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The work conducted under this grant is documented in or contributed to the publications listed below. Abstracts and reprints of these papers are attached to this report.

1) Aschwanden,M.J., Benz,A.O. and Schwartz,R.A. 1993, "The Timing of Electron Beam Signatures in Hard X-Ray and Radio: Solar Flare Observations by BATSE/ Compton Gamma-Ray Observatory and PHOENIX", *Astrophys.J.*, **417**, 790-804.

2) Aschwanden,M.J., Benz,A.O., and Montello,M. 1994, "Coherent-Phase or Random-Phase Acceleration of Electron Beams in Solar Flares", *Astrophys. J.*, **431**, 432-449.

3) Benz,A.O., Kosugi,T., Aschwanden,M.J., Benka,S.G., Chupp,E.L., Enome,S., Garcia,H., Holman,G.D., Kurt,V., Sakao,T., Stepanov,A.V., Volwerk,M., 1994, "Particle Acceleration in Flares", *Solar Phys.*, **153**, 33-53.

4) Aschwanden,M.J. and Benz,A.O. 1995, "Chromospheric Evaporation and Decimetric Radio Emission in Solar Flares", *Astrophys. J.*, **438**, 997-1012.

5) Aschwanden,M.J., Montello,M.L., Dennis,B.R. and Benz,A.O. 1995, "Sequences of Correlated Hard X-Ray and Type III Bursts During Solar Flares", *Astrophys. J.*, **440**, 394-406.

6) Aschwanden,M.J., Benz,A.O., Dennis,B.R., and Schwartz,R.A. 1995, "Solar Electron Beams Detected in Hard X-Rays and Radiowaves", *Astrophys. J.*, **455**, 347-365.

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THE TIMING OF ELECTRON BEAM SIGNATURES IN HARD X-RAY AND RADIO: SOLAR FLARE OBSERVATIONS BY BATSE/*COMPTON GAMMA-RAY OBSERVATORY* AND PHOENIX

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ABSTRACT

We analyzed two solar flares of 1992 September 5 and 6, using the high time resolution (64 ms) hard X-ray data from BATSE/*CGRO*, and 100–3000 MHz radio (100 ms) dynamic spectra from PHOENIX. The broad-band radio data reveal a separatrix frequency (at 620 and 750 MHz in the two flares) between normal- and reverse-drifting radio bursts, indicating a compact acceleration source where electron beams are injected in both the upward and downward direction. We find a mean injection rate of 1.2 bursts s^{-1} in one flare and more than 0.7 bursts s^{-1} in the other. From 12 broad-band, reverse-drifting radio bursts we find in five cases an unambiguous one-to-one correlation between the reverse-drifting radio bursts and hard X-ray (HXR) pulses of similar duration (400 $\pm$ 220 ms). The high significance (15 $\pm$ 6 σ) of the HXR pulses and the small scatter ($\pm$150 ms) in the relative timing strongly supports a close causal connection. The cross-correlation between HXR and radio pulses shows that the HXR pulses are coincident (within the instrumental time resolution) with the reverse-drifting bursts at the injection frequency (880 $\pm$ 50 MHz), and lead the radio bursts by 270 $\pm$ 150 ms at the highest observable frequency (1240 $\pm$ 100 MHz). The average drift time of the downward propagating radio bursts is measured to 150 ms, corresponding to a drift rate of 2350 MHz s^{-1}.

We examined various effects to model the observed timing of radio and HXR pulses (propagation delays, radio wave growth and damping, group velocity delays, radio wave scattering, radio wave ducting, light path differences, etc.). Assuming an exciter velocity of $v_R/c = 0.2 \pm 0.1$ for the reverse-drifting radio bursts, we infer an altitude difference of $H = 8000 \pm 3000$ km between the injection site and the HXR source. The most likely explanation for the retarded radio emission seems to be a combination of the following two effects: (1) HXR-emitting (>25 keV) and radio-emitting electrons have different energies (the exciter velocity of the reverse-drifting radio bursts is associated with $\lesssim$5 keV electrons), and (2) a low (marginal) growth rate for plasma emission at the second harmonics. Delay effects caused by group velocity, collisional damping, wave scattering, and wave ducting are found to be minor (<30 ms each).

