Statistics of “Cold” Early Impulsive Solar Flares in X-Ray and Microwave Domains

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Abstract
Solar flares often happen after a preflare/preheating phase, which is almost or entirely thermal. In contrast, there are the so-called early impulsive flares that do not show a (significant) preflare heating, but instead often show the Neupert effect—a relationship where the impulsive phase is followed by a gradual, cumulative-like, thermal response. This has been interpreted as a dominance of nonthermal energy release at the impulsive phase, even though a similar phenomenology is expected if the thermal and nonthermal energies are released in comparable amounts at the impulsive phase. Nevertheless, some flares do show a good quantitative correspondence between the nonthermal electron energy input and plasma heating; in such cases, the thermal response was weak, which results in them being called “cold” flares. We undertook a systematic search for such events among early impulsive flares registered by the Konus-Wind instrument in the triggered mode from 11/1994 to 4/2017, and selected 27 cold flares based on relationships between hard X-ray (HXR) (Konus-Wind) and soft X-ray (Geostationary Operational Environmental Satellite) emission. For these events, we put together all available microwave data from different instruments. We obtained temporal and spectral parameters of HXR and microwave emissions of the events and examined correlations between them. We found that, compared to a “mean” flare, the cold flares: (i) are weaker, shorter, and harder in the X-ray domain; (ii) are harder and shorter, but not weaker in the microwaves; (iii) have a significantly higher spectral peak frequencies in the microwaves. We discuss the possible physical reasons for these distinctions and implication of the finding.

Key words: Sun: flares – Sun: radio radiation – Sun: X-rays, gamma rays

1. Introduction
Explosive energy release that results in efficient acceleration of charged particles and heating of the ambient plasma is ubiquitous in astrophysics. In the solar atmosphere, this energy release is observed as transient brightening at various wavelengths, most notably during solar flares. In solar flares, the excessive magnetic energy can be promptly released at a timescale as short as seconds, while generating nonthermal particles with high energies as large as 1 MeV and heating the ambient plasma up to several dozens of millions of degrees Kelvin. Although particle acceleration and plasma heating are typical for many astrophysical objects, the solar flares offer a unique natural laboratory where these processes can be studied at the extremely short spatial and temporal scales needed to address the key dynamics of the explosive energy release. It is puzzling that the proportions of the energy that initially go to either particle acceleration or plasma heating vary dramatically between different solar flares. Indeed, there are entirely thermal flares (Gary & Hurford 1989; Battaglia et al. 2009; Fleishman et al. 2015) where no nonthermal emission is detected, while in some other flares, an exceptionally strong nonthermal emission is accompanied by a very modest thermal component (White et al. 1992; Bastian et al. 2007; Fleishman et al. 2011; Masuda et al. 2013). Not surprisingly, there are cases with all possible proportions between the aforementioned extremes of purely thermal and entirely nonthermal flares.

It is not yet clear what physical process or parameter combination is decisive for the initial energy partitions in the flares, nor what is the fundamental difference between a “normal” solar flare, in which the thermal and nonthermal energies are initially comparable, and those dominated by the nonthermal component. In this study, we are going to advance these questions using a statistical comparison between events from various subgroups described below.

There are numerous statistical studies of solar flares in the X-ray and microwave domains that employ data from many past or existing instruments. In particular, Tanaka et al. (1983), based on HINOTORI data, and Dennis (1985), based on SMM/HXRB data, performed statistical analyses of the X-ray bursts registered during solar cycle 21 and revealed three types of X-ray solar flares: the first type represents soft hot flares with minor hard X-ray (HXR) emission; flares of the second type have noticeable HXR emission, impulsive time profiles, and soft-hard-soft spectral evolution with typical power-law spectral indices between −2 to −8; and flares of the third type are characterized by extended durations, soft-harder spectral evolution, and power-law indices ≤4.5 (Bai & Sturrock 1989). Dennis (1985) also established that the occurrence rate distribution of the HXR peak fluxes obeys a power law with index −1.8. Later, power laws were also found for distributions of HXR fluxes with power-law indices between −1.53 and −1.77 and HXR durations with power-law indices between −1.76 and −2.54 ( Crosby et al. 1993; Aschwanden 2011). The statistical comparison between HXR and microwave flare components performed by Kosugi et al. (1988) shows that HXR emission in impulsive flares at ~100 keV and microwave emission at 17 GHz are highly correlated and presumably the results of nonrelativistic down-streaming electrons, while microwaves in extended flares are emitted by relativistic electrons trapped in coronal loops. Silva et al. (2000) performed an analysis of correlations between parameters of HXR bursts registered by CGRO/BATSE and microwave by Owens Valley Solar Array (OVSA). This analysis also revealed that HXR fluxes in ≤200 keV and
microwave fluxes are generally correlated, while HXR and microwave spectral parameters are often unrelated. One of the most detailed statistical studies in the microwave domain was performed by Nita et al. (2004) for flares registered by the OVSA during 2001–2002.

Su et al. (2008), based on the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) data, introduced three solar flare types according to their relationship between thermal and nonthermal emission. Type 1, “accordantly gradual flares,” are purely thermal, with no obvious emission above 25 keV. Type 2 flares, called “accordantly impulsive flares,” demonstrate impulsive nonthermal emission in HXRs, along with more gradual thermal soft X-ray (SXR) emission. In the case of type 3 flares, the “early impulsive flares” first proposed by Sui et al. (2007), an impulsive nonthermal phase is followed by thermal emission. In a subset of impulsive flares, the so-called Neupert effect is observed (Neupert 1968). Originally, Neupert (1968) discovered a correlation between the flare time profiles in SXR, where the thermal emission is observed, and the cumulative integral of the time profile in microwaves, where the emission is generated by nonthermal particles. Later, a similar relationship was revealed between SXRs and HXRs. Taken at face value, the Neupert effect implies that the thermal plasma is heated by nonthermal electrons. However, this heating by nonthermal electrons might not be the only heating occurring during the flare. Indeed, if the thermal plasma is somehow impulsively heated directly by the magnetic energy release at the same timescale as that of the electron acceleration, the light curves of thermal emission will still demonstrate the Neupert effect because the thermal plasma cooling is a much slower process than the impulsive energy release. Such additional heating was proposed by Veronig et al. (2005) in a subset of events that demonstrate the phenomenology of the Neupert effect. In addition, other ways of plasma heating are observed or implied in solar flares, so the Neupert effect is not always observed (Su et al. 2008; Battaglia et al. 2009).

Although the presence of the Neupert effect does not, in general, guarantee that the plasma heating is solely driven by the nonthermal electrons, it would not be unreasonable to expect that there are flares in which this heating mechanism does dominate. Most likely, such flare would represent a subset of early impulsive flares, whose thermal emission is very low before the impulsive phase, so the thermal plasma is likely heated by almost only nonthermal particles. Such cases, called “cold” solar flares (CSFs hereafter), which show very low thermal response relative to nonthermal energy of accelerated particles, have been reported in previous case studies (White et al. 1992; Bastian et al. 2007; Fleishman et al. 2011; Masuda et al. 2013). However, the criteria to classify a given flare as a “cold” one were somewhat subjective; typically, the reported CSFs showed a noticeable HXR and/or microwave burst that happened without any reported Geostationary Operational Environmental Satellite (GOES) flare. However, no formal criterion has been developed to quantify how weak the thermal response must be compared to the nonthermal emission for the flare to be classified as a cold one. Accordingly, with all the variety of statistical studies described above, no focused statistical study on the flares with weak thermal response, the “cold” flares, has yet been available.

It is important to realize that there are two formal reasons to render the low thermal SXR emission: (a) low plasma temperature (as in the cases reported by Bastian et al. 2007; Masuda et al. 2013) or (b) low emission measure due to either a low plasma density (as in the tenuous flare reported by Fleishman et al. 2011) or a small volume of the flaring loop (as in the main flaring loop in the flare reported by Fleishman et al. 2016); thus, in case (b), the observed thermal response can remain low even if the plasma temperature is high. With this caveat, here we will use the term “cold flare” for any event with a reasonably weak thermal signature (see below for formal criteria), because it is not at all easy to sort out cases (a) and (b) at the stage of the event selection.

Here, we take advantage of the availability of an almost uniform database of solar flares recorded by the Konus-Wind (Aptekar et al. 1995) during two solar cycles (between 1994 November and 2017 April) to build a statistically significant subset of the cold flares and study their properties as compared to other flares. Based on the performed statistical analysis, we discuss what flare properties or parameter combinations make the CSF different from the “normal” flare, and what are the likely main causes of the apparent lack of thermal emission in this class of solar flares.

2. Instrumentation and Event Selection

2.1. X-Ray Domain: Uniform Input from the KONUS-WIND and the GOES

Given that CSFs occur relatively seldom, the statistical study of these events requires a reasonably long series of observations. From this perspective, we employ HXR data from the Konus-Wind and SXR data from the GOES; both data sets are available over a time period longer than two full solar cycles (White et al. 2005).

2.1.1. GOES SXR Data

Spacecraft of the GOES series have observed the Sun almost continuously since 1974. We used data of GOES X-ray sensors in two broadband SXR channels, softer channel 1–8 Å, and harder channel 0.5–4 Å, with a temporal resolution that varied from 3 to 2.046 s during our observational history.

2.1.2. KONUS-WIND HXR Solar Data

Konus-Wind was launched on 1994 November 1, onboard the Wind spacecraft, to detect gamma-ray bursts and solar flares in HXR domain. It operates in interplanetary space and has been located near Lagrange point L1 at ~5 light seconds from the Earth since 2004 July. Konus-Wind consists of two identical 13 cm × 7.5 cm Na iodide (TI) detectors, S1 and S2, with Be entrance windows. Detectors are located on opposite sides of the spacecraft, observing the southern and northern ecliptical hemispheres correspondingly (Aptekar et al. 1995).

The Konus-Wind works in two modes—the waiting mode and the triggered mode. In the waiting mode, only the light curves with accumulation time >2.944 s are available in three wide energy bands: G1 (nominal range 13–50 keV), G2 (nominal range 50–200 keV), and G3 (nominal range 200–750 keV). The Konus-Wind energy boundaries changed

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4 In this flare, the thermal response was very weak at the impulsive phase because a small loop with a correspondingly small volume produced the impulsive HXR and microwave emission. However, another much larger loop was also involved in the flaring, which was responsible for a delayed thermal response in this rather unusual event.
Switching to the triggered mode\textsuperscript{5} occurs at a statistically significant background excess on a 1 s or 140 ms timescale in energy band G2. In the triggered mode, the light curves are recorded in the same three energy bands with a high time resolution (varying from 2 to 256 ms as the burst progresses) during 230 s, along with accumulation of 64 multichannel energy spectra. Multichannel spectra are measured in partially overlapping energy ranges: nominal boundaries are 13–750 keV for the first range and 250 keV–15 MeV for the second range. Now the spectral ranges have changed from the original 13 keV–10 MeV to ~25 keV–18 MeV for the S1 detector and ~20 keV–15 MeV for the S2 detector. Each energy range consists of 63 energy channels. The accumulation time for each of the first four spectra is 64 ms, while the accumulation time for the subsequent S2 spectra varies from 256 ms to 8.192 s according to the count rate in G2 energy band. For a stronger HXR flux, the accumulation time is proportionally shorter. For the latest eight spectra, the accumulation time is fixed at 8.192 s. When accumulation of the triggered mode light curves and energy spectra has been completed, both triggered and waiting mode measurements are interrupted by a gap of ~1 hr because of the data readout.

