

PARTICLE ACCELERATION IN FLARES *

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(Received 8 February, 1994; in revised form 15 April, 1994)

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.

* Report of Team 3, Flares 22 Workshop, Ottawa, May 25–28, 1993.

1. Introduction

Radio observations from metric to millimeter waves, hard X-rays and γ -ray emissions have shown that particle acceleration is a general phenomenon of solar flares. The first quantitative interpretations of flare hard X-rays by bremsstrahlung of energetic electrons suggest that particle acceleration is a major flare process (e.g., Brown, 1971). The initial flare process may be considered as an electron accelerator. Unfortunately, we still have no accurate determination of its efficiency. Estimates range from 0.1 to 40%, and it may well be variable and depend on the flare type. Simultaneously with electrons, the process also accelerates ions, but with unknown efficiency. Detailed data have given an estimated energy fraction of up to 20% residing initially in $\gtrsim 20$ keV electrons (Duijveman, Hoyng, and Machado, 1982). Thus acceleration is not merely a secondary process during flares, but an essential part of the primary energy release.

The free mobility of charged particles in a dilute plasma and the difference in inertia between electrons and ions make it likely that acceleration occurs in every major impulsive process. If the flare releases energy stored in the preflare magnetic field, this free magnetic energy must reside in an electric current having an associated electric field already before the flare. Much larger electric fields can build up during a flare by induction, beam motion, shocks, etc. In addition, waves of various types – from MHD to collisionless – are expected to be excited by the flare and are also able to accelerate particles in resonance. Therefore, from a plasma physics point of view, acceleration is not surprising; however, which acceleration process dominates is controversial.

This report is a summary of 10 half-day meetings with presentations and discussions. Here we present some selected topics of current research, not a review. For a general overview on particle acceleration in solar flares, the reader is referred to the numerous reviews in the literature (e.g., Trottet, 1986; Vlahos *et al.*, 1986; Benz, 1987; Vlahos, 1989; Melrose, 1990). In the workshop the various contributions by observers and theoreticians were mixed. This report is ordered for clarity into sections of observations, theory, and conclusions.

2. Observations

2.1. HARD X-RAY IMAGING OBSERVATIONS FROM YOHKOH

Imaging observations with the Hard X-ray Telescope (HXT; Kosugi *et al.*, 1991; 1992) on board the *Yohkoh* satellite, launched in August 1991, have revealed several interesting characteristics of hard X-ray sources. A preliminary summary is given by Kosugi (1993) as follows:

- The hard X-ray flares observed in HXT L-band (14–23 keV) usually show one or more long, thin structures which seem to trace magnetic loops. In fact, hard X-ray images generally resemble the corresponding soft X-ray images taken with the *Yohkoh* Soft X-ray Telescope (SXT).

- At higher energies, on the other hand, the sources become more compact and patchy. Typically, two separate sources are observed at both ends of the long, thin structure seen in the L-band, suggesting that the electrons (possibly accelerated near the loop top) propagate along the magnetic loops and stream into the lower atmosphere at the footpoints.

- Correspondingly, the average height of hard X-ray sources decreases with increasing photon energies (Matsushita *et al.*, 1992).

- Sometimes a sudden shift of the hard X-ray source is observed from one location to another during impulsive peaks, suggestive of successive flaring of adjacent loops.

The double-source structure at $\gtrsim 30$ keV is pronounced at the times of individual peaks, whereas hard X-rays at 20–30 keV at the valleys between the peaks originate from near the apex of the flaring loop (Figure 1; Sakao *et al.*, 1992). This is compatible the DC electric field–runaway acceleration model by Benka and Holman (1992; see Section 4.1). Further studies by Sakao (1993) have confirmed (i) that double sources vary in intensity almost simultaneously with time lags less than a fraction of a second, (ii) that the brighter source tends to correspond to a footpoint where the magnetic field is the weaker (irrespective of the polarity of the magnetic field), and (iii) that the brighter source (per pixel) tends to show the harder hard X-ray spectrum than the weaker source. These evidences provide clues to the acceleration site and the propagation of energetic electrons inside an asymmetric loop. In a well-observed event (1991 November 15), a systematic increase of the separation between the double sources is found together with a systematic rotation in position angle of the line connecting the double sources, suggestive of a multiple loop system flaring successively with rising energy release site (Sakao *et al.*, 1992).

The acceleration efficiency in the primary energy release, or the total amount of energy supplied to acceleration with respect to that going directly into heating and/or plasma motion, appears to be variable from one flaring loop to another. This can be shown dramatically in the case of a super-hot thermal flare of 1992 February 6 (Kosugi *et al.*, 1993). The flare was composed of two loops. The southern loop began to brighten at about 03:10 UT, peaked at 03:16 UT, and lasted for less than a few minutes (FWHM). Hard X-rays originated mainly from the two footpoints of this loop, and showed a power-law spectrum. On the contrary, the northern loop peaking at 03:25 UT showed typical superhot thermal flare characteristics: a gradual broad peak lasting for longer than 10 min, a thermal hard X-ray spectrum with temperatures exceeding 30 millions K, and lack of associated microwave burst. The hard X-ray source first appeared near the loop top and then gradually expanded downwards, while a soft X-ray source, representing ~ 10 million-K plasma, brightened first at one of the two footpoints and gradually expanded upwards. It seems that the ambient plasma density in the flaring loops caused the different behavior of the northern and southern loops.