Subject headings: Sun: corona — Sun: flares — Sun: particle emission — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

For several decades the dynamics of rapid energetic processes in solar flares has been explored by analyzing the various radiative signatures of accelerated particles, such as nonthermal hard X-rays (HXRs), gamma rays, and coherent radio emission. A simple technique to investigate the nature of particle accelerators operating in solar flares is to count and measure radio type III bursts, the most unambiguous tracers of propagating electron beams in the solar corona. However, in order to ensure that the radio bursts and their evolution is related to the primary energization process and not to secondary effects, it is highly desirable to establish a correlation of electron beam signatures in different physical processes, e.g., HXR bremsstrahlung and coherent radio emission. One of the most crucial tests is a correspondence of fine structures in widely separated wavelength regimes, and the relative timing of correlated fine structures.

First correlative studies were concentrated on groups of metric/decimetric type III bursts and multiple X-ray spikes (Kundu 1961; Kane 1972; Kane, Pick, & Raoult 1980; Kane & Raoult 1981; Kane 1981; Kane, Benz, & Treumann 1982a; Benz, Bernold, & Dennis 1983a). Kane et al. (1982a) claimed a one-to-one correspondence between three HXR peaks and single type III bursts. The radio bursts were found to be delayed by 0.1–0.8 s at less than 273 MHz. A flare with seven HXR subsecond spikes has been compared with simultaneous reverse-drifting radio bursts with a time resolution of 0.1 s (Dennis et al. 1984), but no systematic trend has been found for the relative time delays, although one single case was coincident within 0.1 s. Statistical correlations of HXR spikes with the next following type III burst revealed radio delays of 0.5–1.5 s in the 163–391 MHz range (Benz et al. 1983b), with the shorter delays for the bursts with the higher start frequency.

One of the major obstacles in determining the timing of radio bursts is their frequency-time drift, which makes their timing frequency-dependent. At a decimetric frequency of 1.6 GHz, where the frequency-depending time delay is expected to be much smaller than at metric frequencies, the unexpected

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COHERENT-PHASE OR RANDOM-PHASE ACCELERATION OF ELECTRON BEAMS IN SOLAR FLARES

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ABSTRACT

Time structures of electron beam signatures at radio wavelengths are investigated to probe correlated versus random behavior in solar flares. In particular we address the issue whether acceleration and injection of electron beams is coherently modulated by a single source, or whether the injection is driven by a stochastic (possibly spatially fragmented) process.

We analyze a total of ≈ 6000 type III bursts observed by Ikarus (Zurich) in the frequency range of 100–500 MHz, during 359 solar flares with simultaneous ≥ 25 keV hard X-ray emission, in the years 1980–1983. In 155 flares we find a total of 260 continuous type III groups, with an average number of 13 ± 9 bursts per group, a mean duration of $D = 12 \pm 14$ s, a mean period of $P = 2.0 \pm 1.2$ s, with the highest burst rate at a frequency of $\nu = 310 \pm 120$ MHz. Pulse periods have been measured between 0.5 and 10 s, and can be described by an exponential distribution, i.e., $N(P) \propto e^{-P/1.0\,\mathrm{s}}$. The period shows a frequency dependence of $P(\nu) = 46\nu_{\mathrm{MHz}}^{-0.6}$ s for different flares, but is invariant during a particular flare. We measure the mean period P and its standard deviation σ_P in each type III group, and quantify the degree of periodicity (or phase-coherence) by the dimensionless parameter σ_P/P. The representative sample of 260 type III burst groups shows a mean periodicity of $\sigma_P/P = 0.37 \pm 0.12$, while Monte Carlo simulations of an equivalent set of truly random time series show a distinctly different value of $\sigma_P/P = 0.93 \pm 0.26$. This result indicates that the injection of electron beams is coherently modulated by a particle acceleration source which is either compact or has a global organization on a timescale of seconds, in contrast to an incoherent acceleration source, which is stochastic either in time or space.