Due to the adopted implementation of the trigger algorithm, in the triggered mode the Konus-Wind registers only reasonably hard flares that show a rather rapid increase in HXR intensity, while only waiting mode data are available for softer and smoother events. Because of the limited duration of the trigger record (~240 s for time history and ~480 s maximum for energy spectra), the recording ends before the actual end of longer flares (Pal’shin et al. 2014). Given the lack of spatial resolution, an algorithm is needed to distinguish solar bursts from other astrophysical sources. There are a number of criteria to conclude whether a Konus-Wind triggered mode event is a solar flare or not. First, as Konus-Wind detectors are pointed transversely to the ecliptic plane, emission from solar flares reaches Konus-Wind at angles ~90° and is seen in both detectors S1 and S2—in one detector in triggered mode, and in the other in the waiting mode (the trigger may only occur in one detector at a time). Second, we check the GOES X-ray event list\textsuperscript{6} for event notification or look for an increase in the GOES SXR flux at that time. The Fermi trigger reports may also be used\textsuperscript{7} for a subset of jointly observed events.

2.1.3. Selection of Early Impulsive Flares

To form an initial list of the event candidates, we employed the following formal criterion for the “solar flare”-like burst registered by Konus-Wind in the triggered mode to be listed as early impulsive flare: we require that no GOES X-ray event has been reported at the time of the Konus-Wind trigger. This means that either the corresponding GOES event began later than the Konus-Wind trigger time or there was no reported GOES event at all. The goal of using that strict criterion is to exclude events with SXR emission due to plasma preheating by any other agent than the nonthermal flare-accelerated electrons.

This automatic search yielded 84 events. Some of these events were then discarded manually because of failures in the Konus-Wind data; some other events were identified as false alarms caused by energetic particles, not HXR emission. Three events are missing from the GOES event list for an unknown reason, though they demonstrate noticeable increase of GOES 1–8 Å flux before the HXR impulsive phase, and thus we do not obey the entry criterion. Two event were discarded due to failures in the GOES data.

Finally, we approved 42 solar flares, whose properties are consistent with those of early impulsive flares proposed by Sui et al. (2007): no increase in SXR flux must be seen earlier than 30 s prior to the increase in the HXR flux. For all 42 events, there is no corresponding reported GOES flare. Thus, our criterion for the early impulsive flare selection is really rather strict. The absence of a solar flare in the GOES event implies that it did not obey the adopted GOES flare selection criterion: a solar flare is listed as a GOES flare if it demonstrates monotonous flux increase in the GOES 1–8 Å channel during at least one minute, as compared to the previous standard of three minutes. Thus, short events and events during unstable background could be missed from this list. In what follows (see Section 3.1), based on cross-correlation analysis between HXR and SXR data, we selected only 27 cold out of these 42 early impulsive flares for a more detailed analysis, listed in Table 1. Konus-Wind time profiles for these events are presented in Figures 1 and 2.

2.1.4. Selection of Reference Flares

Because of the trigger nature of the Konus-Wind instrument, which records only reasonably hard impulsive HXR bursts (see Section 2.1.2 above), we could not make a meaningful direct comparison of our cold flare subset with previously available statistical studies. This forced us to form and use a reference set of other bursts recorded by the Konus-Wind in the triggered mode, with which the CSFs are to be compared. Accordingly, from all 1000+a solar flares recorded by Konus-Wind in the triggered mode, for the reference set we selected flares that (i) have constant Konus-Wind and GOES background and (ii) are fully covered by the Konus-Wind time history record (both in the waiting and in the triggered mode), i.e., which ended before the end of the trigger record (but may begin in the waiting mode record before the trigger mode record begins). This last condition implies discarding long-duration flares. In this way, we selected 405 C, M, and X GOES class flares to form the reference set.

2.2. Microwave Domain: Nonuniform Input

Historically, the microwave data have played a primary role in identification and analysis of the cold flares (White et al. 1992; Bastian et al. 2007; Fleishman et al. 2011, 2016; Masuda et al. 2013); thus, we have to fully utilize all available microwave data. Unfortunately the only quasi-uniform set of radio instruments is the Radio Solar Telescope Network (RSTN, Guidice et al. 1981), which has many disadvantages, including clock errors, calibration errors, large gaps between the working frequencies, and a limited spectral coverage. For this reason, in addition to RSTN, we use several other radio instruments; namely the OWSA (Hurford et al. 1984; Gary & Hurford 1994), the Nobeyama Radio Polarimeters (NoRP; Torii & Tsukiji 1979), the Solar Radio Spectropolarimeters

\textsuperscript{5} Light curves and spectra of solar flares registered by Konus-Wind in the triggered mode can be found at http://www.isdef.ru/LEA/kwun/.

\textsuperscript{6} GOES event list http://ftp.swpc.noaa.gov/pub/indices/events/.

\textsuperscript{7} Fermi trigger information https://gcn.gsfc.nasa.gov/fermi_grbs.html.
Table 1

Konus-Wind Cold Solar Flare List

| N  | strIDa | Date      | ha, mm:ss | Coordinates [decay, first] | Instrument |
|----|--------|-----------|-----------|---------------------------|------------|
| 1  | SOL1998-05-07T19952 | 1998 May 07 | 05:32:37.072 | [554°, 495°] | EIT, 195 Å |
| 2  | SOL1999-06-19T82485 | 1999 Jun 19 | 22:54:49.788 | [−916°, 233°] | NoRH |
| 3  | SOL1999-07-30T82686 | 1999 Jul 30 | 22:58:09.675 | [−490°, 320°] | NoRH |
| 4  | SOL1999-11-09T30381 | 1999 Nov 09 | 08:26:21.703 | ... | ... |
| 5  | SOL1999-11-14T53708 | 1999 Nov 14 | 14:55:08.244 | ... | ... |
| 6  | SOL1999-12-02T72060 | 1999 Dec 02 | 20:01:00.012 | ... | ... |
| 7  | SOL2000-03-10T15704 | 2000 Mar 10 | 04:21:48.688 | [−776°, −211°] | NoRH |
| 8  | SOL2000-03-18T82870 | 2000 Mar 18 | 02:25:10.567 | [717°, −294°] | SSRT |
| 9  | SOL2000-05-18T26517 | 2000 May 18 | 07:21:59.706 | [−33°, −257°] | SSRT |
| 10 | SOL2000-05-18T82777 | 2000 May 18 | 22:59:39.777 | [177°, −319°] | NoRH |
| 11 | SOL2001-10-12T72630 | 2001 Oct 12 | 07:40:31.941 | [−900°, 238°] | SSRT |
| 12 | SOL2001-11-01T55062 | 2001 Nov 01 | 15:17:42.772 | [320°, 125°] | OVASA |
| 13 | SOL2002-05-29T72786 | 2002 May 29 | 07:39:46.864 | [−343°, 122°] | SSRT |
| 14 | SOL2002-08-10T85808 | 2002 Aug 10 | 23:50:09.293 | [−938°, −79°] | NoRH |
| 15 | SOL2002-08-18T83478 | 2002 Aug 18 | 23:11:19.740 | [300°, −300°] | OVASA |
| 16 | SOL2002-08-20T71727 | 2002 Aug 20 | 19:55:28.476 | ... | ... |
| 17 | SOL2003-10-23T30262 | 2003 Oct 23 | 22:17:39.620 | [−938°, −307°] | RHESSI |
| 18 | SOL2005-09-08T30814 | 2005 Sep 08 | 02:15:49.966 | ... | ... |
| 19 | SOL2011-09-19T27816 | 2011 Sep 19 | 07:43:40.791 | [−806°, 345°] | RHESSI |
| 20 | SOL2012-07-08T90826 | 2012 Jul 08 | 02:43:50.647 | [894°, −206°] | NoRH |
| 21 | SOL2013-11-05T13819 | 2013 Nov 05 | 03:50:24.588 | [−771°, −250°] | NoRH |
| 22 | SOL2014-01-02T26907 | 2014 Jan 02 | 05:45:01.390 | [−948°, −83°] | NoRH |
| 23 | SOL2014-01-31T67053 | 2014 Jan 31 | 16:52:37.461 | [−504°, 331°] | RHESSI |
| 24 | SOL2014-02-08T20965 | 2014 Feb 08 | 05:49:29.848 | [856°, −150°] | RHESSI |
| 25 | SOL2014-10-18T10152 | 2014 Oct 18 | 02:49:17.710 | [−909°, −335°] | RHESSI |
| 26 | SOL2014-10-27T11681 | 2014 Oct 27 | 03:14:46.862 | [640°, −290°] | RHESSI |
| 27 | SOL2015-05-07T45695 | 2015 May 07 | 12:41:40.415 | ... | ... |

Notes.

a The Konus-Wind trigger time in seconds without time of light propagation corrections, to match the format used in http://www.ioffe.ru/LEA/kwsun/.

b The Konus-Wind trigger time after corrections for the light propagation to the Earth are applied.

c The instrument used for the event localization.

NoRH observe the intensity and circular polarization at six frequencies (1, 2, 3.75, 9.4, 17, and 35 GHz) and the intensity only at 80 GHz, with time resolutions of 0.1 s in the flare mode and 1 s in the background mode (no 80 GHz data).

SRS and BBMS are spectropolarimeters supporting science with the Siberian Solar Radio Telescope. SRS measures the integrated flux over the whole solar disk, within the 2–24 GHz frequency range, in two circular polarizations at 16 frequencies with a temporal resolution of 1.6 s (Muratov 2011). BBMS is the 4–8 GHz spectropolarimeter, which measures the integrated flux over the whole solar disk in two circular polarizations at 26 frequencies with a temporal resolution of 10 ms (Zhdanov & Zandanov 2011). KMAS measure the integrated solar flux at two frequencies, 6.1 and 9.0 GHz, with a time resolution of 1 s. No polarization measurements are available from KMAS.

2.2.2. Building the Microwave Burst Database

The most comprehensive study of the solar microwave burst spectral properties has been performed using the OVSA database, accumulated over a complete two years of observations during 2001–2002 (Nita et al. 2004), so it would be beneficial to use a similar database here to make a fair comparison of our subset of the data to the statistical distributions of all bursts reported by Nita et al. (2004). Unfortunately, only very few events from our list have...
microwave OVSA data. Nevertheless, we have taken all possible steps to prepare all available data from other radio instruments in a form as similar as possible to the OVSA data; see the Appendix for the details. In particular, we combined data obtained by various instruments, fixed clock errors and amplitude calibration errors, and addressed dissimilar time resolution of the various instruments. Finally, we built a microwave database composed of the 26 events out of the 27 events in the Konus-Wind list; for the remaining event, no microwave data were available. Microwave instruments available for each event are listed in Table 6.

