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Extended decimeter radio emission after large solar flares

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Abstract

The large solar flares of October and November 2003 were accompanied by extremely intense radio emissions at decimeter wavelengths. The radio emission continued long after the main phase of the flares and reached an unprecedented peak flux density at 410 MHz of $6.3(\pm 0.7) \times 10^5$ solar flux units on 2003, October 28. The unusual number of large flares from the same active regions yields a homologous set ideal for statistical analysis. We have compared the coherent radio emissions (as observed by the Zurich and Trieste instruments) with the X-rays measured by RHESSI and GOES. As major results, we find that the total duration, the peak flux, and radiated energy of the radio emissions correlate with the flare energy released (measured in soft X-rays). Enhanced hard X-rays (>12 keV) are always observed during the time of enhanced radio emission. In 27% of the radio subpeaks covered by RHESSI, we find X-ray subpeaks. The most intense radio emissions are not due to electron beams, but are post-flare emissions apparently not directly related to the primary energy release and acceleration process. These radio emissions, generally classified as Type IV and DCIM bursts, have previously been interpreted by loss-cone emission of trapped electrons. However, radio and hard X-ray subpeaks do not show a detailed correlation or Neupert effect, and long-term trapping can be excluded. Possible acceleration mechanisms after the main flare phase are discussed and compared with the observations.

Keywords: Solar flares; Radio emission; Hard X-rays; Decimeter Type IV bursts; Energy release; Particle acceleration

1. Introduction

In October and November 2003, three active regions on the Sun produced an unusual set of powerful flares. Some of them were accompanied by extremely strong and long lasting radio emissions in the short meter and decimeter wavelength ranges. The radio emissions even had direct effects on terrestrial activities: They interfered with aviation radar and navigation (GPS phase tracking loop). The events were well covered by many ground-based and space instruments.

Long-duration continuum radio emissions associated with flares are traditionally termed Type IV bursts (Boischot, 1957). In meter wavelengths, Type IV bursts are often associated with CMEs and thus of interest for space weather. Continuum decimetric emissions, however, were found so frequently that a different name, DCIM, had to be used to avoid false alarms by overrating its associated flare's importance. The high-frequency cutoff of stationary meter-wave Type IV events lies often in the decimeter range. Stationary Type IV events sometimes develop into noise storms (for the terminology see Pick, 1986). The emission mechanism of stationary Type IV events is generally believed to be a coherent plasma process as they sometimes have a narrow bandwidth (Benz and Tarnstrom, 1976), spectral fine structures (Slottje, 1972; catalogue by Bernold, 1980), and are preferentially polarized corresponding to ordinary mode (Kundu, 1965). Stepanov (1975) and Kuijpers (1975) proposed the instability of a loss-cone electron distribution as the cause of the emission. The origin of such a distribution may be partial trapping of charged particles in magnetic fields. As the delay sometimes greatly exceeds the collision time, the radio emissions appear to be signa-

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tures of some late-phase acceleration (Svestka et al., 1982; Klein et al., 1983). Benz et al. (2002) observed DCIMs (narrowband spikes, at 432 MHz) near loop tops, 15,000–290,000 km from the X-ray sources. Saint-Hilaire and Benz (2003) reported decimetric pulsations between 9000 and 140,000 km from the X-ray flare position. Kahler (1982) already proposed that the emitting electrons are accelerated in post-flare loop systems. If this were the case, what is the X-ray evidence? The relation between DCIM (in particular decimetric pulsations) and hard X-rays has been studied by Aschwanden et al. (1990), using ISEE-3 and reporting no or only weak simultaneous hard X-ray flux >26 keV.

We investigate the association of decimetric emissions after the main phase of flares with hard X-rays and in particular with hard X-ray subpeaks. As the study is limited to three active regions observable for nearly 2 weeks, the data set is unusually homologous and suitable for statistical analysis.

2. Observations

The RHESSI satellite (Lin et al., 2002) observes the full Sun from 3 keV to 17 MeV. Its data allow for the reconstruction of the light curves with a resolution near 1 keV at low energies. The time resolution is milliseconds in principle, but we use here the rotation period (about 4 s) for simplicity.

