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MICROWAVES AND HARD X-RAYS ULTRAFAST TIME STRUCTURES AT THE IMPULSIVE PHASE OF SOLAR BURSTS

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ABSTRACT. Recent results on ultrafast time structures observed at microwaves and hard X-rays in the impulsive phase of solar bursts are briefly reviewed in terms of diagnostics and implication on interpretation of accelerating mechanisms.

Key words: Solar Bursts, microwave/X-rays bursts.

The use of antennas with large collecting areas has improved considerably the sensitivity and time resolution in centimeter and millimeter wavelengths in solar bursts (Kaufmann, et al. 1975, 1982a; Butz et al. 1976; Tapping, 1983a). The 45ft radome-enclosed antenna of Itapetinga, Brazil, operating at 22 GHz and 44 GHz, was used intensively during the SMM operation, providing data with unprecedented sensitivity(0.03 s.f.u. in single linear polarization) and high time resolution (1 ms) revealing various new aspects of low level solar activity as well as detailed fine structures in larger bursts. In essentially all bursts analyzed so far with high sensitivity at mm-microwaves, fine time structures (< 1 sec) are identified superimposed to the slower time structures (seconds). The repetition rate of the ultrafast stuctures appear to be higher, for higher mean flux (see Fig. 1). Kaufmann et al. (1980a) and (1980b) suggested that a possible explanation is a quasi-quantization in energy of the burst response to the energetic injections. An early suggestion on flare - response to quasi-quantized energetic injections was derived from statistical properties of a collection of X-ray bursts (~ 10 KeV) (Kaufmann et al.1978). A trend similar to that in Fig. 1, was found independently at 10.6 GHz for various bursts (Wiehl and Mätzler, 1980) but at larger flux and time scales. It appears now that the identification of faster repetition rates is a sensitivity-dependent parameter. For a given burst flux level S there is a minimum repetition rate of ultrafast structures R, such as $S < k.R$ where k is a constant. One of the faster repetition rates was found at the peak of an intense spike-like burst (Fig. 2) also observed at hard X-rays by HXRBS at SMM (Kaufmann et al. 1984a). A striking example obtained simultaneously at microwaves and hard X-rays is the burst of November 4, 1981 at 1928 UT (Takakura et al. 1983a) (Figs. 3, 4). High-sensitivity 10.6 GHz data for the same burst was obtained with the 45-m antenna at Algonquin Radio Observatory, HIA, NRC, Canada (Tapping 1983b). The presence a "ripple" is evident at all microwave frequencies and is very significant at 30-40 keV range (HXM, Hinotori). The ripple relative amplitude ($\Delta S/S$) is of about 30% at 30-40 keV, 1% at 22 and 44 GHz and 0.4% at 10.6 GHz. The apparent lack of phase agreement for certain peaks might or might not be real. Confirmation of a nearly one-to-one correspondence of mm-microwave vs hard X-ray association of superimposed ripples was obtained for the November 13, 1981, at 1102 UT solar burst (Fig. 5). A summary of the most important results are the following: (a) the slow time structures (seconds) are often poorly correlated, or not correlated, at 4 Microwaves frequencies (7, 10.6, 22 and 44 GHz) and at 30-40 keV X-ray; (b) the superimposed "ripple" components are present and correlated (although phase differences might be present) in data obtained simultaneously by two radio-observatories widely separated from each other (Brazil and Canada) and by a X-ray space experiment (HXM, HINOTORI).

At hard X-rays there were several other independent evidence on subsecond time structures (Hurley and Duprat 1977 ; Charikov et al. 1981; Dennis et al. 1981; Kiplinger et al. 1983; and Hurley et al. 1983). The hard X-rays burst fluxes might also be proportional to the repetition rates of basic units of energy injection (quasi-quantized) (Kaufmann et al. 1984a).