2.3. Cold Early Impulsive Flare Localization

We used available imaging information from various instruments to determine flare positions. Whenever available, we used instruments in the X-ray and microwave ranges, including OVSA, Siberian Solar Radio Telescope (Grechnev et al. 2003), Nobeyama Radio Heliograph (NoRH; Nakajima et al. 1994), and RHESSI (Lin et al. 2002). For one flare, 1998 May 7, we used brightening in the SoHO/EIT (Domingo et al. 1995) 195 Å data, although this identification may not be reliable because it corresponds to thermal emission, which is low for CSFs. Eventually, we determined locations for 21 of 27

Figure 1. CSF time profiles in the HXR range measured by Konus-Wind in the sum G1+G2+G3 channels (∼20–1200 keV, black curve, left axes) and in the G2 channel (∼80–300 keV, blue curve, right axes). For ease of comparison with Figure 13, here we show 15 cases for which the microwave data allowed spectral fitting.
CSFs, while no relevant spatial information was found for the remaining six flares. The heliocentric coordinates of the flares and instruments used for their localization are listed in Table 1. Locations of the flare are also illustrated in Figure 3, which shows that most flares are located on the solar disk, but four flares are near the very limb, and one flare, 2003 October 23, demonstrates a source above the solar limb.

3. Data Analysis

3.1. Relationships between HXR and SXR Emissions and Identification of the Cold Early Impulsive Flares

To compare Konus-Wind and GOES time profiles, corrections for the light propagation time from the Wind spacecraft to the center of the Earth were applied to the Konus-Wind data. Such an approach gives an error within \( \sim 20 \) ms for the light propagation to any ground-based or earth orbiting instrument, which is a satisfactory accuracy for the presented study.

The duration of the flare impulsive phase was determined in the Konus-Wind G2 channel, the boundaries of which changed from \( \sim 50–200 \) keV to \( \sim 80–300 \) keV during its operational history. This channel was selected because it does not contain any contribution from the thermal emission. The Konus-Wind background was approximated by a constant in the time range within an interval selected between \(-1000 \) s and \(-200 \) s before the flare, with fit probability \( \geq 5\% \). The duration of the flare impulsive phase was estimated using the so-called \( t_{90} \), which is the difference between \( t_{95} \), the accumulation time of 95\% of the flare integral counts, and \( t_{5} \), the accumulation time of 5\% of the flare integral counts (see Figure 4). We employed \( t_{90} \) because this value is less sensitive to the choice of signal-to-noise ratio than the total duration, \( t_{100} \) (Kouveliotou et al. 1993). Values of \( t_{90} \) are listed in Table 3.

To quantify the thermal response, which is needed to identify the outliers with relatively low SXR emission compared to the early impulsive flares that show a more standard heating during the impulsive phase, we measured the increase of the GOES flux at the 1–8 Å channel (\( \Delta GOES \)) during or following the

Figure 2. CSF time profiles in the HXR range measured by Konus-Wind in the sum G1+G2+G3 channels (\( \sim 20–1200 \) keV, black curve, left axes) and in the G2 channel (\( \sim 80–300 \) keV, blue curve, right axes). For ease of comparison, here we show 12 cases corresponding to Figure 14.
impulsive HXR emission (see Figure 4). In the case of constant background, the increase of the GOES flux in the 1–8 Å channel was obtained as the difference between the GOES flux at \(f_{G3}\) and that at \(f_3\). In the case of a monotonically varying preflare GOES flux, the background was approximated by a three-order polynomial and subtracted, then the difference between the fluxes at \(f_{G3}\) and \(f_3\) was calculated. In the case of the absence of an observable response in the GOES 1–8 Å channel, upper limits for \(\Delta GOES\) were estimated as 15% of GOES flux in the 1–8 Å channel, which corresponds to the GOES error in this channel (Garcia 1994).

The peak time frame was calculated on a 1024 ms timescale according to counts in the G2 channel, and the HXR peak count rate was taken as the sum of the count rates in the G1 +G2+G3 channels after background subtraction (see Figure 4). For one flare, the peak time frame was defined on a 2.944 s timescale because of a failure in the G2 trigger time history.

Results for \(\Delta GOES\) versus HXR peak count rate regression for the early impulsive flares and the reference set are shown in Figure 5(a) and listed in Table 3. The gray hatched area in the left of the figure indicates a sort of selection effect that the Konus-Wind cannot register flares with such low HXR peak count rates in the triggered mode. We calculated regression coefficients and the confidence interval using the python scipy.stats.linregress function between decimal logarithms of observed values hereafter. The correlation coefficient for the cold flares, \(r = 0.73\), is larger than the coefficient for all events, \(r = 0.56\), and \(p\)-values are negligible in both cases.

The Konus-Wind HXR integral counts during the impulsive flare phase were estimated as the background subtracted sum of the G1+G2+G3 counts during \(t_{60}\), as defined by the G2 channel. The relationship between the HXR integral counts and \(\Delta GOES\) is presented in Figure 5(b) and Table 3. As in Figure 5(a), the black and blue solid lines represent linear regressions for all flares and the cold flares, respectively; dotted lines represent the 68% confidence band for all flares, which were obtained similarly to Figure 5(a). The meanings of the labels are the same as those in Figure 5(a). The largest correlation coefficient, \(r = 0.82\), is for all flares; \(r = 0.71\) is for CSFs, and the \(p\)-values for these two groups are close to zero. Outliers for this relationship were defined in the same manner as for the \(\Delta GOES\) versus HXR peak count rate relationship. For most cases, the “cold” early impulsive outliers in Figure 5(b) are also the outliers in panel (a). The only exception is the event of 2000 May 18, 22:59 UT.

As the Konus-Wind energy boundaries changed with time, it is reasonable to compare the relationships obtained from the instrumental HXR characteristics, such as HXR peak count rate and HXR integral counts, to those obtained from unfolded characteristics, namely HXR peak flux and HXR integral flux. To find HXR fluxes in physical units (for example, erg s\(^{-1}\) cm\(^{-2}\)) especially in the case of rather broad energy

### Table 2

| Instrument | Frequencies, GHz | Obs. Time, UT | Time Res., High/Low, s |
|------------|-----------------|--------------|----------------------|
| OVSA       | 1.2–18; 40 Channels | ~16:00–24:00 | 4/8*                |
| NoRP       | 1, 2, 3.75, 9.4, 17, 35, 80 | ~23:00–07:00 | 0.1/1               |
| SRS        | 2–24; 16 Channels | ~00:00–10:00 | 1.6/1.6             |
| BBMS       | 4–8; 26 Channels | ~00:00–10:00 | 0.01/0.01           |
| RSTN       | 0.6, 1.4, 2.7, 4.995, 8.8, 15.4 | 24 hr | 1/1                  |
| KMAS       | 6.1, 9.0 | ~08:00–20:00 | 1/1                  |

Notes.

* During dedicated campaigns, the OVSA time resolution was higher at the expense of reducing the number of frequency channels.

* Data at 80 GHz are unavailable in the background mode.
channels, a spectral model should be selected, then spectral fitting performed, and HXR fluxes calculated based on the obtained fitting parameters. To keep the fitting results uniform, three-channel fitting rather than a multichannel one was employed, because a fraction of the flare impulsive phase might have occurred before the Konus-Wind trigger, i.e., in the waiting mode data, where no multichannel spectra are available.

Results of three-channel and multichannel fitting with a power-law model were compared for peak spectra of early impulsive flares and some reference flares (see Section 3.2). Results with fit probabilities <1% were neglected. Comparisons between the results of the three-channel and multichannel fitting are presented in Figure 6; namely, comparison between the power-law indices (left) and between HXR fluxes in the 20–1000 keV range (right). Errors on both plots refer to the 68% confidence level. A dashed line indicates the expected y = x equality of fit results, while the solid line refers to the linear regression between multichannel and three-channel fit results. As can be seen from Figure 6, the results of multichannel and three-channel fitting are in good agreement, with the exception of one event. Thus, we do not apply any extra corrections to three-channel fitting results.

Relationships between ∆GOES and the HXR peak flux or the integral flux are presented in Figure 7 and Table 3. Meanings of labels and lines are the same as in Figure 5(a). From comparison between Figures 5(a) and 7(a), it is clear that the same flares form the set of “cold flare” outliers in both plots. Thus, the Konus-Wind energy boundary variations do not significantly affect our selection of the CSFs. The values of the correlation coefficients for regressions shown in Figures 5(a) and 7(a) are also close to each other. Specifically, for all flares: r = 0.60 for the HXR peak flux, versus r = 0.56 for the HXR peak count rate, and the p-value is also negligible. For the CSFs: r = 0.68 versus r = 0.73, and the p-value is 1.9e-3.

The situation is similar when comparing Figures 5(b) and 7(b): the correlation coefficient for all flares remains r = 0.83 and the CSF’s correlation coefficient also did not change significantly. The probability that correlations are elusive is close to zero for all two groups. However, some CSFs move closer to the main regression line, compared to the relation between ∆GOES and HXR integral counts. This can be caused by underestimation of integral flux while averaging flux over flare duration in the fitting procedure.

Thus, in the case of flares for which unfolded HXR fluxes were obtained, we conclude that the Konus-Wind energy boundary’s evolution does not significantly affect the proportions between HXR and XRF characteristics. Therefore, to select the CSF group, we formulate the criterion based on instrumental HXR estimations. At least one of the following statements must hold for a flare to be classified as “cold”: either (1) the ratio between ∆GOES and HXR peak count rate is greater than that for the majority (84%) of flares.
is more universal than using the unfolded data because these observational measures can be obtained for all events. This approach yielded 27 CSFs, listed in Table 1, upon which we focus in this paper.

The relationship between increases in GOES channel 1–8 Å and $t_{00}$ is plotted in Figure 8. As expected, a high correlation between $\Delta Goes$ and $t_{00}$ is observed for all flares $r = 0.74$. CSFs are grouped in the area of low $\Delta Goes$ and low $t_{00}$, excepting two events, and thus they do not demonstrate significant correlation, $r = 0.31$.

### 3.2. Spectral Properties of the HXR Bursts

The HXR spectral analysis was performed using the Konus-Wind multichannel data for 25 of 27 CSFs, because spectral data were damaged for two events. In addition, multichannel fits were obtained for 71 events from the non-cold-flare reference set that occurred during years 2010–2016.

The HXR spectrum fitting was performed on the peak spectra; the peaks were defined according to the count rates in G2 channel (see Section 3.1). The photon energy range between 20 and 1000 keV was considered for analysis of both cold and reference flares; 20 keV corresponds to the low-energy boundary of Konus-Wind, while no photons above 1000 keV were considered, even when present, because the nuclear de-excitation line emission may contribute to the spectrum at those high energies, in addition to the nonthermal electron bremsstrahlung. The spectral channels were grouped to have a minimum of 10 counts per channel, to ensure the validity of the $\chi^2$ statistic. The spectral analysis was performed using XSPEC 12.9.0 (Arnaud 1996).