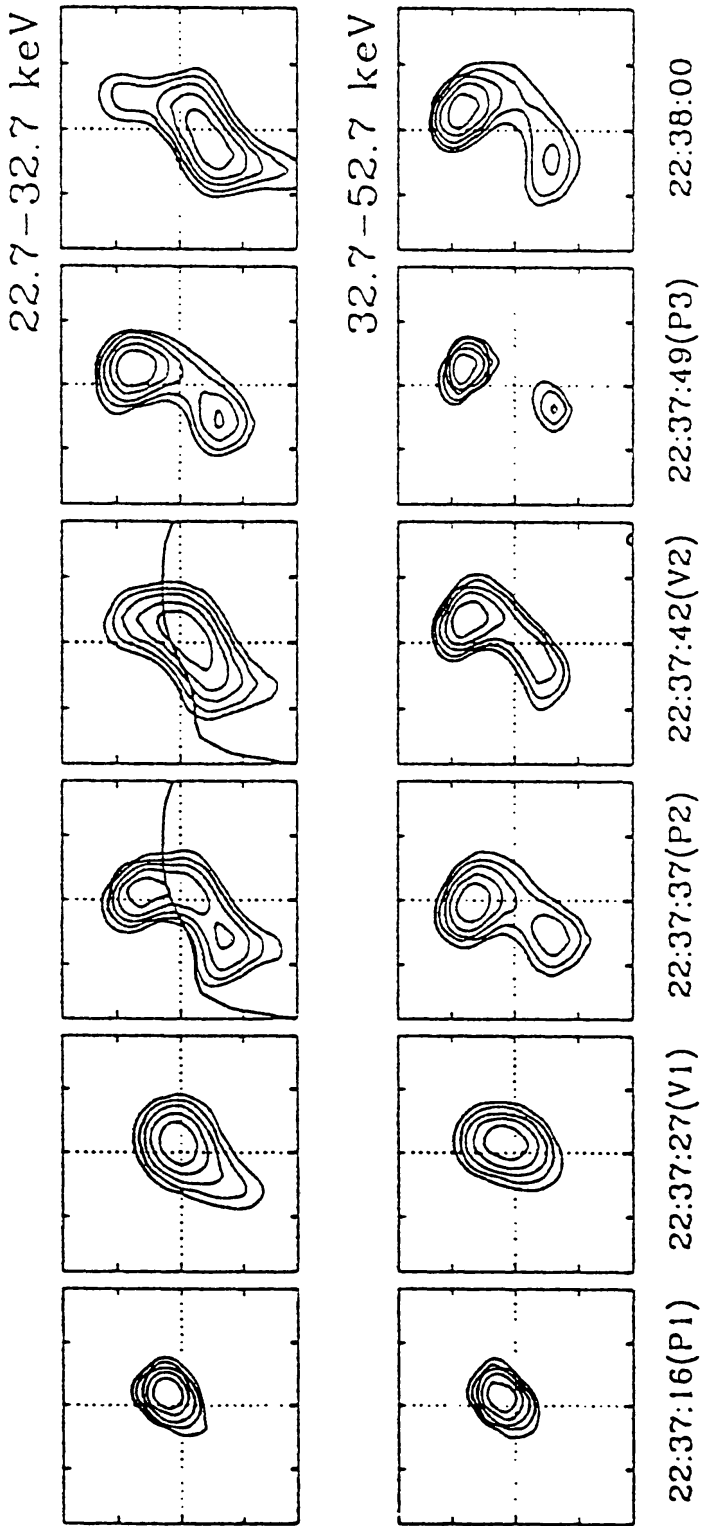


Fig. 1. *Yohkoh*/HXT images for the 1991 November 15 flare at the peaks (P) and valleys (V) of spikes during the impulsive phase ($37'' \times 37''$ FOV). Images taken in the 22.7–32.7 keV energy range are shown in the upper row, while those in the 32.7–52.7 keV range in the lower row. Magnetic inversion lines are denoted by thick curves in P2 and V2 images in the 22.7–32.7 keV range (from Sakao *et al.*, 1992).

Two crucial problems remain unsolved for an estimate of the acceleration efficiency: (i) the lower energy cutoff of the energized power-law electrons (to be discussed in Section 4.1), and (ii) the ratio between the thermal energy content of the directly heated plasma and the high-temperature plasma produced as a byproduct of the thermalization of energetic electrons. To investigate these questions, the chromospheric evaporation process is currently studied by Wülser *et al.* (1993) and Culhane *et al.* (1993).

Hard X-ray images, if compared with the corresponding microwave images, enable estimates of the number of energized electrons as well as magnetic field intensity and ambient plasma density. As summarized by Enome *et al.* (1993), the Nobeyama Radioheliograph has started routine observations in June 1992. It has imaging capabilities of the whole Sun with ~ 10 arc sec spatial and 50-ms temporal resolutions, and has already discovered several interesting features, including rapidly fluctuating microwave sources with durations of ~ 100 ms. Collaborative studies using simultaneously-taken hard X-ray and microwave images have just begun.

2.2. HARD X-RAY DIRECTIVITY

If energetic electrons precipitate towards the loop footpoints as suggested in the previous subsection, one can expect anisotropy or directivity of hard X-ray emission, at least at photon energies above ~ 100 keV. Li *et al.* (1993) challenged this problem using stereoscopic observations of 28 flares, which were simultaneously observed with the SIGNE spectrometers on the two VENERA spacecraft (V-13 and V-14) and HXRBS on SMM. The ratio between two flux values measured by two spacecrafts does not show any significant, systematic deviation from unity as a function of viewing angle difference. This result is consistent with the previous one by Kane *et al.* (1988), who adopted the same method but used PVO and ICE data for the energy range of 100 to 500 keV. Note, however, that the present result does not agree with the statistical study by Vestrand *et al.* (1987), who examined the center-to-limb variation of the occurrence frequency of SMM GRS flares and concluded that the flare emission at the energy range of 300–800 keV is anisotropic with a significant excess of limb events.

Theoretically, the lack of anisotropy in the 100–500 keV hard X-ray emission requires a near-isotropic distribution of electrons in the emission region. Since the *Yohkoh* HXT observations strongly support high-energy electron precipitation into a thick target, this suggests that an anomalous pitch-angle scattering must take place instead of normal Coulomb scattering. For example, wave-particle interactions may seriously modify electron precipitation.

2.3. RELATIVE TIMING OF ELECTRON AND ION ACCELERATION

Whether ions are simultaneously accelerated with electrons or not helps to constrain the acceleration mechanism. By use of multiwavelength observations from Nançay, Meudon, and SMM GRS, Chupp *et al.* (1993) examined the evolution of

electron and ion acceleration during the 09:09 UT solar flare on 1989 September 9. The event is characterized by changes in the energetic photon spectrum as new radio sources appear, reflecting changes in electron and ion acceleration. The right panel in Figure 2 shows the time history of the SMM GRS emission in the 4.1–6.4 MeV energy band. The event is initiated by a noise storm (S1) commencing at 09:09:20 UT and a second radio source (S2) begins at a different location at 09:09:30 UT. As the flare develops in energetic photon emissions, the hard X-ray emission increases sporadically and low level nuclear line emission appears in the time interval 09:09:47–09:10:36 UT. The deconvolved SMM GRS γ -ray spectrum for this time interval is shown by the lower figure in the left panel of the figure and clearly indicates the presence of nuclear lines above 0.8 MeV. A third distinct coronal radio source (S3) appears at 09:10:34 UT just before the major increase in intensity of energetic photons commencing at 09:10:36 UT, when the power-law bremsstrahlung spectrum hardens significantly and protons >10 MeV are produced. The GRS spectrum for the 16.384 s ending at 09:10:52 UT, during the major burst, is shown in the upper curve of the figure. During this increase the electron and proton interaction rates are enhanced, respectively, by factors of 8 and (11–16) above those in the previous interval marked (I). It is of particular interest that a new eruptive $H\alpha$ feature appears outside the main flare ribbons in association with the major phase of the flare.

The major results of the study show:

- The appearance of new radio emitting sources in the corona is closely associated in time with the time evolution of increased electron and ion production as reflected in changes in the spectra of hard X-rays and nuclear γ -rays. The times of occurrence of $H\alpha$ brightenings also fit this scenario.
- γ -ray line and neutron production is detectable before the major burst of energetic photons which also shows a canonical γ -ray spectrum. This feature of a solar flare is consistent with the SMM discovery that electrons and γ -ray producing ions are accelerated together.
- If the electron and ion interaction rates, throughout the event, reflect the properties of the acceleration mechanisms, then it is suggested that the γ -ray producing ions are accelerated more efficiently during the major burst than are electrons above 0.5 MeV.

2.4. PROLONGED γ -RAY, X-RAY, AND MICROWAVE EMISSION

In several major flares a prolonged or delayed enhancement of γ -ray, X-ray, and microwave emission sometimes follows the impulsive phase (Cliver, 1983; Kai *et al.*, 1986). It is probable that a prolonged energy release including acceleration takes place during the post-impulsive phase.