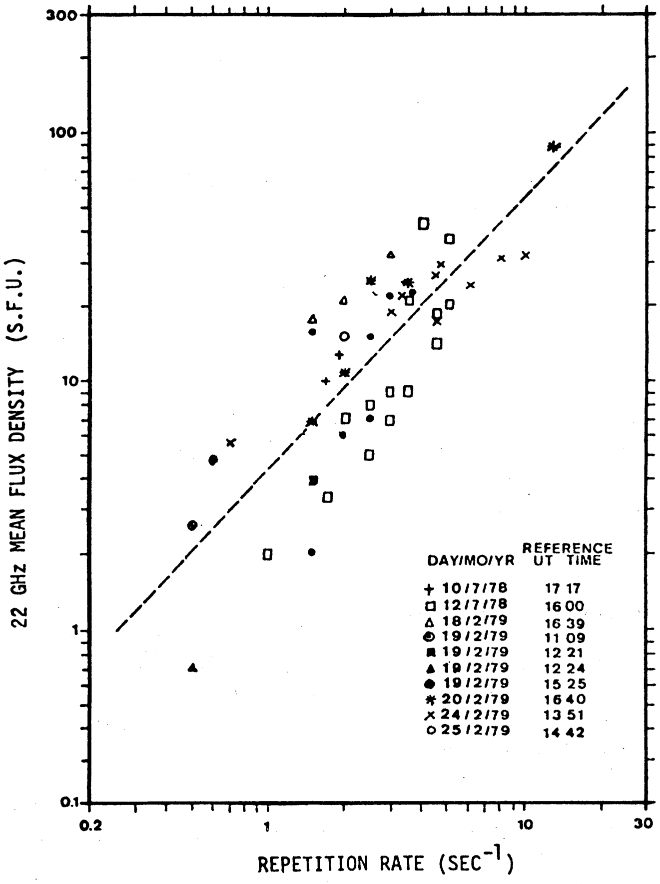

FIGURE 1. Sccatter diagram of repetition rates R(s^{-1}) of fast time structures superimposed on solar bursts at 22 GHz against the mean flux value S(s.f.u.) for various bursts observed in 1978-1979 with the 13.7-m Itapetinga antenna (Kaufmann et al. 1980a).

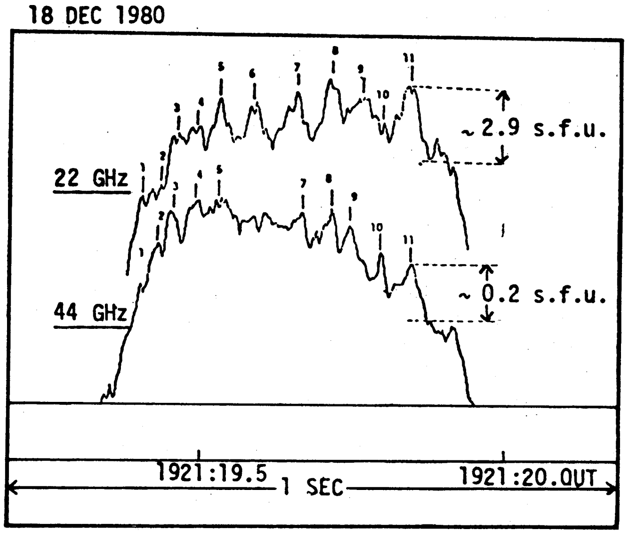

FIGURE 2. One-second section at the peak of an intense spike-like burst, displaying ultrafast time structures repeating every 30-60 ms at 22 GHz and 44 GHz (Kaufmann et al. 1984).

