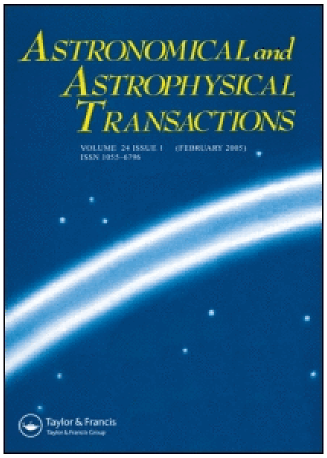

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Violent solar events of October–November 2003 as recorded by IZMIRAN radio observations

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The extreme solar activity of October–November 2003 was recorded at IZMIRAN with digital radiospectrographs at 25–270 MHz and fixed-frequency radiometers at 169, 204 and 3000 MHz. An outstanding metre-wavelength noise storm took place during the fist passage of the grandiose evolving active complex across the disc which testifies to permanent electron acceleration over the complex with energy of up to tens of kiloelectronvolts. Against this background, intense metric and microwave radio bursts were recorded in association with several outstanding flare and huge coronal mass ejection (CME) events. The dynamic spectra of these events display multiband and sometimes fine-structure type II bursts, initiated by coronal shocks, and various continuum emissions. In some cases, a corresponding microwave burst at 3000 MHz includes not only an impulsive component coinciding with a flare maximum but also a predominating delayed long-duration component with a smooth time profile. The latter component is thought to be linked with a post-eruptive energy release and particle acceleration when the magnetic field, strongly disturbed by a CME, relaxes to a new quasi-equilibrium configuration via reconnection in high coronal levels.

Keywords: Sun; Corona; Flare; Coronal mass ejection; Radio emission

1. Introduction

An extremely intense increase in the solar activity in October–November 2003 was associated with the appearance of a global complex consisting of three large, remote but connected active regions (AR): AR 484 (Carrington coordinates, N04; $L = 354$), AR 486 (S15; $L = 283$) and AR 488 (N08; $L = 291$). It was accompanied by a series of powerful flares and large coronal mass ejections (CMEs) as well as by strong space weather disturbances (see, for example [1, 2]). General characteristics of the period and features of the large-scale CME-associated activity, mainly obtained from the SOHO–EIT data, have been described, for example, in [3] (see also various illustrative materials at [4]).

During two passages of the active complex across the visible disc, regular everyday observations in the 06–12 Universal Time (UT) interval have been carried out of IZMIRAN with

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digital radiospectrographs at 25–270 MHz [5] and with three fixed-frequency radiometers at 169, 204 and 3000 MHz. The spectrographs have time and frequency resolutions of 0.04 s and 0.2 MHz respectively. The digital recording allows one to form multi-scale radio spectra. Detailed high-resolution spectra are suitable for study of the fine structures of radio bursts. Spectra with intermediate-timescale display the usual pictures of type III and II bursts. The so-called compressed multihour spectra enable the development of long-duration type IV and continuum emissions as well as noise storms to be traced.

In this paper, we present and discuss some results of IZMIRAN radio observations for the October–November 2003 period. First, general characteristics of the background emission at centimetre and metre wavelengths are given. Then radio emission of three flare–CME-associated events, including the most geoeffective of 28 October and 18 November 2003, are described as typical examples. Data on all outstanding radio events, observed at IZMIRAN in October–November 2003, can be found at [6].

2. Background emission at centimetre and metre wavelengths

As figure 1 shows, the first passage of the active complex was accompanied by an especially great enhancement of the background microwave emission (the so-called S-component) and by very intense noise storms. The first peaks of both emissions on 21–22 October 2003 appeared to be caused by AR 484 and the maxima on 29 October 2003 were certainly associated with ARs 486 and 488 when the corresponding region were located in the central zone of the disc. As a whole, the S-component flux increased from 100 to 300 sfu (solar flux unit) (1 sfu $= 10^{-22}$ W m^{-2} Hz^{-1}). In the most intense noise storms, the metre-wavelength flux at 204 MHz increased by a factor of several hundreds. On the daily compressed spectra (figure 2), the noise storm looks like a combination of an enhanced continuum and numerous short-duration bursts and drifting features. One can see, for example, that on 21 October 2003 the noise storm occupies the whole observational range, the type III bursts predominating at low frequencies. The noise storm of 25 October 2003 is generated mainly at $f > 45$ MHz. The spectrum in figure 2(c) illustrates how the similar noise storm of 28 October 2003 is transformed into intense radio bursts associated with a powerful flare and halo CME (see below).

