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Thermal instability in the impulsive phase of solar flares with sub-THz component

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Abstract. Coronal rain is formed in the post-impulsive phase of solar flares due to the thermal instability of coronal plasma in EUV loops. As a result, the sub-terahertz (sub-THz) emission flux in the post-impulsive phase of solar flares can be increased due to the increasing of the optical thickness of the thermal source. This suggests that sub-THz observations can be used as a diagnostic tool for coronal rain.

This work is aimed to analyse the relationship between the sub-THz radiation and variations of the temperature and the emission measure of the EUV coronal plasma during the post-impulsive phase of the SOL2022-05-04T08:45 solar flare.

Based on the two-dimensional temperature and emission measure distributions obtained from the AIA/SDO EUV intensity data, it was found that the temperature decreases whereas the emission measure reaches the maximum near the sub-THz flare peak. This circumstance and peculiarities of the radiation time profiles in different wave ranges show evidence in favor of the significant contribution of the thermal coronal loop plasma to the flare sub-THz radiation at least for some flare events. The sub-THz emission may be associated with a coronal condensation, accompanied by the formation of coronal rain.

Keywords. Sun, flares, sub-therahertz radiation

1. Introduction

Recently, it became possible to observe weak solar flares with the high spatial resolution at the sub-therahertz (sub-THz, 0.3-3 mm) radio range with the Atacama Large Millimeter/submillimeter Array (ALMA) radio interferometer. Five microflares of GOES class B have been analyzed by Skokić *et al.* (2023). Authors concluded that the sub-THz sources of the flares can be located at the tops or footpoints of hot ($T > 1$ MK) coronal loops and hence, the hot plasma can provide a significant contribution to the sub-THz radiation. This inference contradicts some works wich suggest that the sub-THz radiation is determined by the chrormospheric plasma (Trottet *et al.* 2002; Tsap *et al.* 2016, 2018). This requires additional study of chromospheric and coronal sources of sub-THz emission.

It should be stressed that the peak of sub-THz radiation from solar flares can be observed in a post-impulsive flare phase (Smirnova *et al.* 2023), when the flare-driven coronal rain is formed. Moreover, the temperature T of the coronal loops drops near the sub-THz flare maximum for some events (Figure 1). This suggests that in the post-impulsive flare phase the thermal instability can play an important role in variations of plasma parameters in the sub-THz flare source (Antolin *et al.* 2023).

The goal of this work is to analyze the relationship between sub-THz radiation and the development of the thermal instability in coronal loops observed in the SOL2022-05-04T08:45 solar flare, which can be responsible for the formation of coronal rain.

2. Methodology and data analysis

The method is based on the assumption that the evolution of the sub-THz flare emission can be determined either by the temperature T or by the emission measure $EM = n^2V$ of optically thick ($F1$) and optically thin ($F2$) thermal sources, since

$$F_1 \propto TS, F_2 \propto \frac{n^2V}{\sqrt{T}}, \tag{1}$$

where S and V - the area and the volume of the emission source, respectively. Thus, by comparing the evolution of the temperature T and the emission measure EM of the flare source with the behavior of the sub-THz radiation time profile, one can estimate the contribution of the optically thick/thin sources to the thermal sub-THz radiation.

We analyzed observations of the SOL2022-05-04T08:45 solar flare by GOES X-ray class M5.7 in various spectral ranges, including data at a frequency of 93 GHz obtained with the RT-7.5 Bauman Moscow State Technical University radio telescope (Tsap *et al.* 2016). Time profiles of the flare at different spectral bands (SXR, HXR, microwave) are presented in Figure 2. The impulsive phase of the flare was observed in HXR and microwaves whereas it was not detected in the sub-THz emission.

Previously Smirnova *et al.* (2023) calculated the expected sub-THz radiation based on the differential emission measure (DEM) of SOL2022-05-04T08:45 according to AIA/SDO data in the temperature range $0.5 \leq T \leq 32$ MK (Hannah & Kontar 2012). This allowed us to conclude that the coronal plasma makes a significant contribution to the sub-THz emission of this flare which turned out to be ~ 40 sfu.

3. Results

A detailed analysis of the evolution of the flare temperature T and the emission measure EM was carried out in the time range 08:43-09:15 UT with a step of 12 s.

Left panel of Figure 3 shows a comparison of the T and EM time profiles with the sub-THz emission profile at 93 GHz. Using AIA images (https://iris.aws.lmsal.com/data/level2/2022/05/04/) in 304 Å passband, we can conclude that the peaks of the sub-THz emission and the emission measure coincide with the beginning of coronal rain. Consequently, taking into account Equation (1), we can conclude that the sub-THz emission is determined by the optically thin source connected with the plasma condensation in coronal loops.