Observations by the Phoenix-2 radio spectrometer (Benz et al., 1991; Messmer et al., 1999) were used to survey the radio emissions. Phoenix-2 operated in the full range from 100 MHz to 4 GHz with a time resolution of 0.1 s, recording both the total flux density and circular polarization. The calibration was compared with observations from Trieste Astronomical Observatory and RSTN at the 6 available frequencies and, where necessary, was improved. Both Phoenix-2 and the Trieste observations saturate at some 10^4 solar flux units. The new radio spectrometer Callisto (Benz et al., 2005) was put temporarily into operation at ETH Zurich on October 27, covering some of the high activity in parallel with Phoenix-2. Callisto was not saturated by any of the large flares and was calibrated relative to Phoenix-2 and Trieste.

As an example, Fig. 1 displays the observations of a large flare (GOES class X17.2). It consists of an M9 preflare (at 10:30) followed by the main peak occurring in the same active region. RHESSI missed the first peak and started to observe at the main hard X-ray peak. Both peaks were associated with strong gyro-synchrotron emission extending from the instrumental limit at 4 GHz down to about 2 GHz. In the low-frequency part of the spectrogram, shock signatures (Type II and decimetric drifting ridge) are associated with both peaks. The second, saturated in Fig. 1, is visible in the Callisto record, drifting from beyond 800 MHz at 11:04 to 250 MHz (Fig. 3). A noise storm starts at 09:34, a few minutes before the first X-ray enhancement, from below 100 MHz up to 250 MHz. It is relatively intense, but later nearly outshone by the flare emission. After the main impulsive phase of the flare, starting around 11:20 (see Fig. 3), a bursty continuum

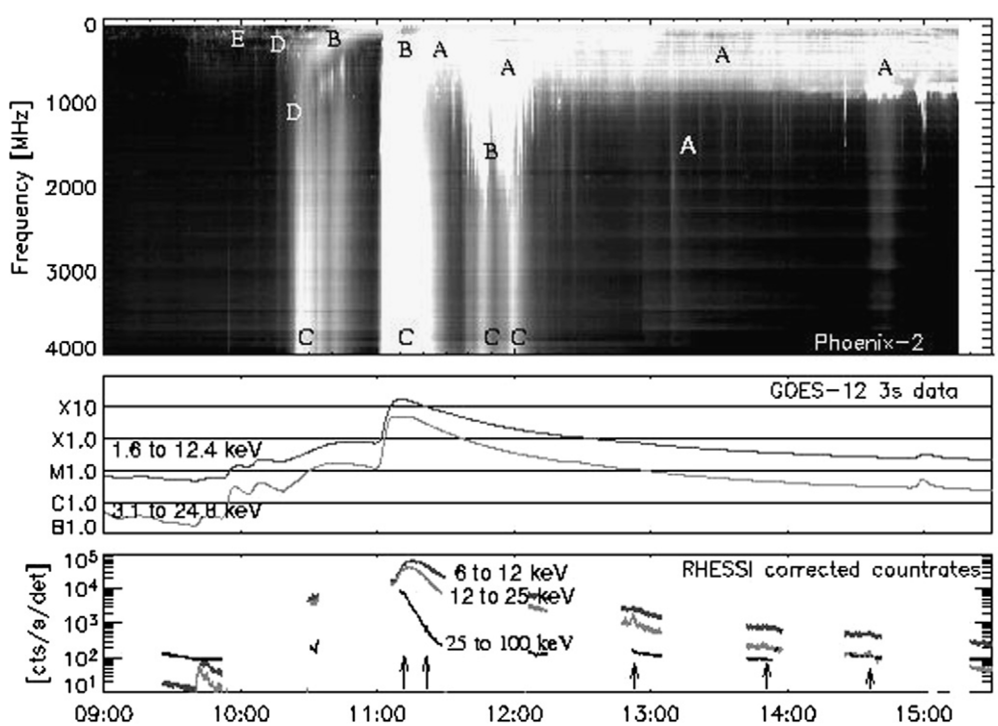

Fig. 1. Observations of the X17 flare on 2003, October 28, by Phoenix-2 (top), GOES (middle), and RHESSI (bottom). The various radio emissions have been identified in enlargements (e.g., Fig. 2) and are marked by A for 'after main impulsive phase', B for drifting structures, C for high-frequency continuum (gyro-synchrotron emission), D for Type III bursts, and E for noise storm. Subpeaks in hard X-rays are indicated by arrows.