During the second passage of the complex in the second half of November 2003 (figure 1), the flux enhancements were much less in both the microwave and the metre ranges. The total flux at 3000 MHz was about 150–180 sfu, and a moderate noise storm was observed on 16–19 November 2003 only.

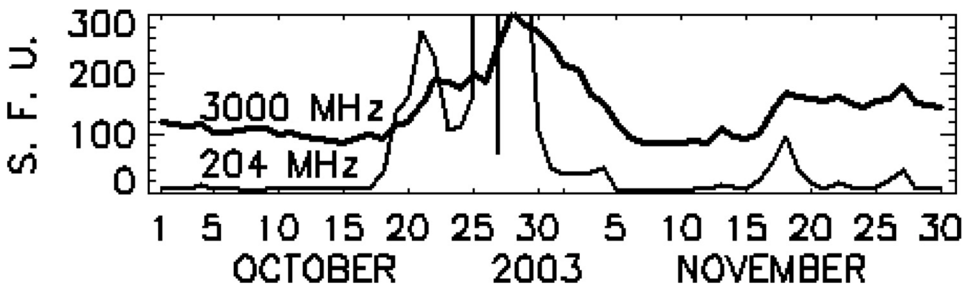

Figure 1. Variations in the background radio flux at 204 and 3000 MHz showing the development and intensity of metric noise storms and the microwave S-component in October–November 2003 during two passages of the active complex across the disc.

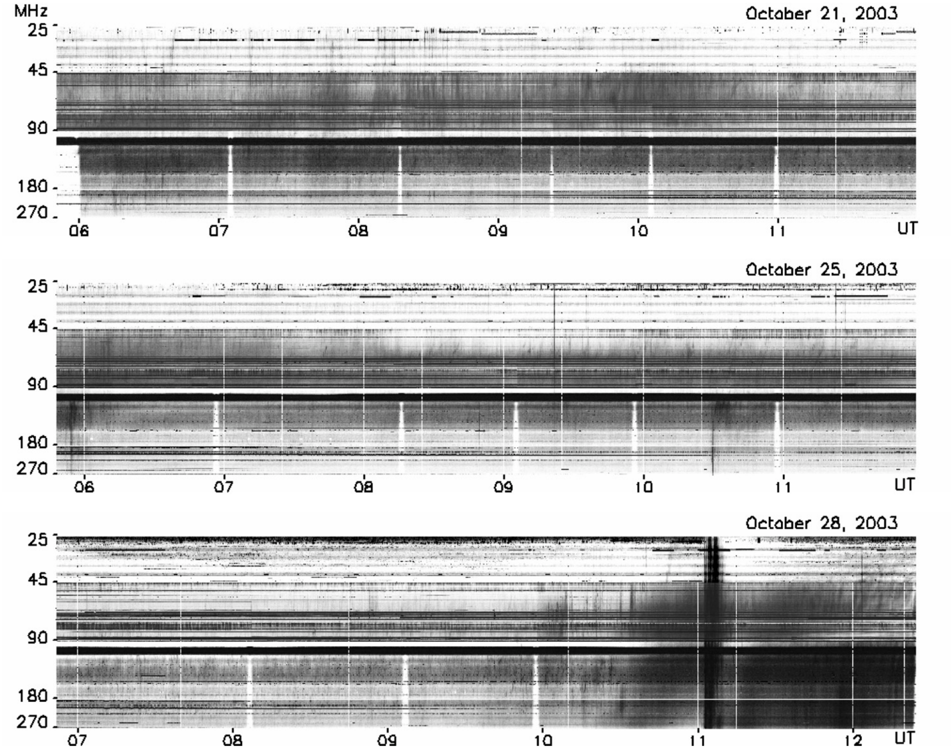

Figure 2. Some daily compressed dynamic spectra in the 270–25 MHz range with intense noise storms. In the spectrum of 28 October 2003 in (c), one can see the transformation of the noise storm into a strong radio outburst associated with a powerful flare and huge CME.

