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# Modeling of the solar flare chromosphere and sub-THz radiation with FLARIX and RADYN

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**Abstract.** The origin of the sub-terahertz (sub-THz) component of radio emission from solar flares, which is characterized by the increase flux with frequency in the 100-400 GHz range, is considered. On the basis of equations of 1D non-LTE radiation hydrodynamics we simulated the altitude distribution of the plasma density and temperature inside the flare loop caused by the interaction of non-stationary beam of accelerated electrons in the form of a triangular pulse with the chromospheric plasma. The FLARIX numerical code was used to calculate the dynamics of the flare plasma parameters at different heights which are compared with the RADYN numerical code. We found that the characteristic heights of the formation of sub-THz emission vary over a wide range with time for both codes. The main contribution to the sub-THz emission comes from the chromospheric and transition region plasma with temperatures of $10^4 - 10^5$ K.

**Keywords.** Sun: Flares - Sun: X-rays, EUV, Radio emission, sub-THz emission

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## 1. Introduction

Solar flares are not yet fully understood explosive phenomena. Namely processes of particle acceleration – one of their most significant features – are still subject to many controversies. Understanding the mechanism of energy release and conversion in the flares is important not only *per se*, but also as a key to the space-weather predictions. Moreover, explosive events similar (not just phenomenologically, but by theoretical models also in their nature) to the flares happen in other astrophysical contexts, too, ranging from stellar flares to the bursts generated in the accretion discs surrounding the black-holes. Our Sun is just close enough to provide a unique laboratory for studying this kind of processes. Enhanced solar sub-terahertz (sub-THz) radiation, which is directly related to the energetic particles accelerated in the flares, represents an important and in many respects novel diagnostic tool. Understanding its generation at the Sun can shed light to the so far bit mysterious sub-THz burst at the other starts, too. Indeed, in 2017, Atacama Large Millimeter Array (ALMA) detected for the first time a number of mm-emission

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bursts on M-dwarfs (MacGregor et al. 2021), however, the origin of their emission still remains unclear.

A large number of studies have focused on sub-THz (0.3-3 mm) emission of solar flares (see, e.g., Krucker et al. 2013; Tsap et al. 2016; Kontar et al. 2018). Radio observations at the Solar Submillimeter Telescope (SST) at 212 & 405 GHz (Kaufmann et al. 2001) and the Köln Observatory for Submillimeter and Millimeter Astronomy (KOSMA) at 230 & 345 GHz (Lüthi et al. 2004) found that for almost half of the observed strong flares (M and X-class), the radio flux decreases with the increase of the frequency, i.e. the slope of the spectrum is negative, as expected if the gyrosynchrotron spectrum continued to higher frequencies (Lüthi et al. 2004; Trottet et al. 2002; Raulin et al. 2004). However, in the rest of the cases, the so-called sub-THz events (*STE in further*), the slope of the spectrum is positive and the fluxes can increase tens of thousands of times during the flare energy release (see, e.g., Krucker et al. 2013; Kaufmann et al. 2015). Several emission mechanisms have been proposed to explain the *STEs*: gyrosynchrotron, thermal free-free, Cherenkov or the plasma mechanism, however, all of them have their caveats (e.g., Fleishman and Kontar 2010).

A recent statistical study by Kontar et al. (2018) showed that thermal optically thick plasma of the chromosphere and transition region with temperatures $T = 2 \times (10^4 - 10^5)$ K and densities of $10^{11} - 10^{12}$ cm$^{-3}$ can produce the observed *STEs* through the thermal free-free mechanism. Moreover, it was shown that due to rapid radiative cooling, the time profiles of sub-THz and hard X-ray emissions, up to sub-second (0.1-1 s) time scales, behave similarly. The authors revealed that there is a positive correlation between the flare ribbons area and the sub-THz fluxes, and that the spectral index $\delta \leq 2$, which is consistent with the thermal mechanism. However, validation of the model in the sub-THz frequency range is still lacking for observational confirmation. In this connection, numerical modeling can provide additional information on the contribution of the chromosphere, transition region, and corona to sub-THz radiation and thus additional constraints on the existing emission mechanisms. Previously Morgachev et al. (2020), using F-CHROMA models (Carlsson et al. 2023) calculated with RADYN code, showed that chromospheric inhomogeneities can have a significant effect on generation of sub-THz emission from solar flares.

Here we apply non-LTE models of the flare chromosphere and transition region obtained with radiation-hydrodynamic (RHD) numerical codes FLARIX (Varady et al. 2010) and RADYN (Carlsson and Stein 1992, 1997) to model the response of the chromosphere to an electron beam bombardment during solar flares. With these two codes we calculate a flare solar atmosphere and its evolution to model the thermal sub-THz emission. We also calculate the altitude distributions of the temperature, density, and contribution function, to determine the input of different atmospheric layes to the sub-THz radiation for different time moments.

