Millimeter emission of solar flares

V. G. Nagnibeda[1], V. V. Smirnova[1,2], V. S. Ryzhov[3] and A. V. Zhiltsov[3]

[1] Sobolev Astronomical Institute, Saint Petersburg State University, Universitetsky pr.28, St. Petergof, 198504, Russia
[2] Central (Pulkovo) Astronomical Observatory, Russian Academy of Sciences, Pulkovskoe shausse 65, St.Petersburg, 196140, Russia
[3] Bauman Moscow State Technical University, 2 Bauman street 5, Moscow, 105005, Russia

E-mail: vvsvid.smirnova@yandex.ru

Abstract. We analyzed two unique radio observations of millimeter solar flares at 93 and 140 GHz with the THz component in these spectra. Data were obtained from ground-based radio-telescope RT-7.5 operated by Bauman Moscow State Technical University (BMSTU) with the spacial resolution of 2.5 and 1.5 arc-minutes. We analyzed temporal structure of observed radio-bursts and their dynamics in comparison with soft and hard X-ray light-curves obtained from GOES and RHESSI space-based observations. It was found the 140 GHz emission enhancement at the spectra that is new independent confirmation of the THz component existance. Also, we analyzed data of microwave solar flares with the emission enhanced at 35 GHz obtained from Nobeyama radioheliograph (NoRH) and radiopolarimeter (NoRP). It was found that the maximum of the flux density spectra was shifted toward high frequencies that didn't agree with the model spectrum obtained from microwave observations. We assumed, that such kind of spectra are associated with the gyro-synchrotron radiation of the significant number of high-energetic electrons emission with energies of about 500 keV. The emission mechanism at millimeter waves is the gyro-synchrotron radiation. However, if the energetic electrons are not enough the thermal emission mechanism could be dominant factor at millimeter radiation that could also explain the spectral maximum shift to high frequencies.

1. Introduction

Millimeter and sub-millimeter radio-burst observations allow us to obtain the important information about flare plasma parameters, the spatial distribution of energetic electrons, and flare source location in the solar atmosphere. But short millimeter solar observations are very limited by the instrument requirements and weather conditions. It is well known that observations obtained from the Solar Submillimeter Telescope (SST) at 212 and 405 GHz [5] and observations from the Köln Observatory for Submillimeter and Millimeter Astronomy (KOSMA) at 230 and 345 GHz [9] confirm THz emission in solar flares. But these observations are not enough to provide the interpretation of the THz component appearing in flares because they consist only of a few points and not of a complete microwave-millimeter spectrum.

It is generally accepted that non-thermal microwave emission during large solar flares is produced by the gyro-synchrotron mechanism which involves coronal magnetic fields of at least a few hundreds of Gauss and electrons of hundreds of keV [1],[3],[16].

In the typical microwave spectrum (Figure 1, left panel) the maximum of the flux density corresponds to frequency in the range of 5–10 GHz [7]. But some flares show peculiarities in