3. Event of 28 October 2003

This 28 October 2003 event, which was one of the most powerful events, included in particular an extremely intense long-duration flare of the 4B/X > 17.2 class, centred in AR 486 (coordinates S16 E08) and peakeing at about of 11:10 UT, and a huge high-speed ($V \approx 2300\,\mathrm{km\,s^{-1}}$) full-halo CME with very bright emittance all around the occulting disc of the SOHO–LASCO coronagraph. In the extreme untraviolet (EUV) region, according to SOHO–EIT data, it was accompanied by a coronal wave propagating throughout the northern hemisphere and by global dimmings (i.e. transient coronal holes) extending over all the southern hemisphere [3]. The corresponding space weather disturbances are characterized by an extremely strong increase in the high-energy proton flux ($J(E > 10\,\mathrm{MeV}) \approx 7 \times 10^3$–$10^4\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$) as well as by a severe geomagnetic storm ($D_{\mathrm{st}} \approx -363\,\mathrm{nT}$).

As the compressed spectrum shows (figure 2(c)), the metric radio emission includes a comparatively short burst at 11:02–11:07 UT and a prolonged, enhanced and structured continuum. In the more detailed dynamic spectrum (figure 3(a)), one can see that the burst consists of a group of rapidly drifting type III bursts and complicated system of more slowly drifting diffuse type II bands such as band 1–2 and some other bands between points 3 and 4. According to estimations, the observed frequency drift rate of band 1–2 in the range 130–60 MHz is about $-1.3\,\mathrm{MHz\,s^{-1}}$, which is several times faster than an average drift of type II bursts (see for example, [7, 8]). In general, it appears to agree with the unusually high speed of a CME and great flare importance and, therefore, with the speed of either the driven or the blast wave shock being an exciter of the type II burst.

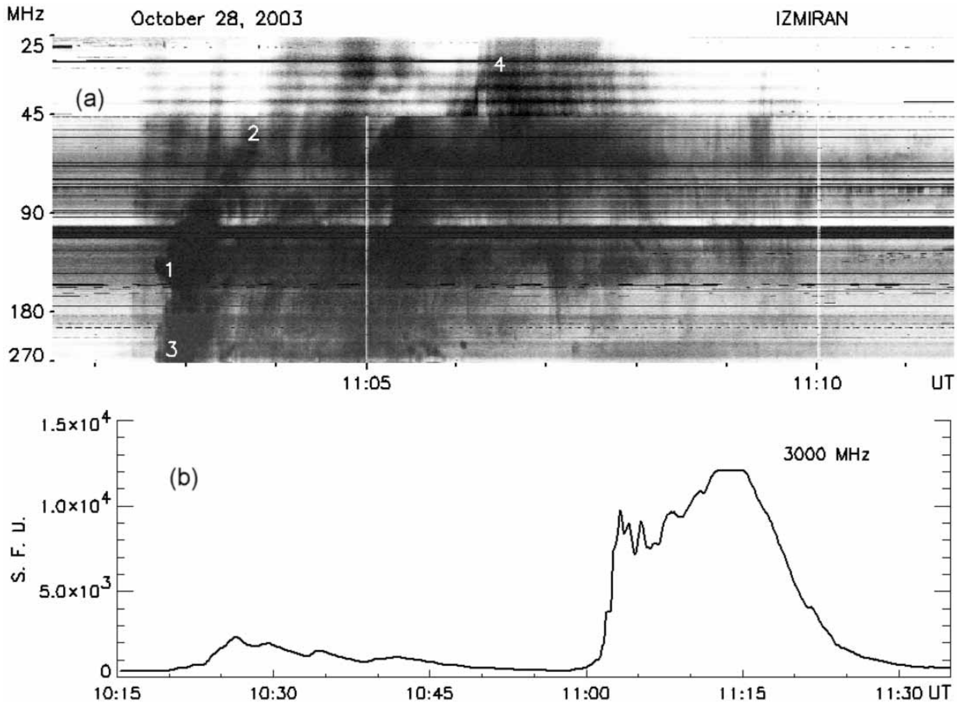

Figure 3. Radio emission of the 28 October 2003 event: (a) the metric dynamic spectrum with several diffuse type II bands; (b) the strong microwave burst with a delayed predominating post-eruptive component.