## 2. Sub-THz radio emission from FLARIX and RADYN models

To date, it has been possible to develop numerical methods to determine the temporal evolution of flare plasma parameters as a result of solar atmosphere interaction with the accelerated electron flux in the framework of RHD (see as a recent review Kerr 2023). Recent comparison of RADYN and FLARIX (Kašparová et al. 2019) has shown that both codes are relatively well matched. However, in the context of sub-THz events, the results of the use of FLARIX has not yet been examined in detail. Thus, the aim of the work is to compare FLARIX and RADYN models in terms of sub-THz observations.

We calculated the temporal evolution of sub-THz thermal bremsstrahlung emission (Fig. 1) for 1D models of the flare chromosphere and transition region obtained with

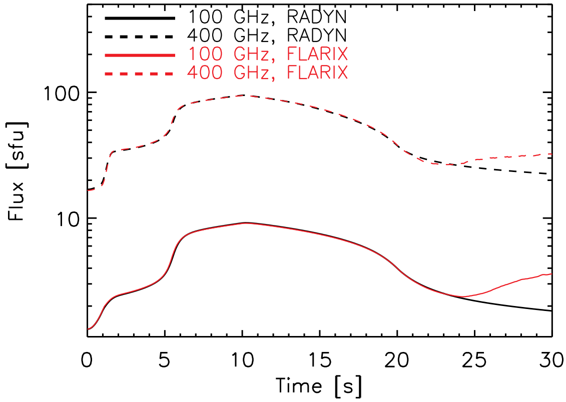


**Figure 1.** The time profiles of the sub-THz emission of RADYN (black) and FLARIX (red) models at frequencies 100 (solid line) and 400 GHz (dashed line).

the FLARIX and RADYN codes. The FLARIX and RADYN models were taken from (Kašparová et al. 2019). Both models describe the response of an unperturbed solar atmosphere, i.e. the model C from Vernazza et al. (1981) to a beam of non-thermal electrons. FLARIX and RADYN have differences in approaches (Fokker–Planck versus test particles), radiation losses, etc. In order to compare the results of the two simulations, the initial parameters were taken to be the same: the VAL-C undisturbed solar atmosphere and the nonthermal electron flux in the form of a symmetrical triangular time profile peaking at 10 s with duration of 20 s. The parameters of the electron beam were as follows: the spectral index of 3, the low-energy cutoff of 20 keV, the total energy of the electron flux of $10^{11}$ erg s$^{-1}$ cm$^{-2}$.

Each model contains a set of plasma parameters varying with height: temperature, electron density, hydrogen density, degree of ionization, etc. over a time interval of 30 s with a time step of 0.1 s. The modelled height distributions of temperature, and electron density are shown in Fig. 2.

To infer the total spectral flux $F_\nu$ (its thermal (free-free) bremsstrahlung at frequencies $\nu = 100$ and 400 GHz) the model altitude dependences of plasma temperature and plasma number density at each time were used:

$$F_\nu(H) = \frac{S}{R^2} \int_0^H CF(h)dh. \tag{1}$$

Here the height begining from the photosphere $H = 10000$ km corresponds to the full source thickness, $S$ is the source area, $R$ is the Sun-Earth distance, and the contribution fuction of an individual chromospheric layer at the height $h$ to the total intensity is

$$CF(h) = \eta_\nu(h) \exp{(-\int_h^H k_\nu dh')}, \tag{2}$$

where $\eta_\nu$ is the emissivity (see e.g. Morgachev et al. 2020), and $k_\nu$ is the absorption factor (Dulk 1985).

The calculated time profiles of the thermal bremsstrahlung emission at $\nu = 100$ and 400 GHz are shown in Fig. 1. The calculations of the sub-THz emission found that a spectral slope between 100 and 400 GHz remains positive at all times. The maxima of the time profiles of the electron beam and sub-THz emission coincide. The time profiles at 100 and 400 GHz for both models behave similarly: they have a rise phase during time

