(14) If shocks are formed in a few seconds, can they be responsible for the prompt acceleration of ions and electrons? How are these shocks related to large-scale shocks which are responsible for the Type II bursts?

(15) Can the electron-cyclotron maser spread the acceleration region?

(16) Which of the acceleration mechanisms discussed above can explain the observed energy spectra?

We concentrate on these questions in Sections 2.2, 2.3 and 2.4. In Section 2.4 we also review the progress made during the last few years on mechanisms for particle acceleration in flares and in the last Section we summarize the still open observational and theoretical questions. We will attempt to answer the questions (1)-(16) in Sections 2.2.7, 2.3.6 and 2.4.8. Hence, for a quick review of the status of our understanding of the problem of particle acceleration in flares the reader may go directly to these Sections and Section 2.5.

Section 2.2 was prepared by M. Machado and L. Vlahos from inputs from C. Alissandrakis, T. Bai, D. Batchelor, A. O. Benz, G. Holman, S. R. Kane, P. Kaufmann, M. R. Kundu, R. P. Lin, A. Mackinnon, H. Nakajima, M. Pick, J. Ryan, D. F. Smith, G. Trotter, S. Tsuneta. Section 2.3 was prepared by R. Ramaty and R. J. Murphy from contributions from T. Bai, E. Chupp, D. Ellison, P. Evenson, D. J. Forrest and M. Peses and Section 2.4 was prepared by L. Vlahos from inputs from G. Holman, R. P. Lin, D. F. Smith and G. Van Hoven.

Finally, it is important to stress that this is a report of the discussions carried out during the Workshops and reflects strongly the opinions (and in many Sections even the biases) of the authors.

2.2 PHENOMENA ASSOCIATED WITH MILDLY-RELATIVISTIC ELECTRONS

In this Section we focus our discussion on phenomena associated with mildly relativistic electrons (10-400 keV) while in the next we concentrate on phenomena related to energetic ions and relativistic electrons (E \geq 500 keV). This division is in many ways artificial, since particles of all energies are produced during a flare. Thus, our discussion in this Section overlaps with Section 2.3 and vice-versa. In fact, our effort in this chapter will be to unify aspects related to subjects of Sections 2.2 and 2.3.

Hard X-ray imaging from SMM and HINOTORI satellites and the stereoscopic hard X-ray observations made with the International Sun Earth Explorer 3 (ISEE-3) and Pioneer Venus Orbiter (PVO) spacecraft are reviewed in this Section. Imaging of microwave bursts is also one of our main new sources of information about particle acceleration. The results from the Very Large Array (VLA) telescope have made a large impact on our understanding of flare models. The spatial maps from the Nancay (France) Radioheliograph obtained with a high time resolution (0.04 secs) provide several new features of the topology of field lines near the acceleration site. The high time and spectral resolution of the Zürich radio spectrometer and 45 ft. radome-enclosed antenna at Itapeninga (Brazil), have opened a new window on the microinstabilities in flares. Balloon measurements with sensitive hard X-ray detectors have also been carried out with remarkable success.

2.2.1 Soft and Hard X-ray Source Structure, Location and Development

2.2.1.1 X-ray Imaging

Before the launch of the SMM and HINOTORI spacecraft, only isolated observations were available on the spatial structure of hard X-ray emission from flares. These were mainly provided by stereoscopic observations from two spacecrafts (PVOs and ISEE-3, see Kane, 1983 and 2.2.1.2 below). Real imaging was first provided by the Hard X-ray Imaging Spectrometer (HXIS) aboard the SMM, and subsequently by the Hinotori hard X-ray telescopes, (SXT).

The HXIS imaged simultaneously in six energy bands within 3.5-30.0 keV, with temporal resolution between 1.5 and 7 seconds and a spatial resolution of 8" x 8" (van Beek et al., 1980). The SXT's spatial resolution was 15" x 15" and the temporal resolution 7 seconds (Oda, 1983; Makishima, 1982; Tsuneta, 1984).

A heated controversy on the interpretation of impulsive phase hard X-ray emission motivated the early studies of hard X-ray images. Two competing models were, and still are, considered. The nonthermal model (Brown, 1971; Lin and Hudson, 1976; Hoyng et al., 1976) postulates that most of the flare energy is carried by a beam of fast electrons which are created within an active region loop and precipitates at its chromospheric footpoints, where it produces hard X-rays by thick target emission. On the other hand a qualitative model was developed, postulating that a large fraction of the hard X-ray emission at low energies (tens of keV) could be due to thermal bremsstrahlung (Brown et al., 1979; Smith and Lilliequist, 1979; Vlahos and Papadopoulos, 1979; Emslie and Vlahos, 1980). This model relies on the possibility of creating a hot source (T \approx 5 \times 10^7 K), confined by plasma instabilities which lead to ion acoustic turbulence at the expanding conduction fronts which move at the ion sound speed (see discussion on 2.2.6.2).