The microwave emission at 3000 MHz (figure 3(b)) reveals a complicated flux–time profile and extremely high intensity. The main burst started at about 11:00 UT. By 11:03 UT, the radio flux increased to the first peak of approximately 10^4 sfu. Essentially then, after some decrease, a new delayed, more powerful and prolonged component with a gradual profile took place. For 4 min, from 11:12 to11:16 UT, its flux exceeded the maximum threshold of recording at a level of 1.3×10^4 sfu.

4. Event of 3 November 2003

This event occurred in another AR, namely AR 488 (N08 W77), and was not so intense as the previous even, although its characteristics were rather impressive too. A corresponding flare at 09:55 UT was classified as 2F/X3.9. The CME in this case looked like a thick, wide and bright loop propagating throughout the whole northwest quadrant with a speed of 1400 km s^{-1}.

The main peculiarity of the dynamic spectrum shown in figure 4(a) is that the type II burst consists of many slowly drifting narrow fine-structured bands and elements (see the enlarged fragments of the spectrum). In particular, band 1–2, drifting with an average rate of -0.28 MHz s^{-1}, is composed of numerous overlapping stria elements with a bandwidth of 0.4–0.7 MHz. Some of these elements have a positive frequency drift. Moreover, between 10:00 and 10:08 UT and in the 90–30 MHz frequency range, the type II burst is formed by many filament-like elements that are characterized by a somewhat narrower instantaneous bandwidth than strias, by a total duration of 0.5–2 min, by a total frequency range of 5–10 MHz and by a negative frequency drift with a rate $-(0.07–0.12)$ MHz s^{-1} typical of type II bursts.

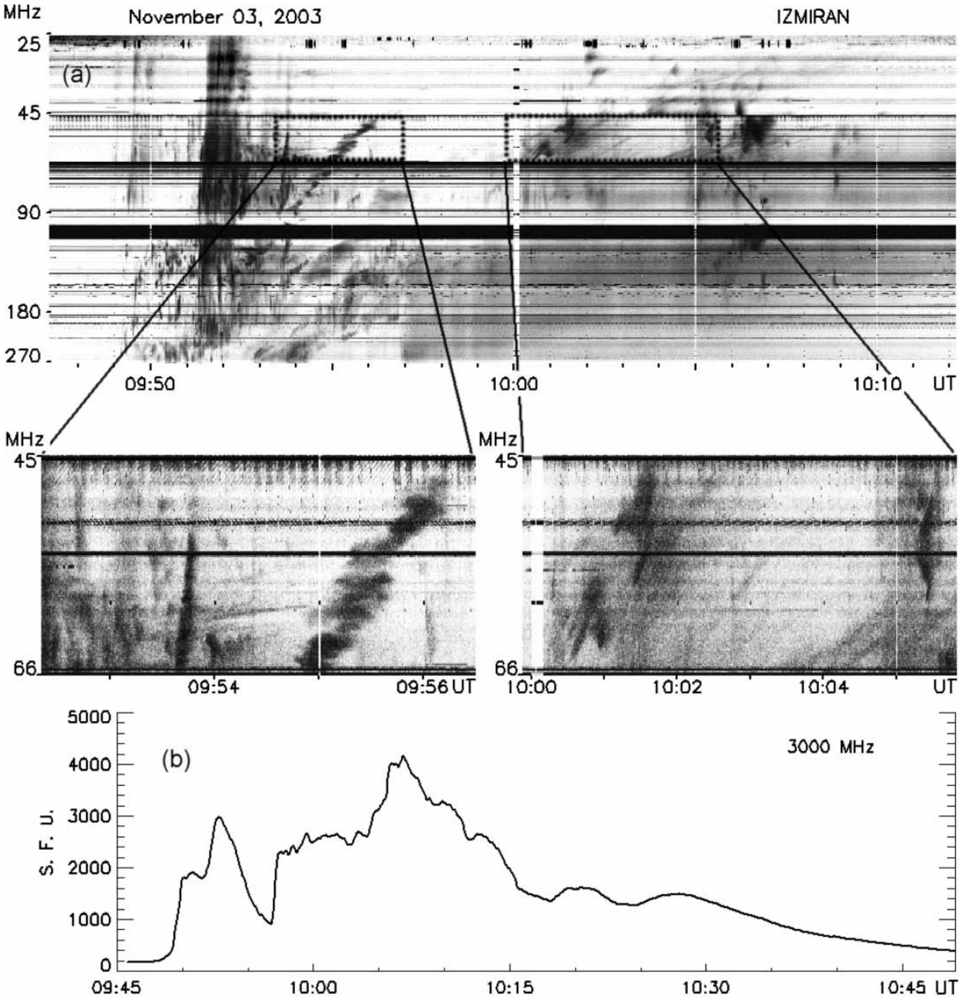

Figure 4. Radio emission of the 3 November 2003 event: (a) the metric dynamic spectrum with fine-structured type II bands; (b) the microwave burst with a delayed predominating post-eruptive component.