Akimov *et al.* (1993) have analyzed observations of two white-light, two-ribbon flares, for which γ -ray emission with energies up to hundreds of MeV was observed with the γ -ray telescope GAMMA-1. Figure 3 shows time histories of γ -rays in comparison with that of microwaves for the 1991 March 26 flare. Two components

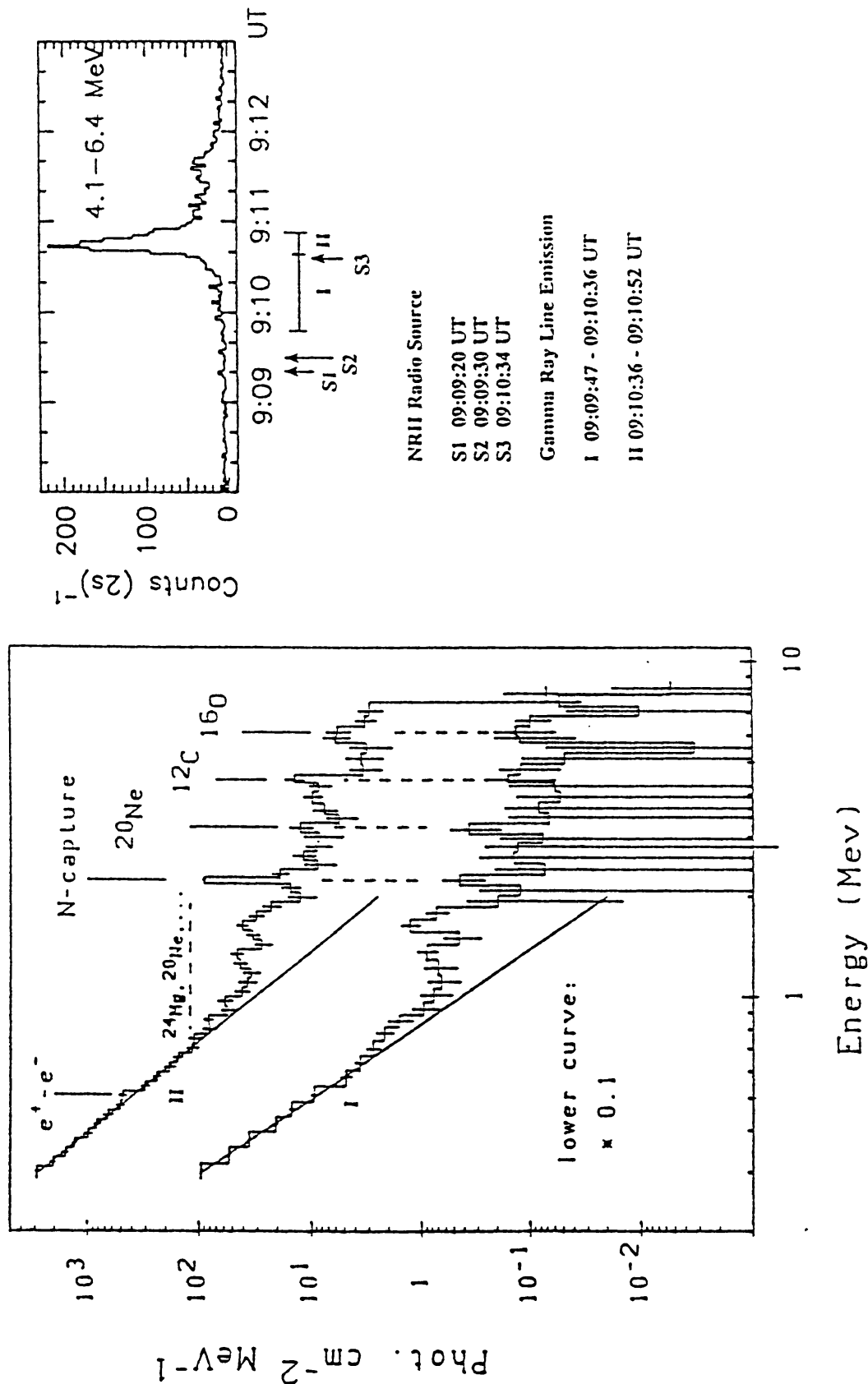


Fig. 2. The γ -ray spectra for the 1989 September 9 flare (*left*) at the two intervals shown in the time history (*right*, roman numerals). Interval I is in the pre-flash; interval II is the flash phase of the flare. The arrows labeled S1, S2, and S3 under the time history mark the time of appearance of new radio sources. For details, see text.

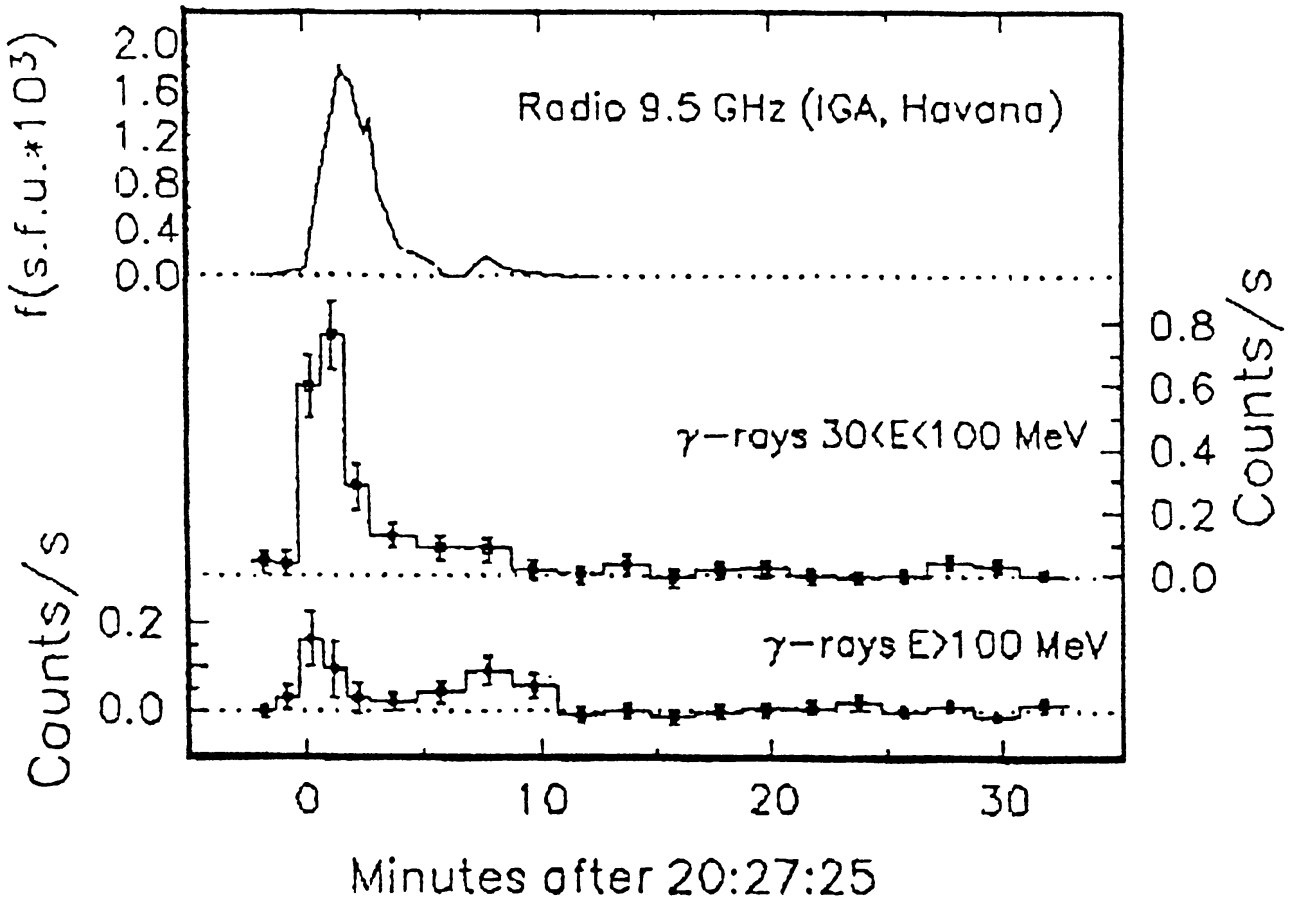


Fig. 3. γ -ray and microwave time histories of the 3B/X4.7 flare on 1991 March 26. A second maximum or a delayed enhancement is more pronounced in the γ -rays at energies >100 MeV. Note that the corresponding hump can be seen in the microwave time plot at 9.5 GHz.