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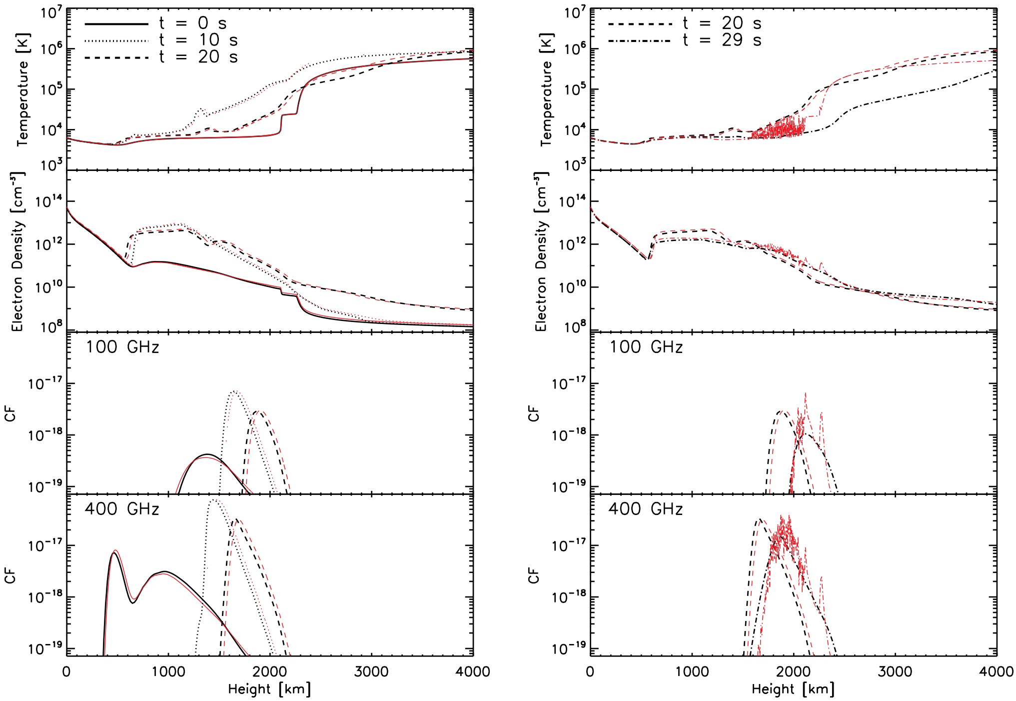


**Figure 2.** From top to bottom: height distribution of temperature, electron plasma density, contribution function $CF(h)$ at 100 and 400 GHz for the RADYN (black) and FLARIX (red) models at times $t$ = 0, 10, 20 s (left panel) and $t$ = 20, 29 s (right panel).

interval $t = 0 - 10$ s, a peak at time $t = 10$ s, and a decay phase till $t = 30$ s. However, for the FLARIX model the decay phase changes to a rise from $t \approx 24$ s till the end of the simulation. The results from both codes behave similarly till $t = 22$ s.

A good coincidence between the corresponding curves is seen in height distributions of temperature, electron density, and contribution functions till $t \approx 22$ s (Fig. 2). At around $t = 22$ s the FLARIX results start to have numerical oscillations at height $\sim 2$ Mm, which increase in width and grow over time. It is clear that the oscillations in temperature, electron density result in the oscillations of the contribution function $CF(h)$ (Fig. 2, right panel) and then contribute to the rise of the total spectral flux (Fig. 1). Besides the numerical oscillations a difference particularly in the temperature distribution from RADYN shows up at heights above 2 Mm.

The difference between the results of numerical calculations can be explained as follows. The used FLARIX model does not allow for temperature decrease because of the boundary condition, which is not quite correct for modeling relaxation of flaring atmosphere after $t \approx 22$ s for this simulation. This artificial condition means that the atmosphere cannot cool below its initial state. However, due to the moving shocks and condensations this is not always true. We cannot observe chromospheric condensations with FLARIX because of the temperature constraint while the RADYN temperature can significantly drop. These circumstances result in differences in simulations.

It is interesting to consider the height distribution of the contribution function $CF(h)$ from different levels of the chromosphere (Fig. 2, two bottom panels) because it determines the altitude at which sub-THz emission is generated. At frequencies 100 and 400 GHz the main contribution comes from a layer in the chromoshere and transition region

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of 400-500 km thickness at a height of about 2000 km with temperatures of $10^4 - 10^5$ K, which is heated by precipitating particles and moves to higher layers with time.

## 3. Conclusions

We calculated and compared evolution of the thermal bremsstrahlung emission in the sub-THz range for the RADYN & FLARIX models. For both models the characteristic heights of the formation of sub-THz emission is about 2000 km, which corresponds to the chromosphere and transition region, and vary over a wide range with time. The regions of formation of sub-THz emission in the RADYN & FLARIX models differ by less than 100 km. According to the evolution of the contribution function $CF(h)$, the main contribution to the sub-THz emission is made by the chromospheric and trasition region plasma with temperatures of $10^4 - 10^5$ K. The difference in the radiation flux does not exceed 15%. The maxima of the electron pulse and millimeter emission coincide. The region of low temperature and high plasma density (chromospheric condensation) with FLARIX was not observed due to the temperature constraint. Hovever, the same results were obtained with RADYN.

New sub-THz radio observations (ALMA, RT-7.5, SST) will help to diagnose the properties of flaring plasma in the transition region/chromosphere. More numerical simulations (e.g., with FLARIX) are needed.

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