We discuss the constraints on the size of the acceleration region resulting from electron beam propagation delays and from Alfvénic synchronization during a pulse period. We discuss two periodic processes in flares, which potentially control quasi-periodic particle acceleration: (1) MHD oscillations, and (2) current sheets with oscillatory dynamics.

Subject headings: acceleration of particles — Sun: flares — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

The issue whether the energy release in a solar flare is triggered at a critical place and spreads randomly like a chain reaction to many independent local dissipation processes (also referred to as "statistical flare"), or whether the energy dissipation is controlled by a global condition which coherently modulates the dissipation process in the entire flare volume, can be investigated either by spatially resolving observations or by means of time series analysis. Spatially resolved flare observations in hard X-rays and radio are still sparse, and the anticipated intrinsic spatial scale of flare kernels, inferred from theoretical arguments (e.g., size of X-point reconnection regions, islands of tearing mode instability, current sheets, or current filaments, see review by Kuperus, Ionson, & Spicer 1981), is likely to be beyond the instrumental resolution of state-of-the-art capabilities. On the other hand, large data sets of spatially unresolved observations with high time resolution ($\Delta t \leq 100$ ms) are available in radio and hard X-rays, which allow us to probe energetic phenomena (propagating with Alfvénic speeds v_A) down to spatial scales of $l = v_A \Delta t \lesssim 100$ km.

In particular, we address in this study the issue, whether the time characteristics of electron beam injection, inferred from the periodicity of type III burst groups, is consistent with a stochastic process or with a temporally coherent process. Figure 1 illustrates the convolution of spatial and temporal structures. A stochastic time signal can be produced by both a temporally (Case 2 in Fig. 1) or spatially incoherent process (Cases 5–8 in Fig. 1). However, the presence of a coherent signal (Case 3–4 in Fig. 1) rules out both a spatially or temporally incoherent process and would constitute strong evidence for a coherent modulation of a spatially unfragmented source. In this study we attempt to determine the degree of periodicity of radio type III burst groups, in order to probe coherent versus stochastic time behavior.

While hard X-ray (HXR) observations generally suffer from photon count statistics to establish the presence of subsecond time structures during flares, a wealth of noise-free, subsecond time structures has been recorded in radio. Recent high-sensitivity observations in hard X-rays by the *Compton Gamma Ray Observatory* (*CGRO*) (M. Machado 1993, private

PARTICLE ACCELERATION IN FLARES *

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Abstract. Particle acceleration is intrinsic to the primary energy release in the impulsive phase of solar flares, and we cannot understand flares without understanding acceleration. New observations in soft and hard X-rays, γ-rays and coherent radio emissions are presented, suggesting flare fragmentation in time and space. X-ray and radio measurements exhibit at least five different time scales in flares. In addition, some new observations of delayed acceleration signatures are also presented. The theory of acceleration by parallel electric fields is used to model the spectral shape and evolution of hard X-rays. The possibility of the appearance of double layers is further investigated.

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CHROMOSPHERIC EVAPORATION AND DECIMETRIC RADIO EMISSION IN SOLAR FLARES

