CORRELATED RADIO BURSTS OBSERVED AT METRIC AND MILLIMETRIC WAVELENGTHS

P. ZLOBEC$^1$, S. URPO$^2$, B. VRŠNAK$^3$, R. BRAJŠA$^3$
and V. RUŽDJAK$^3$

$^1$Trieste Astronomical Observatory, I-34131 Trieste, Italy
$^2$Metsähovi Radio Observatory, SF-02150 Espoo, Finland
$^3$Hvar Observatory, HR-10000 Zagreb, Croatia

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Abstract. Characteristics of the bursts that occur almost contemporaneously at metric and millimeter wavelengths are presented. It is found that such events are rather rare. The correlated impulsive bursts observed at 237 MHz and at 37 GHz start in average almost simultaneously (time difference 0.3±2.8 s). The first peaks at 37 GHz are delayed few seconds (3.1±3.0 s) in respect to the 237 MHz peaks, whereas for the bursts maxima the delay is about 1s in average (1.0±2.7 s). A weak correlation between peak fluxes at 37 GHz and 237 MHz is found. Spectral characteristics of these events indicate electron beams of extremely high energies. The association of the gradual bursts observed at 37 GHz and the phenomena at 237 MHz is not so clear, however in some cases a relationship was established.

Key words: solar radio bursts - metric wavelengths - millimeter wavelengths - correlations

1. Introduction

Nearly simultaneous bursts activities at metric and mm-wavelengths were investigated by several authors. Raoult et al. (1989) studied a series of events observed at 22 GHz (Itapetinga radiotelescope) and 169 MHz (Nançay Radioheliograph) that occurred on 22 and 23 November 1982. They found a high degree of association between microwave
and type III bursts. Out of 34 type III groups, 26 of them (77%) were accompanied by 22 GHz emission. A very good peak to peak time association was found, mainly at the initial phase of the events. The authors concluded that the bursts at the two frequencies so far apart were produced by a common injection of electrons, lasting for a few seconds. Most of the associated maxima coincided within 0.5 s. There is a slight peak in the distribution that corresponds to a small delay (0.2 s) of the 22 GHz peaks in respect to the type III bursts maxima. The inferred electron speed was estimated to be at least 0.6 c corresponding to energies up to 640 keV.

In the paper by Trevisan et al. (1990) two events of the same set, observed at 22 GHz and at 408, 327 and 237 MHz were studied. In one event the peaks at 22 GHz were either preceding or coincident with the associated metric burst peaks (time difference smaller than 0.5 s). In the other event the results were opposite: the peaks of mm burst were delayed by 0.2-0.7 s after the peaks at metric wavelengths. Previously, Sawant et al. (1984) analysed the same events and had found that the time profiles at 22 GHz fit better the trend at 237 MHz than those at 327 or 408 MHz.

Ruždjak et al. (1996) investigated 11 impulsive events that were recorded at 37 GHz (Metsähovi Observatory) and nearly simultaneous type III bursts found at metric wavelengths in the dynamic spectra recorded on film at Weissenau Observatory. The distribution of time lags of 27 individual bursts showed delays of the 37 GHz frequency events in respect to the type III burst ranging from 1 to 5 s.

Robinson and Benz (2000) considered the "bidirectional" type III bursts from the theoretical standpoint. They concluded that the emission at frequencies above 1 - 2 GHz can escape with a considerable intensity only if it originates from a high density source region with a steep density gradient.

2. The Data Set

In preparing this paper simultaneous observations recorded during the years 1978-1984, 1989-1993 and 1999-2000 at 37 GHz (Metsähovi Observatory) and at 237 MHz (Trieste Astronomical Observatory) were
considered. The data include also a few records at 22 and 87 GHz meanwhile data of the TAO at 327, 408 and 610 MHz were also at disposal. The time accuracy was better than 1s. The list of the events recorded at Metsähovi at the time of the TAO radiotelescope observations contains about 400 entries. Preliminary results based on the selected events that are considered here were presented by Urpo et al. (1999).