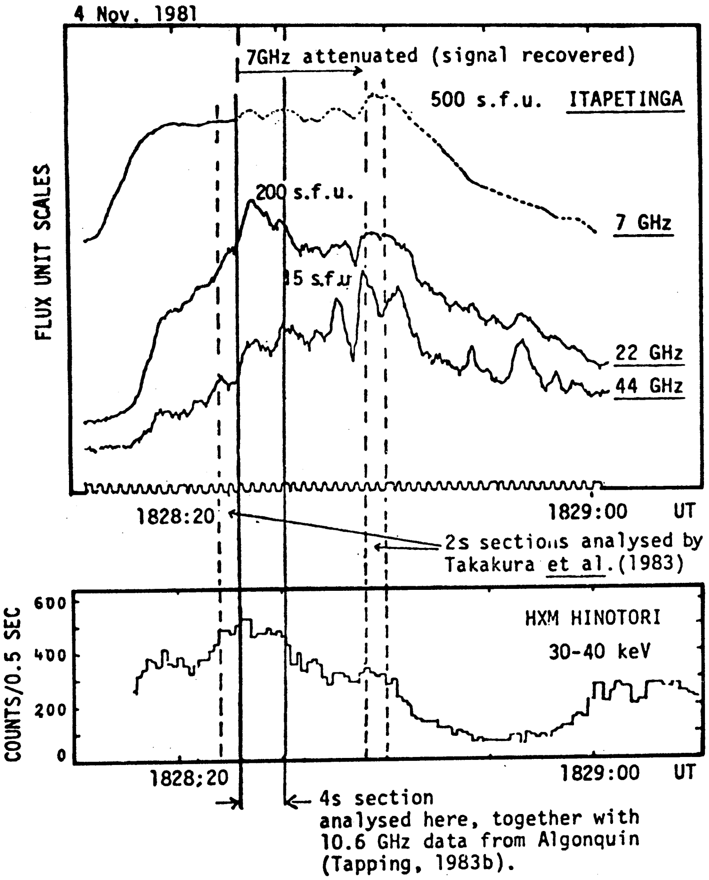

Fig. 3. Solar burst of 4 November 1981, 182 UT in compressed time scale, with emission at radio (7, 22 and 44 GHz from Itapetinga) and hard X-rays (30.40 KeV, from HXM at HINOTORI). A 4s section is expanded in Fig. II.25, with the addition of 10.6 GHz data (from Algonquin, Canada). Note that the slower time structures (seconds) are in general not well correlated at the different radio frequencies and hard X-rays.

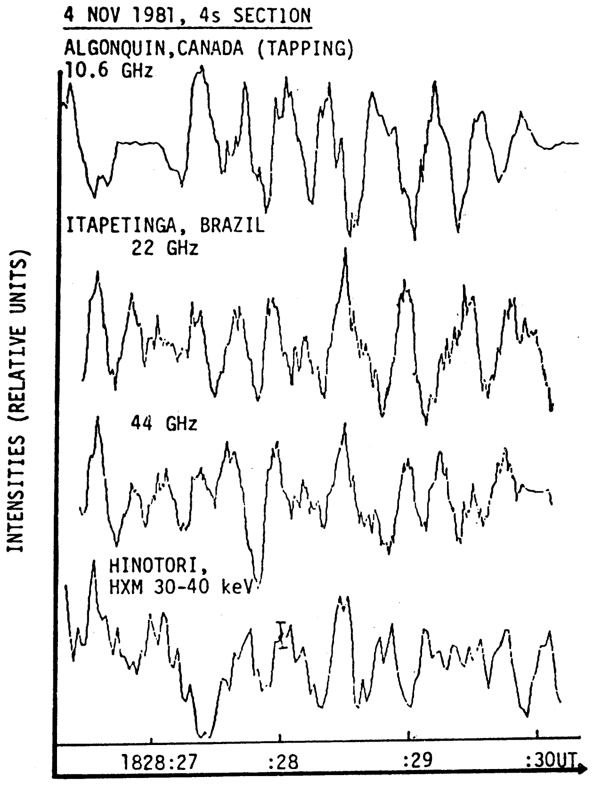

Fig. 4. 4s expansion of the burst section indicated in Figure 3, exhibiting the superimposed fast time structures (repeating at about 2.5 s^{-1}), observed simultaneously at 10.6 GHz by Algonquin 45-m antenna (Tapping 1938b), at 22 GHz and 44 GHz by Itapetinga 13.7-m antenna, and at 30-40 KeV by HXR at HINOTORI.