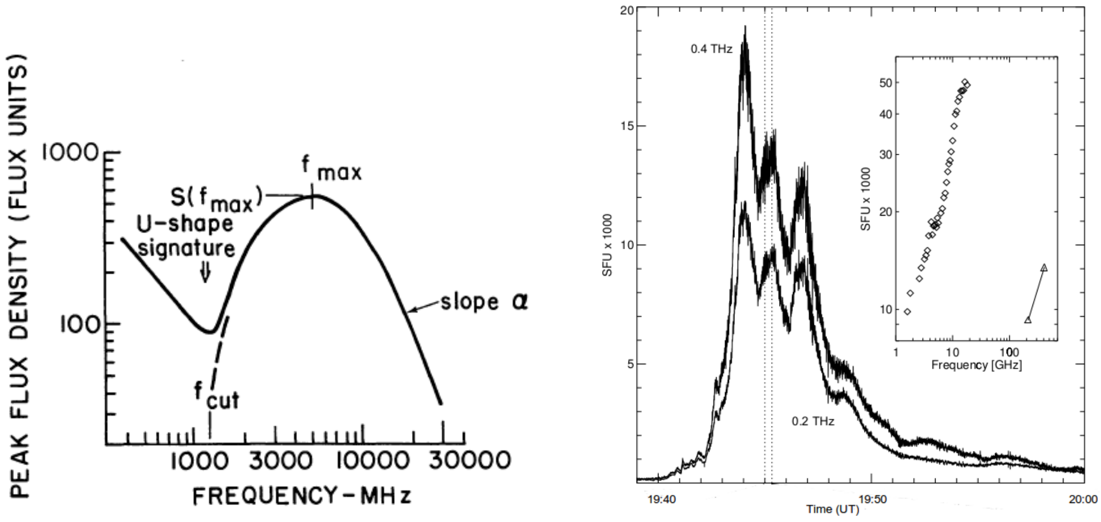

Figure 1. Left panel: typical spectrum of microwave radio bursts [7]. Right panel: the largest sub-mm solar burst observed by the SST telescope that occurred on November 4, 2003 showing the time profiles at 0.2 and 0.4 THz. The inner panel shows the double spectral features, with the well known microwaves and the new THz component [10].

their spectra at high frequencies [2]. These peculiarities, such as a spectral flattening or even an excess of the high-frequency emission, are interpreted by authors as the superposition of multiple sources of gyro-synchrotron radiation or optically thin bremsstrahlung of the evaporated flare plasma.

In some flares the short millimeter part of the spectrum is significantly 'hard', in disagreement with the model spectrum (see Figure 1, right panel) [10]. In these kinds of events the flux density of millimeter emission is high and sometimes even exceeds the microwave flux. This behavior has been observed more often in X-class flares (by GOES classification) and interpreted by several authors as synchrotron radiation of relativistic electrons with energies more than 500 keV [8]. But it is difficult to give a clear interpretation about what mechanism dominates at short millimeter wavelengths during the flare process, because there are not enough multi-frequency millimeter data with high spatial resolution.

In this contribution we present new unique observations of solar flares at 93 and 140 GHz obtained from the RT-7.5 radio-telescope operated by Bauman Moscow State Technical University (BMSTU). Relatively few data at 93 GHz have been obtained with any instruments. But at 140 GHz radio-frequency such observations have never been provided. Thus, data obtained from RT-7.5 are unique and very useful for the analysis of short millimeter emission in flares. We also present an analysis of microwave radio-burst data obtained from the Nobeyama radioheliograph (NoRH) and the Nobeyama radiopolarimeter (NoRP).

2. RT-7.5 BMSTU: observations at 93 and 140 GHz

The RT-7.5 radio-telescope is a Cassegrain-type of antenna with a diameter of 7.75 m. It located in Dmitrov (Moscow region, Russia). It has two receivers for 93 GHz and 140 GHz (3.2 mm and 2.2 mm). The beam size of the telescope is 2.5 arc-minutes at 93 GHz and 1.5 arc-minutes at 140 GHz. The antenna can provide solar disk mapping, active region mapping, and tracking of a selected point. The maximum temporal resolution is 0.125 s [12], [13], [14].

