise for the radiation flux in this energy range. The other explanation has to do with the high-temperature nature of the flare source and with the fact that the observed electrons have a thermal distribution by energies. The number of electrons decreases enough quickly with energy increasing and becomes insufficient to make a significant contribution to the SSP generation in the studied energy range. But probably, a combination of the above-described factors offers the most likely explanation for the observed features.

ANALYSIS AND CONCLUSIONS

It has already been stated above that several different generation mechanisms—the electron cyclotron maser model, the plasma mechanism, and the gyrosynchrotron radiation of short-lived beams of nonthermal electrons—were suggested in order to explain the observations of microwave SSPs. The studied loop was small and rather dense and had a magnetic field of about 50 G at the top (Kashapova et al., 2013), so in this case the electron cyclotron maser mechanism could hardly be operating. A correlation between the time profiles of X-ray emission and SSPs or proof of the presence of an accelerated electron flux could be used as direct indication of the presence of the gyrosynchrotron radiation of short-lived beams of nonthermal electrons.

The RHESSI observations show that the 6–50 keV X-ray sources were located near the southern footpoint of the loop (Kashapova et al., 2013). The observations with the Siberian Solar radiotelescope (SSRT) (see Fig. 1, left panel) show that the MW flare source was also located near the southern footpoint of the loop. The accuracy error of pointing of the RATAN-600 beam and the fact that it is not possible to correct it accurately due to the presence of sources at the limb make the optical identification based on RATAN-600 inaccurate. Therefore, our conclusion about the X-ray and microwave emission sources bases on more precise data by SSRT. However, the time profiles of X-ray photons with energies exceeding 26 keV were not closely associated with the microwave emission observed during SSPs, while the correlation between these two types of radiation was evident during the main burst.

It should be remembered that the high-temperature source located at the southern base of the loop is the main flare emission source during the discussed event. We analyzed the subsecond timescale correlation between the time profiles of the microwave emission, the electron temperature, and also the $EM^{1/2}$ value that characterizes the electron density (the emission measure by volume (EM) is equal to Ne^2V, where Ne is the average value of the squared number of electrons in a volume unit and V is the volume). The value of $EM^{1/2}$ may be used to estimate the electron density under the assumption that the volume of a source does not vary during SSPs. The left panel of Fig. 3 shows that the microwave flux reduced to on the X-ray radiation timescale is closely correlated with the electron temperature, while the value of $EM^{1/2}$ (i.e., the electron density) increases gradually and is not in any way associated with the SSP time profile. These facts show that the SSP source was closely associated with the high-temperature source. More precise definition of the generation mechanism of these SSPs requires using theoretical modeling results.

Based on the above, we conclude the following:

(1) SSPs were registered with RATAN-600 for the first time in the frequency range 3.5–8 GHz, and independent observations carried out using the 4–8 GHz Siberian Solar spectropolarimeter confirm that.

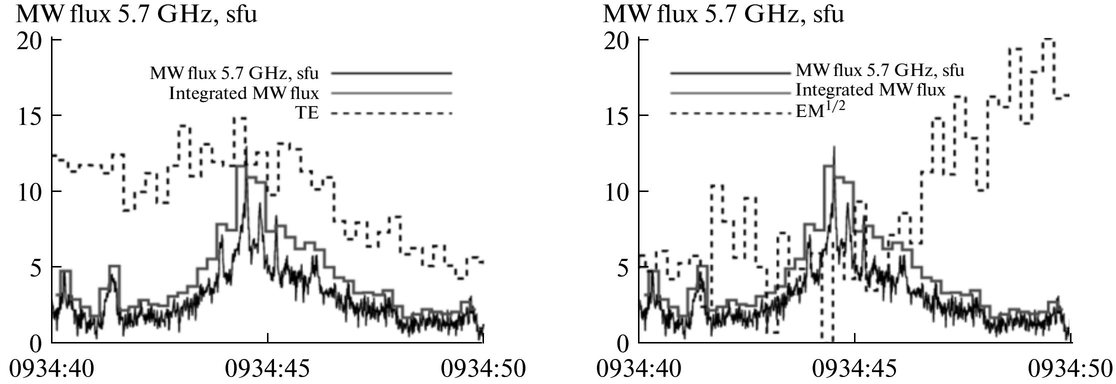

Fig. 3. Left panel: a comparison of the SSP time profiles at 5.7 GHz and the electron temperature obtained from the X-ray spectra with a time resolution of 250 ms. Right panel: a comparison of the SSP time profiles at 5.7 GHz and the square root of the emission measure that was also obtained from the X-ray spectra. The dark grey line in both panels shows the microwave emission integrated for time intervals of 225 ms.

(2) The nature of both the flare emission and the detected SSPs was determined by a high-temperature source ($T > 30$ MK).

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