Initially, we attempted to fit the spectra using the single power-law (PL) model, but the peak spectra were inconsistent with this simple model for many flares, because of a spectral break. Thus, for spectra inconsistent with PL, we used the phenomenological broken power-law model, 2PL:

$$I(E) = \begin{cases} A \left( \frac{E}{100 \text{ keV}} \right)^{-\gamma_1} & E \leq E_{\text{break,ph}} \\ AE_{\text{break,ph}}^{-\gamma_1} \left( \frac{E}{100 \text{ keV}} \right)^{-\gamma_2} & E_{\text{break,ph}} < E \end{cases}$$

where $A$ is the normalization at 100 keV in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$. Photon flux was calculated in the 20–1000 keV range using the $cflux$ convolution model in XSPEC, assuming spectrum integration within 20 and 1000 keV.

In cases when both the PL and 2PL models were consistent with the data, the preferred model was chosen according to an F-test (Bevington 1969), i.e., the decrease in $\chi^2$ versus the decrease in degrees of freedom: the criterion for accepting the 2PL model (a model with two more free parameters than the PL model) was a decrease of $\chi^2 > 13.5$ when using the 2PL model compared to using the PL model, which corresponds to a chance probability of such a decrease being $p \leq 0.1\%$. One CSF and three flares from the reference group were excluded.
because they showed fit probabilities of $p \leq 0.1\%$ for both the PL and 2PL models.

Examples of CSF spectra fitted by the PL and 2PL models are presented in Figure 9, and the fit results for all CSFs with successful fits are listed in Table 4. The PL model successfully fits 16 of 25 CSFs and 25 of 71 reference flares. Distributions of obtained fitting parameters $\gamma$ and photon flux are presented in Figures 10(a)–(b). On each plot, the median values and 50% ranges are marked for cold flares (blue) and reference flares (gray), the value “$p$” denotes probability obtained by the Kolmogorov–Smirnov test hereafter in the assumption that distributions for cold flares and reference set are similar. The Kolmogorov–Smirnov test was performed using python scipy.stats.ks_2samp function. The median values of the photon spectral indices $\gamma$ for the CSFs and reference flares are equal to 3.3 and 3.5, respectively; though the difference between the median values is not high, but 50% range is narrower for CSFs and $\gamma$ distribution is shifted toward lower values, thus CSFs are significantly harder ($p$-value that two distributions are equal is $\sim 1\%$). The median value of the photon flux for CSFs is almost two times lower than for the reference set, $3.1 \times 10^{-6}$ versus $5.8 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$.
There are no events with peak fluxes greater than $10.0 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ among CSFs, while the peak fluxes for reference flares extend up to $40.0 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$, $p$-value is also low, 0.75%.

Fitting using the 2PL model was successful for 8 CSFs and 43 flares from the reference set. This means that the 2PL model was required much more rarely for CSFs than for the reference flares. This might happen, at least for a fraction of flares, because the CSFs are lower intensity flares, for which low signal-to-noise ratio in higher energy range did not allow to detect the energy break even if existed. Distributions of the fitting parameters $\gamma_1$, $E_{\text{break, ph}}$, $\gamma_2$ and photon flux for 2PL are plotted in Figure 10(c)–(f). Distributions of the low-energy photon power-law index $\gamma_1$ show that, for the 2PL model, the CSFs are also harder: their median value for CSFs is 2.6, versus 3.2 for the reference group. The overall shape of the histogram is shifted toward lower values of $\gamma_1$, as compared to the reference flares, and the $p$-value is $p = 3.7\%$. The median values of photon break energies $E_{\text{break, ph}}$ for both groups are close to 70 keV. There are no events with breaks below 60 or 50 keV for CSFs or the reference group, respectively. The probability of $E_{\text{break, ph}}$ distribution coincidence for CSFs and the reference set is 83%. The median value of the high-energy photon power-law index, $\gamma_2$, for CSFs is also slightly harder than for the reference set, 4.4 versus 4.5, but this difference is insignificant. There is a very high probability that $\gamma_2$ distributions for CSFs and reference set distributions are equal: 87%. Photon flux distributions are presented in Figure 10(f); these values may differ from those listed in Table 3 because they were obtained on a different timescale. The median value for the reference set is $8.1 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$, which is higher than that for CSFs, $5.5 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$, but also it could be insignificant: $p = 23\%$. For both CSFs and reference flares, $\gamma_2$ is always larger (by absolute value) than $\gamma_1$; thus, no break-ups were observed in the entire analyzed data set. A likely reason for this finding, which is in apparent contrast with many reports of HXR spectra with break-ups, is the trigger nature of Konus-Wind, which only records flares with reasonably hard spectra, while the break-ups are typically observed when the low-energy part of the HXR spectrum is steep.

To recover the spectrum of accelerated electrons from the photon spectrum, we used a collisional thick-target model...
(Brown 1971) with a power-law spectrum of nonthermal electrons (brmThickPL):

$$F(E) = \begin{cases} 
0 & E < E_{\text{cut,low}} \\
\times A E^{-\delta} & E_{\text{cut,low}} \leq E \leq E_{\text{cut,high}}, \\
0 & E_{\text{cut,high}} < E 
\end{cases}$$

where $A$ is the electron flux in electron keV$^{-1}$ s$^{-1}$. This model gives a simple relationship between the electron and photon power-law indices, $\gamma = \delta - 1$ (Brown 1971; Somov & Syrovatskii 1976).

For a fraction of both CSFs and reference flares, the spectral break is observed and the brmThickPL model is not applicable in these cases. In principle, some spectral flattening may be caused by an instrumental pile-up effect. Thus, we performed a Monte Carlo simulation, which revealed that, for the Konus-Wind spectra, this effect becomes significant for count rates $>5 \times 10^5$ counts s$^{-1}$ (dead-time corrected), but among both CSFs and the reference flares used for multichannel fitting, there are no such intense events. A spectral flattening at low energies may also be induced by several physical effects: photospheric albedo (Kontar et al. 2006), non-uniform target ionization (Holman et al. 2011), and energy losses associated with a return current (Holman et al. 2011). These effects give spectral breaks at lower energies of the HXR nonthermal spectra, while $E_{\text{break,ph}} \geq 60$ keV for all CSFs. Thus, we conclude that spectral flattening at low energies is caused by a non-power-law spectrum of accelerated electrons, and in addition to the brmThickPL model, we use collisional thick-target model with broken power-law spectrum of nonthermal electrons (brmThick2PL):

$$F(E) = \begin{cases} 
0 & E < E_{\text{cut,low}} \\
\times E^{-\delta_1} & E_{\text{cut,low}} \leq E \leq E_{\text{cut,high}}, \\
\times E^{-\delta_2} & E_{\text{cut,high}} < E < E_{\text{break,el}} \\
0 & E_{\text{break,el}} \leq E \leq E_{\text{cut,high}} \\
0 & E > E_{\text{cut,high}} 
\end{cases}$$

To minimize potential contributions from photospheric albedo, non-uniform target ionization, and return current to the spectrum formation of reference flares, we excluded nine flares from the reference group where $E_{\text{break,ph}} \leq 60$ keV. To fairly compare the electron fluxes in all cases, we decided to fix $E_{\text{cut,low}} = 10$ keV, which is approximately the lower bound for nonthermal electrons found in CSF case studies (Fleishman et al. 2011, 2016; G.G. Motorina et al. 2018, in preparation).

For some events, fitting by the brmThick2PL model gave unstable solutions and high correlations between parameters. This means that the data agree with a broad range of fitting parameters and we should choose the most physically valid ones among them. Thus, in those cases, we froze the high-energy spectral index according to the thick-target model relationship between the photon and electron spectral indices $\delta_2 = \gamma_2 + 1$ (Brown 1971; Somov & Syrovatskii 1976). In some cases, spectral steepening at energies $>200$ keV was very sharp, and the number of counts in this region was not enough to determine $\delta_2$, so we determined just the lower limits of $\delta_2$.

For all events fitted with the photon PL model, the brmThickPL model was used. Most events with an energy break in the photon spectrum also have a break in the electron spectrum, except 1 CSF, 2002 August 20, which was fitted by the 2PL model in the photon domain, but with a single brmThickPL model in the electron domain.

Distributions of the spectral parameter $\delta$ and the electron flux for brmThickPL model are presented in Table 5 and Figures 11(a)–(b). Similar to the photon spectral index, the electron spectral index is harder for CSFs, the median value is 4.1, while median value for reference flares equals to 4.3, and this difference is rather significant: the probability that $\gamma$ distributions for CSFs and the reference group match is only 0.7%. The electron flux for CSFs is weaker than for the reference set: the median values are $8.0 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$ and $18.0 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$, respectively. The electron flux ranges from $\sim 0.4$ to $\sim 100 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$ for CSFs, and from $\sim 1$ to $\sim 300 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$ for the reference group.
Distributions of the spectral parameters $\delta_1$, $E_{\text{break,el}}$, $\delta_2$, and the electron flux for the brmThick2PL model are presented in Table 5 and Figure 11(c)–(f). The median values of the electron low-energy power-law index $\delta_1$ for CSFs and the reference group are 2.5 and 3.2, respectively, which is very close to the median values for $\gamma_1$ in Figure 10. A probable reason why $\delta_1$ and $\gamma_1$ strongly deviate from the expected relationship $\gamma_1 = \delta_1 - 1$ for both groups may be the large contributions from higher-energy electrons to the photon spectrum at lower energies. Distributions of the electron spectrum break energies $E_{\text{break,el}}$ are presented in Figure 11(d). The median values for the two groups are close to each other: 188 keV for CSFs and 158 keV for the reference group. The probability of distribution equality is large: $p = 54\%$. Distributions of the electron high-energy power-law index $\delta_2$ demonstrate that the reference flares might be slightly harder than CSFs, but this difference is insignificant: $p = 44\%$. The median value of CSF electron flux is much smaller than that for the reference group: $1.3 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$ versus $7.2 \times 10^{35}$ el keV$^{-1}$ s$^{-1}$. The probability that those distributions for CSFs and the reference group are equal is low: $p = 0.3\%$.

### 3.3. Cold Solar Flare Timescales in HXR

The duration of the impulsive flare phase in HXR was estimated using $t_{90}$ in the G2 channel (see Section 3.1 and Figure 4). Values of $t_{90}$ for CSFs are listed in Table 3, and distributions of $t_{90}$ for the reference group and CSFs are presented in Figure 12. It is apparent that CSFs are significantly shorter than flares from the reference group: the median duration of CSFs is 8 s, while that for the reference set is 48 s. Most CSFs have $t_{90}$ between 5 and 20 s, five events have $t_{90}$ between $\sim 2$ and $\sim 5$ s, while there are three relatively long outliers: the longest event is 2000 May 18, 22:59 UT, $(t_{90} \approx 86 \text{ s})$, and the other two are flare 2000 March 18 ($t_{90} \approx 23 \text{ s}$) and flare 2014 October 18 ($t_{90} \approx 63 \text{ s}$).