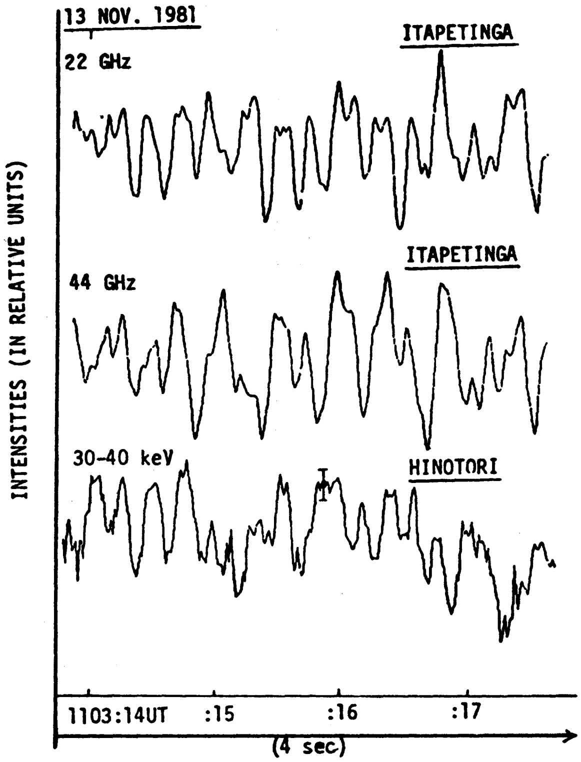

FIGURE 5. Confirmation of ultrafast time structures (about 4 s^{-1}) superimposed to another solar burst emission (13 November 1981, 1103UT) observed simultaneously at 22 and 44 GHz (Itapetinga) and at 30-40 keV (HINOTORI) (Takakura, 1983).

The observed superimposed "ripple" might not necessarily represent actual time scales of the fast structures (Correia 1983; Kaufmann et al. 1984a; Loran et al. 1984). The "pilling up" effects of many superimposed pulses indicate that bursts can be well simulated by pulses with width considerably larger than the time scales of the "ripple" structures (Fig.6) (Loran et al. 1984). The simplest "microbursts" detected with high sensitivity at microwaves (22 GHz) by Kaufmann et al. (1984b) presented the faster e-folding rise times in the range 50-100 ms. Two categories of microbursts were suggested: the micro-impulsives (e-folding rising time $0.05 \text{ s} < t \ll 1 \text{ s}$) and micrograduals ($0.5 \text{ s} < t < \text{s}$), and therefore extending the classical Covington scatter diagram (Covington and Harvey 1958) into much smaller scales of fluxes and durations (Fig. 7).

A number of complex microwave bursts were analyzed at various frequencies, and quite often the time structures were not correlated in time. Delays of peak emission at different microwave frequencies range from near coincidence to 3 sec, both toward higher and toward lower frequencies (Kaufmann et al. 1980a; 1982b). Delays towards lower frequencies only were reported by Uralov and Nefed'ev (1976) and Wiehl et al. (1980). One long-lasting pulsating burst (1.5 sec of quasi-period) has shown a systematic delay of 300 ms of 44 GHz pulses in relation to 22 GHz pulses (Zodi et al. 1984). It might be meaningful, however, to stress out that, qualitatively, the faster time structures found seem to be well correlated (as the case of the "ripple" structures discussed above). In relation to hard X-rays, the microwave burst emission time structures often appear delayed in time. There was an early statistical indication that, for relatively slower (and smoothed) time structures, the hard X-ray were likely to occur 1-2 sec prior to microwave emission (Crannell et al. 1978). One example of a detailed high time resolution analysis was shown by Kaufmann et al. (1983) and Costa and Kaufmann (1983). A major 22 GHz burst structure is delayed by 240 ms in relation to hard X-rays ($\varepsilon > 26$ keV from HXRBS, SMM), and the 7 GHz structure is delayed by 1.5 s in