Right panel of Figure 3 represents the comparison of H_α and 304 Å chromospheric time profiles with the 93 GHz profile of the flare emission. The location of 93 GHz flare maximum is not coincided with the emission peaks observed in H_α and 304 Å. Thus, taking into account this circumstance and the formation temperatures of the H_α line and the emission at the 304 Å passband we can conclude, that the chromospheric heating does not occur after the sub-THz maximum. This suggests that the thermal plasma of coronal loops plays a dominant role in the generation of the sub-THz component of the SOL2022-05-04T08:45 flare.

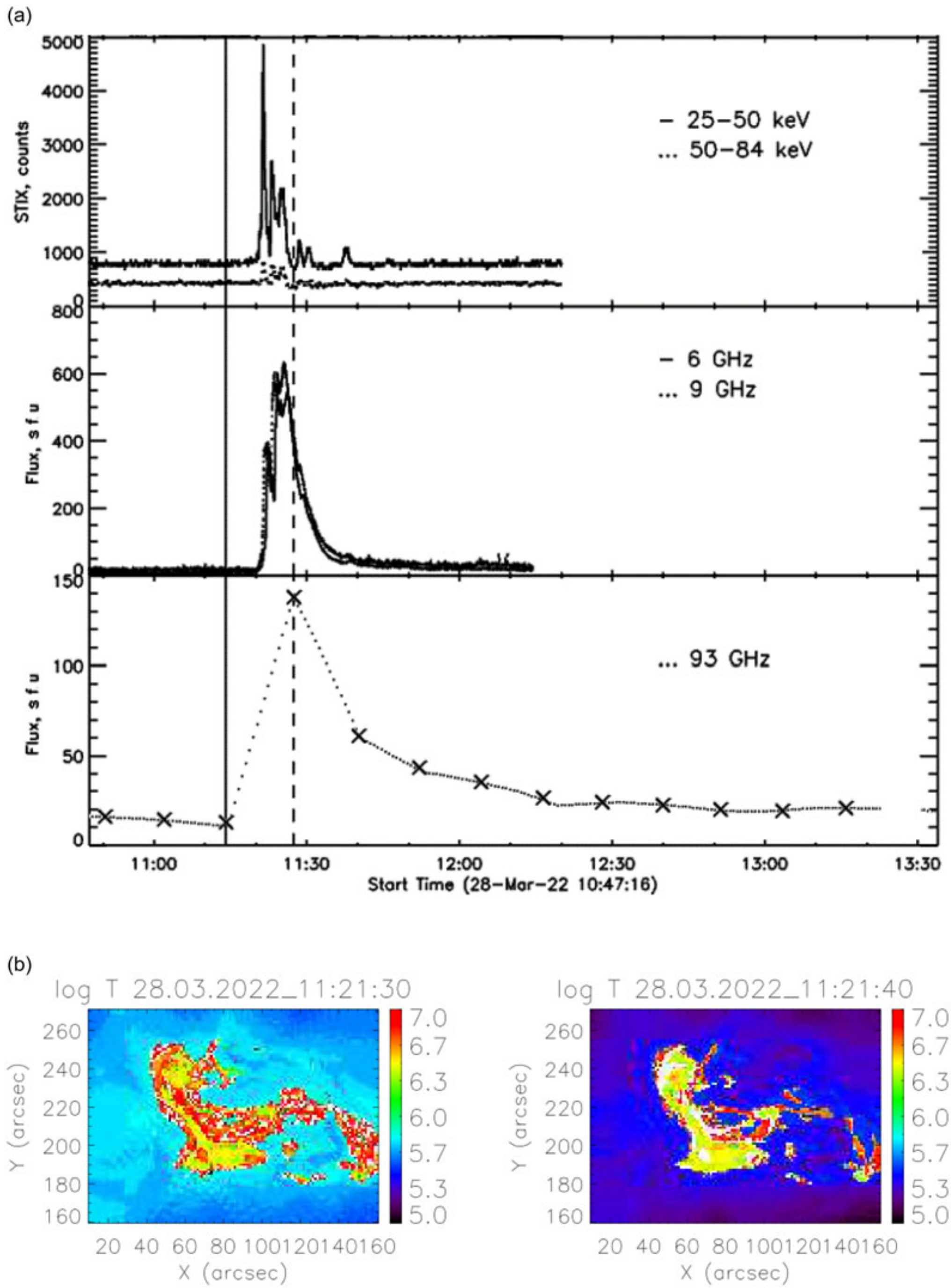

Figure 1. [a]: time profiles of the SOL2022-03-28T11:28 flare obtained with HXR, microwave, and 93 GHz observations. Solid line represents the pre-impulsive phase of the flare. Dashed line shows the maximum of the emission at 93 GHz. [b]: AIA temperature maps obtained near the maximum at 93 GHz.