#### 3.4. Spectral Properties of the Microwave Bursts

Given that the data files (IDL sav files) were created in a format identical to the OVSA data files, we took advantage of having the OVSA software from the SSW library. Specifically, the composite OVSA-like sav files have been read by OVSA_Explorer widget, which has all the functionality needed for handling that data, including the background subtraction and sequential spectral fitting.

Here, we are only interested in the microwave bursts produced by gyrosynchrotron (GS) emission of energetic electrons, but ignore any component that could be attributed to a coherent plasma emission. The GS spectrum $S(f)$ is characterized by a maximum flux density $S_{\text{peak}}$ at a frequency $f_{\text{peak}}$ and two spectral slopes $\alpha_{\text{fl}}$ and $\alpha_{\text{br}}$ in the high frequency range (Stahli et al. 1989). We performed spectral fitting with the OVSA_Explorer's built-in generic spectral function:

$$S = e^{\alpha \text{ff}} / [1 - e^{\alpha \text{fl}}].$$

(4)
where $f$ is the frequency in GHz, while $A$, $B$, $\alpha$, and $\beta$ are the free fitting parameters, which yield the physical parameters of interest. For example, the low-frequency spectral index $\alpha_{\text{lf}} \equiv \alpha$, while the high-frequency spectral index is $\alpha_{\text{hf}} = \alpha - \beta$.

The peak frequency $f_{\text{peak}}$ and the flux density at the peak frequency $S_{\text{peak}}$ are calculated via parameters of the function $S$ (see Nita et al. 2004 for more details).

Because microwave data for different events have dissimilar time cadences, before performing spectral parameter analysis, we first brought all the data to the same cadence, selected to be 1 s. To this end, the multifrequency time profiles of three OVSA events, which were available with a cadences of 5 or 4 s, were interpolated to 1 s resolution using the IDL interpolate routine; in the remaining cases, the available 1 s data were used. This means that, in the case of NoRP data, we used the 1 s background data rather than the flare mode data. However, when the high-frequency light curves were deemed critical for the fitting, we also added the time-averaged NoRP 80 GHz light curve, available only in the flare mode, to the background 1 s record.

Having the combinations of the microwave data recorded by different instruments raises several problems with the data handling and analysis. The three main problems are: (i) different flux calibrations at different instruments, (ii) different background levels, and (iii) possible clock errors and consequent timescale mismatches. We dealt with all these issues individually for each event. As was mentioned above, we used the NoRP clock as the reference time and adjusted clocks of other instruments using the lag-correlation between the light curves (cf. Fleishman et al. 2016). Total flux corrections were introduced, based on comparison of the
preflare signal levels, but this correction was not always successful; see the prominent horizontal stripes in a few panels of Figure 13, most notably the upper left panel.

The frequency- and time-dependent background level was subtracted manually, using the corresponding built-in functionality of the OVSA _Explorer_, which allows the definition of a flat or polynomial background for each frequency channel. In most cases, it was sufficient to subtract a flat off-burst background level, although in some cases the background was time-dependent. In such cases, the background was approximated by an appropriate polynomial. In one case (2003 October 23), observed with both NoRP and OVSA, the short radio burst of interest occurred on top of a much more gradual broadband burst, whose dynamic spectrum is shown in the upper left panel of Figure 14. The (sub)burst of interest is seen at this dynamic spectrum as a short red dash at around 22:17:40 UT at the high-frequency end of the spectrum. One can notice a few more similar short bright subbursts later in the event; they are not artifacts, as the same subbursts are detected by NoRP with higher time resolution (see the corresponding panel in Figure 13). Thus, for our quantitative analysis of this event, we use the 1 s cadence NoRP+RSTN data from which the gradual burst emission was subtracted.\(^a\) As a result, a data set with the background subtracted has been created and separately saved; the microwave dynamic spectra for all these events are given in Figures 13 and 14.

This set of the background-subtracted dynamic spectra was used to perform a sequential spectral fit for each 1 s time frame. The spectral fitting frequency range was chosen individually for each event, in order to contain the main microwave component; we excluded low-frequency channels if a secondary, presumably coherent, component was present there, or high-frequency channels in case they were too noisy to aid the fitting. Although every attempt has been made to create accurate data files, a successful spectral fit was possible for only slightly more than half of all events (15 of 26); the corresponding dynamic spectra are gathered in Figure 13. In the remaining 11 cases, the fit failed entirely\(^9\); see Figure 14. Visual inspection of Figure 14 suggests that the fit might fail for the following reasons: (i) too small a number of channels with meaningful signal and/or (ii) too high a spectral peak frequency (15.4–35 GHz), such that a substantial fraction of the high-frequency microwave spectrum is outside the spectral coverage of the available instruments, which is the case for 5 of 11 events with no fit. The fit results for every successful time frame were saved in specifically designed OVSA med files.

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**Table 5**

| N | Date       | \(t_0\), hh:mm:ss | \(\delta_1\) | \(E_{peak, el}\) keV | \(\delta_2\) | Electron Flux \(10^{35} \text{ cm}^{-2} \text{s}^{-1}\) | \(\chi^2/\text{dof}\) | Prob. |
|---|------------|------------------|--------------|---------------------|-------------|---------------------------------|----------------|-------|
| 1 | 1998 May 07 | 05:32:37.072     | 2.09±0.03    | 171±2.28            | 5.3          | 0.8±0.2                         | 52.5/58        | 6.8e-01 |
| 2 | 1999 Jun 19 | 22:54:49.788     | 2.7±0.04     | 242±2.28            | 6.0          | 0.41±0.16                       | 48.0/58        | 8.1e-01 |
| 3 | 1999 Jul 30 | 22:58:09.675     | 4.09±0.15    | ...                 | ...          | 6.5±0.1                         | 11.8/26        | 9.9e-01 |
| 4 | 1999 Nov 09 | 08:26:21.703     | 2.8±0.02     | 213±3.26            | 6.3±0.09     | 2.3±0.1                         | 39.3/41        | 5.4e-01 |
| 5 | 1999 Nov 14 | 14:55:08.244     | 3.45±0.24    | ...                 | ...          | 0.39±0.09                       | 24.4/26        | 5.5e-01 |
| 6 | 1999 Dec 02 | 20:01:00.012     | 4.29±0.17    | ...                 | ...          | 9.8±0.2                         | 23.4/25        | 5.5e-01 |
| 7 | 2000 Mar 10 | 04:21:48.688     | 4.12±0.14    | ...                 | ...          | 8.0±0.1                         | 27.8/26        | 3.7e-01 |
| 8 | 2000 Mar 18 | 02:25:10.567     | 3.2±0.03     | 124±1.12            | 6.2          | 2.01±0.3                        | 43.4/58        | 9.2e-01 |
| 9 | 2000 May 18 | 02:21:59.706     | 3.0±0.1      | 145±1.17            | 7.1          | 1.3±0.1                         | 67.0/59        | 2.0e-01 |
| 10 | 2000 May 18 | 22:59:39.777     | 4.59±0.12    | ...                 | ...          | 35±2.1                          | 29.7/25        | 2.3e-01 |
| 11 | 2001 Oct 12 | 07:40:31.941     | 3.96±0.10    | ...                 | ...          | ...                             | 8.0±0.2         | 35.2/27 | 1.3e-01 |
| 12 | 2001 Nov 01 | 15:17:42.772     | ...          | ...                 | ...          | ...                             | ...             | ...    |
| 13 | 2002 May 29 | 07:39:46.864     | 4.12±0.09    | ...                 | ...          | 15.3±3.4                        | 29.9/21        | 2.3e-01 |
| 14 | 2002 Aug 10 | 23:50:09.293     | ...          | ...                 | ...          | ...                             | ...             | ...    |
| 15 | 2002 Aug 18 | 23:11:19.740     | 4.02±0.18    | ...                 | ...          | 5.2±0.2                         | 31.7/26        | 2.0e-01 |
| 16 | 2002 Aug 20 | 19:55:28.476     | 3.77±0.08    | ...                 | ...          | 8.1±1.2                         | 45.0/33        | 7.9e-02 |
| 17 | 2003 Oct 23 | 22:17:39.620     | 2.5±0.4      | 140±2.22            | 6.8±0.7      | 2.1±1.0                         | 46.0/44        | 3.9e-01 |
| 18 | 2005 Sep 08 | 02:15:49.996     | 2.0±0.3      | 390±5.23            | 5.8          | 0.31±0.23                       | 71.0/54        | 5.9e-02 |
| 19 | 2011 Sep 19 | 07:43:40.791     | 4.03±0.14    | ...                 | ...          | 6.6±0.24                        | 18.1/23        | 7.5e-01 |
| 20 | 2012 Jul 08 | 02:43:50.647     | 4.15±0.22    | ...                 | ...          | 10±0.5                          | 47.0/25        | 5.0e-03 |
| 21 | 2013 Nov 05 | 03:50:24.588     | 3.50±0.12    | ...                 | ...          | 1.5±0.6                         | 26.5/20        | 3.3e-01 |
| 22 | 2014 Jan 02 | 05:45:01.390     | 4.03±0.15    | ...                 | ...          | 4.1±1.2                         | 32.3/22        | 7.2e-02 |
| 23 | 2014 Jan 31 | 16:52:37.461     | 4.98±0.11    | ...                 | ...          | 9.2±0.5                         | 43.8/21        | 3.0e-03 |
| 24 | 2014 Feb 08 | 05:49:29.848     | 4.16±0.12    | ...                 | ...          | 9.4±2.2                         | 36.4/24        | 5.0e-02 |
| 25 | 2014 Oct 18 | 02:49:17.710     | ...          | ...                 | ...          | ...                             | ...             | ...    |
| 26 | 2014 Oct 27 | 03:14:45.862     | 4.15±0.22    | ...                 | ...          | 5.6±2.6                         | 16.9/22        | 7.7e-01 |
| 27 | 2015 May 07 | 12:41:42.415     | 3.61±0.13    | ...                 | ...          | 1.8±0.8                         | 29.8/27        | 3.2e-01 |

Notes.

\(a\) The Konus-Wind trigger time after corrections for the light propagation to the Earth are applied.

\(b\) Lower limits.

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8 This burst shares some apparent properties with the 2002 March 10 cold flare with delayed heating (Fleishman et al. 2016), but studying the delayed component is beyond the scope of this statistical study.

9 The fit is possible for the upper left case, but this is the case treated as a background for a more impulsive subburst, as explained above.
which are in fact a special form of the IDL sav files (see Nita et al. 2004, for more detail).\(^{10}\)

It should be noted that, even though the data were processed to create as uniform database as possible, there are some unavoidable biases related to the individual instrument limitations and some anomalous features of the bursts. We will return to these biases later, when discussing the implications and significance of the results of our statistical analysis.

