On the origin of sub-THz emission from solar flares

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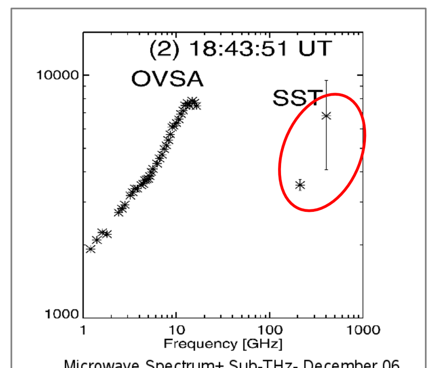
Abstract: Time delays between sub-THz (> 100 GHz) and soft X-ray emission from solar flares with the positive spectral slope at sub-THz frequencies are considered. For 11 solar events we did the cross correlation analysis of light curves obtained with KOSMA (230 GHz), SST (212 GHz), RT-7.5 (93 GHz), and GOES satellites in the 1-8 Å channel in order to detect the Neupert effect. All flares were divided into two types. Type I includes four X -class flares with well pronounced Neupert effect. Type II includes seven M-class flares where Neupert effect was not clearly defined, and time delays do not exceed 30 s. To explain the obtained results within the framework of the thermal chromospheric model we consider hard X-ray and radio emission from the SOL2012-07-04T09:55 solar flare with the positive spectral slope at sub-THz frequencies. The temporal evolution of thermal bremsstrahlung of chromospheric plasma observed at sub-THz frequency range from this flare has been studied. For that reason we employ F-CHROMA models based on RADYN code which describes the response of chromospheric plasma to the flux of accelerated electrons in the triangular pulse. The region of low temperature and high plasma density in a flare chromospheric source, which moves to the higher altitudes and absorbs the sub-THz emission has been revealed. The calculated time profile of sub-THz emission suggests that we cannot explain Type II events in terms of the proposed model. The plasma of solar chromosphere heated by accelerated coronal electrons produces the sub-THz emission several times less than the observed sub-THz emission fluxes during the SOL2012-07-04T09:55 flare. The interpretation of the results is proposed.

The peculiarity of some flares – a **positive spectral slope at high frequencies (100-400 GHz).**



Microwave Spectrum+ Sub-THz- December 06, 2006 – 18:30UT (Adapted from Kaufmann et al, 2009 – S.Phys. 255, 131)

Many models were proposed. Kontar et al. (2018) have explained a positive spectral slope of the spectrum at sub-THz part (93-405 GHz) by the thermal radiation of the flare ribbon plasma observed in UV, with the temperature of 10^4-10^6 K. The growth of sub-THz radiation occurs due to the thermal bremsstrahlung of the optically thick plasma of the chromosphere and transition region with the temperature of 0.01–1 MK heated by the precipitation of non-thermal electrons. This model suggests the Neupert effect for sub-THz and soft X-ray time-profiles. As can be seen from the formula for the flux of optically thick sub-THz radiation, the area of the flare source and the temperature play an important role here.