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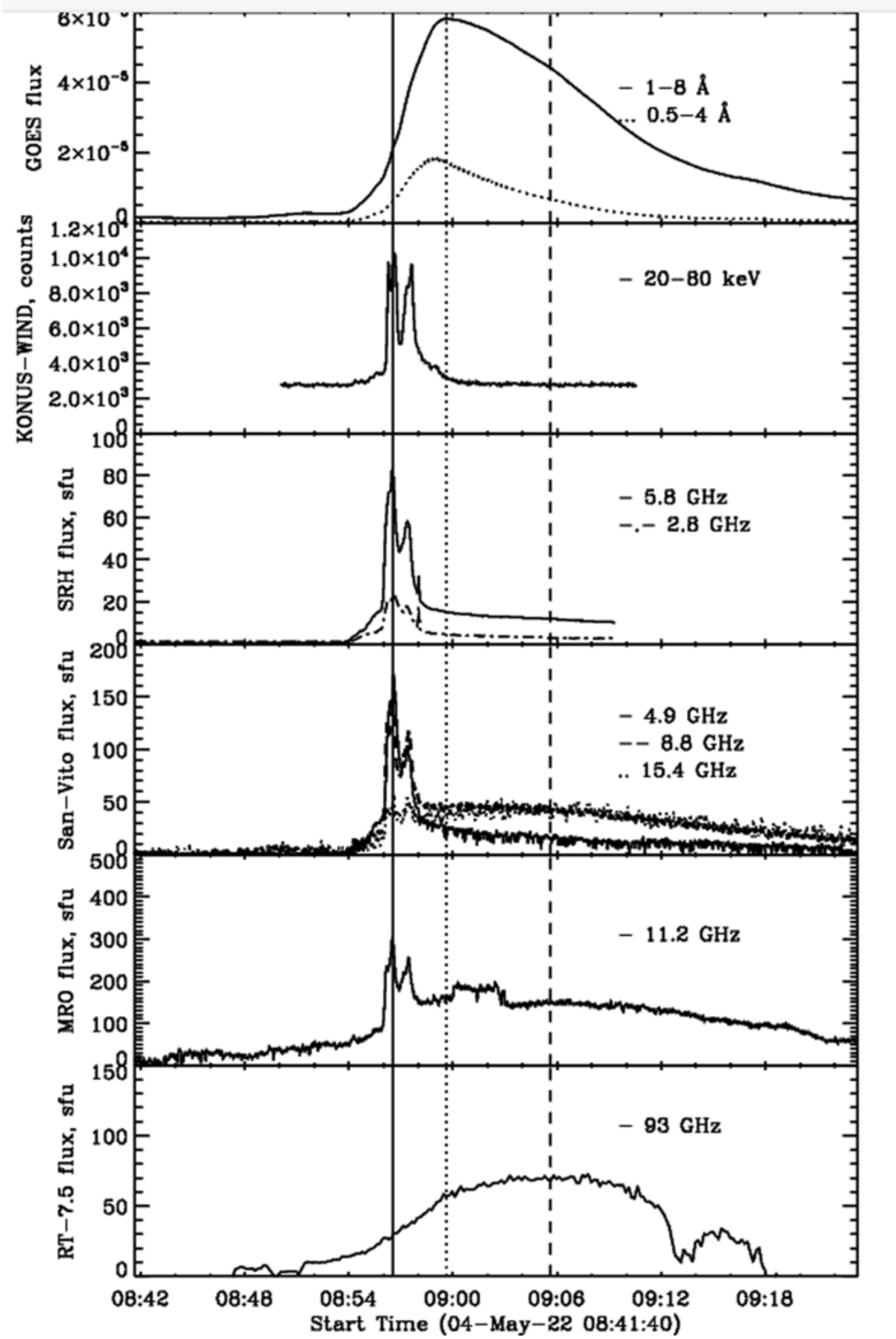

Figure 2. Time profiles of the SOL2022-05-04T08:45 flare. The vertical solid line corresponds to the peak of the impulsive phase of the flare, dashed line shows the 93 GHz flare maximum, and dotted line shows the begining of the sub-THz maximum.