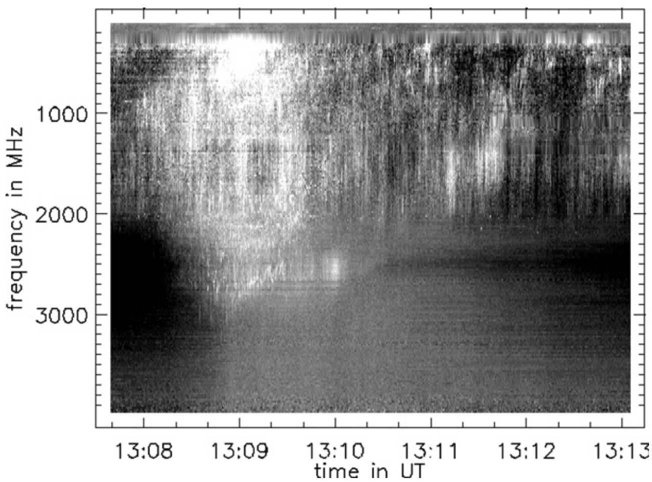

Fig. 2. Enlargement of Phoenix-2 spectrogram at a time marked with a white A in Fig. 1. The background at 13:05 UT was subtracted.

extending from meter waves up to 1000 MHz appears and remains until sunset at 15:19 UT. We identify this continuum with the classical meterwave Type IV event. It is intermingled with bright, narrowband emissions (marked A in Fig. 1). These latter emissions are the issue of this study. An enlargement of one of them is shown in Fig. 2. Note decimetric emissions extending to 4000 MHz at 13:11:30 UT, including fine structures in the form of pulsations, spikes and intermediate drift bursts (fibers). Superposed is a high-frequency continuum, decreasing in flux density from 4000 MHz down to 2000 MHz.

The peak decimeter flux density in the event of October 28 was measured at 11:17 UT in a pulsating structure (DCIM, see Fig. 3). At the well calibrated frequency of 410 MHz, its value was determined by Callisto to be $6.3(\pm 0.7)\times 10^5$ sfu. It is the highest flux ever measured by a Zurich radio spectrometer observing digitally since 1978 in the decimeter range.

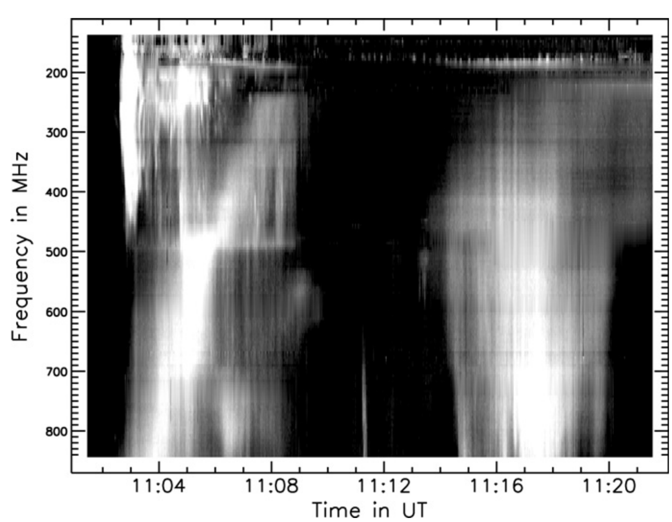

Fig. 3. Radio spectrogram observed during the X17 flare on 2003, October 28, by Callisto. The data are not calibrated, but the pre-flare background is subtracted.

3. Results

Active regions 484, 486, and 488 were visible from 2003, October 19 until November 5. In this time interval, there were 22 flares both larger than M1.0 and jointly observed by RHESSI and Phoenix-2. Coherent radio emissions were observed after 21 flares. The only exception with no coherent emission was the flare on November 5, 1049 UT, occurring over the limb and very late in the period of activity.

As an ‘extended decimetric emission’ we defined continua in the 0.3–2 GHz range after the main flare hard X-ray phase, including decimetric Type IV bursts and DCIM (pulsations, patches, drifting structures, narrowband spikes, and all kinds of fine structures). Type III bursts and noise storms were excluded.