In the Metsähovi list of events the position of the active region that was observed is reported. As the TAO radiotelescope has a very poor spatial resolution, we are not able to localize the burst sources. Therefore we only checked if the position of the associated Hα flare coincided with the Metsähovi radio position. Only if this condition was fulfilled, we considered an association possible. The radio sources were distributed in the central meridian distance range ±60°.

The possible candidates of correlated activity were carefully checked and for that purpose some radio spectra from Ondřejov and Nançay observatories were also used, as well as the records at fixed frequencies of Tremsdorf Observatory. Preliminary, 26 events were selected (that corresponds to about 6% of the Metsähovi selected events), afterwards few of these appeared doubtful and were skipped.

We realized that a correlated activity resembling the events recorded in November 1982 (Raoult et al., 1989) is extremely rare. Similar events were found only during 6 and 8 June 1980, when the considered bursts were associated with an active region that was rather close to the disk center (S15E40 and S15E05 respectively).

The selected events were categorized as ”impulsive” and ”gradual” according to the Metsähovi classification. The number of the bursts in the Metsähovi lists (during the common observing time) was 298 and 96, respectively. The events of the first group last up to one minute, the others are considerably longer. Some events are complex showing both components.
Figure 1: An example of correlated impulsive bursts at 237 MHz (top) and 37 GHz (bottom).

3. Impulsive 37 GHz Events

3.1. Relative Timing

An example showing correlated impulsive bursts at 37 GHz and 237 MHz is presented in Figure 1. Let us stress that the events of this kind, exposing a certain degree of morphological similarity, were found only on 6 and 8 June 1980. It is worth noting that the time profiles at the two frequencies are similar only at the beginning of the burst, so the shortest events show the greatest similarity. In the following, two impulsive events were considered as associated if their onsets, or the
Figure 2: a) Time differences between onsets of the 37 GHz and 237 MHz bursts (crosses) and between the first peaks (triangles). b) Time differences between the beginning of the main microwave peak and the start of the strongest type III burst (crosses) and between main maxima (triangles). In the insets the time differences are shown in a form of a cumulative distribution. The corresponding mean values are drawn by dotted and full lines, respectively.
main burst maxima, were in the time interval of 10 s.

First, the onset times of 37 GHz bursts \(t^{b1}_{MW}\) were compared with the start of the associated type III burst groups at 237 MHz \(t^{b1}_{III}\) and their differences \(Dt_{b1} = t^{b1}_{MW} - t^{b1}_{III}\) were determined. In four events the start at both frequencies was coincident and for other nine cases it was \(Dt_{b1} \leq 6\) s (see Figure 2a). The mean value amounts to \(\overline{Dt_{b1}} = 0.3 \pm 2.8\) s.

Next, the relative timing of the first maximum at 37 GHz \(t^{m1}_{MW}\) and the first maximum at 237 MHz \(t^{m1}_{III}\) was considered. No time difference \(Dt_{m1} = t^{m1}_{MW} - t^{m1}_{III}\) was negative. In three cases \(Dt_{m1} = 0\) was found and in seven cases the differences were up to 5 s. The mean value amounts to \(\overline{Dt_{m1}} = 3.1 \pm 3.0\) s.

The values of \(Dt = t^{b1}_{MW} - t^{b1}_{III}\) and \(Dt = t^{m1}_{MW} - t^{m1}_{III}\) are shown graphically in Figure 2a. Each line represents one event. In the inset of the same figure the results are represented in the form of cumulative distributions, emphasizing more clearly the general timing pattern.

When the beginning of the fast rise towards the maximum of a 37 GHz burst is compared with the start of the strongest type III burst at 237 MHz, the time differences (\(Dt_{b2}\)) are generally negative (Figure 2b). In average the start of the strongest burst at 237 MHz was delayed by \(3.6 \pm 4.5\) s. On the other hand, the main maxima of 37 GHz bursts show in average a delay of \(\overline{Dt_{m2}} = 1.0 \pm 2.7\) s after the strongest type III bursts (Figure 2b).

In order to check the associated events at the dm and cm band the Tremsdorf records at single frequencies in the range 778 - 9500 MHz were used. It was found that bursts were present at about the same time as at 37 GHz, except one event in which no burst was recorded at these frequencies.