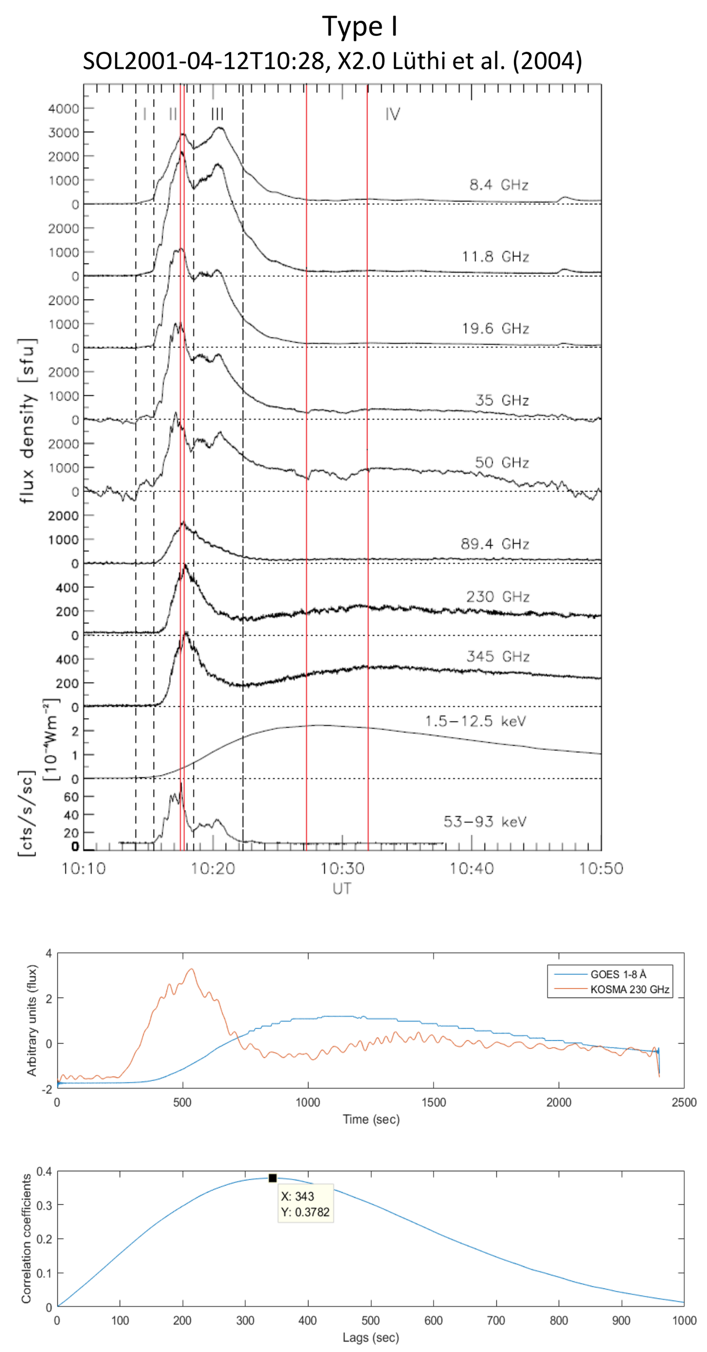
$$F = \frac{2\nu^2 k_B T}{c^2}\frac{A}{R^2} \simeq 722\left(\frac{\nu}{100\,\mathrm{GHz}}\right)^2\left(\frac{T}{10^6\,\mathrm{K}}\right)\left(\frac{A}{10^3\,\mathrm{arcsec}^2}\right)[\mathrm{sfu}]$$

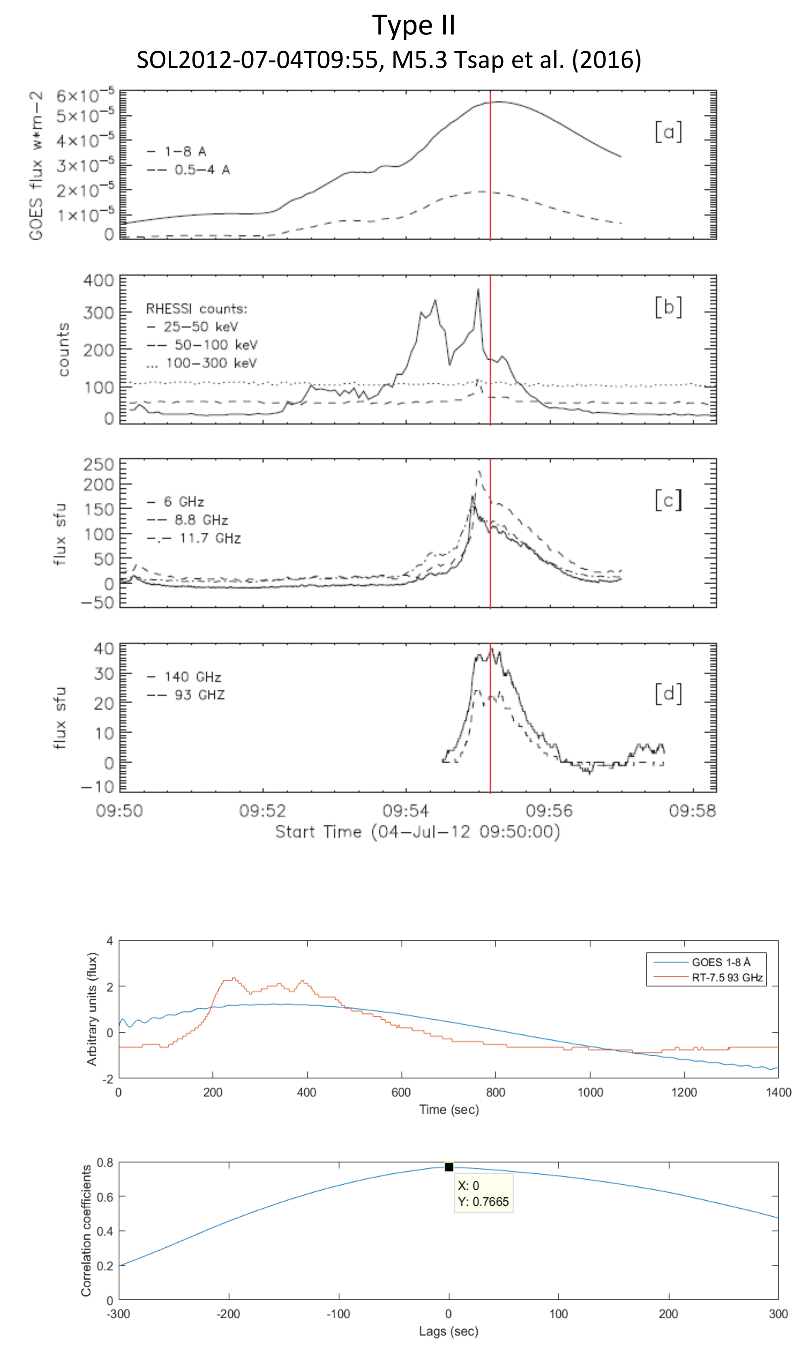
The aim of our work is to analyze the time profiles of soft X-ray and sub-THz emission of solar flares, with a positive spectral slope.