of γ -ray emission were observed within the total duration of about 10 min. The first, impulsive one, lasted for several tens of seconds, maybe originating from bremsstrahlung of electrons at a high plasma density region ($n \gtrsim 10^{14} \text{ cm}^{-3}$). The time profile for γ -rays with energies above 100 MeV exhibits a delayed component about 8 min after the flare onset. A comparative spectral analysis of the excess in terms of flux ratio, $R = N(>100 \text{ MeV})/N(<100 \text{ MeV})$, revealed that $R = 1.1$ for the delayed component, much larger than $R = 0.2$ for the impulsive component. This difference is significant at the confidence level of 4σ . The relatively hard spectrum of the delayed component may be attributed to a decay of neutral pions produced in nuclear interactions of high-energy ions accelerated to many hundreds MeV at the late stage of the flare. The radio time profile at 9.5 GHz provides evidence for additional energy release taking place just at the time of the delayed γ -ray component.

During the post-impulsive phase the magnetic field above the active region, strongly disturbed by a CME, relaxes to its initial state through magnetic reconnection. This process may result in particle acceleration, where protons can be accelerated into a power-law distribution up to 20 GeV.

2.5. SOLAR ENERGETIC PARTICLE EVENTS (SEPs)

Solar energetic particle events (SEPs) are frequently associated with a rare type of flare characterized by smooth, long duration light curves in both soft and hard X-rays. These flares are known as long duration events (LDEs) in soft X-rays and as gradual hard burst events (GHXs) in hard X-rays. This flare type is often found to be associated with great height, type II and type IV metric radio bursts, microwave richness, and progressively hardening spectra in hard X-rays (see, e.g., Kiplinger, 1993).

Garcia (1993) recently found from a statistical study that soft X-ray flares of this type have anomalously low electron temperature for weak to moderate intensities up to approximately NOAA X1-class. This low-temperature characteristic of SEP events gradually diminishes for higher intensity flares, $\gtrsim$ X1, where the trend is to greater SEP production at all temperatures. Although the physical implication of this result is not obvious, it may be evidence against the concept of a single acceleration mechanism operating in the solar flare. Rather, they may provide evidence for ubiquity of particle acceleration in the coronal environment, or for coexistence of several acceleration mechanisms operating in the active region corona.

2.6. THE TIMING OF ELECTRON BEAMS IN HARD X-RAYS AND RADIO

The propagation of electron beams during solar flares can be most unambiguously traced by type III, type U, and reverse-drifting type III radio bursts. Recent broadband radio observations by the new Phoenix spectrometer of ETH Zürich (in the 0.1–3.0 GHz range) during the 1992 September 5 and 6 flares show evidence for electron beams simultaneously injected in upward and downward direction (Aschwanden, Benz, and Schwartz, 1993). The mean injection frequency of such oppositely drifting burst pairs was found at 880 ± 50 MHz, corresponding to an electron density of $5 \times 10^9 \text{ cm}^{-3}$, assuming harmonic plasma emission. The downward injected (reverse-drifting) electron beams have a mean drift rate of 2350 MHz s^{-1} could be traced up to 1240 ± 100 MHz, with an average pulse width of 380 ± 80 ms at the highest frequency.

Simultaneous hard X-ray observations by the COMPTON Gamma-Ray Observatory (for instrumental descriptions see Fishman *et al.*, 1992) with the BATSE large area detectors having a time resolution of 64 ms show hard X-ray pulses (>25 keV) with a mean duration of 400 ± 220 ms, that are unambiguously correlated with reverse-drifting radio bursts (Figure 4). The reverse-drifting radio bursts occur nearly simultaneous with the HXR pulses at the injection frequency (with an insignificant delay of 100 ± 120 ms), but are delayed at the highest observed frequency of 1240 MHz. The mean delay is 270 ms, but shows a large scatter with a standard deviation of 150 ms. The close timing and identical pulse width of these correlated pulses in hard X-ray and radio gives strong evidence for an interpretation in terms of precipitating electron beams. The delay of the radio

emission can largely be explained by the fact that the radio-emitting electrons have a lower velocity than the HXR-emitting electrons. Considering the collisional lifetime of the injected electron beams, a kinetic energy of <5 keV is likely for the radio-emitting electrons. Neglecting other effects that delay the radio emission and using the typically observed beam exciter velocity of $\beta_R = 0.2 \pm 0.1$ for the reverse-drifting radio bursts, we can infer from the relative timing a height of $H = 8000 \pm 3000$ km for the propagation distance between the injection site and the precipitation site of the 25 keV thick-target HXR source.

2.7. NARROWBAND SPIKES

Narrowband spikes of a few tens of microsecond duration are another type of coherent radio emission well associated with hard X-rays. Spikes occur in clusters of sometimes more than 10^4 bursts spread over up to a minute in time and an octave in frequency. At a given frequency, they are distributed stochastically in time (Isliker and Benz, 1994). Clusters often have structure in frequency, harmonic bands, or mutual information within small frequency intervals (i.e., an enhanced likelihood of occurrence at a displaced frequency if a spike appears at a given frequency, Schwarz *et al.*, 1993).

The emission mechanism of spikes is not known, although the narrow bandwidth (from a few percent to less than 10^{-3} of the center frequency, Csillaghy and Benz, 1993) points to a radiation mechanism at the electron gyrofrequency or a harmonic of it.

The total flux and burst rate of rich spike clusters correlate in detail with hard X-rays, sometimes with a delay of some seconds (Aschwanden and Güdel, 1992).

Here we concentrate on small groups of spikes, frequently found near the start of metric type III bursts in frequency and time. They have been named 'metric spikes' to distinguish them from the rich spike clusters at higher frequencies. It is not clear whether they are physically the same as the rich clusters (called decimetric or microwave spikes). High-resolution spectrograms (Figure 5) show a detailed correlation in time between single type III bursts and small subgroups of spikes including about 10 bursts or less.

The circular polarization of metric spikes is always higher than the type III burst polarization, and sometimes of opposite sign. In the case of Figure 5, the type III bursts are 5% right circularly polarized, the spikes 15% left. It is compatible with the proposition that the two emissions are caused by different mechanisms.

The metric spikes of Figure 5 are not located on the extrapolated trajectory of the type III bursts in the spectrogram. The centroid of the small group of spikes is either delayed in time, up-shifted in frequency, or both.