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ABSTRACT

We have discovered decimetric signatures of the chromospheric evaporation process. Evidence for the radio detection of chromospheric evaporation is based on the radio-inferred values of (1) the electron density, (2) the propagation speed, and (3) the timing, which are found to be in good agreement with statistical values inferred from the blueshifted Ca XIX soft X-ray line. The physical basis of our model is that free-free absorption of plasma emission is strongly modified by the steep density gradient and the large temperature increase in the upflowing flare plasma. The steplike density increase at the chromospheric evaporation front causes a local discontinuity in the plasma frequency, manifested as almost infinite drift rate in decimetric type III bursts. The large temperature increase of the upflowing plasma considerably reduces the local free-free opacity (due to the $T^{-3/2}$ dependence) and thus enhances the brightness of radio bursts emitted at the local plasma frequency near the chromospheric evaporation front, while a high-frequency cutoff is expected in the high-density regions behind the front, which can be used to infer the velocity of the upflowing plasma. From model calculations we find strong evidence that decimetric bursts with a slowly drifting high-frequency cutoff are produced by *fundamental* plasma emission, contrary to the widespread belief that decimetric bursts are preferentially emitted at the harmonic plasma level.

We analyzed 21 flare episodes from 1991–1993 for which broadband (100–3000 MHz) radio dynamic spectra from Phoenix, hard X-ray data from BATSE/*CGRO*, and soft X-ray data from *GOES* were available. We detected slowly drifting high-frequency cutoffs between 1.1 and 3.0 GHz, with drift rates of -41 ± 32 MHz s^{-1}, extending over time intervals of 24 ± 23 s. Developing a density model for type III–emitting flare loops based on the statistically observed drift rate of type III bursts by Alvarez & Haddock (1973), we infer velocities of up to 360 km s^{-1} for the upflowing plasma, with an average of $v_{CE} = 236 \pm 130$ km s^{-1} for episodes with 5–15 s duration. The mean electron density of the upflowing plasma is $n_e = 5.2(\pm 3.1) \times 10^{10}$ cm^{-3} when it is first detected in radio, at coronal altitudes of $h_0 = 9.2 \pm 2.3$ Mm.

Subject headings: Sun: chromosphere — Sun: flares — Sun: radio radiation

1. INTRODUCTION

In the early phase of a solar flare, the plasma in a flare loop displays dynamic processes such as turbulent motion (with velocities exceeding 100 km s^{-1}) and high-speed plasma upflows (with bulk velocities of 300–400 km s^{-1}), as inferred from the line broadening and blueshift of soft X-ray (SXR) lines in Ca XIX and Fe XXV (Antonucci et al. 1982; Antonucci, Gabriel, & Dennis 1984). The upward motion of the flare plasma in the early impulsive phase is generally referred to as "chromospheric evaporation" (Sturrock 1973) and is believed to be a consequence of local heating of the chromosphere near the footpoints of flare loops, produced either by collisions from precipitating electrons (Canfield et al. 1980) or by heat conduction (Antiochos & Sturrock 1978). Chromospheric evaporation is considered to be the main mechanism for transporting the hot SXR-emitting flare plasma to coronal levels (Antonucci et al. 1984). Reviews on this subject can be found in Doschek et al. (1986), Antonucci (1989), Doschek (1990), and Antonucci et al. (1994).

The chromospheric evaporation process has thus far been studied chiefly in SXRs and Hα. In this paper we address for the first time observational evidence at radio wavelengths. The basic idea is that the local disturbance of the electron density and temperature, introduced by the upflowing chromospheric plasma, is detectable from radio bursts emitted at the local plasma frequency. Plasma emission produced by electron beams has been observed in the lower corona up to a frequency of 8.4 GHz (Benz et al. 1992). The detection of plasma emission at such high frequencies requires overdense flux tubes, so that plasma emission can escape in a direction perpendicular to the flux-tube axis, where the density scale height is much shorter than in a homogeneous corona, and thus, free-free absorption is substantially reduced. In the event of chromospheric evaporation, we expect that the upflowing plasma surrounds overdense flux tubes and seals off escape routes for plasma emission, because the additional plasma material, if sufficiently dense, makes the escape routes optically thick owing to free-free absorption. Since the evaporating plasma propagates upward with a bulk speed of ≈ 300 km s^{-1}, it is expected to produce a slowly drifting high-frequency cutoff for plasma emission. This high-frequency cutoff is thought to apply to any kind of plasma emission originating in "evaporating" flare loops, e.g., to type III bursts excited by precipitating electron beams. The drift rate of this high-frequency cutoff for plasma

