MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Morphology of average time profiles of solar flares in the microwave range

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Abstract. Average flare time profiles are useful tools for determining energy evolution mechanisms both in the Sun and in stars. The study related to their construction and analysis was done in the visible and ultraviolet spectral ranges. Microwave emission, which is sensitive to various emission mechanisms, was not included in such studies. In this paper, we present the first results of reconstruction and analysis of average time profiles of solar flares using observations with the Siberian Radioheliograph. The events under consideration are flares with simple temporal behavior (without multiple bursts), but emitted in a wide frequency range. The latter feature was necessary to separate the emission of optically thick and optically thin sources. In total, we used 116 events detected during five months of observation in 2023 for the reconstruction. Each profile was normalized to its maximum value and the time scale was transformed into a universal length for all events, by deriving seconds into units equal to half the width of 50% of the maximum value for each event ($t_{\frac{1}{2}}$). The time profiles of optically thin and optically thick emission sources demonstrate similar behaviour. The pulse phase fits well to a fourth-order polynomial function. The decay phase is fitted by two exponential functions. The emission dominance, fitted by one exponent over another, changes at $t_{\frac{1}{2}}$, which is approximately equal to 1.5.

Keywords: Sun: flares; decay phase; microwave emission; average profile

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1 Introduction

The time profile of a flare provides information about the dynamics of energy release and transfer processes. Comparison of the time profiles obtained for the same event or object in different spectral ranges usually helps to understand the altitude dynamics of evolution. By comparing the time profile of an event with that of a well-understood process or averaged time profiles, we can confirm or reject a hypothesis. As both solar and stellar flares are often complicated events, the time profiles of simple or "classic" shapes are of special interest for study. Such profiles (and hence flares) have only one peak, with a rapid increase before the peak and a gradual decline after it, without significant fluctuations in intensity. The "classical" averaged time profiles have been obtained and analysed for the UV emission from solar flares (Kashapova et al. 2021), and white light emissions from red dwarf flares (Davenport et al. 2014). The microwave (MW) emissions of flares, and especially solar flares, are assumed to be a powerful instrument for studying plasma processes. However, the averaged time profiles in this spectral range have not been obtained yet. The aim of our study is to construct and carry out a preliminary analysis of the averaged MW time profile based on observations of simple or "classical" solar flares.

2 Observational data and analysis

Usually, microwave emission from solar flares is produced by the gyrosynchrotron mechanism, and their spectra combine the emission from both optically thick and thin sources (Dulk 1985). So, the temporal behaviour of emissions from these parts can differ. For this reason, we need to construct two average time profiles for the optically thin and optically thick spectral parts. To separate MW emissions of different types, we need to analyse the spectrum over a wide range of frequencies with high spectral resolution. The Siberian Radioheliograph (SRH) is a radio telescope for observing the Sun, which allows not only to obtain images in the spectral range of 3–24 GHz, but also information about the "Sun-as-a-star" fluxes with high temporal and spectral resolution. In our study, we reconstructed time profiles using correlation plots by SRH. Time profiles of the sum of the correlation coefficients between pairs of antennas are available, and a more sensitive flux equivalent is assumed (Lesovoi & Kobets 2017). Since we normalize each event time profile, the normalized correlation graphs will from now on be thought of as normalized flux time profiles.

Automatic flare detection provided more than 600 candidates during the period from July to September 2023 and May 2024 (Rozhkova et al. 2024). Of this set, only 116 events meet the criteria for a "classical" flare. Then, on the dynamic spectrum,

