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Sub-THz emission from stellar flares and energy release diagnostics

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Abstract. A comparative analysis of sub-THz emission of stellar flares from red dwarfs has been carried out. ALMA observations indicate that the sub-THz emission flux from stellar flares with a duration of 10 s is an order of magnitude greater than for solar flares. The sub-THz emission is linearly polarized and decreases with frequency. The degree of polarization can reach tens of percent. We show that these types of spectrum slopes and linear polarization can be caused by the synchrotron emission of ultrarelativistic electrons. The origin of the observed relationships between sub-THz, low frequency radio, and X-ray emissions of stellar flares are discussed.

Keywords. stellar flares, sub-THz emission, energy release mechanism

1. Introduction

Regular solar observations in the sub-THz range at 212 and 405 GHz (Kaufmann *et al.* 2001) began only two decades ago mainly due to the Solar Submillimeter Telescope (SST) with a 1.5-meter reflector placed in the Argentina Andes at the altitude of 2.5 km. This opened a new window for studying nonstationary solar phenomena. Despite of many researches devoted to sub-THz observations of solar flares the origin of this emission is not yet fully understood. The study of solar flare events in sub-THz range ($10^2 - 10^3$ GHz) using the unique Atacama Large Millimeter Array (ALMA) with high spatial and temporal resolution started in 2013 is still difficult due to the specifics of the ALMA tools. In this regard, sub-THz observational data on flare stars, where the energy release model is believed to be similar to the solar one (Gershberg 2005) can be very useful.

Red dwarfs are the most common stars in the Galaxy due to the smallness of their mass $< 0.3M\odot$, which, with a high degree of probability, have planets comparable in size to the Earth in the habitable zone (Wandel & Gale 2020). Although solar flares and stellar flares have much in common (Gershberg 2005), nevertheless, the energy of stellar flares is often several orders of magnitude greater than for solar flares, and the luminosity of stars during a flare can increase tens of times. Stellar flares occur much more frequently than solar flares. Besides, the correlation of light curves in different wave bands sometimes is not revealed or has a dependence different from the solar one (MacGregor *et al.* 2018, 2021; Howard *et al.* 2022). For example, a sub-THz event on May 1, 2019 at the Proxima Centauri (Prox Cen) with a short duration of about 10 s, observed with ALMA in spectral windows with a bandwidth of 2 GHz, centered on 225, 227, 239, and 241 GHz (MacGregor et. al 2021) was not accompanied by radio emissions at frequencies below a few GHz, despite the correlation with ultraviolet emission observed with the Hubble Space Telescope. In this case, the radiation flux reached 112 ±

10.4 mJy, the spectral index $\alpha = -2.23 \pm 0.48$, and the lower limit of linear polarization was 0.19 ± 0.07. The millimeter event on May 6, 2019 at the Prox Cen turned out to be the weakest millimeter event so far observed by ALMA; the maximum flux value corresponding to the second radiation peak was 38 ± 5 mJy, $\alpha = -5.1 \pm 3.9$, and the minimum linear polarization was 0.18 ± 0.11. This flare, about 40 min long, was also recorded by the Chandra space observatory in the soft ($0.4 - 10$ keV) X-ray range. The X-ray light curve had a complex structure with a sharp increase and a slow decrease and consisted of three peaks. Millimeter short bursts observed with ALMA lasted less than 10 s. These bursts approximately corresponded in time to the soft X-ray peaks (first peak was not detected due to calibration). The flare was also observed in the optical range using the Las Cumbres Observatory Global Telescope (LCOGT) in the U band for 30 min. It is also interesting to note that millimeter bursts corresponded in time to the decaying branch of soft X-rays (Howard *et al.* 2022), which contradicts to observations of sub-THz solar events (Smirnova *et al.* 2021).

Thus, the mechanisms of energy release and radiation of stellar flares, despite their magnetic origin, may have features that differ from those predicted by the standard flare model.

Below, using the example of one flare event at the Prox Cen, we analyze the sub-THz observations of stellar flares detected by ALMA, and give probable interpretation of the revealed features.

2. Observations and interpretation of sub-THz radiation from Prox Cen

In spite that the Prox Cen is the quite typical red dwarf, it occupies a special place among the dwarf stars because it is the closest star to us. The rate of occurrence of powerful events exceeding the level of quiescent radiation by 10 times is one event per several days. In optics, the frequency of occurrence of flare events has approximately the same occurrence rate as in soft X-rays, that is, several flares per day. Moreover, according to Davenport *et al.* (2016), extrapolation suggests eight superflares per year with an energy greater than 10^{33} erg.