In the imaging data, for the range of energies covered by the HXIS and SXT, the distinction between the two models is, ideally, quite clear (see e.g., Emslie 1981b, and 2.2.1.3 below for the complications). The beam model predicts strong emission at the footpoints of loops, while the dissipative thermal alternate should show a bright, expand-
source within the coronal loop, and minor contribution from the footpoints, due to the escaping tail of electrons which traverse the turbulent fronts.

Figure 2.2.1 (from Duijveman et al., 1982) shows that, in at least some cases, the HXIS observations seem to favor the nonthermal model. Widely separated footpoints are seen in three flares shown in the Figure, even as far as 70,000 km away from each other (November 5, 1980 footpoint C in Figure 2.2.1c). These footpoints overlay regions of enhanced chromospheric and transition zone emission, which brighten in temporal coincidence, in ultraviolet radiation, with the hard X-ray peaks (see Canfield et al. in this volume and references therein). Duijveman et al. (1982) analyzed the events and concluded that the observations were consistent only with thick target emission in which the beam power implied a 20% acceleration efficiency during the early impulsive phase.

This result is not general however, and the HINOTORI investigators (Tanaka, 1983; Ohki et al., 1983 and Tsuneta, 1983b) have been able to identify at least three types of hard X-ray flares from the characteristics of the hard X-ray image, spectrum and impulsiveness of the time profile. The general characteristics of the three types (A, B and C) are listed in Table 2.2.1.

The three flares shown in Figure 2.2.1 correspond to the type B, which are typical impulsive burst events. Their duration ranges from tens of seconds to minutes, and the time profile consists of an impulsive phase with spiky structure and effective power law index ranging from 3 to 5, and a gradual phase, generally softer, with smoother structure. During the gradual phase the hard X-ray morphology changes drastically, the footpoints disappear and a single elongated source is seen at high altitude. This behavior of type B flares is shown in Figure 2.2.2 (from Machado, 1983a; see

![Figure 2.2.1 HXIS contour plots in soft (top) and hard (bottom) X-rays, for three flares discussed by Duijveman et al. (1982). The integration is over the impulsive spikes and the dashed lines show the magnetic neutral lines. The hard X-ray footpoints (16 - 30 keV) are labelled as A, B and C.](image)

Provided by the NASA Astrophysics Data System
Table 2.2.1 Main Characteristics of Solar Hard X-Ray Flares

<table>
<thead>
<tr>
<th>Type</th>
<th>Time Profile (E ≥ 20 keV)</th>
<th>Hard X-ray spectrum (E &gt; 15 keV)</th>
<th>Hard X-ray image (E ~ 20 keV)</th>
<th>Electron density (cm⁻³)</th>
<th>Magnetic field strength (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E ≤ 40 keV intense smooth time profile</td>
<td>very soft</td>
<td>γ ~ 7–9</td>
<td>small point-like</td>
<td>~10¹¹</td>
<td>≥ 330</td>
</tr>
<tr>
<td>A</td>
<td>hot plasma (T = 3×10⁸ K) (EM = 10⁴⁹ cm⁻³)</td>
<td></td>
<td>hard X-ray source (~ 15 arcsec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E &gt; 50 keV no substantial emission with small spikes</td>
<td>dominantly contributed</td>
<td>E ≤ 40 keV.</td>
<td>low altitude</td>
<td>(~ 5000 km)</td>
<td></td>
</tr>
</tbody>
</table>

**Impulsive phase**

<table>
<thead>
<tr>
<th>B</th>
<th>scale of sec.</th>
<th>power-law (10 – 70 keV)</th>
<th>footpoint double source</th>
<th>≤10¹⁰</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradual phase</td>
<td>smooth with time scale of min.</td>
<td>thermal sp. (T = 3×10⁷ K below 40 keV) + power-law</td>
<td>coronal loop-like hard X-ray source</td>
<td>≥10¹¹</td>
<td>550</td>
</tr>
</tbody>
</table>

**Smooth time profile with time scale of min. even above 100 keV**

| C    | power-law γ ~ 3 – 5 | systematic | high altitude (~ 40000 km) coronal hard X-ray and microwave sources | 3×10¹⁰ | 50 |

Figure 2.2.2 Hard X-ray (16 to 30 keV) observations of the April 10, 1980 flare. The doubled shaped structure (left) corresponds to the time of the impulsive burst (see Duijveman et al. (1982)), and the single structure to the gradual burst (see Machado et al. (1982)). The edge of the HXIS field of view is shown as reference. The soft X-ray emission (not shown) encompass the entire region with its maximum located at the position of the gradual component in the second image. The scale corresponds to 16 arc secs.