Finally, it is important to specify the type of the spectral characteristics of the associated type III events. We found that all, except one, of the 15 studied type III burst groups were of the subtype described in the paper by Benz and Zlobec (1978) as ”large” type III bursts. Poquérusse (1994) studied these phenomena in detail and called them ”type IIIId”. He found that they are generated by electron beams at speeds probably larger than about 0.8 c, so the energy of the electrons can be in the order of 1 MeV. This is consistent with the conclusion by Bastian, Benz and Gary (1998) that MeV electrons are responsible
for bursts at mm-wavelengths.

3.2. Summary and Interpretation

Since the considered bursts at 37 GHz and 237 MHz are well associated in time, showing also a certain degree of similarity in time profiles, it is reasonable to assume that the electrons exciting the emission were accelerated by the same process. The beginnings of the associated events approximately coincide in time whereas the first maxima of the mm emission are delayed in average by about 3 s.

To interpret these results let us consider a model in which the acceleration site is located at the height of about 30000 km above the source of the mm radiation and that the origin of the observed type III burst emission is situated at the height of \( \approx 150000 \) km (see Stewart, 1976). In such a case the emission from the 37 GHz layer needs about 0.5 s to reach the 237 MHz layer. This means that the excitation at the 37 GHz source starts in fact 0.5 s earlier than the excitation of the 237 MHz layer. On the other hand, the maximum of the mm flux is emitted in fact 2.5 s after the electrons had reached the 237 MHz layer. So, it can be concluded that the first electrons come to the mm source about 0.5 s earlier than to the 237 MHz layer. However, the majority of electrons producing type III bursts reach the 237 MHz layer about 2.5 s before the majority of electrons emitting the mm radiation reaches the 37 GHz layer. An ad hoc explanation can be proposed assuming that the mm radiation maximum is attained only after the electrons with large pitch angles reach the source region from the acceleration site. Due to the large pitch angles these electrons propagate downwards along the field lines much slower than the electrons of the same energy but with smaller pitch angle. The electrons with a velocity of \( \frac{2}{3} \) c=200000 km/s and small pitch angles need about 0.75 s to overcome the height difference of 150 Mm. Since the first electrons producing mm radiation reach the source region 0.5 s before this, one finds that their velocity component along the field lines has to be \( v_\parallel = \frac{30000}{0.25} = 120000 = \frac{2}{5} \) c. Taking into account that we have considered electrons accelerated to velocities up to \( \frac{2}{3} \) c, one finds that the corresponding pitch angle is about 50°.
Considering the time delay of the first maximum, one finds the value of $87^\circ$ for the pitch angle.

Aschwanden et al. (1995) found that the dm/m emission associated with hard X-ray peaks is delayed for about 0.35 s. Since hard X-rays need about 0.5 s to reach the radio emission layer, one finds that the electrons reach the hard X-ray source 0.85 s earlier than the radio source. This is consistent with the time that the electrons need to reach the radio emitting layer, implying that the hard X-ray emission is caused by small pitch angle electrons whose motion is negligibly affected by the magnetic mirror effect.

There is another fact that has to be taken into account when electrons with large pitch angles are considered. The downward streaming electrons penetrate into the region of increasing magnetic field and due to the magnetic mirror effect their longitudinal velocity decreases. So, they spend a rather long time in the mirroring region in comparison with the travel time near the acceleration region. It means that newcomers increase the number of high energy electrons gyrating in this region and emitting microwave radiation. Thus, a kind of cumulative effect has to be expected. That is supported by the fact that 37 GHz events normally last longer not only than a type III burst but also longer than a group of such bursts.

To summarize, the observations can be interpreted in a rather simple way: metric and hard X-ray emissions are generated by fast electrons with small pitch angles, whereas the microwave radiation is caused by fast electrons with large pitch angles. The delay of the microwave emission can be explained as a result of two effects: the comparatively small longitudinal velocity component, and by the longitudinal deceleration in the mirroring region, causing the accumulation of gyrating electrons in the source region. When we look at the relative maxima in the 37 GHz records, we find different peaks at 237 MHz that should be associated. That depends on the generally multiple presence of type III bursts in a group. However, we considered this possible association to be strongly biased on random association and therefore not adequate for further study.