We analysed two radio-bursts that occurred in active region NOAA 11515. Dates of

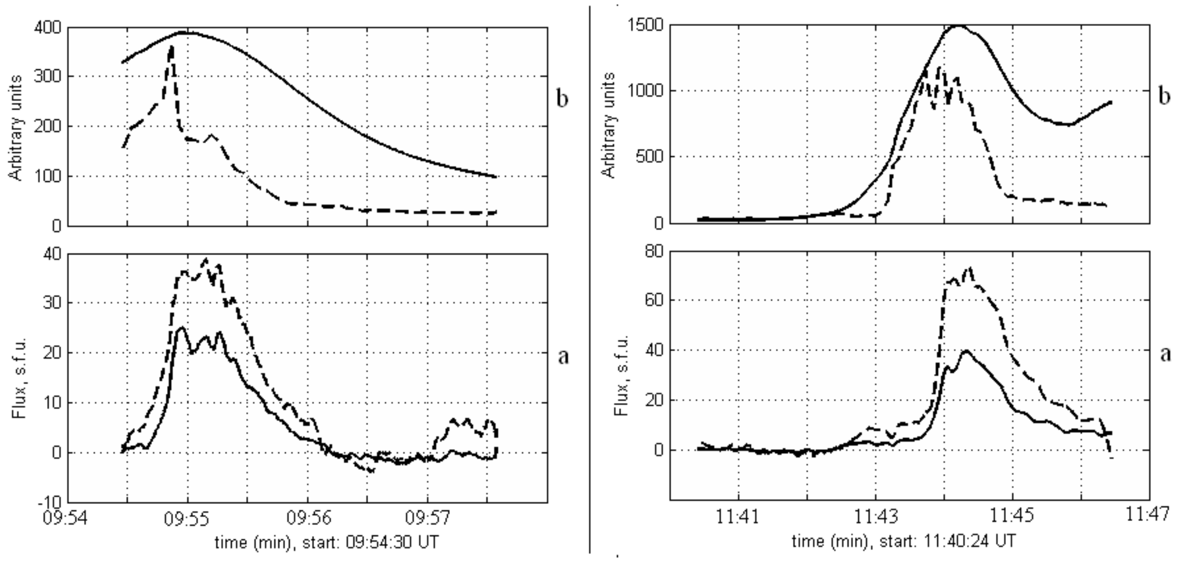

Figure 2. Left panel: a) radio flux density temporal profiles obtained from the observations at 93 GHz (solid line) and 140 GHz (dashed line) for SOL2012-07-04. b) GOES 1-8 Å SXR light-curve (solid line) and the RHESSI 25-50 keV HXR light-curve (dashed line). Right panel: the same, but for SOL2012-07-05.

observations: 2012/07/04 and 2012/07/05. GOES class of flares: M5.3 and M6.1. The weather conditions were good during the radio-observations.

Figure 2 (panels (a) solid and dashed lines) shows the temporal structure of the bursts at 93 and 140 GHz. We also examined soft and hard X-ray data simultaneously with radio emission (see Figure 2, panels (b)). Soft X-ray data were obtained from GOES-15 observations at 1-8 Å. The temporal evolution of the SXR emission during the impulsive phase of flares was smooth and longer than radio flux of the bursts but the maximum value was reached at the same time. Hard X-ray data were obtained from the RHESSI observations at the energetic channel 25-50 keV. The maximum of the HXR emission at 25-50 keV appeared earlier than the radio maximum in both cases.

The radio flux density spectra for the moments of the flare maxima are shown in Figure 3. The errors in the flux density were estimated using the beam pointing accuracy and sensitivity of the receivers.

We found the 11.7 GHz data obtained from the Metsähovi radio-observatory (Finland) for the SOL2012-07-04 event (see Figure 3, left panel). Unfortunately there were no microwave data for the SOL2012-07-05 flare. Observations at 11.7 GHz were additionally obtained for the event of 2012/07/04. But in both cases the flux density at 140 GHz is higher than at 93 GHz. This situation is similar to the observations in KOSMA (Figure 1, right panel).

3. NoRH and NoRP: observations, data analysis and results

We analysed several radio bursts using Nobeyama radioheliograph (NoRH) data at 17 and 34 GHz and Nobeyama radiopolarimeter (NoRP) data at 1, 2, 3.75, 9.4, 17, 35 and 80 GHz [11]. Temporal structures of the chosen bursts were complex with a number of impulses on the extended rise-and-fall background.

We present the flare event analysis for 2005/09/13 in NOAA 10808. The GOES class of the flare is X 1.7. The temporal structure of the radio-burst at 35 GHz is presented in Figure 4

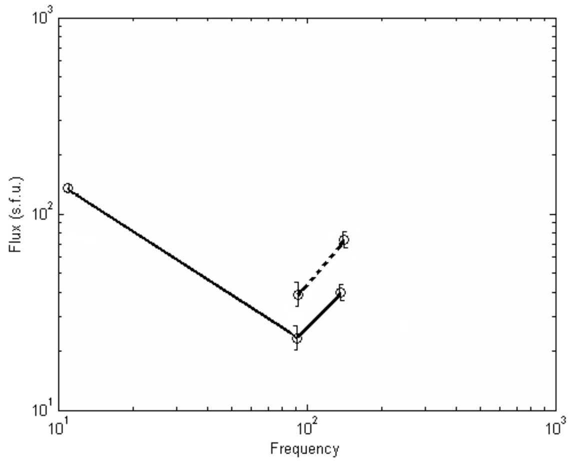

Figure 3. Flux density spectra. Left panel: spectrum obtained at 11, 93 and 140 GHz. Date of observations: 2012/07/04, time: 09:55:00 UT. Right panel: spectrum obtained at 93 and 140 GHz. Date of observations: 2012/07/05, time: 11:44:30 UT.