The emission frequency of spikes must exceed the plasma frequency for the radiation to propagate. Assuming that the type III emission is close to the plasma frequency, the location of the spike sources must be near the start of the type III bursts. A possible explanation is that the upcoming electron beam excites both the type III and, somewhat earlier and at a higher frequency, spikes. Another possibility

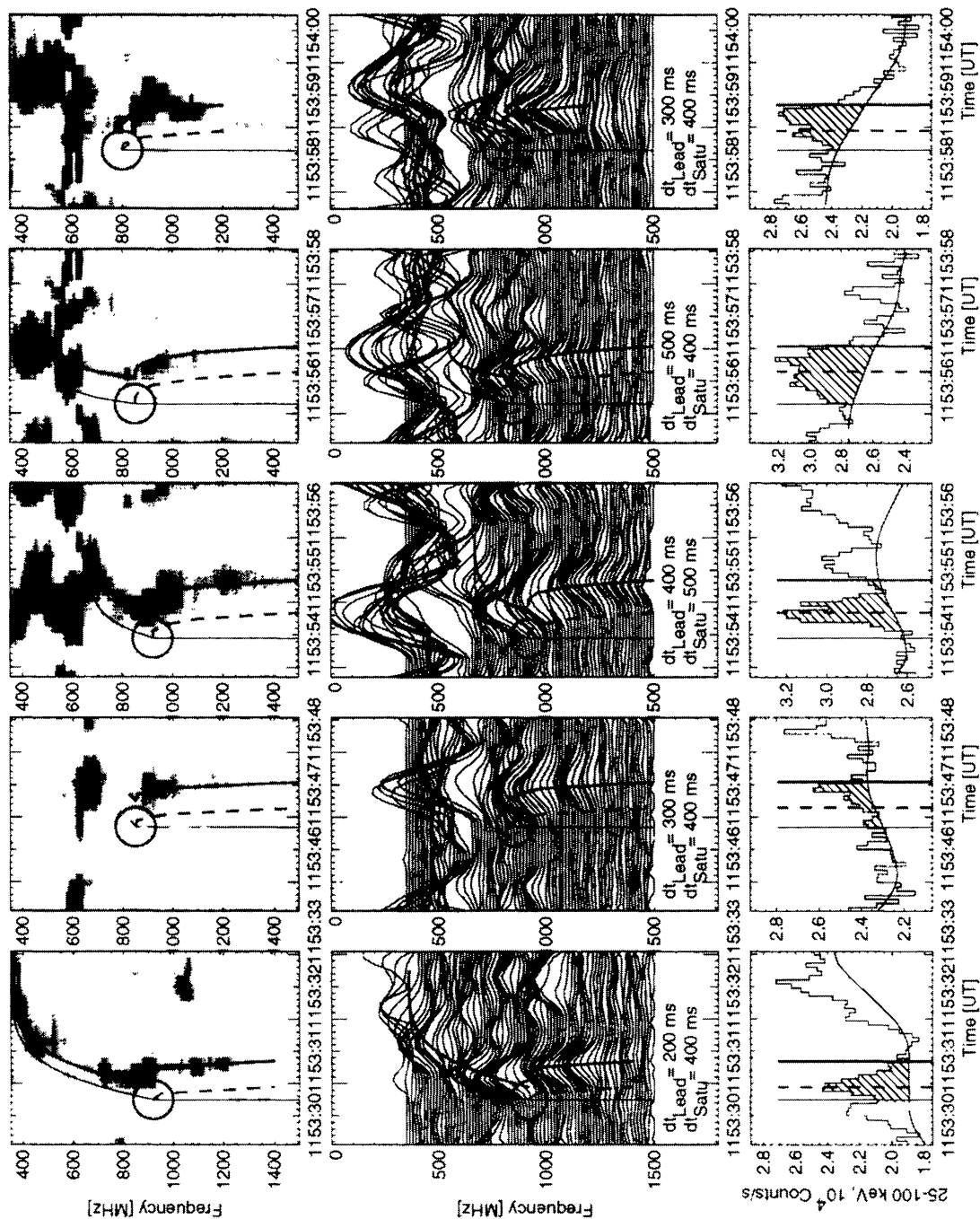


Fig. 4. *Top*: radio flux of type III bursts measured in many frequency channels by the Phoenix spectrometer (ETH Zürich) on 1992 September 6. Each image displays 3 s of data. First emission (thin line), leading edge (dashed) and peak flux (thick curve) are indicated. *Bottom*: BATSE observations of hard X-rays with shaded peaks in possible coincidence (from Aschwanden, Benz, and Schwartz, 1993).

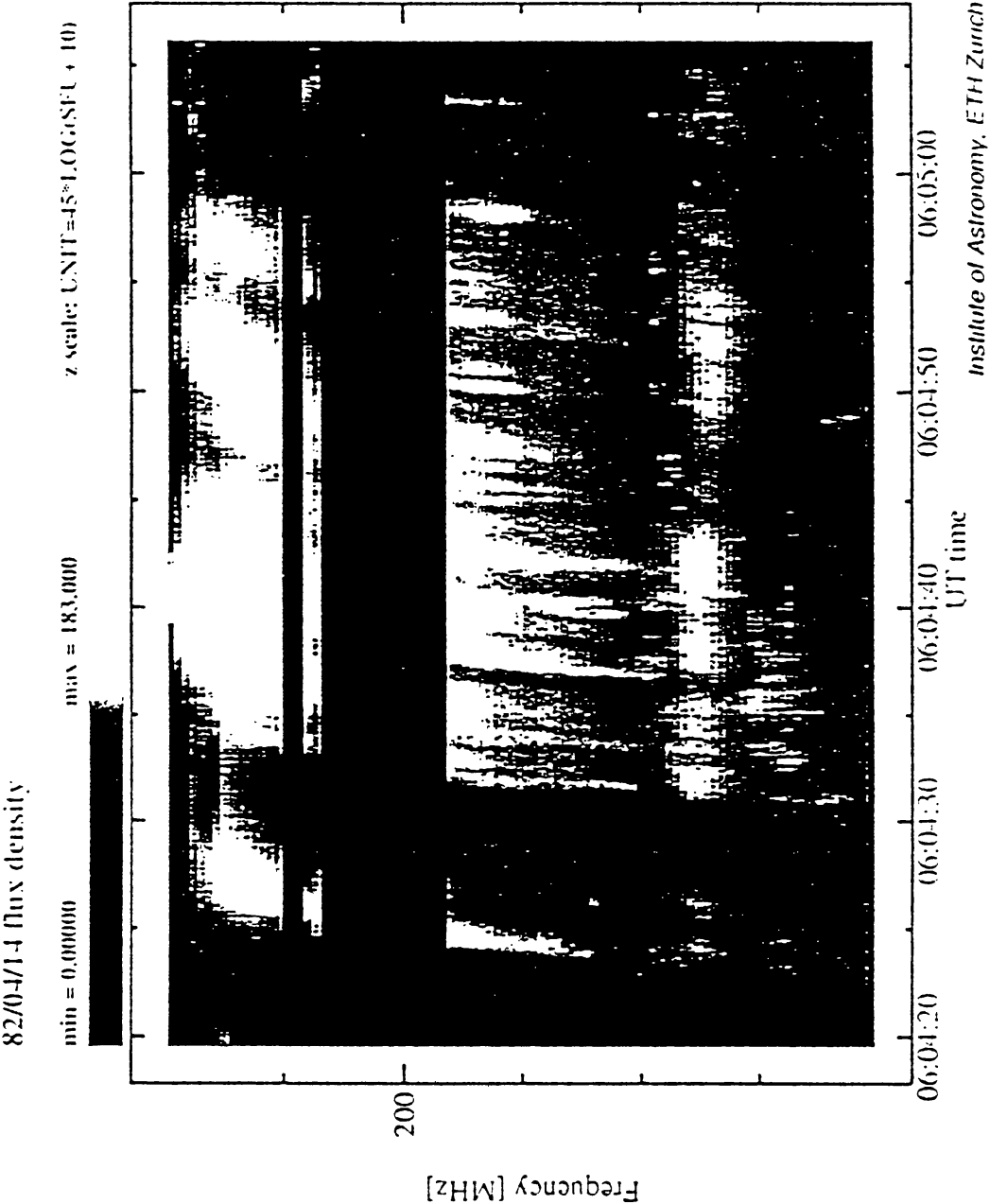


Fig. 5. Radio spectrogram of type-III-associated spike bursts. Enhanced radio flux density is presented bright in the frequency (down) vs time plane. Narrowband spikes appear around 330 MHz, type II bursts start at 310 MHz.

is that metric spikes are closely linked to the acceleration region or even produced by wave turbulence within the acceleration region.