We searched for simultaneous emissions in the RHESSI light curves. Often no features are discernible in the two GOES energy bands, nor in the RHESSI light curves below 12 keV. However, RHESSI detected many subpeaks (secondary flares) in the 12–50 keV range during the extended emissions. Their rate is more than one per hour in Fig. 1. During 7 out of 56 decimetric enhancements, a coincident X-ray subpeak was found within 2 min, indicating a possible but not necessarily causal association. This association rate of 13% increases to 28% during times of RHESSI coverage. However, these small peaks are not correlated with the radio structures at the 4 s scale.

The total duration of extended decimetric emissions is defined as the interval from hard X-ray peak time to the end of the last patch of decimetric emission. The radio emission was fitted with a two-dimensional Gaussian in frequency and time. Its duration and bandwidth are defined by the $1/e$ points. When RHESSI data were incomplete, the time derivative of the GOES flux was used as a proxy for hard X-rays. As the decimetric emissions are often intermittent and consist of several bursts, the total duration of extended emission can be determined only if it stops long before sunset. We used a limit of 1 h and found 14 complying flares. The total duration is shown in Fig. 4 in relation to flare size. Fig. 4 indicates an increase of total duration of extended radio emission for large flares. The correlation

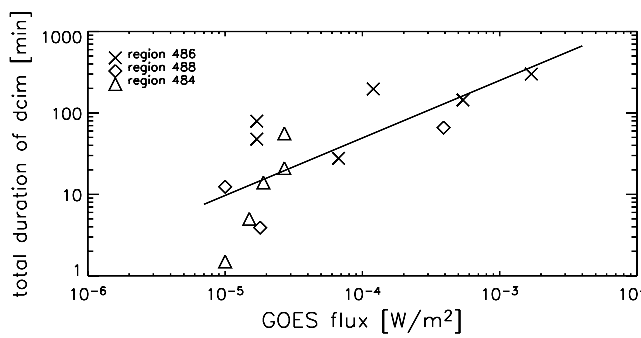

Fig. 4. Total duration of extended decimetric emissions vs. GOES peak soft X-ray flux (1.8–12.4 keV) in 14 flares >M1.0 of October/November 2003. The regression line of duration vs. flux is also shown.

coefficient between total duration (dependent variable) and GOES flux in log–log representation is 0.84, having a 95% significance range between 0.56 and 0.94. Thus, it is statistically significant. The duration decreases rapidly from X to M class. At low M classes, the scatter becomes large (two orders of magnitude in duration), and the three active regions appear to behave differently. A cutoff at a soft X-ray flux of 10^{-5} W/m^2 is introduced by the flare selection (>M1.0). The regression of total duration in terms of soft X-ray flux implies a relation,

$$D = 3.28 \times 10^4 F_{SXR}^{0.706} \quad [min], \qquad (1)$$

where the total duration D is in minutes and F_{SXR} is the GOES flux from 1.8 to 12.4 keV in units of W/m^2. No correlation was found between the duration of individual enhancements in decimeter emissions and flare GOES class.

The peak flux of major individual decimetric enhancements of the post-flare phase, approximated again by Gauss fits, is displayed in Fig. 5 vs. GOES flux. Where necessary, saturated Phoenix values were replaced by Callisto measurements. Not surprisingly, there are weak enhancements in all flares. Nevertheless, Fig. 5 suggests that large flares have higher peak decimeter wave fluxes.

If the end of the extended emissions is known, the radiation can be integrated in time and frequency to determine the total energy radiated, assuming isotropic emission at the Sun. The result is shown in Fig. 6, indicating again a correlation with peak soft X-ray flux. The correlation coefficient is 0.75, with a 95% significance range between 0.34 and 0.92. The total energy emitted in radio waves, E_{radio}, sharply increases on the average with the peak soft X-ray flux, F_{SXR}. The scatter, but also the increase is particularly large at low M classes (cutoff at soft X-ray flux of 10^{-5} W/m^2). The regression of the total energy radiated in decimeter bursts vs. soft X-ray flux implies a relation,

$$E_{radio} = 1.92 \times 10^8 F_{SXR}^{1.42} \quad [erg], \qquad (2)$$

where the total radio energy E_{radio} is in units of 10^{20} erg and F_{SXR} is the GOES flux from 1.8 to 12.4 keV in units of W/m^2.