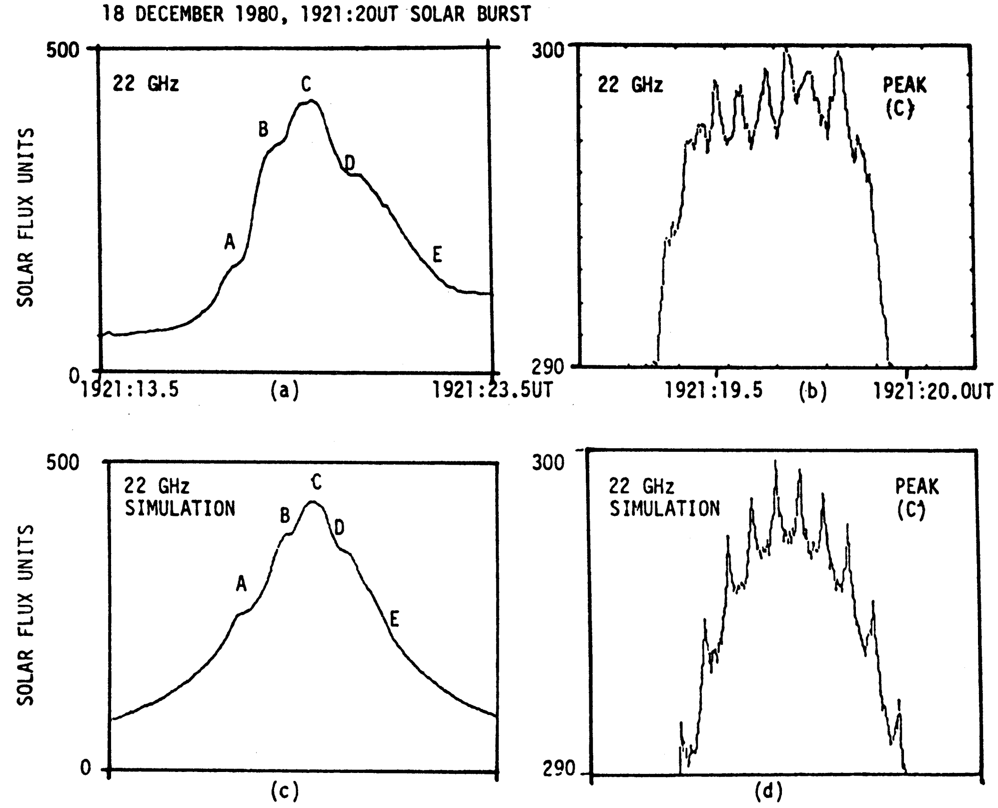

FIGURE 6. The spike-like burst of 18 December 1980, 1921:20UT as observed at 22 GHz, in a 10s time scale (a) and 1s time scale (b) (see Fig. 2. The same event is simulated below, (c) and (d) by the combined superposition of five trains of cusp like pulses, each one with different repetition rates and number of pulses at A,B,C,D and E, respectively (Loran et al. 1984).

relation to 22 GHz. The temporal behaviour of delays of a 22 GHz burst emission in relation to 30.40 keV X-rays (from HXM, HINOTORI) exhibited on overall delay of about 500 ms, with different time structures displaying different delays, ranging from 200 ms - 1 sec (Costa et al. 1984) (Fig. 8). Cornell et al. (1984) found delays for 10.6 GHz burst emission (OVRO) in relation to hard X-rays (HXRBS, ε > keV) by about 200 ms, in average, for five bursts. Finally one burst structure was analyzed at hard X-rays (HXRBS), OV and Fe XXI Lines (UVSP), Hα and HeI De lines (Big Bear) and at 22 GHz (Itapetinga) (Tandberg-Hanssen et al. 1983). The 22 GHz emission was delayed by a large amount (6 sec) in relation to hard X-rays and OV time profiles, which were nearly coincident in time.