2.8. SUDDEN REDUCTIONS AND PULSATIONS

Sudden reductions and pulsations of decimetric type IV bursts are well-known phenomena at frequencies below 1 GHz. New measurements at the Crimean Astrophysical Observatory have also discovered them at 2.5 and 2.85 GHz range during the present cycle of activity. Figure 6 shows time profiles at both frequencies presenting a mixture of irregular sudden reductions with 20–50 ms duration and trains of quasi-periodic pulsations with periods of 40–80 ms. Sudden reductions have a negative frequency drift rate of 10–40 GHz s⁻¹ and appear like fast-drift absorption bursts at <1 GHz. Quasi-periodic pulsations are almost synchronous at both frequencies. It is interesting that sudden reductions with time scale of 20–100 ms and quasi-periodic structures have also been observed in AD Leo at 1435–1716 MHz (Güdel *et al.*, 1989) and in YZ Canis Minoris at 435–425 MHz (Bastian *et al.*, 1990).

The event is interpreted in terms of coherent plasma emission driven by the loss-cone instability. To explain sudden reductions we have used a well-known model for absorption bursts (Zaitsev and Stepanov, 1975; Benz and Kuijpers, 1976). According to this model a sudden reduction is the result of plasma wave absorption by fast electrons injected into a coronal magnetic loop and filling the loss-cone. For quenching the loss-cone instability of plasma waves the number density of injected particles, n_2 , can be a few times less than the density of trapped electrons, n_1 . Using sudden reduction characteristics we conclude that 40–300 keV electrons have been injected upward into a flare loop from a loop footpoint.

Furthermore, we suggest that the pulsations appear due to nonlinear oscillations of the plasma level in resonant (W) and nonresonant (W') regions near the center-type singular point (Zaitsev, Stepanov, and Sterlin, 1985),

$$W \approx W' \approx 10An_1T, \quad (1)$$

where coefficient A describes the loss-cone anisotropy and T is the background plasma temperature. Multiple injections of particles into magnetic traps are accompanied by particle scattering on waves. As a result, the number density of trapped particles grows. Nevertheless, the anisotropy A decreases more rapidly than n_1 increases during quasi-continuous injection (≈ 1 s) in the second train of pulsations. Thus, the position of the center-type point is lower than before injections and the microwave emission oscillates at a lower level compatible with the observations (see Figure 6).

The event of 1991 November 17 as well as radio spectra from late-type dwarfs may be considered as an illustration of important effects of plasma physics: injection of charged particles into magnetic traps and nonlinear oscillations of plasma waves.

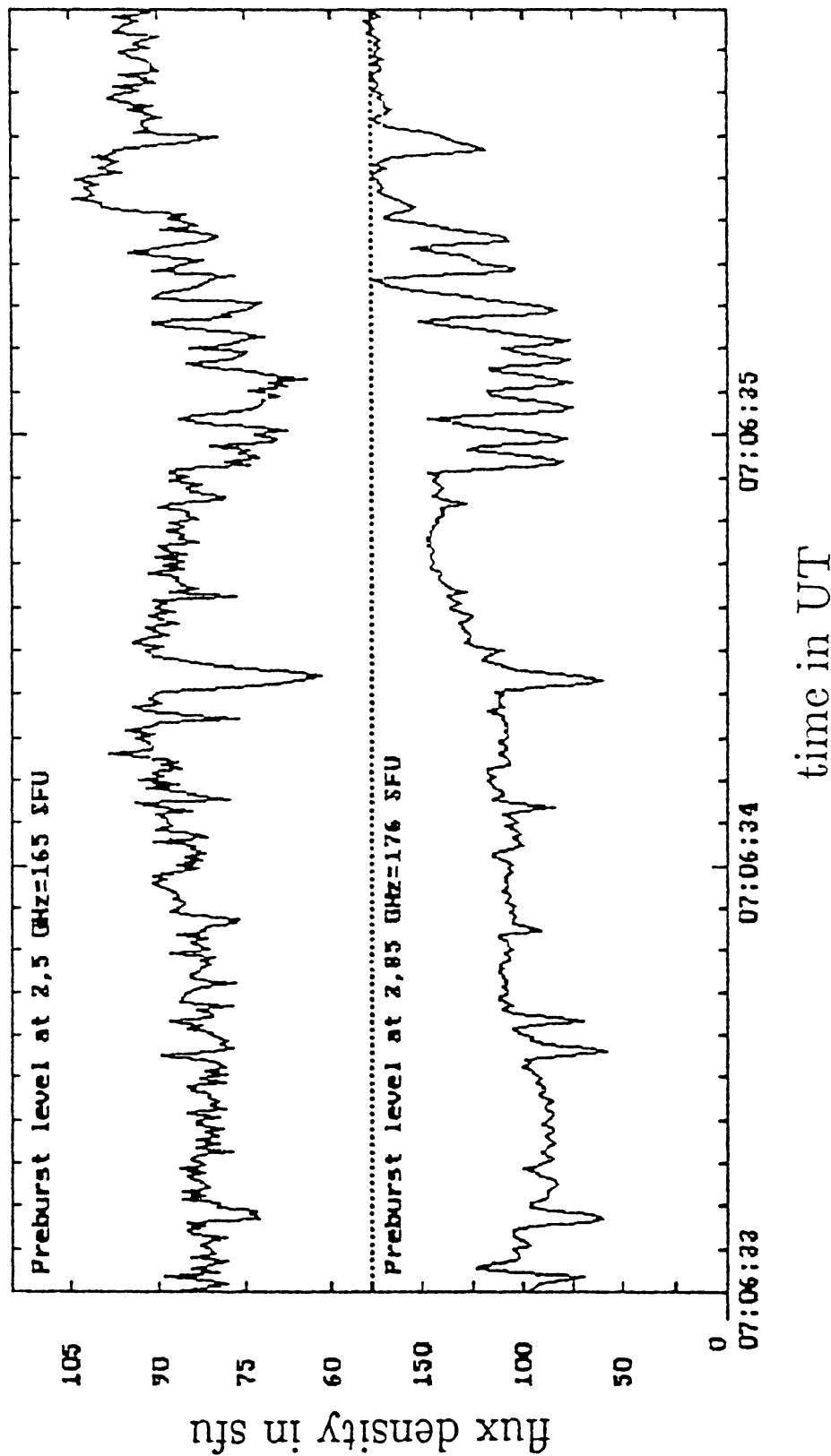


Fig. 6. Single-frequency observations of sudden reductions (e.g., at 07:06:34.45 UT) and pulsations observed at the Crimean Astrophysical Observatory on November 17, 1991. *Top*: 2.5 GHz. *Bottom*: 2.85 GHz (from Fleischman, Stepanov, and Yurovsky, 1994).

3. Theory

The conversion of free magnetic energy into accelerated particles can be accomplished by several processes. It is likely that more than one occurs during a flare and its secondary effects. The most widely discussed processes can be grouped into 3 types:

- electric field parallel to the magnetic field;
- resonant acceleration by waves (second-order Fermi, including stochastic acceleration);
- parallel and perpendicular shocks (first-order Fermi).

We concentrate here on the first and second type, believed to be of major importance during the primary energy release of flares.