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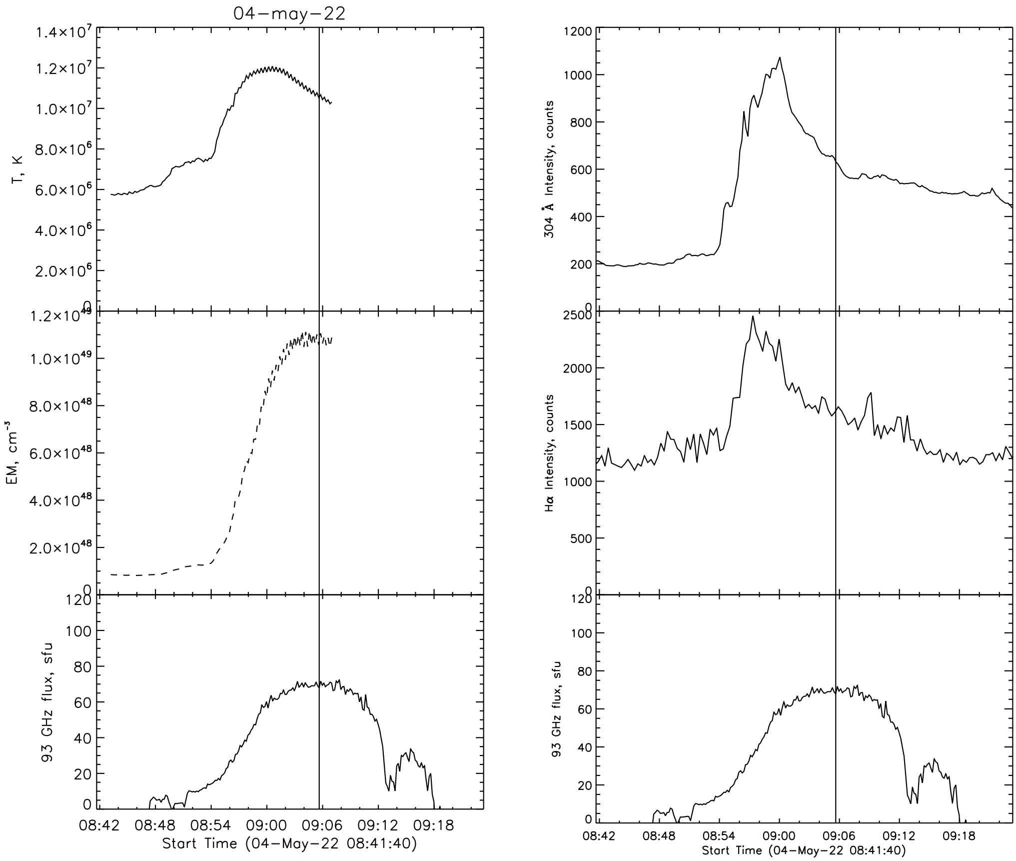

Figure 3. The comparison of time profiles of the AIA temperature T, emission measure EM (left), emission at 304 Å and H_α (right) with sub-THz observations.

4. Conclusions

(1) A multi-wave analysis of the SOL2022-05-04T08:45 flare event was carried out.
(2) The peaks of the sub-THz and emission measure time profiles of the flare are coincided, that indicates a significant contribution of optically thin coronal plasma to the sub-THz radiation.
(3) The sub-THz emission, at least for some flare events, may be associated with a coronal condensation, accompanied by the formation of coronal rain.

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References

Antolin, P., Dolliou, A., Auchére, F., et al. 2023, Astronomy & Astrophysics, 676, A112.
Hannah I.G. & Kontar E.P., 2012, Astronomy & Astrophysics, 539, A146.
Skokić, I., Benz, A. O., Brajša, R., et al., 2023, Astronomy & Astrophysics, 669, A156.

https://doi.org/10.1017/S1743921323005185 Published online by Cambridge University Press

Smirnova V.V., Tsap Yu.T., Motorina G.G., Morgachev A.S., Bárta M., 2023, Geomagnetism & Aeronomy, 63, 5, 527.

Trottet G., Raulin J.P., Kaufmann P., 2002, Astronomy & Astrophysics, 381, 694.

Tsap Yu.T., Smirnova V.V., Morgachev A.S., Motorina G.G., Kontar E.P., Nagnibeda V.G., Strekalova P.V., 2016, Advances in Space Research, 57, 7, 1449.

Tsap Yu.T., Smirnova V.V., Motorina G.G., Morgachev A.S., Kuznetsov S.A., Nagnibeda V.G., Ryzhov V.S., 2018. Solar Physics, 293, 3, 50.