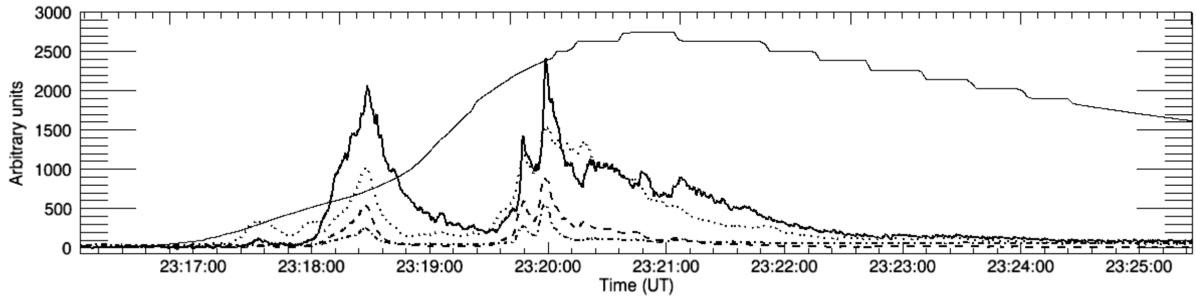

Figure 4. 35 GHz light-curve (solid bold), GOES plot (——) and HXR plots: 25-50 keV (······), 50-100 keV (- - - -), 100-300 keV (— · —).

(solid-bold line). Here one can see the GOES 1-8 Å light-curve (solid line) and HXR light-curves obtained from RHESSI observations. It is known that the soft X-ray emission is generated by the thermal emission of hot plasma. So, time-variations of SXR emission reflects the thermal development of the flare source. Figure 4 shows the temporal profile of the GOES soft X-ray flux that coincides well with the microwave and millimeter burst background. Thus we can use the GOES profile to divide the microwave bursts into an impulsive component, which we could interpret as a non-thermal part of a burst, and the thermal background. Hard X-ray emission was associated with the impulsive phase of the flare. In Figure 4 it is clear that the burst's impulsive component corresponded well to the impulses in HXR emission.

In Figure 5 the radio-burst spectra at the moments of the first and second impulse are shown. The spectral maximum is shifted toward the millimeter range. That is different from the classic microwave spectrum (see Figure 1, left panel) where the maximum is located at 5 GHz.

4. Discussion

There is no simple interpretation of the impulsive non-thermal component of the spectrum with the millimeter emission enhancement. However, in connection with a rather good correlation of the millimeter burst impulsive part and the hard X-ray emission, we suggest in this case that the

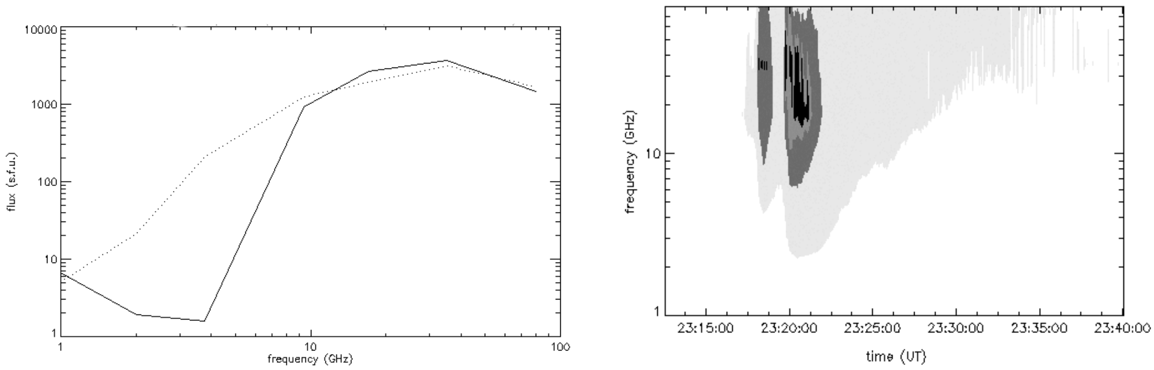

Figure 5. Left panel: radio-intensity spectra: first maximum (——), second maximum (······). Right panel: frequency dynamic spectrum.

maximum shift in the radio-spectra is associated with the injection of high energetic electrons in the flare source. During the powerful flares a greater density of energetic electrons could affect the microwave spectrum, and be responsible for the flux density increasing at high frequencies.