Let us consider a typical sub-THz flare of the Prox Cen (Fig. 1) observed by ALMA on March 24, 2017, which lasted about 1 min, while the peak flux density $F_\nu = 100$ mJy (MacGregor, 2018) corresponds to the luminosity $L_\nu = 2 \times 10^{14}$ erg/(s Hz), which is approximately an order of magnitude greater than the radio emissions flux F_ν of the most powerful solar events (see Howard et al., 2022). The negative spectrum index $\alpha = -1.8$ and linear polarization (≈ 20 %) indicate the synchrotron origin of sub-THz radiation.

Following Kaufmann *et al.* (1986), it can also be assumed that electrons first emitted softer quanta due to the synchrotron mechanism, which then became harder due to Compton scattering on relativistic electrons (inverse Compton effect). Thus, the generation of sub-THz radiation was determined by synchrotron self-Compton model, which, in particular, is used to interpret the X-ray and gamma radiation of blazars. Meanwhile, Compton losses will dominate over synchrotron losses only if the photon energy density U_{ph} exceeds the magnetic one (Kaufmann *et al.* 1986), i.e.

$$U_{ph} > \frac{B^2}{8\pi}.$$

Taking into account the magnetic origin of solar and stellar flares, the last inequality in the region of flare energy release seems unlikely because a significant part of the free energy of the magnetic field is used to the plasma heating and the large-scale MHD motions.

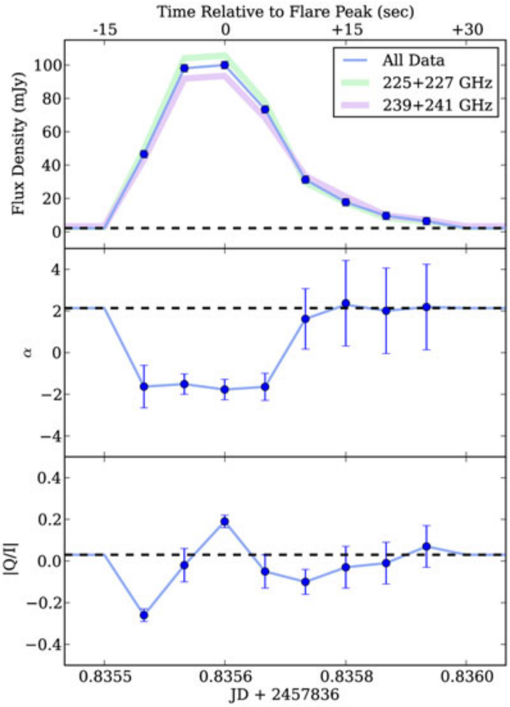

Figure 1. The flux density (top), spectral index with frequency, α, where $F_\nu \propto \nu^\alpha$ (middle), and lower limit on the fractional linear polarization ($|Q/I|$; bottom) during the observed stellar flare on 2017 March 24. The dashed line indicates the quiescent value of each parameter. In the top panel, the flux density of the 225 + 227 GHz (green) and 239 + 241 GHz (purple) spectral windows separately, along with the flux density for all spectral windows combined together (blue) are plotted. The figure has been taken from MacGregor *et al.* (2018).

Thus, based on the hypothesis of the synchrotron origin of the sub-THz component of stellar flares, we will do some estimates. The maximum synchrotron radiation of a relativistic electron with total energy E corresponds to the frequency (Ginzburg & Syrovatskii 1964)

$$\nu_s = 1.2 \times 10^6 B\gamma^2 \text{ [Hz]}, \tag{1}$$

where $\gamma = E/(mc^2)$ is the Lorentz factor, $mc^2 = 511$ keV is the electron rest energy, and $B(G)$ is the magnetic field. Then, from Eq. (1) it is easy to obtain the expression

$$\gamma_s \approx 10^{-3}\sqrt{\nu_s/B}. \tag{2}$$

Adopting the frequency $\nu_s = 2.3 \times 10^{11}$ Hz and $B = 500$ G, from Eq. (2) we obtain $\gamma_s \approx 20$, which corresponds to the electron energy $E_s \approx 10$ MeV. In the case of a negative spectral index of the millimeter radiation the value of E_s can be considered as an upper limit, because the frequency of the spectral maximum should be less than ν_s.

The rate of synchrotron energy loss by an electron is (Ginzburg & Syrovatskii 1964)

$$dE/dt \approx 1.6 \times 10^{-15} B^2\gamma^2 \text{ erg/s}. \tag{3}$$

For a quasi-isotropic distribution of relativistic electrons, the number of energetic particles N_s, taking Eq. (3) into account, can be estimated as

$$N_s = L_s/dE/dt = 6.25 \times 10^{14} L_s/(B^2\gamma^2), \tag{4}$$

where L_s is the luminosity in the sub-THz range. Setting $L_s \approx L_\nu \nu_s \approx 5 \times 10^{25}$ erg/s, $\gamma = 20$, and $B = 500$ G, we find from Eq. (4) that $N_s = 3 \times 10^{32}$. The resulting rough lower estimate for the number of relativistic electrons seems to be quite adequate for the following reasons.