We selected 11 flare events with a growing sub-THz spectrum (see Table). Data were obtained from SST, frequencies of 212 and 405 GHz (Kaufmann et al., 2001), KOSMA, frequencies 230 and 345 GHz (Lüthi et al., 2004) and RT-7.5 BMSTU, frequencies 93 and 140 GHz (Smirnova et al., 2016). Data on the soft X-ray radiation were obtained from the GOES satellite (White et al., 2005) in the 1–8 Å channel. The cross-correlation analysis was carried out using the method described in (Buck et al., 2002).

Two types of flares were defined:
Type I: events, for which the Neupert effect is presented, when the sub-THz flux is 2–9 min ahead of the soft X-ray flux (4 events, purple rows in the Table).
Type II: events, for which Neupert effect is not defined with the accuracy of 30 s.

#	Date/Time (UT)	GOES class	Type	Lags (min)	Article
1	SOL2001-04-12T10:28	X2.0	I	6	Lüthi et al. (2004)
2	SOL2003-11-02T17:25	X8.3	I	3	Silva et al. (2007), Kaufmann et al. (2009),
3	SOL2006-12-06T18:47	X6.5	I	3	Kaufmann et al. (2009)
4	SOL2014-10-27T14:47	X2.0	I	6	Fernandes et al. (2017)
5	SOL2003-10-27T12:43	M6.7	*	9*	Trottet et al. (2011)
6	SOL2011-02-14T17:25	M2.2	II	-	Silva et al. (2019)
7	SOL2012-07-04T09:55	M5.3	II	-	Tsap et al. (2016)
8	SOL2012-07-05T11:44	M6.1	II	-	Tsap et al. (2018)
9	SOL2013-04-12T19:52	M3.3	II	-	Fernandes et al. (2017)
10	SOL2013-02-17T15:50	M1.9	II	-	Fernandes et al. (2017)
11	SOL2017-04-02T07:50	M5.4	II	-	Morgachev et al. (2018)





Interpretation

Thus, for many sub-THz events the Neupert effect is not observed.
To explain the obtained results within the framework of the thermal chromospheric model we have considered hard X-ray and radio emissions from the SOL2012-07-04T09:55 solar flare with the positive spectral slope at sub-THz frequencies using the numerical simulation. The temporal evolution of thermal bremsstrahlung of chromospheric plasma observed at sub-THz frequency range from this flare has been studied. We used F-CHROMA models based on RADYN code, which describes the response of chromospheric plasma to a triangular pulse of the accelerated electrons.

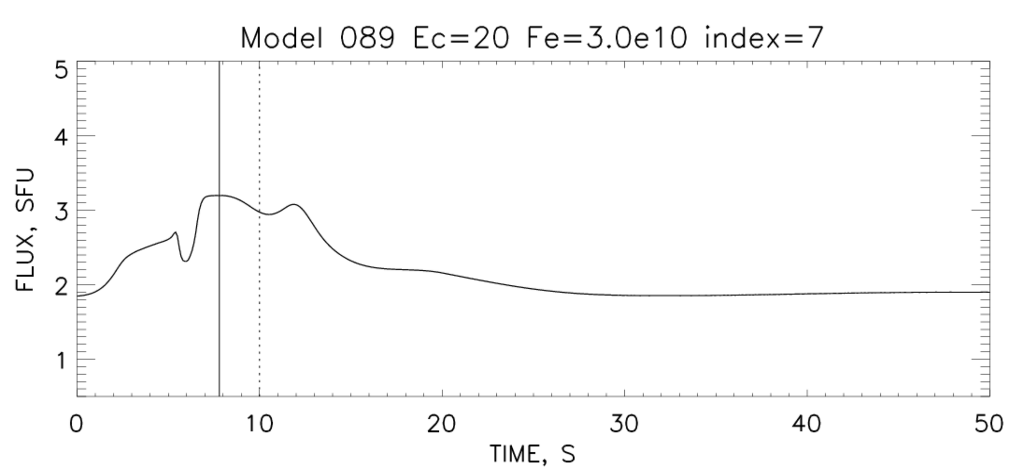
We considered the model of the flare atmosphere No. 89, obtained in the framework of the international project F-CHROMA (https://www.fchroma.org). The model describes the response of an unperturbed solar atmosphere of the VAL-3C type (Vernazza, Avrett, Loeser, 1981) to an electron flux in the form of a triangular pulse. The electron spectral index δ = 7 low energy cutoff E_0 = 20 keV and the integral flux P = 3×10^{10} erg x $s^{-1}cm^{-2}$ were obtained from RHESSI observations. Using the model height dependences of the temperature and plasma concentration at each time instant, the spectral flux of thermal bremsstrahlung was calculated for the height h:

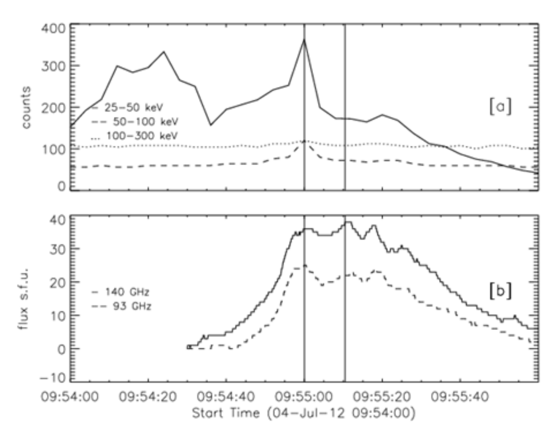
$$F_\nu(h) = \frac{S}{R^2}\int_0^h \eta_\nu e^{-\tau_\nu}dh,$$

where η_ν - emission coefficient, τ_ν – optical thickness, *S* – source area, *h* – height above the solar photosphere. To estimate the height of the formation of sub-THz emission, the contribution function of each chromospheric layer to the total intensity of the source was calculated:

$$CF(h) = \eta_\nu(h)\exp\left(-\int_h^H k_\nu dh\right)$$

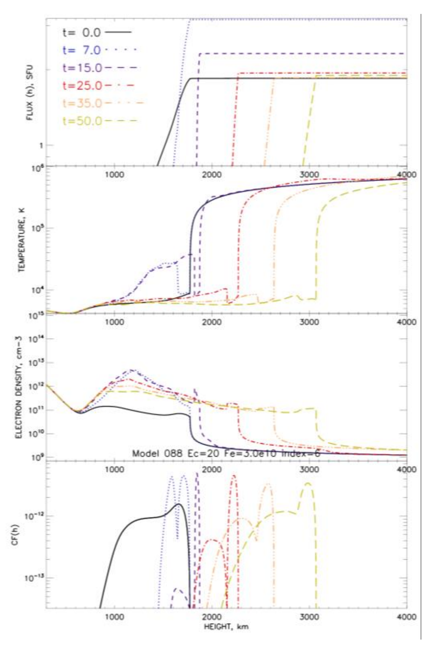
Simulation results





Time profiles of thermal bremsstrahlung of the F CHROMA 089 chromospheric model at a frequency of 140 GHz. The dashed vertical line corresponds to the maximum of a triangular pulse of accelerated electrons; solid vertical line corresponds to the maximum of the sub-THz flux. Despite the fact that the absolute values of the flux are not high, it can be seen that the time profile, as in the observations, have a pulsating character with several individual maxima, the main of which is reached before the peak of the flux of accelerated electrons by several seconds.

Model fluxes of sub-THz radiation turned out to be an order of magnitude smaller than the observed values. This can be explained by the fact that the considered mechanism of sub-THz radiation is not adequate enough, but rather a combination of several mechanisms takes place at once. In this case, one should not exclude the important role of an additional source of energy release located directly in the chromosphere. Even a weak flux of accelerated electrons can lead to the formation of chromospheric condensation moving upward, which has a noticeable effect on the time profile of sub-THz emission. This opens a new window for the study of flare processes in the chromosphere of the Sun and stars. However, more detailed studies require multifrequency sub-THz observations with high spatial and temporal resolution.



If we consider the height distributions of the temperature and electron density of the chromospheric model at different times (see Figure, second and third panels), we can see a region of lowered temperature and increased plasma density, so-called "chromospheric condensation" (Kostiuk, Pikelner, 1975; Livshits et al ., 1981), which moves upward. From the height distribution of the flux *F(h)* and the source function *CF(h)* at a frequency of 140 GHz (see Figure, first and fourth panels), it can be seen that the condensation has a significant effect on the model radiation. In this case, the evolution of the temperature and plasma concentration determines the complex time profile of the sub-THz flux.