Interpretation of delays between different microwave frequency emissions, and of microwaves with respect to hard X-rays should in fact depend largely on which time scales we are concerned, the sensitivity and time resolution of the data being analysed and the consideration of various smoothing - out effects. Such delays can be explained by assuming convolution effects of multiple emitting kernels (Brown et al., 1980, 1983; Mackinnon and Brown 1984). Another possibility assumes the microwaves emitting source moving in a varying magnetic field (Costa and Kaufmann 1983). To account for large delays of microwaves in relation to hard X-rays (several seconds), it has been suggested that microwave emission originates from another population that produced the X-rays (Tandberg-Hanssen et al. 1983). Finally, the long-enduring persistent quasi-periodic pulsations in bursts, presenting delays at different microwave frequencies, might be a phenomenon of different nature, and might be

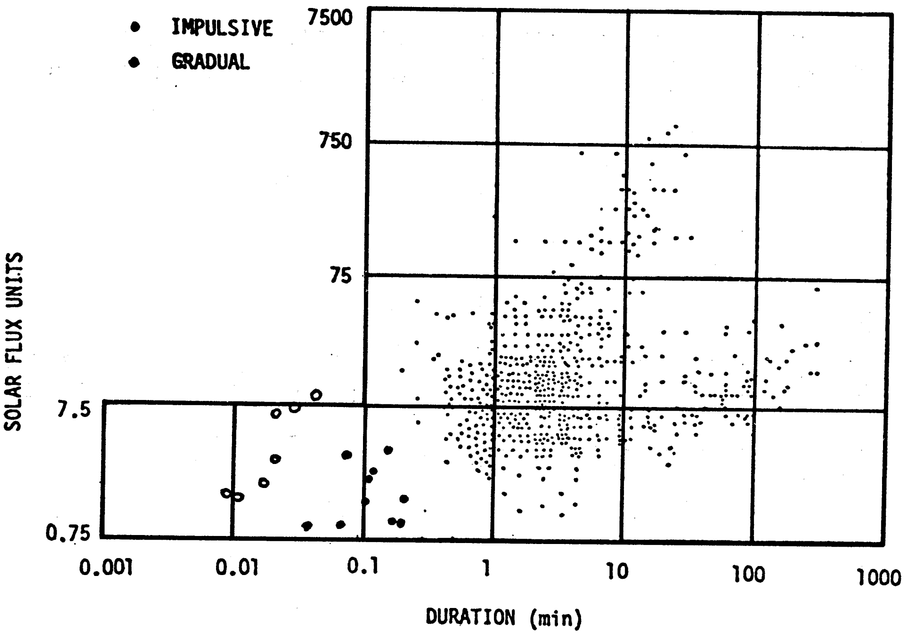

FIGURE 7. The original Convington and Harvey (1958) scatter diagram of 2.8 GHz bursts durations vs. flux units, and 22 GHz "microburst" gradual (filled circles) and impulsive (open circles) added for a qualitative comparison (Kaufmann et al. 1984b).