At a fixed time moment, for example at 10:02 UT, one can count simultaneously more than ten elements.

As for microwave emission (figure 4(b)), in this case again the presence of two components in the flux–time profile at 3000 MHz is obvious. The first impulsive component, at 09:53 UT, appears to correspond to a group of type III bursts visible in the dynamic spectrum. The second long-duration component again is more intense, and its maximum is observed with a time delay of 15 min relative to the peak of the impulsive component.

5. Event of 18 November 2003

The main features of this event, occurring at the second passage of the active complex, are determined by the fact that it was caused by the disappearance of a large Hα filament approximately at 07:40 UT southwards and southwestwards of AR 501 (return of AR 484; coordinates, N00 E18). Also, a prolonged two-ribbon 2N flare was observed and two short soft X-ray bursts

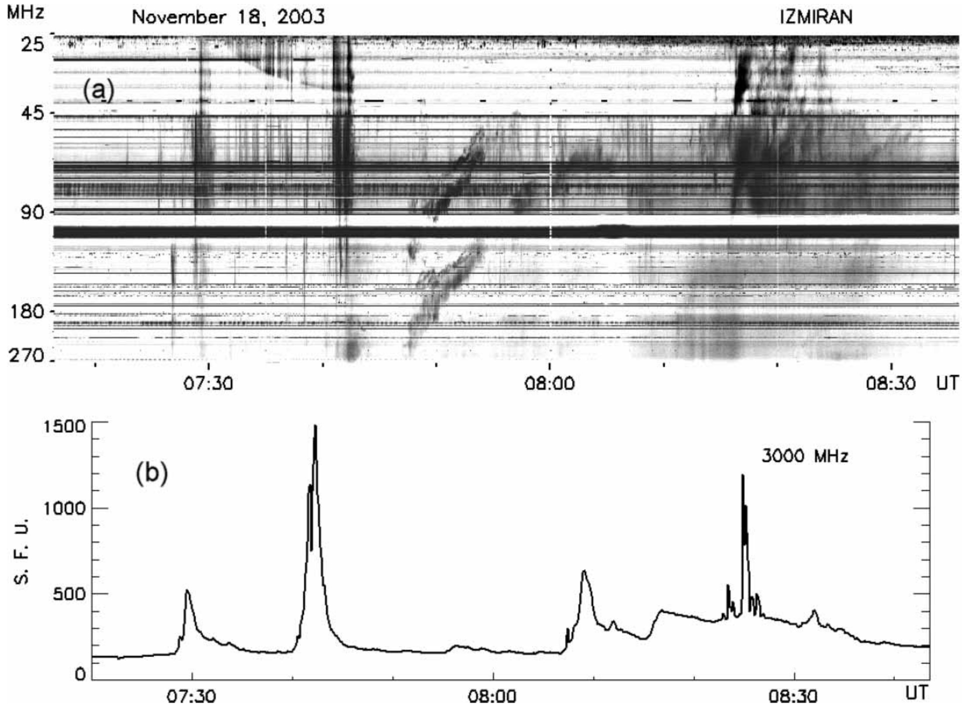

Figure 5. Radio emission of the filament-disappearance event of 18 November 2003 event: (a) the metric dynamic spectrum with the classical type II burst; (b) several microwave impulsive bursts against a background of the prolonged enhancement of the gradual-rise-and-fall burst.

of M3.2 and M3.9, peaked at 07:52 UT and 08:31 UT respectively. This flare was accompanied in particular by a huge CME that looked at first like a bright wide high-speed ($1820\,\mathrm{km\,s^{-1}}$) loop and then developed into a full halo. The associated EUV disturbances, including a coronal wave, clear dimmings and other large-scale transient features, covered almost the whole southern half of the disc [3]. In spite of the relatively faint electromagnetic emission, this large CME was a source of one of the strongest geomagnetic storms with $D_{\mathrm{st}} \approx -472\,\mathrm{nT}$.