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SEQUENCES OF CORRELATED HARD X-RAY AND TYPE III BURSTS DURING SOLAR FLARES

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ABSTRACT

Acceleration and injection of electron beams in solar flares can be traced from radio type III (or type U) bursts and correlated hard X-ray pulses with similar timescales and nonthermal spectra. We perform a systematic survey of such correlated radio and HXR pulses with timescales of $\lesssim 2$ s in flares simultaneously observed with the radio spectrometer Ikarus and the Hard X-Ray Burst Spectrometer (HXRBS) on *SMM*. We applied an epoch-folding technique to enhance correlated time patterns in burst sequences at the two wavelengths. We present the results from the strongest (10) flares with a HXRBS count rate ≥ 3000 counts s^{-1}, which have a satisfactory signal-to-noise ratio for subsecond pulses. The major findings of this study are as follows:

1. Sequences of correlated HXR and radio bursts with equal burst durations and intervals at the two wavelengths are found in all strong flares.
2. The sequences were found to contain between two and nine correlated pulses in HXR and radio.
3. The epoch-folded HXR pulses (with respect to the peak times of the type III bursts) were found to have a high statistical significance of 6–57 σ.
4. The duration of these correlated pulses varies from 0.2 to 2.0 s, the pulses have a duty cycle of about 50%, and the pulse duration in HXR and radio is highly correlated.
5. The radio bursts (detected at ≈ 300 MHz) are systematically delayed with respect to the HXR pulses by 0.4 ± 0.6 s.
6. The best correlation was found for a lower energy cutoff of 40 ± 22 keV in HXR.
7. The altitude of the particle injection site, inferred from energy-dependent (time-of-flight) delays of HXR-emitting electrons, was found in the range of 18–32 Mm in three flares.

These observations strongly suggest that particle acceleration in solar flares occurs in a pulsed mode where electron beams are simultaneously injected in upward and downward directions. Since the sequences of correlated HXR and radio bursts show identical durations and intervals at the two wavelengths, they are believed to reflect most directly the temporal dynamics of the underlying common accelerator. As a consequence, thick-target models should be reconsidered under the aspect of electron injection with pulse durations of 0.2–2.0 s and duty cycles of $\approx 50\%$.

Subject headings: acceleration of particles — Sun: flares — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

A number of mechanisms have been proposed for particle acceleration during solar flares, such as shock waves, DC electric fields, double layers, electric currents, wave turbulence or wave resonance, but their observational identification and nonlinear dynamics still remain one of the most elusive problems. The promptest tracers of particle acceleration are electron beams with mildly relativistic energies. These can produce beam-driven plasma emission that can be observed at radio wavelength and bremsstrahlung that is detectable in hard X-rays (HXR). There is a general consensus that radio type III bursts are produced by electron beams propagating along open or closed coronal magnetic field lines. Also, nonthermal HXR (above energies $\gtrsim 25$–50 keV) are thought to be produced by bremsstrahlung of precipitating electron beams that hit the chromosphere (thick-target model). These are two well-understood processes that allow us to trace electron transport in solar flares. Combining these two signatures of electron beams into a single model, we propose that flare acceleration sources often produce bidirectional electron beams that are responsible for correlated time structures in radio and HXR. In this study we report on sequences of correlated time structures in HXR and radio, which are believed to reveal most clearly repetitive particle injection from a common accelerator. The aim of this study is to show that one-to-one correlations between HXR fine structures and radio type III bursts occur in a much more systematic way than one gets the impression from previously reported occasional coincidences of sporadic bursts.