As a reference group in the microwave domain, we used the database from Nita et al. (2004), kindly provided by Dr. Gelu M. Nita. The microwave emission in our sample of events is undoubtedly the incoherent gyrosynchotron emission, even though the spectral peak frequencies vary in a wide range between \(\sim 1\) and \(35\) GHz. The reference group of events, reported by Nita et al. (2004), contains both gyrosynchotron and coherent bursts. Nita et al. (2004) found an empirical boundary at \(2.6\) GHz, which demarcates decimetric (D-type; often coherent) and centimetric (C-type; mainly gyrosynchotron) bursts. In addition, a group of bursts with multiple spectral peaks in both centimeter and decimeter ranges was separated and called the CD-type. For a fair comparison between our event sample and the reference set, we only included the C-type bursts and the centimeter component of the CD-type bursts in the statistical distribution of the reference

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\(^{10}\) The created database of the composite microwave spectra is available at [http://www.ioffe.ru/LEA/SF_AR/Radio.html](http://www.ioffe.ru/LEA/SF_AR/Radio.html).
group. This resulted in minor deviations in our numbers, compared to those presented by Nita et al. (2004), but those deviations are not statistically significant.

As microwave spectral parameters may vary significantly during the microwave burst duration (Melnikov et al. 2008; Fleishman et al. 2016), for the statistical study we used parameters obtained on each time frame, with a successful fit during each microwave burst peak. Peak durations were estimated as time intervals during which the flux density at the local peak frequency is above 80% of the corresponding peak flux (see Nita et al. 2004, for more detail).

Burst-averaged microwave spectral parameters for cold solar flares are presented in Table 6, while a comparison of the spectral parameters of CSFs to the reference set for each time frame is illustrated in Figure 15. Even though we used essentially the same set of data, the displayed parameter distributions for the reference group differ from those described by Nita et al. (2004) because we display a slightly different set of entries—only those that are required for our study.

The peak frequency distributions for the CSFs and the reference set are presented in Figure 15, top left. Histogram bins are the same as in Nita et al. (2004), for more straightforward comparison of the results. For the peak frequency distribution of CSFs, a small maximum near 1.5 GHz is observed, followed by a broad minimum. Next, after 2.6 GHz, the distribution function begins to grow and has two more maxima, one near ~6–9 GHz, which is close to the distribution maximum for the reference group, and the second maximum between 11 and 18 GHz. Given that the histograms include the outcome of each time frame with a successful spectral fit, inputs from longer events have proportionally larger weights than those from shorter events. We checked and found that the two prominent peaks correspond to contributions from two long events: 2014 October 18 (the spectral peak frequency varies within 7–9 GHz) and 2000 May 18, 22:59 UT (the spectral peak frequency varies within 11–18 GHz); we will return to this bias later. The median spectral peak frequency for CSFs is 11.2 GHz, which is significantly larger than the median value for the reference group, 6.2 GHz. In fact, the true mismatch between the spectral peak frequencies is even stronger. Indeed, we have already learned from Figure 14 that there are many (five, which is ~20%) of the total number of CSFs events whose spectral peak frequencies are outside the available spectral range, i.e., at least above 15.4 GHz; such values, if properly added to the distribution, would further increase the median value of the spectral peak frequency of CSFs. However, those events do not contribute to the histograms because no fit was possible for them. Although we used NoRP data with a wider frequency range, extending up to 35 GHz in the background mode, the region 11–18 GHz lies within the OVSA coverage used by Nita et al. (2004). Thus, we can conclude that the higher spectral peak frequencies in the CSF set are not due to a selection effect, but have a physical origin. However, it should be noted that, along with events having unusually high spectral peak frequencies, there are a few events with rather low peak frequencies, f_{peak} ~ 2–3 GHz, similar to the cold, tenuous flare described by Fleishman et al. (2011).

Distributions of the peak flux density are plotted in Figure 15, top right. These distributions have bell shapes with maxima between 20 and 50 sfu. The median values for the CSFs and the reference flares are close to each other, being equal to 33 sfu and 45 sfu, respectively. A minimum peak flux density for the time intervals where the spectral fitting for CSFs was successful is ~4 sfu, while the maximum peak flux density is ~600 sfu; the 50% probability range is from 17 sfu to 71 sfu. The reference group 50% probability range is between 17 sfu and 256 sfu; no extremely intense burst with a peak flux density >1000 sfu was found among the CSFs.

Distributions of high- and low- frequency spectral indices for both groups are presented in Figure 15, bottom. For the high-frequency spectral index (negative region), the CSF median value is −1.7, and the 50% probability range is between −3.8 and −1.1. The median value for the reference group is −2.1; thus, the CSFs are slightly harder, while the 50% range for the reference flares is narrower and falls between −3.0 and −1.4. The low-frequency spectral index (positive region) median value for the CSFs is 2.3, which is significantly larger than that for the reference group, characterized by a median value of 1.3. However, as in the case of high-frequency index distribution, the low-frequency slope distribution for CSFs has a wider 50% range, 1.5–3.5, than the reference set distribution, 0.8–2.1. Such wide ranges of the spectral indices for CSFs come from long distribution “tails” in the regions where the spectral indices are large in absolute value. Some contribution to these tails can come from fitting artifacts, where the low- or high-frequency slope is only constrained by one spectral channel in cases when the spectral peak frequency is either very large or small. In such cases, the corresponding spectral index is determined with a large error. In what follows, we do not draw any physical conclusion based on the presence of these tails. If we neglect the second peak (tail), i.e., values $< -4.5$, of the high-frequency spectral index histogram, the median value for reference flares does not change significantly and becomes −2.0, while the median for the CSFs moves to −1.4 and coincides with the strongly pronounced maximum of CSF high-frequency slope distribution.

The use of the entire flare duration in the statistics described above is justified by the fact that there are cases with an...
extremely prominent spectral evolution, such as in a cold flare described by Fleishman et al. (2016) where the spectral peak frequency varied within 1.5 orders of magnitude. In such cases, characterization of the event with only the peak value or a few “representative” time frames could be misleading. On the other hand, a “cold” flare reported by Fleishman et al. (2011) did not show any spectral evolution, so a single time frame would be sufficient to fully describe its spectral shape. To balance such extremes in our statistical study, we complement the described treatment by an alternative one. Specifically, now we characterize each distinct temporal peak by exactly five time frames on the flare duration, which gives equal weight to every peak. These five time frames are selected at the beginning and end of the peak, at the peak maximum, and in the middles of the raising and declining phases. The microwave spectral parameter distributions for the input specified in this way are presented in Figure 16.

Compared to Figure 15, the most significant change is observed in the peak frequency distribution of CSFs. In Figure 16, top left, the mid-frequency peak at ∼7 GHz has almost vanished, while the high-frequency one has raised such that the median value for CSFs is now 12.4 GHz, which is significantly larger than the median value for the reference group, 6.6 GHz.

Distributions of the peak flux density (Figure 16, top right) have changed only slightly. The median values for CSFs and the reference flares are close to each other: 39 SFU and 27 SFU, respectively. Distributions of the high- and low-frequency spectral indices for both groups are presented in Figure 16, bottom. For the high-frequency spectral index (negative region), the CSF median value is −2.1, and the 50% probability range lies between −4.1 and −1.1. The median value for the reference group is −2.3; the 50% range for the reference flares is narrower and falls between −3.3 and −1.6. Though the medians for the CSFs and reference group became closer to each other, the maximum between −2.0 and 0.0 for CSFs distribution still remains. Thus, the conclusion that there are significantly harder events among the CSFs is confirmed.

The median value of the low-frequency spectral index (positive region) of CSFs is 2.0, which is larger than for the reference group (characterized by a median value of 1.6) and coincides with the maximum of the CSFs’ distribution. Like the

Figure 13. Microwave dynamic spectra for 15 flares with successful spectral fits. Vertical dashed-dotted line corresponds to the flare beginning in HXR range t₅. Vertical dotted line corresponds to the flare ending in HXR range t₉₅ (see Section 3.1).
high-frequency spectral index distribution, the low-frequency one has a wider 50% range, 1.6–3.0, for the CSFs than for the reference set distribution, 0.9–2.6. We attempted a few other selections of the time frames for the statistical analysis, but did not find any trend differing from those reported above.

3.5. Cold Solar Flare Timescales in Microwaves

To characterize the timescales of the microwave bursts, we used the same approach as Nita et al. (2004), who calculated the duration at the absolute peak frequency (see Nita et al. 2004 for more detail). For events with multiple temporal peaks, the main peak was taken. This approach allows using the built-in OVSA_Explorer functionality for the peak duration determination, and then a direct comparison of our results to those obtained by Nita et al. (2004). An unavoidable downside of this approach is that it can only be applied to 15 of 26 flares for which the spectral fits were obtained. The results are listed in Table 6 (column Δt) and presented in Figure 17. Microwave peak durations for CSFs extend from 7 to 195 s, but most events last less than 30 s. The 2000 March 18, 2000 May 18, 22:59 UT, and 2014 October 18 flares, the same as in the HXR range, have a relatively longer duration. The estimated median value of the burst duration is 16 s. This is much shorter than that for the reference flares, for which the median value is 104 s and the durations extend up to thousands of seconds.

3.6. Relationships between X-Ray and Microwave Flare Parameters

HXRs are often associated with the injected population of flare-accelerated nonthermal electrons, and microwaves with the trapped component (Kosugi et al. 1988). Thus, the study of relative timing and relationships between HXR and microwave spectral characteristics can shed light on properties of both these important ingredients of solar flares, and therefore on conditions of nonthermal electron propagation in flaring loops.

Figure 14. Microwave dynamic spectra of 11 flares for which spectral fitting did not succeed, and the long duration spectrum for 23 October 3, which was not used in the microwave spectral parameter distributions. Vertical dashed–dotted line corresponds to the flare beginning in HXR range t_b. Vertical dotted line corresponds to the flare ending in HXR range t_e (see Section 3.1).
3.6.1. Time Delays between Microwave and HXR Emission

Delays of microwave emission relative to HXR emission often indicate trapping of nonthermal electrons in flaring loops. To calculate these delays, we used the Konus-Wind HXR time profiles in the G2 channel, because this channel is not contaminated by thermal emission. In the microwave range, we took time profiles at the highest frequency, $f_{\text{high}}$, where microwave burst was observed, which corresponds to optically thin gyrosynchotron emission. In addition to $f_{\text{high}}$, we examined microwave emission delays relative to HXR emission at the lowest frequency with observable gyrosynchotron emission, $f_{\text{low}}$. The frequencies $f_{\text{low}}$ and $f_{\text{high}}$ were selected for each flare via visual inspection.

The Konus-Wind time profiles were corrected for the light propagation time (see Section 3.1) and then interpolated to have the same time bins as the microwave time profiles. A lag-correlation between an HXR light curve and a microwave light curve was calculated using IDL function c.correlate, then the correlation coefficient dependence on the time delay was cubic-spline-interpolated with a step of 0.1 s. The time lag corresponding to the peak of this function was adopted as the time delay between the HXR and microwave light curves. Time delays between the HXR and microwave light curves were obtained for 21 of 26 events for which appropriate microwave data were available. For the remaining five events, it was not possible to compute the delays because of the low signal-to-noise ratio and faults in microwave data.