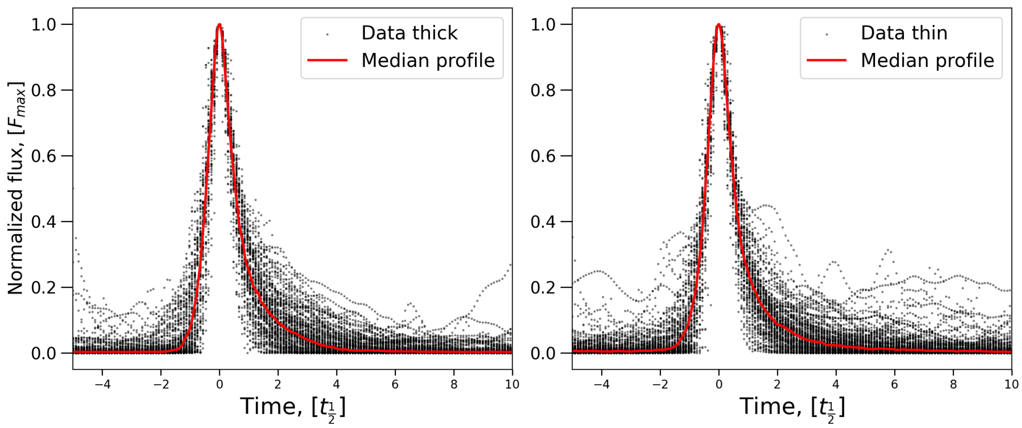

Fig. 1. Overlay of all 116 profiles of optically thick (left panel) and optically thin (right panel) parts of flare emission. Profiles scaled to relative time $t_{\frac{1}{2}}$ and maximum of flux $F_{\max}$.

we found the peak frequency for each event and separated the frequencies of emissions from optically thick and thin sources to get two time profiles. Each profile was normalized and time-scaled as done in Davenport et al. (2014). The timescale unit is the half-width of the time interval between the moments when the time profile reaches 50% of its maximum value ($t_{\frac{1}{2}}$). The temporal resolution of the time profiles was $0.001 \times t_{\frac{1}{2}}$. The average time profiles of optically thick and thin sources (shown in Fig. 1 by the red lines) are constructed by taking the median value for each time bin. The comparison of average time profiles revealed similar behaviour of optically thick and optically thin emissions (Fig. 2, left panel). As microwave gyrosynchrotron emission is the magnetic bremsstrahlung of electrons, this similarity indicates the absence of any additional factors that could distort the emission in an optically thick source, such as heated plasma or cold plasma from eruptions on the flare loop top.

3 An analytical template and summary

An important part of the analysis of the average time profile is its fitting to an analytical template that allows it to be described by a set of analytical functions. We did it for the average time profile of an optically thin source only using approaches from Davenport et al. (2014) and Kashapova et al. (2021). The rise phase is well-fitted by a fourth-order polynomial (Fig. 2, middle panel). We fitted the decay phase (right panel of Fig. 2) with two exponential functions, as was done in previous studies. The breakpoint between the domination of one exponent over another is approximately $1.5\, t_{\frac{1}{2}}$, which coincides with the times obtained by Kashapova et al. (2021) for 1600 Å

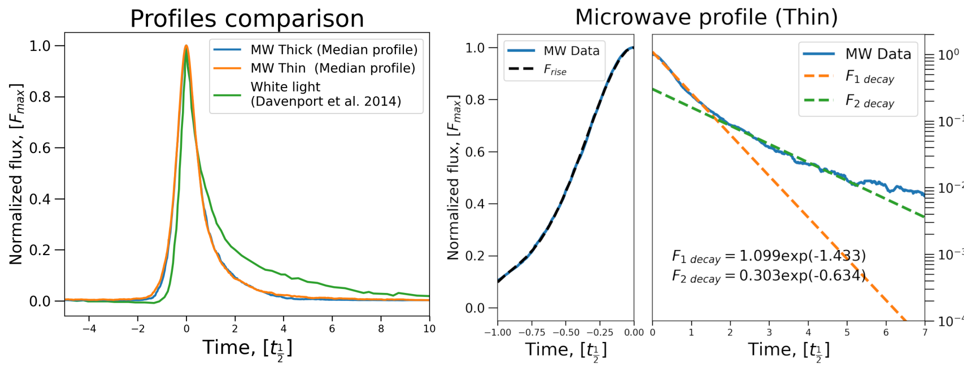

Fig. 2. Comparison of the MW time profiles of optically thick and optically thin radiation with the white light profile from Davenport et al. (2014) (left panel), the MW time profile fitted by 2 exponential functions

and 304 Å spectral bands. The 1700 Å spectral band observed by SDO/AIA is considered to be mostly related to higher levels of energy release. As the time intervals for exponential functions are the same as in Kashapova et al. (2021) ($0 < t_{\frac{1}{2}} < 1.5$ and $3 < t_{\frac{1}{2}} < 6$), then we can compare the dynamics demonstrated by analytical functions. For both exponents, it can be seen that the MW emission decays faster than the UV 1700 Å emission (-1.433 vs -0.800 in $F_{1\ \mathrm{decay}}$ function and -0.634 vs -0.336 in $F_{2\ \mathrm{decay}}$ function for MW and UV 1700 Å emissions, respectively).

This fact indicates that the "pure" gyrosynchrotron mechanism is characteristic of flares with a simple time profile. The obtained average time profiles and analytical templates derived for impulsive and decay phases can be used to analyse flare energy balance and mechanisms in more complex events.

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