For the selected events we also considered the maximum flux of the meter and mm associated events (see Figure 3). The measured values
Figure 3: The 237 MHz peak fluxes are shown versus the associated 37 GHz peak fluxes. One event was saturated (arrow).

are very scattered, however a trend is evident, i.e. higher fluxes at 37 GHz are tendentially accompanied by stronger maxima at 237 MHz.

4. Gradual 37 GHz Events

A possible relationship and relative timing of gradual 37 GHz events and two types of activity at 237 MHz are investigated: a) impulsive bursts (type III) and b) gradual events (gradual rise and fall (GRF) and type IV bursts). It is important to stress that in gradual events at 37 GHz the flux increase is initially very low and often it is difficult to evaluate the starting time adequately. After some minutes the growth of flux becomes significantly faster. Sometimes the slow beginning of the burst is missed.
Figure 4: a) Time differences between onsets of gradual 37 GHz and 237 MHz type III bursts (crosses) and between the maxima (triangles). b) Time differences between onsets of gradual 37 GHz bursts and gradual 237 MHz bursts (crosses) and between the maxima (triangles). In the insets the time differences are shown in a form of a cumulative distribution. The corresponding mean values are drawn by dotted and full lines, respectively.
4.1. Relative Timing of the Associated Type III Bursts

In Figure 4a the relative timing of gradual mm bursts and 237 MHz type III bursts is shown. The time differences between the onset of the fast increase at 37 GHz and the start of the type III group at 237 MHz is generally negative, implying that generally type III burst activity starts after the onset of fast microwave flux rise. Therefore the time difference is still greater when related to the slow increase at mm wavelengths and the relative time differences are not reported here. In four out of ten cases the difference was up to 1 min. The mean value is $-2.6 \pm 4.7$ min.

When the time differences between the maximum of gradual events at 37 GHz and type III bursts are considered one finds that only one out of ten cases shows a slightly negative value, implying that most often the type III burst activity reaches maximum before the mm radiation. In four cases the time difference is smaller than 1 min. The mean value is $2.1 \pm 3.0$ min.

In the inset in Figure 4a the results are presented in the form of cumulative distributions. The steepest parts of the distributions reveal that most often the type III burst activity starts few minutes after the microwave fast rise onset and becomes the highest at the time of the maximum of the mm bursts.

4.2. Timing of the Associated 237 MHz GRF and Type IV Bursts

In 7 cases gradual events at 37 GHz were accompanied by similar events at 237 MHz. The $Dt$ values regarding the slow start were generally rather large (the smallest was 35 s), sometimes exceeding 200 s (three negative and four positive values – see Figure 4b).

It is possible that a part of these events was not physically associated, but it is important to mention at least three particular cases. In the high frequency Tremsdorf records it was found that there was a systematic shift of the starting times in these events. Therefore it is worth evaluating an approximate speed of the agent exciting the radio emission at different coronal layers between the 37 GHz and 237 MHz.
Figure 5: An example of the 237 MHz event associated with a gradual 37 GHz event (October 14, 1983). The y-axis is in arbitrary units.

levels. We assume the same height difference as in section 3.2 and as reference the time of the fast increase at 37 GHz. For the events of 17 June 1982 and 14 October 1983 the inferred velocities were about 3750 km/s and 200 km/s respectively. It is important to stress that the second event showed a similar evolution at 37 GHz and 237 MHz (Figure 5; see Karlický et al., 1987 for details). For the event of 16 May 1981 the start of the type IV burst was recorded first at about 237 MHz and then progressively the activity start was recorded up to 9.5 and 37 GHz, corresponding to a speed of about 40 km/s. The beginnings at lower frequencies were also progressively delayed (Tremsdorf data
down to 40 MHz) corresponding to a speed of about 1500 km/s. It is important to note that for the first two events (GRF burst) the starts appeared first at mm wavelengths, whereas the third event (type IV burst) started in the meter band.