The results are presented in Table 6 and Figure 18. The histogram bin width was selected to be 2 s, which is two times the NoRP background mode data resolution available for the majority of flares. For most CSFs, microwave emission on both $f_{\text{low}}$ and on $f_{\text{high}}$ is delayed relative to HXR. For four flares, microwave and HXR maxima coincide within 1 s. For two flares, light curves on $f_{\text{high}}$ are ahead of HXR, but for one of these flares, only the RSTN data in microwave range are available, so the corresponding time delay may not be reliable. In most cases, the delays of microwave emission do not exceed 10 s; the most frequent delays are between 1 and 3 s. One flare, 2000 May 18, 22:59 UT, based on NoRP has larger delays: 18.4 s on $f_{\text{low}}$ and 12.8 s on $f_{\text{high}}$.

One flare, 2003 October 23, shows a smooth component that demonstrates a significant delay of the microwave $f_{\text{low}}$ emission relative to the HXR emission: $\sim75$ s (Figure 19, left). This is the flare, whose smooth component (top left of the dynamic spectrum in Figure 14) was subtracted as a background in the analysis we have performed thus far. Now we consider the microwave emission as it is, subtracting the preflare background only. The time profiles in the Konus-Wind G2 channel...
and at high microwave frequencies (≥9 GHz) demonstrate impulsive behavior, while the microwave emission at lower frequencies has a smooth time profile. This behavior is similar to that of the cold flare with a delayed heating described by Fleishman et al. (2016). Given the high flux density and steep slopes of the spectrum at both low and high frequencies, the emission is clearly nonthermal; thus, this flare likely contains a nonthermal electron population trapped in a relatively large magnetic flux tube.

On the other hand, the 2000 May 18 07:21 UT flare has a relatively large delay between the HXR and microwave time profiles at high frequency (Figure 19, right). For this event, the light curves in the HXR G2 channel and microwave at lower frequencies (2.0 and 3.8 GHz) are highly correlated, but the emission on $f_{\text{high}}$ is more gradual and its maximum is delayed, relative to the impulsive phase, by ~110 s. This microwave burst is rather weak, ~10 sfu; thus, the delayed component could be produced by the flare-heated plasma by either a free–free or gyro-emission mechanism; cf. the thermal flare reported by Fleishman et al. (2015).

The microwave time profiles at $f_{\text{low}}$ and $f_{\text{high}}$ do not show any delay between each other for seven events, but the light curves at the lower microwave frequencies are delayed relative to the higher-frequency ones for most of the flares (10 cases). There are a few possible effects that could be responsible for such a delay. For example, it may be due to an increase of the brightness temperature of the optically thick, low-frequency emission due to nonthermal electron spectral hardening.
(Melnikov 1994). It also might be due to a decrease of the free–free opacity provided by plasma heating in the case of cold dense flares (Bastian et al. 2007).

3.6.2. Relationship between the Flare Duration in Microwave and HXR

The relationship between the flare timescales in the HXR and microwave ranges is presented in Figure 20. The events are split onto two groups: for one of them, points are close to the solid line, which represents the equality of HXR and microwave durations; the other group presents the microwave burst significantly longer than the corresponding HXR burst. A simple interpretation of these trends is that the first group is composed of trapping-free events, while the trapping plays some role in the events from the second group.

3.6.3. Microwave versus HXR Spectral Indices

Here, we compare the high-frequency microwave spectral indices $\alpha_{hf}$, which correspond to the optically thin gyrosynchrotron emission (and thus are closely linked with the spectral indices of nonthermal electron distribution in the flaring loop), to the HXR spectral indices $\gamma$, which are associated with the spectral indices of injected electrons.

Microwave spectral parameters were obtained on 1 s time-scales, but the multichannel HXR spectra with such time resolution were not available for the majority of flares; thus, the power-law indices in the HXR range, $\gamma$, were calculated using

Figure 16. Distributions of the microwave spectral parameters obtained for five time intervals during each peak of microwave burst. Bin heights are normalized to the total number of entries in each group. Top left: peak frequency distribution for cold solar flares (shaded blue) and the reference group (gray). Top right: peak flux density distribution for cold solar flares (shaded blue) and the reference group (gray). Bottom: spectral index distributions for cold solar flares (shaded blue) and the reference group (gray). Median values and 0.5 probability ranges are presented on each plot.

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three-channel fitting (see Section 3.1) on the time intervals in the 
Konus-Wind G1, G2, and G3 channels corresponding to the 
intervals with successful microwave fits after correction for the 
propagation time. HXR fit results with fit probabilities <1\% 
were discarded. Surprisingly, the scatter plot (not shown) of $\alpha_{HF}$

versus $\gamma$ does not reveal any significant correlation between 
these two parameters, so we investigate this relationship on an 
event-by-event basis.

It is known (Trottet & Vilmer 1984; Melnikov & Magun 1998) 
that, for some flares, the HXR and microwave spectral 
indices behave consistently at the rise phase but show opposite 
trends at the decay phase, which has been interpreted as an 
outcome of Coulomb collisions of the trapped population of the 
nonthermal electrons with the ambient plasma particles. For 
this reason, we separately consider the relationships between 
the microwave high-frequency spectral index, $\alpha_{HF}$, and the 
HXR index, $\gamma$, for the rise and decay phases of microwave 
emission.

The data suitable for comparison between $\alpha_{HF}$ and $\gamma$ were 
obtained for 12 out of 15 CSFs with successful microwave fits. 
Three flares were excluded because no triggered mode data 
were available in the G2 and G3 channels for the 2014 October 
18 flare, while the high-frequency spectral indices could not be 
obtained reliably for the 1998 May 7 and 1999 December 2 
flares due to a small number of spectral data points or a weak 
signal to the right of the turnover frequency. Time frames with 
a weak signal or only one data point above the spectral peak 
frequency were excluded (recall that these same time frames 
contribute to the “tails” of $\alpha_{HF}$ distributions, as has been 
discussed in Section 3.4).

The results of this analysis are presented in Figure 21. All 
CSFs generally follow the soft-hard-soft spectral evolution in 
HXR range, while according to their spectral evolution in 
microwave range and the relationship between $\gamma$ and $\alpha_{HF}$, CSFs 
can be roughly categorized onto three groups. The first group 
(the first column in Figure 21) includes flares 2001 November 1, 
2011 September 19, 2013 November 5, and 2014 January 2, for 
which the correlation between $\alpha_{HF}$ and $\gamma$ is observed. Of these 
four flares, the 2001 November 1 and 2013 November 5 flares 
show a slight correlation between the spectral indices in the 
microwave and HXR ranges during both the rise and the decay 
phases, while no relationship during the rise phase is revealed 
for other two flares from this group. The second group (the second 
column in Figure 21) includes the 1999 November 9, 2000 
March 18, 2002 May 29, 2002 August 18 flares, which are 
characterized by an anticorrelation between $\alpha_{HF}$ and $\gamma$ during 
the decay phase. One flare of this group, 2000 March 18, shows 
correlation between microwave and HXR indices during the rise 
phase, while the corresponding regressions at the rise phase 
either do not show any clear trend or do not contain enough data 
points to draw a conclusion for other three flares. The third 
group (the third column in Figure 21) includes the 2000 May 18, 
22:57 UT, 2003 October 23, 2012 July 8, and 2014 October 27 
flares, which do not show any clear dependence between the 
microwave and HXR spectral indices during the rise or decay 
phases. An interesting feature of the 2000 May 18, 22:57 UT 
and 2003 October 23 flares of this group is a striking difference 
between $\alpha_{HF}$ during the rise and decay microwave phases. For 
the 2000 May 18, 22:57 UT flare, the spectral indices are harder 
at the rise phase than at the decay phase, while the microwave 
spectral indices are harder during the decay phase for the 2003 
October 23 flare. Thus, we can conclude that, for all the flares 
from the second group and one from the third group, microwave-
spectrum hardening is observed. On the other hand, for all flares 
from the first group and one from the third group, the microwave 
spectrum becomes softer during the flare.
There is a correspondence between the flare duration patterns revealed by Figure 20 and the spectral evolution patterns identified in Figure 21, in terms of presence or absence of the trapping in the given event. Indeed, the events elongated along the \( y = x \) duration equality line in Figure 20 are mainly from columns 1 (three events) and 3 (three events) in Figure 21, with only one event from column 2. Three other events from column 2 (showing a microwave spectrum hardening at the decay phase, indicative of spectral evolution of the trapped component of nonthermal electrons) are those with noticeably longer duration in microwave than in the HXR domain, which confirms that trapping plays a role in these flares.

### 3.6.4. Relationships between X-Ray Characteristics and Microwave Peak Frequencies

In Section 3.4, we found that the CSFs have strikingly higher spectral peak frequencies, \( f_{\text{peak}} \), compared to the reference set of the microwave bursts. From this perspective, it is interesting to consider if any other CSF parameter correlates with the microwave spectral peak frequency.

To compare the microwave spectral peak frequencies obtained on individual time frames with X-ray parameters characterizing the entire duration of the solar flare, the peak frequencies for flares with successful fits were averaged over time frames for each flare peak; the corresponding uncertainty of the spectral peak frequency was estimated as the standard error.

**Figure 19.** Example of solar flares with relatively large time delays between HXR and microwave emission. Left panel: solar flare 2003 October 23, \( t_0 = 22:17:42.391 \) s, UT. Right panel: solar flare 2000 May 18, \( t_0 = 07:21:57.787 \) s, UT. (a) Konus-Wind G2 channel and GOES 1–8 Å light curves. (b) Microwave light curves on lower (<9 GHz) frequencies. (c) Microwave light curves on higher (>9 GHz) frequencies.

**Figure 20.** Relationship between the CSFs’ timescales in HXR and microwave. Solid line represents duration equality, dashed-dotted line corresponds to linear regression between these timescales, dotted line reflects regression for the group of flares below the main regression (presumably without trapping), dashed line indicates regression for the flares above the main regression line (presumably with trapping). Explanation of “colored” event groups is given in Section 3.6.3.
Figure 21. Relationship between HXR spectral index $\gamma$ and microwave high-frequency index $\alpha_{hf}$ obtained on each time interval during peaks with successful microwave and HXR spectral fitting. HXR spectral indices with high temporal resolution were obtained using three-channel fitting of Konus-Wind data (see Section 3.1). Red triangles and blue circles correspond to the rise and decay phases of microwave emission, respectively. Red labels indicate relationships between $\gamma$ and $\alpha_{hf}$ during the rise phase, blue labels indicate relationships during the decay phase, black labels indicate relationships during the whole flare.
deviation from this mean. For the “no-fit” flares, in some cases it was possible to specify a lower limit of the spectral peak frequency directly from the dynamic spectra given in Figure 14.