The gyrosynchrotron emission depends not only on the particle energy, but also on the magnetic field strength. It is important to know the position of the radio source in the foot-points or in the top of the flaring loop, to estimate the value of the magnetic field strength, using existing models. However, insufficient angular resolution in radio observations does not allow us to localize the burst radio source in this case.

At the present time interest in the investigation of millimeter and sub-millimeter solar flares is significantly increased. But data available for this range are very limited and do not provide the full spectrum, because of inadequate frequency coverage. Obviously, large systems, such as major radiointerferometers could not provide monitoring observations of the Sun. These instruments have a lot of observational tasks that require time and special calibration methods. For this reason we have started our observations on RT-7.5 at 93 and 140 GHz frequencies that could give the possibility of obtaining new very important points at short millimeter range.

5. Conclusions

1. We have obtained new results that confirmed the THz emission existence in solar flares at short radio-frequencies. New unique flare observations at 93 and 140 GHz were analyzed. The spectra showed the flux density enhancement at 140 GHz. The maximum of the HXR emission did not exceed 25–50 keV in both cases. So, we assumed that these spectra could be interpreted as thermal emission enhancement in the flare sources.
2. We analyzed NoRP and NoRH microwave data, obtained at 1, 2, 3.75, 9, 17, 35 and 80 GHz radio-frequencies. One event on 2005/09/13, appearing in NOAA 10808, was taken as an example. We found, using the dynamic spectra analysis, that the spectral maximum was shifting during the flare toward high frequencies. The HXR emission of the flare reached 300 KeV and was well-correlated with the radio-emission (see Figure 4).

References

[1] Benz A.O., Living Reviews in Solar Physics, vol. 5, no. 1
[2] Chertok, I.M.; Fomichev,V.V.; Gorgutsa, R.V.; Hildebrandt,J.; Krüger, A.; Magun, A.; Zaitsev,V.V., Sol. Phys., Vol. 160, Iss. 1, pp.181-198
[3] Hudson H., 2011, Space Sci. Rev., 158, pp. 541

[4] Kaufmann P.; Marcon R.; Giménez de Castro G.; White S., and 7 co-authors, ApJ, Vol. 742, Iss. 2, article id. 106, 2011
[5] Kaufmann, P., Trottet, G., Giménez de Castro, C. G., Raulin, J.-P., Krucker, S., Shih, A. Y., Levato, H., Sol.Phys. Vol.255, pp. 131-142, 2009
[6] Kaufmann P.; Raulin J-P.; Melo A.M.; Correia E.; Costa J.E.R.; Giménez de Castro C.G.; and 9 co-authrs, ApJ, 574:10591065, 2002
[7] Kundu M.R., Vlahos L., Space Science Reviews 32, 405-462, 1982.
[8] Kundu M.R. et al., The Astrophysical Journal, 547: 1090-1099, 2001.
[9] Lüthi, T., Lüdi, A. and Magun, A., A& A, 420, pp. 361-370, 2004
[10] Marcon R, Kaufmann P, Fernandes L.O.T., and 6 co-authors, 2012, Journal of Infrared, Millimeter, and Terahertz Waves, Volume 33, Issue 2, pp.192-205
[11] Nakajima, H.; Nishio, M.; Enome, S.; Shibasaki, K.; and 13 co-authors, 1994, IEEE Proceedings Vol. 82, pp. 705-713
[12] Rozanov, B. A., 1981, Radioelektronika, vol. 24, p. 3-8.
[13] Solov'ev G.N., Rozanov, B. A., Ivanov V.N., Nagnibeda V.G., Piotrovich V.V., 1990, Radioelectronic devises
[14] Smirnova, V., Riehokainen, A., Ryzhov, V., Zhiltsov, A., Kallunki, J. A& A, 2011, Volume 534, id.A137
[15] Trottet G., Vilmer N., Barat C., Benz A., Magun A., Kuznetsov A., Sunyaev A., and Terekhov O., 1998, A& A, 334, 10991111
[16] White S.M., Krucker S., Shibasaki K., Yokoyama T., Shimojo M., and Kundu M.R., 2003, ApJ, pp. 111-114