Similar to other filament-associated CMEs, this event was followed by rather simple metric radio bursts (figure 5(a)). A very clear, almost classical type II burst with harmonic structure and band splitting was generated between two groups of type III bursts. An average rate of the negative frequency drift of the fundamental type II band can be estimated as $-0.15\,\mathrm{MHz\,s^{-1}}$.

The microwave emission at 3000 MHz (figure 5(b)) was also typical of filament-associated CMEs. It had the appearance of a faint prolonged enhancement (gradual-rise-and-fall burst) against a background in which several short bursts were generated. The two strongest of these appear to be close in time to two type III groups presented in the metric dynamic spectrum.

6. Concluding remarks

Our analysis of the IZMIRAN radio observations of the violent October–November 2003 activity revealed some important points.

The observed strong enhancement in the metre-wavelength noise storm means that a permanent particle acceleration in particular, electrons with an energy of tens of kiloelectronvolts occurred over the large-scale and evolving complex of three huge ARs mainly during its first passage across the disc. The microwave background S-component was strongly enhanced as well. Usually this S-component is attributed to thermal bremsshtrahlung and gyrocyclotron emission over strong sunspots. It is reasonable to suppose that, in this case, the very intense microwave background emission not only was generated because of the thermal mechanisms mentioned above but also had a considerable non-thermal contribution [9], perhaps from the same permanently accelerated electrons.

We have also analysed several sporadic events that took place in the October–November 2003 period. They were associated with very powerful flares and huge high-speed CMEs and were accompanied by large-scale disturbances in the inner corona (e.g. by EUV coronal waves and dimmings [3]). This means that the corresponding shock fronts were also very extended, covered a large area and propagated in the corona with a high speed. In the circumstances, one can expect that metric type II bursts would consist of several rather broad diffuse and even overlapping drifting bands because different parts of the shock front cross simultaneously many coronal structures with different plasma densities and therefore should generate radio emission at different frequencies. The type II burst in the 28 October 2003 event (section 3) seems to be the closest to this picture. However, there are type II bursts which, in spite of certainly a very large extension of a corresponding shock front, have either clear discrete narrow bands with classical harmonic and splitting structures (as in the 18 November 2003 event (section 5)) or even consist of numerous extremely narrow drifting elements (as in the 3 November 2003 event (section 4)). Several other type II bursts with this kind of fine structure have been observed before [10, 11]. The appearance of type II bursts with classical and especially with fine structures appears to remain a puzzle, although Uchida [12] showed that the radio emission should be generated in those discrete sectors of a shock front that propagate via coronal structures with a comparatively faint magnetic field and enhanced plasma density where the Alfvén speed is sufficiently small. In the strongly structured corona, the emission bands generated by an extended shock within numerous separate structures [13] should overlap and merge with each other in the dynamic spectrum. In a series of powerful repeating large-scale events, such as the October–November 2003 activity, the occurrence of type II bursts with classical and fine structures can be additionally impeded by the fact that a shock in the given event propagate via the corona strongly perturbed by a CME from a previous event.

An interesting feature is also displayed by microwave bursts. There are flare–CME-associated events (28 October 2003 (section 3) and 3 November 2003 (section 4)) in which, together with an impulsive component coinciding usually with groups of type III bursts, an additional delayed and often predominating component is observed. This delayed and intense microwave component is identified as a post-eruptive or post-CME component (see for example, [14, 15]). It is thought to be generated in the late stage of the eruptive event when the magnetic field, strongly disturbed by a huge CME, relaxes to a new quasi-equilibrium configuration by means of reconnection high in the corona. The corresponding prolonged energy release manifests itself by particle acceleration (sometimes to high energies) and related long-duration emissions in the microwave, X-ray and other ranges, as well as by the development of large loops, giant arches and arcade. The time delay between impulsive and post-eruptive components can range from 10–15 min to several tens of minutes. According to the estimations of Somov [16], such a delay corresponds to the time required for formation of high coronal current sheets in the process of the post-CME reconnection. In CME-associated events caused mainly by filament disappearance some distance away from ARs (such as that on 18 November 2003), the post-eruptive microwave emission has the appearance of a gradual-rise-and-fall burst.

Acknowledgements

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