The relationship between the thermal-nonthermal (TNT) ratio, \( \eta = \Delta \text{GOES}/(\text{HXR peak count rate}) \), and the mean microwave peak frequencies is displayed in Figure 22. This plot shows that most of the CSFs group between \( \sim 5 \text{ GHz} \) and \( \sim 20 \text{ GHz} \) in the peak frequency, and between \( \sim 4 \times 10^{-11} \) and \( \sim 1 \times 10^{-10} \) in the TNT ratio (see dotted lines in the plot). Some flares fall outside these ranges: the 2000 May 18 flare, which has a rather high TNT ratio; the 2001 November 1 flare, which has a low \( \Delta \text{GOES} \) to HXR peak count rate TNT ratio and a low mean peak frequency (1.4 GHz); the 2013 November 5 flare, which demonstrates a low TNT ratio and an exceptionally high mean peak frequency, 22 GHz; and the 2015 May 7 flare, which has an exceptionally low TNT ratio.

The relationship between the photon power-law index in the lower energy range (\( \gamma \) for the PL model, or \( \gamma_1 \) for the 2PL model) and the mean microwave peak frequencies is presented in Figure 23. The lower-frequency CSFs tend to be harder than the higher-frequency ones. There is no case where a soft spectrum and a low spectral peak frequency would be present simultaneously.

The relationship between the electron power-law index in the lower energy range (\( \delta \) for the brmThickPL model, or \( \delta_1 \) for the brmThick2PL model) and the mean microwave peak frequencies is presented in Figure 24. There is a slight tendency for events with lower peak frequencies to have harder \( \delta \). Here, we see the same trend as in the previous scatter plot of \( \gamma \) versus \( f_{\text{peak}} \).

4. Discussion

In this study, we have identified a statistically significant set of “cold” flares with disproportionately weak thermal emission, relative to the nonthermal. Although a few such cold flares were reported in a number of case studies, all those cases were selected subjectively, without any formal criterion. Thus, to perform this statistical study, we have started by formulating such a formal criterion, which appears to be rather strict. Specifically, we identified a group of early impulsive flares by selecting those events in which the HXR burst started before or
without the corresponding SXR GOES flare. We then computed an SXR enhancement during the HXR bursts and compared this enhancement to a reference set of bursts and early impulsive flares. Finally, we selected the early impulsive flares, which are also the outliers (far below “average” thermal response) in the scatter plots in Figure 5, to form our CSF list. Note that Figure 5 contains many more outliers with a weak thermal response, which are not early impulsive flares according our selection criterion. However, we did not add them to the list because such a relatively weak GOES enhancement during the HXR burst could be an outcome of a strong pre-heating (i.e., the overall GOES enhancement is strong, but the enhancement due to nonthermal electrons is weak) for the non-early impulsive flares—such flares, certainly, would not qualify as cold ones. This selection yielded 27 CSFs, which we analyzed using X-ray and microwave data and the cross-correlations between them.

The statistical study we performed reveals significant differences between the CSFs and other flares. In the HXR domain, the CSFs are harder, shorter, and weaker than the reference flares. However, in the microwave domain, the CSFs are not weaker than the reference bursts. Further, in the microwave domain, the CSFs are shorter and harder at high frequencies than the reference ones, while steeper at the low frequencies. In addition, the CSFs often have a strikingly higher spectral peak frequency than the reference ones in the microwave domain. Nevertheless, we found that CSFs do not represent a uniform group of events, but rather could be separated onto a few subclasses. In particular, some CSFs show signatures of the nonthermal electron trapping in a coronal flaring loop, while others do not show any trapping (as in the main flaring loop in the flare reported by Fleishman et al. 2016); some flares demonstrate a break in the nonthermal electron energy spectrum, while others are consistent with a single power law; some CSFs are likely produced in a dense source, as in the cases reported by Bastian et al. (2007) and Masuda et al. (2013), while others are likely produced in a tenuous one similar to the tenuous flare reported by Fleishman et al. (2011).

Perhaps the key to interpret these distinctions is the combination of a weaker intensity in HXR and normal intensity in microwave. Indeed, weaker HXR emission implies a weaker component of the nonthermal electrons accelerated in the flare. However, to produce a normal level of microwave gyrosynchrotron emission by a weaker population of nonthermal electrons, the magnetic field must be accordingly higher than in the reference flare. The stronger magnetic field further implies a higher spectral peak frequency of gyrosynchrotron emission, as observed. Thus, given that the magnetic field decreases with height in the corona, a strong magnetic field implies a reasonably low height of the radio source, ergo shorter flaring loops, and in turn, shorter burst duration. These more compact loops represent more uniform sources, i.e., they likely contain a narrower range of magnetic field strength than a larger loop, which explains why the low-frequency microwave slope is steeper in the CSFs than in the reference ones. However, this simple interpretation cannot clarify why the spectra of nonthermal electrons are harder in the CSFs than in the reference ones. One possibility is that the acceleration mechanism results in harder spectra in cases of stronger magnetic field/more compact loops. An alternative interpretation is that the spectral hardness does not systematically depend on these flare parameters; rather, in the flares that generate electrons with harder spectra, the thermal response is additionally reduced because now a larger fraction of the nonthermal energy belongs to high-energy electrons that deposit their energy deeper in the chromosphere, thus reducing the chromospheric evaporation and the thermal response.

However, even the relatively compact set of 27 CSFs demonstrates a considerable diversity of these properties, so the CSFs can hardly be fully characterized by a “mean” CSF; rather, they have to be further split into different subclasses. This is particularly true for those CSFs showing a normal or low microwave spectral peak frequency: in such cases, the magnetic field is also supposed to be normal or weak, so the picture drawn above should be patched or replaced, although the short duration still implies a reasonable compact flaring sources. We note that, in such cases, the nonthermal electron spectra are particularly hard, which might further confirm the role of the spectral hardness in the chromospheric evaporation/thermal response. We also note that having a low spectral peak frequency requires that both magnetic field and the plasma density are low. Indeed, a weak magnetic field combined with a high plasma density will result in a high spectral peak frequency due to the Razin effect. Thus, the flares with a low spectral peak frequency are likely tenuous flares similar to that reported by Fleishman et al. (2011).

Another property, which display different patterns within CSFs, is the shape of the nonthermal electron energy spectrum. At this point, we cannot draw any conclusion about significance of this finding, given that the spectral break can be present in the spectrum in some cases, but not recovered in the fit due to insufficient statistics at the high-energy channels.

Finally, we found that the CSFs can be further divided into two groups, depending on whether the nonthermal electron trapping in a coronal flaring loop (or loops) plays a role or not. This is vividly demonstrated by Figure 20, which shows the scatter plot of the microwave versus HXR burst duration. Roughly half of the events show equal durations (no trapping), while the other half present microwave duration a factor of two longer than the HXR duration (a noticeable trapping). This division is also confirmed by relationships of the spectral hardness in the microwave and HXR domains (Section 3.6.3).

5. Conclusions

From the performed statistical analysis, we conclude that our identified set of 27 “cold” solar flares demonstrates properties statistically different from those of a reference (“mean”) flare. We found that the cold flares are typically shorter and harder that the reference flares; their HXR emission is weaker, while microwave emission is comparable to that of the mean flare. They are further different in the microwave domain, as they have a steeper low-frequency spectral slope and (often) strikingly higher spectral peak frequency. From these findings, we conclude that the cold flares are typically produced in more compact structures (presumably short flaring loops) that have stronger magnetic fields than a mean flare. In addition, we found that the group of the cold flares is nonuniform, but rather can be further sub-categorized according to various properties (low or high spectral peak frequency, presence or absence of trapping effect, etc.). Given that all these flares demonstrate the weakest thermal response, compared to a reference flare, we conclude that the “cold” flares described here offer, via the corresponding case studies, the cleanest way to study electron
acceleration in flares and the thermal plasma response driven by the nonthermal electron population.

We note that the CSFs presented here form a promising event list for future case studies, given that the processes of particle acceleration and the thermal plasma response can be quantified much more cleanly with the nonthermal-energy-dominated CSFs than with a “usual” flare, where the nonthermal and thermal energies are initially mixed up with unknown proportions. Such case studies will employ all available imaging and contextual data, and will also incorporate modeling to verify and refine interpretations formulated here, based on the statistical analysis.

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Software: XSPEC (Arnaud 1996), OVSA tool from SSW (Nita et al. 2004).

Appendix
Creation of the OVSA-like Database of the Cold Solar Flares

A generic OVSA data file contains low- and high-time-resolution data, with the resolutions differing by a factor of two from all available antennas. There are OVSA tools developed specifically for reduction and analysis of the OVSA data. However, for our data set, the input microwave data are nonuniform because they have been taken by substantially different radio instruments. To partly reduce the effect of this data nonuniformity on the statistical results, we made a number of manipulations to the input data. For the events jointly observed by more than one instrument, we combined the data from the different instruments into one composite dynamic spectrum to increase the spectral resolution needed for meaningful time-sequential spectral fit of the data. Given the dissimilar time resolution and distinct clock ticks at various instruments, we interpolated the time array of one instrument to exactly match the clock ticks of another instrument, selected to be a reference. Whenever possible, we adopted the NoRP clock ticks to be the reference ones, and resampled the RSTN and/or SRS and BBMS data to exactly match the NoRP time.

We noted that, for the full NoRP time resolution in the flare mode, 0.1 s, the microwave light curves for many events are noisy at many frequencies. For this reason, we integrated the 0.1 s data to degrade the time resolution up to 0.5 s, which is exactly half of the NoRP resolution in the background mode. Having the two sets of observations—one with 0.5 s resolution created from the flare mode data, and the other with 1 s resolution taken from the background mode data—allows us to create a data file with a structure internally identical to the generic OVSA data file. For the events for which NoRP data are unavailable (or only available in the background mode), we created a dynamic spectrum with a single time resolution, 1 s, which is also allowable in the OVSA data format.

Although a combination of more than two instruments is, in principle, possible for a given event, in practice we mainly created the composite data files containing the data from two different instruments; namely, combination of the NoRP and the RSTN data (seven events), the NoRP and the SRS data (two events) or the NoRP and the BBMS data (one event), and in one case, the RSTN and the KMAS data, while a combination of the data from three different instruments (NoRP, RSTN, and SRS) was only available in two cases. Note, that there are often RSTN clock errors,12 which can be as big as many seconds. We corrected these errors by cross-correlation between the RSTN and NoRP data, relying on the NoRP clocks as the most precise. For two events, we built separate dynamic spectra from the OVSA data or the NoRP+RSTN combination, and for another we used the OVSA and NoRP separately. We did not add other instruments to the events observed with the OVSA, because it typically has a sufficient number of the spectral channels to resolve and fit the burst spectrum without adding extra channels. However, considering a separate NoRP or NoRP+RSTN spectrum has the advantage of higher time resolution, which is important to analyze short and rapidly variable events.

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12 This, in particular, implies that using RSTN data alone to measure the time delays between the X-ray and microwave light curves would be inconclusive.

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