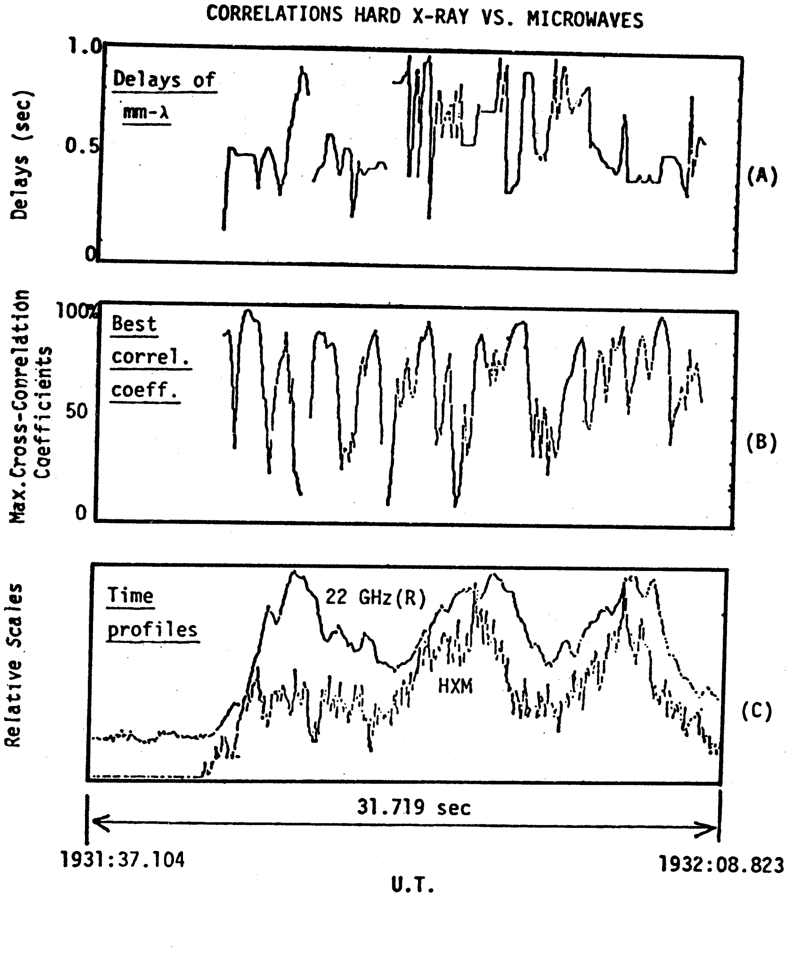

Fig. 8. Solar burst analysed at 22 GHz and at hard X-rays (HXM-HINOTORI) Costa *et al.* (1984). The burst was cross-correlated every one second intervals displaced by 125 ms (total of 192 points). The time profiles are shown in (C). The best correlation coefficients are shown in (B). The delays of microwaves with respect to hard X-rays are shown in (A). There is an overall phase displacement of 500 ms, but individual structures, or different sections of the burst, present distinct delays, ranging from 200 ms to 1 sec.

conceived as simple modulation of synchrotron emission by the magnetic field (Gaizauskas and Tapping 1980) and delays explained by taking into account the different optical depths (Zodi et al. 1984). Some burst appear to be strictly coincident in time, at various microwave frequencies and X-ray energy ranges (to less than < 100 ms) (Kaufmann et al. 1984a). On the other hand, there were no reports of bursts displaying microwave peaks proceding X-rays peaks. Large time structures (tens of seconds-minuts) exhibiting large delays (tens of seconds) observed in very large bursts might not be included in the same framework or scenario. They are discussed elsewhere in the literature and possibly represent macroscopic phenomena undergoing many unresolved composition effects. (Bai and Ramaty 1979; Vilmer et al. 1982; Takakura et al. 1983; Sawant and Kane 1983).

The impulsive phase accelerations (X-ray and microwave emission) examined with high sensitivity and high time resolution data set some constraints which must be satisfied by any model or geometry of the bursting region. Some new evidences to be further developed theoretically are the nature of "ripple" structures, the trend of flux vs. repetition rates, and suggestion of quasi-quantized energetic injections. A suggested general picture conceives the "elementary flare bursts" (5-20 sec) (van Beek et al. 1974; de Jager and de Jonge 1978) as build up by multiple energetic injections which may or may not be associated with the superimposed "ripple" structures (subsecond structures) (Kaufmann et al. 1984a). Sturrock et al. (1985) suggest that "elementary flare bursts" (seconds) arise from the energy release from an array of "elementary flux tubes", which are nearly "quantized" in flux. As a stochastic process of recombination sets in by mode interaction, explosive magnetic islands may develop in each tube, accounting for the ultrafast time structures (or "ripple") in subsecond time scale.

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