Machado et al., 1982 for a complete discussion) for the April 10, 1980 event shown in Figure 2.2.1. We see a transition from footpoint to single source morphology of the 16-30 keV sources; similar behavior has been observed in the other two HXIS flares of Figure 2.2.1 (Hoyn et al., 1981; Duijveman et al., 1982 Machado et al., 1984b).

The transition from footpoint to single hard X-ray structure may reflect, as proposed by Machado et al. (1982) and Tsuneta (1983b), a change in the mode of the energy release from strong particle acceleration to plasma heating. A possible scenario on the way this may happen is described by Smith (1985, see Section 2.2.6.2) and Tsuneta (1985), but we should also be aware of the limitations of available imaging observations, discussed below. However, before reaching a definite conclusion on this subject, we must keep in mind that most of the SMM and HINOTORI type B flares (and all of type A) show single source structure (Duijveman and Hoyn, 1983; Takakura et al., 1985a).

There is, however, good evidence of high temperature plasma components in the gradual phase of some flares. These are given by the recent high resolution spectral ob-
servations of an impulsive flare, obtained with a solid state
detector (Lin et al., 1981). In the impulsive phase the spec-
trum is a power law, while in the gradual phase a hot ther-
nal component with $T \approx 3 \times 10^7$K appears as the power
law gradually fades. Also, observations of a coronal source
seen by the HXIS after the two ribbon flare of May 21, 1980
(cf. later phase of the flare shown in Figure 2.2.1.b), have
been interpreted as evidence of a long lasting high tempera-
ture ($\geq 4 \times 10^7$K) source (Hoyng et al., 1981; Duijveman,
1983). Duijveman (1983) discussed the heat balance of this
source and found that its cooling rate by classical heat con-
duction would have been much larger than the saturated limit.
He finds that the energy needed to maintain the hot source
throughout its life time of several minutes is of the same order
of magnitude as that needed to maintain the cooler (10$^7$K)
soft X-ray emitting component. These imaging and spectral
observations show that high temperature plasma of about
$3 \times 10^7$K or more is generated during the development of
at least some flares.

Further evidence of high temperature components in the
hard X-ray emission is given from the analysis of the type
A flares. Their integrated hard X-ray emission shows smooth
time profiles, a steep power law index (7-9) and a duration
$\geq 10$ minutes. An example of type A flare is the July 17,
1981 flare observed by the HINOTORI (Tsuneta et al.,
1984b). Line ratio analysis of the FeXXVI lines, detected
throughout the flare development (Tanaka et al., 1982;
Moriyama et al., 1983) indicate the presence of 3 to 3.5 $\times$
$10^7$K plasma, with emission measure of the order of 10$^{49}$
cm$^{-3}$. A possible interpretation of this type of flare is that
intense heating occurs from the start of the flare, with lesser
amount of power being spent in particle acceleration (Tsuneta
et al., 1984b). An example of this type of event as observed
by the HXIS is the July 14, 1980 event described by
Duijveman and Hoyng (1983).

Finally, the type C flares show long lasting time profiles
with power law indices of 2 to 5 between 30 and 200 keV,
which tend to decrease with time. An example of this type
is the May 13, 1981 event (Tsuneta et al., 1984a), when a
stationary hard X-ray source was observed at an altitude of
$\approx 4 \times 10^4$ km, coincident with a gyrosynchrotron source
at 35 GHz (Kawabata et al., 1983). These flares seem to
belong to the microwave rich type (Kai and Kosugi, 1985)
which are discussed in Section 2.2.4, and show relatively
large energy dependent delays in X-rays which we treat in
Section 2.2.3.3 and 2.2.6.

A possible interpretation for the type C flares (Tsuneta
et al., 1984a) invokes a coronal thick target trap model. As
shown in Table 2.2.1 the target density of several type C
flares was obtained by assuming that the delay is caused by
complete trapping of nonthermal electrons (Bai and Ramaty,
1979; see 2.2.6 below). Also, Yoshimori et al. (1983) have
found typical time delays of tens of seconds between MeV
and lower energy hard X-ray emission while type B flares
typically show delays of a few seconds. This may indicate
differences in the particle acceleration timescales between
type B and C flares. More details on the characteristics of
these events can be found in the references we have listed.

It is worth pointing out that only a few events (less than
ten total) from each spacecraft can be placed in one of the
types mentioned above. The majority of the events observed
does not fall in any of the above classes of flares. Thus, we
believe that more complex magnetic structures and energiza-
tion processes are at work during a flare (see discussion in
Section 2.2.7).

From the data discussed above, it is clear that hard X-ray
imaging has been achieved with SMM and HINOTORI. The
imaging, however, is restricted to energies below 25-30 keV,
with a spatial resolution of 8'' (5800 km) at most. Let us
now discuss some of the implications of these results, looking
more closely at the data.