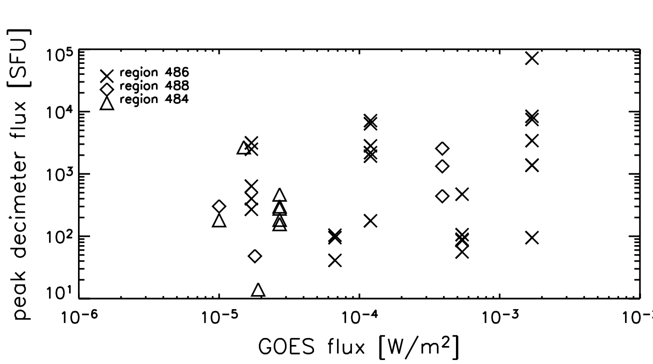

Fig. 5. Peak flux of major individual decimetric enhancements vs. flare peak soft X-ray flux.

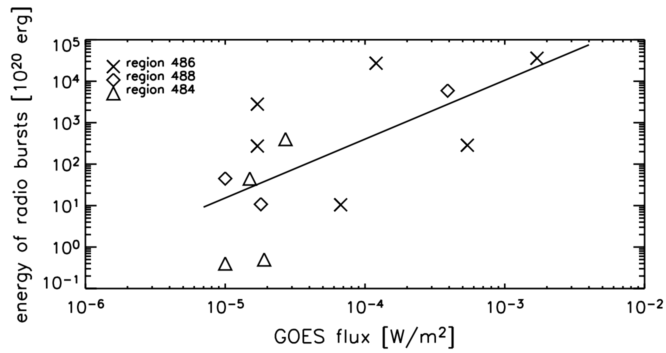

Fig. 6. Total energy of extended decimetric emission vs. soft X-ray peak flux. The radio emission was integrated in time and frequency over individual structures and assumed to be isotropic. The regression line of energy vs. flux is also shown.

4. Discussion and conclusion

The most important results of this study are the correlations found between total duration, peak flux, and total energy of extended decimeter radio emission vs. soft X-ray flux (GOES flare class). The peak of soft X-rays, proportional to the flare emission measure, may be used as a proxy for the total flare energy release.

The study of radio emissions after large flares has shown furthermore that, when RHESSI coverage was available, all of the decimetric radiations occur during periods of enhanced hard X-ray emission (>12 keV). In two good cases (Fig. 1 and 2003, November 2, 08:50) out of 10, the hard X-ray emission >25 keV ended clearly before the radio emission, although some emission below our threshold cannot be excluded. The association rate of radio subpeaks with X-ray subpeaks, however, was found to be low (28% during times of RHESSI coverage).

As demonstrated in Fig. 1, the associated soft X-ray emission often does not show any features, but X-rays harder than 12 keV as observed by RHESSI have frequent subpeaks. The time difference of individual enhancements of radio emissions to the previous hard X-ray subpeak sometimes exceeds 1 h. Obviously, a direct relation then is very doubtful. Even for the best correlations apparent in Fig. 1 (e.g., at 12:50 UT), the observed delay is longer than trapping can explain, considering the collision time with field particles that untrap electrons. (Assuming a plasma with a density of 10^9 cm^{-3}, the collision time of a 50 keV electron is only 34 s.) The interpretation of time delays by trapping becomes unlikely by these observations.

An interpretation of extended radio emissions with shocks does not fit the standard shock signature represented by narrowband radio structures drifting in the spectrogram (Type II radio bursts and decimeter drifting ridges). Such structures in the 2003, October 28 flare, marked B in Fig. 1, occurred only early in the extended emission phase. Therefore, the extended radio emission does not appear to be directly associated with CMEs, traveling far from the radio sources at those times.

Secondary acceleration at the time of the radio emission remains the most likely interpretation of extended radio emissions. Such acceleration may be the result of the reconfiguration of the active region magnetic field after a large flare. This interpretation suggests that the corresponding hard X-ray subpeaks may often be buried in other emissions so that they do not cause a distinct Neupert effect. The suggestion can be tested quantitatively by model calculations in future work. The lack of close temporal correlation between radio emission and hard X-rays remains an enigma.

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