3.1. CURRENTS PARALLEL TO THE MAGNETIC FIELD

Holman (1985), Holman, Kundu, and Kane (1989), Benka (1991), Benka and Holman (1992), and Holman and Benka (1992) have explored the consequences of electric field acceleration in current channels for both electrons and ions. For electrons, Joule heating by the currents and the acceleration of runaway particles are both crucially important. Radiative signatures may be seen in some microwave gyrosynchrotron radiations and hard X-ray emissions from flares. In gyrosynchrotron emission, complex and previously unexplained spectral features at low frequencies are naturally accounted for by gyroresonances (Benka and Holman, 1992). In hard X-rays, the presence of a superhot thermal component, together with nonthermal emission at higher energies, is a natural consequence of the presence of currents.

Benka and Holman (1992) have studied the hard X-ray flare of 1980 June 27, observed with high spectral resolution germanium detectors (Lin *et al.*, 1981; Lin and Schwartz, 1987). The hard X-ray time profile can be interpreted as a series of spikes with distinct spectral character being superimposed on a more gradual component which rises and falls smoothly during the event with a different spectral character. The gradual component shows a combination of thermal emission at the lower photon energies (below ~ 50 keV) and nonthermal emission at higher energies. The spike emission (with the gradual component subtracted off) shows only very hard nonthermal X-rays, with no apparent contribution from the superhot plasma. Furthermore, the observed hardness of this radiation is fully consistent with thick-target emission produced by runaway-accelerated electrons. Such electrons have a distribution function $\sim E^{-1/2}$ over a finite energy range determined by the conditions in the acceleration region. (Note that for such a flat energy distribution the thick target X-ray spectral index is not simply flatter by one. In fact, the X-ray spectrum is steeper than the energy distribution.)

Figure 7 shows the fits to the data from the three largest spikes in this event. The two middle spectra are both from the second spike, and it is clear that the spectrum does not change significantly over the duration of this spike. Since runaway elec-

3.2. DOUBLE LAYERS IN SOLAR FLARES

The topic of double layers (henceforth DLs) in solar flares is a debatable subject, because of the uncertainties on the formation of these structures. To create DLs, it is always necessary to have a very large current density. This can be obtained if the current is confined to many current channels. However, we show that the presence of DLs in the impulsive phase of a solar flare can result in emission features that may be linked to observations.

The main feature of the DL is that it has a finite lifetime. In the case of a strong (non-relativistic) DL, the emanating electron beam will heat the ambient plasma and hence violate the Bohm criterion on a short time scale.

Depending on the behaviour of the DL, influenced by the changing parameters of the ambient plasma, the observable signature varies; if the length of the DL, which is proportional to the initial Debye length, remains constant, the emitted frequency will also remain constant. If the length of the DL follows the development of the Debye length, the emitted frequency will decrease. This means that we can apply our model to both drifting and non-drifting radio bursts of the Sun.

We will now give a description of the processes involved. (A more complete version can be found in Volwerk and Kuijpers, 1993).

A DL can be described by a self-consistent solution to the Vlasov-Maxwell equations. In the stationary case it is easy to just solve Poisson's equation, where the particle densities of the reflected particles can be obtained by assuming a Maxwell-Boltzmann distribution over the DL with the temperature of the ambient plasma. The (relativistically extensible) Bohm criterion has the form

$$\frac{k_{\text{bol}} T_e}{m_e c^2} \leq \left(\frac{i_i}{i_e} \right) \frac{(\gamma_{0,i} + Z\mu\alpha) [\gamma_{0,e} + \alpha]^2 - 1}{\sqrt{(\gamma_{0,i} + Z\mu\alpha)^2 - 1}} \quad (2)$$

where i_x is the current density of species x , $\alpha = e\phi_{\text{DL}}/m_e c^2$ and $\mu = m_e/m_i$.

The emanating electron beam will heat the ambient plasma by direct collisions, classical and anomalous ion-acoustic resistivity (Cromwell, McQuillan, and Bowen, 1988). For a creation time of the DL around 100 μs , which can be related to experiments and theory, the violation time for the Bohm criterion is of the order of 10 ms.

During the existence of the DL the accelerated electrons will scatter the electric field of the DL. This involves a resonance condition (Kuijpers, 1989)

$$\omega_{\text{DL}} - \mathbf{k}_{\text{DL}} \cdot \mathbf{v} = \pm(\omega_t - \mathbf{k}_t \cdot \mathbf{v}) \quad (3)$$

where $\mathbf{v}$ is the velocity of the electrons in the DL; ω_t and $\mathbf{k}_t$ are the frequency and the wave vector of the emitted radiation; and ω_{DL} , $\mathbf{k}_{\text{DL}}$ are the frequency and the wave vector of the DL, where $\mathbf{k}_{\text{DL}} = 2\pi/L_{\text{DL}}$. We will assume that during the lifetime we are dealing with a constant DL so that $\omega_{\text{DL}} = 0$. The results in an emitted frequency vary from the MHz to GHz bands.