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SOLAR ELECTRON BEAMS DETECTED IN HARD X-RAYS AND RADIO WAVES

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ABSTRACT

We present a statistical survey of electron beam signatures that are detected simultaneously at hard X-ray (HXR) and radio wavelengths during solar flares. For the identification of a simultaneous event we require a type III (normal-drifting or reverse-slope–drifting) radio burst that coincides (within ± 1 s) with a significant ($\gtrsim 3\ \sigma$) HXR pulse of similar duration ($\lesssim 1$ s). Our survey covers all HXRBS/*SMM* and BATSE/*CGRO* flares that were simultaneously observed with the 0.1–1 GHz spectrometer Ikarus or the 0.1–3 GHz spectrometer Phoenix of ETH Zurich during 1980–1993. The major results and conclusions are as follows:

1. We identified 233 HXR pulses (out of 882) to be correlated with type III–like radio bursts: 77% with normal-drifting type III bursts, 34% with reverse-slope (RS)–drifting bursts, and 13% with oppositely drifting (III + RS) burst pairs. The majority of these cases provide evidence for *acceleration of bidirectional electron beams.*

2. The detailed correlation with type III–like radio bursts suggests that most of the subsecond fluctuations detectable in ≥ 25 keV HXR emission are related to *discrete electron injections*. This is also supported by the proportionality of the HXR pulse duration with the radio burst duration. The distribution of HXR pulse durations w_X is found to have an exponential distribution, i.e., $N(w_X) \propto \exp(-w_X/0.25\ \mathrm{s})$ in the measured range of $w_X \approx 0.5$–1.5 s.

3. From oppositely drifting radio burst pairs we infer *electron densities* of $n_e = 10^9$–10^{10} cm^{-3} *at the acceleration site*. From the absence of a frequency gap between the simultaneous start frequencies of upward and downward drifting radio bursts, we infer an upper limit of $L \leq 2000$ km for the *extent of the acceleration site* and an *acceleration time* of $\Delta t \leq 3$ ms for the ($\gtrsim 5$ keV) radio-emitting electrons (in the case of parallel electric fields).

4. The *relative timing between HXR pulses and radio bursts* is best at the start frequency (of earliest radio detection), with a coincidence of $\lesssim 0.1$ s in the statistical average, while the radio bursts are delayed at all other frequencies (in the statistical average). The timing is consistent with the scenario of electron injection at a mean coronal height of $h \approx 10^4$ km. The radio-emitting electrons are found to have lower energies ($\gtrsim 5$ keV) than the ≥ 25 keV HXR-emitting electrons.

5. The modulated HXR flux that correlates with electron beam signatures in radio amounts to 2%–6% of the total HXR count rate (for BATSE flares). The associated *kinetic energy in electrons* is estimated to be $E = 4 \times 10^{22}$–10^{27} ergs per beam, or $N_e = 4 \times 10^{28}$–10^{33} electrons per beam, considering the spread from the smallest to the largest flare detected by HXRBS.

6. The average *drift rate of propagating electron beams* is found here to be $|d\nu/dt| = 0.10\nu^{1.4}$ MHz s^{-1} in the frequency range of $\nu = 200$–3000 MHz, which is lower than expected from the Alvarez & Haddock relation for frequencies ≤ 550 MHz.

7. The *frequency distributions* of HXR fluxes (F_X) and radio type III burst fluxes (F_R), which both can be characterized by a power law, are found to have a significantly different slope, i.e., $N(F_X) \propto F_X^{-1.87}$ versus $N(F_R) \propto F_R^{-1.28}$. The difference in the slope is attributed to the fundamental difference between incoherent and coherent emission processes.

In summary, these findings suggest a flare scenario in which bidirectional streams of electrons are accelerated during solar flares at heights of $\approx 10^4$ km above the photosphere in rather compact regions ($L \lesssim 2000$ km). The acceleration site is likely to be located near the top of flare loops (defined by HXR double footpoints) or in the cusp above, where electrons have also access to open field lines or larger arches. The observed bidirectionality of electron beams favors acceleration mechanisms with oppositely directed electric fields or stochastic acceleration in an X-type reconnection geometry.

Subject headings: acceleration of particles — Sun: flares — Sun: particle emission — Sun: radio radiation — Sun: X-rays, gamma rays

[1] Also Hughes STX.