The values of the time lags between the fast increase at 37 GHz and the start of the GRF (and type IV) events at 237 MHz are summarized in Figure 4b. Three values were negative and three positive. The scatter is rather large. The mean value amounts to 1±10 min. The time differences between the maximum of the gradual events at 37 GHz and the maximum of the metric long lasting bursts are also widely scattered. The mean value amounts to −0.8±8.1 min. The cumulative distributions are shown in the inset in Figure 4b.

We are confident that a relationship between gradually evolving events at the two so apart frequencies exists not only for the events presenting evident spectral drifting, as the movement of the source agent can be different for each phenomenon and in particular it can be directed towards higher or lower coronal layers.

4.3. Summary and Interpretation

Most of the type III bursts activity accompanying gradual mm events occurs during the fast rise phase of microwave events. Quite often the maximum of the type III activity is almost contemporaneous with the maximum of the mm event (Figure 4a). This is consistent with the results obtained by Vršnak et al. (2000). In interpreting the results one has to bear in mind the different nature of mechanisms that generate these two types of events, i.e. acceleration and escape of fast electrons exciting type III bursts and trapping of electrons generating high frequency events. So, the relation between type III bursts and microwave events indicates that the latter process is a cumulative effect of an acceleration process.

Metric GRF and type IV bursts associated with gradual events in the mm wavelength range are suggestive of a perturbation drifting over wide range of frequencies. The inferred motions are not very different than the normally considered coronal Alfvén velocities. Such events are usually associated with the lift-off phase of CMEs (Aurass et al.,
1999) when large coronal volumes are perturbed.

5. Conclusions

Only electrons accelerated to extremely high energies can cause contemporaneous impulsive bursts at metric and mm wavelengths. Strong, highly sheared fields, such as found above large sunspots in Z-flares, are needed to provide a sufficiently efficient acceleration. Furthermore, the energy release site must be connected to open field lines to enable escape of the electrons exciting type III bursts. These constraints explain why such events are so rare. The time delays of impulsive mm and metric bursts indicate that most of the mm events are radiated by electrons having large pitch angles, in excess of 50°. Gradual bursts are probably related to the launch of CMEs.

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References

KORELIRANE PROVALE RADIO ZRAČENJA NA METARSKIM I MILIMETARSKIM VALNIM DUŽINAMA

P. ZLOBEC\textsuperscript{1}, S. URPO\textsuperscript{2}, B. VRŠNAK\textsuperscript{3}, R. BRAJŠA\textsuperscript{3}
i V. RUŽDJAK\textsuperscript{3}

\textsuperscript{1}Trieste Astronomical Observatory, I-34131 Trieste, Italy
\textsuperscript{2}Metsähovi Radio Observatory, SF-02150 Espoo, Finland
\textsuperscript{3}Hvar Observatory, HR-10000 Zagreb, Croatia

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\textbf{Sažetak.} Prikazuju se svojstva provale radio zračenja koja se skoro istovremeno odvijaju na mm i m valnim dužinama. Ustanovljeno je da su takvi događaji prilično rijetki. Korelirane impulzivne provale radio zračenja opažane na 237 MHz i 37 GHz u prosjeku započinju skoro istovremeno (razlika u vremenu 0.3\pm0.2 s). Prvi vršci emisije na 37 GHz zaostaju nekoliko sekundi (3.1\pm0.3 s) za onima na 237 MHz, dok zaostatak iznosi prosječno (1.0\pm0.2 s) za maksimum emisije provala radio zračenja. Nađena je slaba korelacija između najvećih tokova zračenja na 37 GHz i 237 MHz. Spektalne karakteristike tih događaja ukazuju na pojavu ekstremno visokoenergetskih snopova elektrona. Korelacija postepenih provala radio zračenja opažanih na 37 GHz i 237 MHz nije tako jasna, međutim za neke slučajeve utemeljena je povezanost.

\textbf{Ključne riječi:} Sunčeve provale radio zračenja - metarske valne dužine - milimetarske valne dužine - korelacija