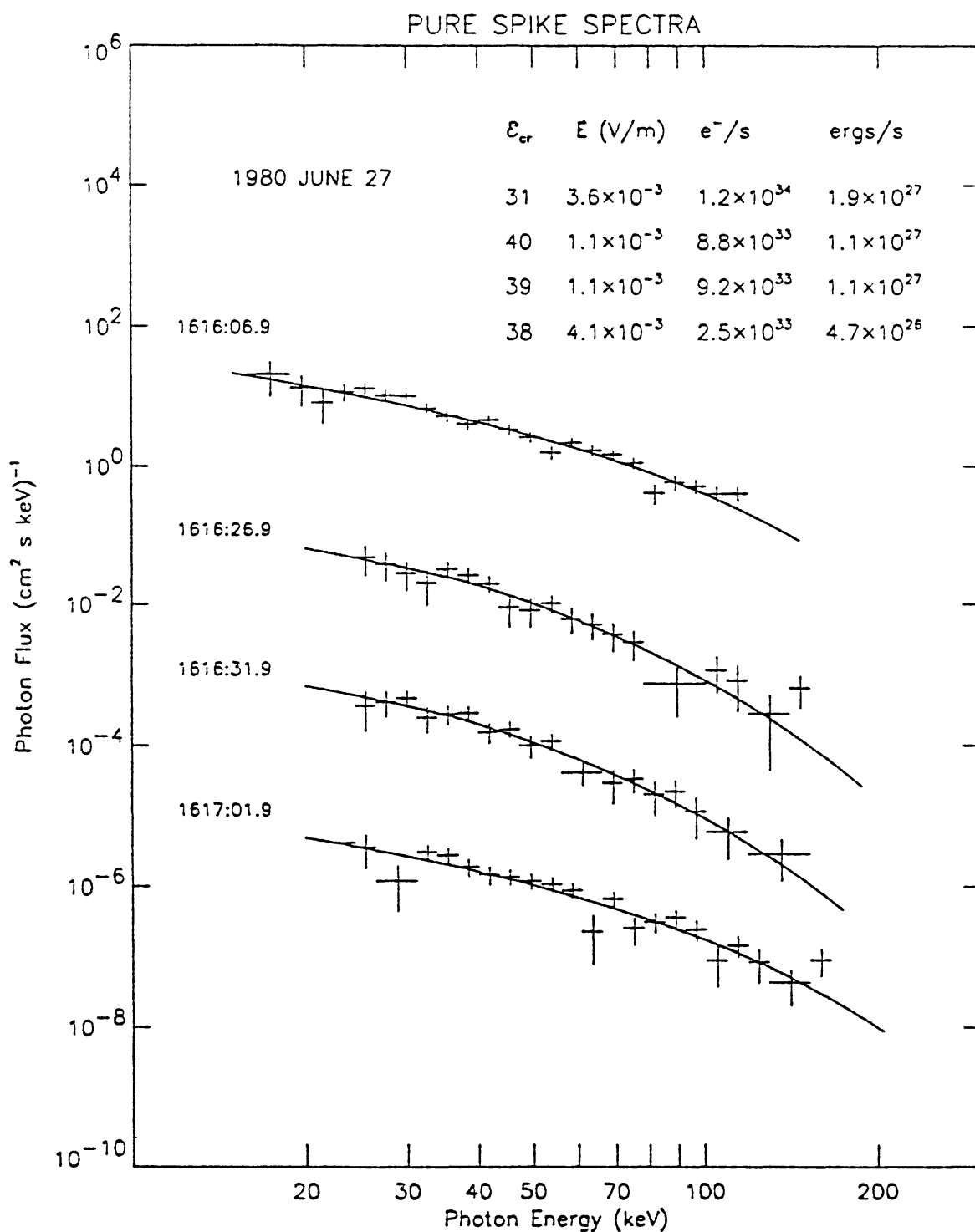


Fig. 7. Fits to hard X-ray spikes from the flare of 1980 June 27, showing pure nonthermal emission consistent with that from runaway accelerated electrons. Also shown are the deduced low-energy cutoff (ε_{cr} keV), electric field strength, and nonthermal electron and energy fluxes for each spectrum, respectively. Each spectrum is time-integrated for 5 s, and the two middle spectra are for the same spike. All fits have $\chi^2 < 1.5$.

trons are only generated above a critical energy ε_{cr} , the fits provide the low-energy cutoff for the nonthermal electrons which is tabulated (in keV) in Figure 7. Also shown are the deduced electric field strengths and energetics for each of these spectra.

There are only three fitting parameters: ε_{cr} discussed above; the *high*-energy cutoff to the accelerated electrons, ε_{co} ; and the normalization. The first two parameters characterize the acceleration region, e.g., by assuming its length is 3×10^9 cm, we obtain the electric fields indicated in Figure 7. It is important to stress that compared to a broken power-law fit, this model uses one less parameter and reduces the nonthermal electron and energy fluxes by factors ranging from three to thirteen for the displayed spectra. The nature of the acceleration can thus be studied by examining the emission in the hard X-ray peaks. This model also addresses the Joule heating due to the currents and the evolution of the superhot component, visible in the 'gradual' emission between the spikes (Benka and Holman, 1993). Although this model is not the only one consistent with the data, it provides a simple interpretation and plausible results.

The currents which are responsible for electron runaway can also cause ions to runaway, though the results are markedly different. The number of ions above v_e , the electron thermal speed, is negligible unless the ion temperature is much greater than the electron temperature. As a result, ions are not as readily available as electrons to be freely accelerated by the electric field. The collisional drag force on the ions, however, unlike that on the electrons, has a minimum near $0.1v_e$. If the force exerted on the ions by the electric field exceeds this minimum drag force, ions will be pulled out of the thermal distribution. For mild electric field strengths ($E < E_D$, where E_D is the electron Dreicer field), the ions are limited by electron drag to a velocity between 0.1 and $1 v_e$. Protons drift in the direction of the electric field, while heavier ions are dragged along with the drifting electrons. In a strong field ($E > E_D$), ions may be directly accelerated to higher velocities.

The threshold for the generation of these suprathermal protons in the solar corona is $E \simeq 0.5E_D$, while for $^3\text{He}^{+2}$ and $^4\text{He}^{+2}$ it is $E \simeq 0.2E_D$ (Holman, 1993). Since the electron thermal velocity exceeds $10\,000 \text{ km s}^{-1}$ at flare temperatures of 10^7 K and higher, the ions attain velocities $\approx 1000\text{--}10\,000 \text{ km s}^{-1}$, and energies $\approx 10\text{--}1000 \text{ keV nucleon}^{-1}$. These velocities fall within the same range as the Alfvén speed in flaring loops. They are the velocities required for ions to be picked up and accelerated by Alfvén waves. Hence, these runaway ions can provide the seed particles required for further acceleration by waves. Alternatively, the ions may be accelerated in the current channels themselves if the electric field strength exceeds the Dreicer field. In either case, the runaway process can provide the ions required for a solar γ -ray burst when the electric field strength is comparable to the Dreicer field.

4. Conclusions

Solar flares occur on a scale of 10^9 cm. Radio observations and more recently hard X-ray observations predict that the relevant acceleration processes must occur on scales of 10^7 cm and less. What can acceleration tell us about the global process?

Radio bursts of type III strongly suggest that acceleration consists of a large number of subprocesses (fragments) triggered by a global condition. The organization of the bursts reveals several other interesting aspects regarding the time scales and spatial fragmentation of particle acceleration. They show time structure on different time scales which appear to be related to the macroscopic organization of flare-unstable active region plasma: (1) The total duration of recurrent activation of subsequent impulsive phase comprises each ~ 10 min, where (2) each impulsive phase lasts about 1 min (episode of contiguous acceleration, characterized by rapid fluctuations in HXR and temporally correlated clusters of radio type III bursts). The HXR emission in each impulsive phase is further modulated by (3) so-called 'elementary bursts' with 5–10 s duration each, that contain (4) subbursts with ~ 500 ms duration roughly corresponding to the duration of individual type III bursts and supposedly representing 'quantized' injections of accelerated electrons. The mean injection rate of these electron bursts is 1.2 s^{-1} (Aschwanden, Benz, and Schwartz, 1983) constituting an average duty cycle of $\approx 50\%$ for this quasi-periodic accelerator. The plasma frequency at the injection site was found to be confined to a narrow range at 750 ± 50 MHz and 610 ± 20 MHz in two flares. The narrow-bandness of the injection frequency suggests a relatively small variation of the electron density in the acceleration region, and thus a relatively small spatial fragmentation (within a few 1000 km). (5) An extremely short scale is indicated by narrowband spikes lasting a few tens of microsecond.

HXT on the *Yohkoh* satellite frequently sees double or multiple compact sources at photon energies $\gtrsim 30$ keV. Since double sources are seen in many flares and since there is no measurable time delay between their brightening, energetic electrons must be injected near the top part of the loops (or are accelerated in both directions along the loop) and precipitate towards the both ends. In some flares repetitive acceleration is found to take place with a systematic change of the source locations. This may be evidence for the successive flaring of adjacent loops, or it may support the idea that collisions between adjacent loops are the key ingredient of a flare energy release process. In other example HXT sees that several well-separated loops are involved in a flare and that they show different characteristics from each other from a viewpoint of acceleration; some with high acceleration efficiency and the other dominated by direct heating. Plasma parameters such as density and plasma β , or the intensity ratio between the poloidal and toroidal magnetic field components, probably produce this difference. Further detailed studies need be done on this point.

The acceleration of electrons is still unclear, but nevertheless there is strong evidence that ion and electron acceleration are closely coupled. Acceleration by

electric fields (including double layers) and wave turbulence are both likely. They differ by their capability to accelerate ions. A crucial observation will be energetic ions, their ratio and delay compared to electrons. New high-sensitivity observations are needed that clearly identify the parameters of emissions produced by electrons and ions.

Considering that a sizable fraction of the primary energy first accelerates particles, there is compelling evidence that the primary release includes kinetic processes at a central point in the process. The study of acceleration will eventually reveal this important piece of flare physics.

Acknowledgements

We are grateful to V. Gaizauskas to provide the perfect organizational frame of this Workshop at the University of Ottawa that made this meeting possible and greatly stimulated our discussions.

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