If the electron spectrum $N(E) \propto E^{-\delta}$, the total number of accelerated electrons in the source is (Tsap *et al.* 2023)

$$N_0 \approx N_s (E_s/E_0)^{\delta - 1}, \tag{5}$$

where $\delta = 2|\alpha| + 1$ is the electron spectral index and E_0 is the lower threshold of the kinetic energy of accelerated electrons. Putting into Eq. (5) the electron energy $E_0 = 20$ keV, $E_s = 10$ MeV, the electron spectral index $\delta = 4.6$, and $N_s = 3 \times 10^{32}$, we find $N_0 \approx 10^{42}$. Note that Tsap *et al.* (2023) made an arithmetical error in the calculation of N_0. This minimum estimate of the number of energetic particles N_0 seems quite reasonable, because the total number of thermal electrons contained in the energy release region can be estimated as $N_{th} \sim n_e l^3 = 10^{41} - 10^{42}$, where we have taken the characteristic scale $l = 10^{10}$ cm, and the number density of thermal electrons $n_e = 10^{11} - 10^{12}$ cm^{-3}. Consequently, the total number of accelerated electrons N_0 and the number of thermal electrons N_{th} are the same order of magnitude.

3. Discussion and conclusion

We have shown that the synchrotron mechanism can be responsible for the sub-THz flaring emission from the Prox Cen. Because the stellar bursts exceeded solar ones by an order of magnitude, this indicates a more efficient acceleration of relativistic electrons. At the same time, we did not consider the problem of the observed weak correlation between sub-THz and low frequency radio emission. This problem is resolved if we take into account that the flare energy release occurs in denser layers of the stellar atmosphere (chromosphere/photosphere). This approach makes it possible to explain the absence of low-frequency radio emissions by a high number density of background electrons n_e. In fact, if the electron plasma frequency in the burst generation region is higher than the electron gyrofrequency, then electromagnetic radiation can escape the source only in the case when the wave frequency is greater than the plasma frequency. This suggests that for $\nu = 3 \times 10^{11}$ Hz the number density of thermal electrons $n_e > 10^{11}$ cm^{-3} and the low-frequency radio emission will be suppressed. Moreover, due to the high number density of the plasma and, accordingly, large radiation losses, the heating of the plasma by accelerated electrons to high temperatures, which is necessary for the generation of soft X-ray radiation in the energy release region, may turn out to be ineffective.

Consequently, although the sub-THz radiation flux, spectrum, and linear polarization of Prox Cen flares testify to the synchrotron origin of the radiation the analysis did not confirm the complete analogy of events with the standard model of solar flares. Moreover, there are some indications that the synchrotron mechanism can be responsible for the optical spike bursts during a giant flare of UV Ceti (Beskin *et al.* 2017).

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References

Beskin, G., Karpov, S., Plokhotnichenko, V., Stepanov, A., & Tsap, Yu. 2017, *PASA*, 34, id.e010.

Davenport,J.R.A., Kipping, D.M., Sasselov, D., Matthews, J.M., & Cameron, C. 2016, *ApJ*, 829, L31.

Gershberg, R.E. 2005, Solar-Type Activity in Main-Sequence Stars (Springer Berlin, Heidelberg)

Ginzburg, V.L. & Syrovatskii, S.I. The Origin of Cosmic Rays (Pergamon, Oxford–New York).

Howard, W.S., MacGregor, M.A., Osten, R, Forbrich, J., Cranmer, S.R. *et al.* 2022, *ApJ*, 938, 103.

Kaufmann, P., Correia, E., Costa, J.E.R., & Zodi Vaz, A.M. 1986, *A&A*, 157, 11.

Kaufmann, P., Raulin, J.-P., Correia, E., Costa, J.E.R., Guillermo, C., de Castro, Giménez, Silva, A.V.R., Levato, H., Rovira, M., Mandrini, C., Fernández-Borda, R., & Bauer, O. 2001, *IAU Symp.*, 203, 283.

MacGregor, M.A., Weinberger, A.J. Wilner, D.J., Kowalski, A.F., & Cranmer, S.R. 2018, *ApJ*, 855, L2.

MacGregor, M.A., Weinberger, A.J., Loyd, R.O., Shkolnik, E. Barclay, T. *et al.*, 2021, *ApJ*, 911, L25.

Smirnova, V.V., Tsap, Yu. T., Morgachev, A.S., Motorina, G.G, & Bárta, M. 2021, *Geomagnetism and Aeronomy*, 61, 993.

Tsap, Yu.T., Stepanov, A.V. & Kopylova Yu.G. 2023, *Geomagnetism and Aeronomy*, 63, 937.

Wandel, A. & Gale, J. 2020, *Iternational J. Astrobiology*, 19, 126.