MacKinnon et al. (1985) emphasized that analyses of
HXIS data to date have not adequately considered instrumen-
tal effects and data noise. The claim that three flares (April
10, May 21 and November 5, 1980) display "footpoint"
emission, and therefore constitute evidence for the thick tar-
get beam interpretation of hard X-ray emission, has rested
on morphological conclusions drawn from non-deconvolved
images. Further, the count levels in these images are some-
times so low that consideration of photon shot noise must
lead one to question the reality of morphological features.
MacKinnon et al. (1984) developed a deconvolution routine,
which takes into account all the instrumental effects, by use
of the Maximum Entropy (ME) method. The advantages of
this method, particularly the way it assesses reality of fea-
tures are discussed in MacKinnon et al. (1984). MacKin-
non et al. applied the above operation to images produced
in the energy range 16-30 keV for the three HXIS flares
which showed distinct bright points (Duijveman et al., 1982
and earlier references therein) and concluded that, in the
16-30 keV range, the presence of distinct bright points is
stable to these procedures, and to the addition of noise
(although other morphological features may be changed, as
may such quantities as "contrast ratio"); it should also be
stated that this is not always true in the 20-30 keV range due
to poor counts statistics.

Further, evidence for distinct bright points has taken the
form of comparison of individual pixel time profiles, either
to establish simultaneity of footpoint brightening or to di-
stinguish the footpoint pixels from their neighbors (see
Duijveman et al., 1982). MacKinnon et al. have investigated
these conclusions quantitatively using cross-correlation
coefficients. These findings, detailed in MacKinnon et al.
(1984), vary slightly over the three flares, but in general they
find that such comparisons do not serve to distinguish the
"footpoints" either because the count statistics are not good
enough, or because other, non-footpoint pixels also brighten
simultaneously. Finally, they emphasize that all the above

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conclusions are based on band 5 data (16-30 keV), since the lower bands are not really “hard” X-rays. However, it has been pointed out that the correlation of points A and C in the November 5, 1980 (see Figure 2.2.1) flare is well borne out in the lower energy channels where the number of counts is much higher. MacKinnon et al. feel that this must be a question which requires careful consideration, in view of the undoubted role of hot (a few × 10^7K) thermal plasmas in these energy bands.

2.2.1.2 Stereoscopic Observation

Simultaneous observations of solar hard X-ray bursts from two widely separated spacecrafts has recently offered new possibilities for testing source models, in terms of both directivity and spatial distribution of the emission (Kane et al., 1979, 1982; Kane, 1981b). Such stereoscopic observations of the sun, using the ISEE-3 and PVO spacecraft, have shown that most of the impulsive hard X-ray emission originates at altitudes ≤ 2500 km above the photosphere (see Figure 2.2.2). The five events analyzed so far fall into two groups according to the occultation altitude involved. First, there is the series of three successive events occurring in a single active region on November 5, 1979, which were occulted from PVO at low chromospheric altitudes, increasing from about zero for the first event to about 2500 km for the third, due to the rotation of the Sun (Kane et al., 1982). For each of these events the ratio of occulted to unocculted flux was evaluated at photon energies of 150 and 350 keV, and for the third event the time evolution of this ratio was determined. Second, there are two events (October 5, 1978 and September 14, 1979) for which the occultation altitudes are coronal (25,000 km and 30,000 km respectively). Flux ratios are again available at two energies and their time evolution is known for the September 14 event. The main conclusions are: (a) about 90% of the impulsive X-ray emission and about 70% of gradual (extended) X-ray emission originate at altitudes ≤ 2500 km above the photosphere. In the 100-500 keV range, this altitude dependence is essentially independent of photon energy. (b) The brightness of the impulsive X-ray source decreases rapidly with increase in altitude, in a manner similar to that shown in Figure 2.2.3.

2.2.1.3 Implications of Hard X-ray Imaging and Stereoscopic Observations

Following the work of Brown and McClintock (1976) and Emslie (1981b), Machado et al. (1985) have computed the spatial distribution of hard X-rays in flare loops and the chromosphere by applying Brown and McClintock’s method to the analysis of some well-observed SMM flares. Their results show that, due to the combination of spatial resolution and rather low energy imaging, only under particular circumstances could chromospheric footpoints be seen in the images. This is readily seen from the fact that, under the best conditions, the flare loops have to cover three HXIS pixels (i.e. ≥ 15000 km) to be able to show separated footpoints. This implies that in order to have a strong chromosphere brightening at 20 keV, electrons with similar or higher energy must have a collisional mean free path equal to or larger than the above distance, or in other words the loop densities should be ≤ 4 × 10^{10} cm^{-3}.

A transition from footpoints to single source hard X-ray structures was observed (cf. 2.2.1.1) in the November 5, 1980 flare studied by Duijvesman et al. (1982). This transition occurred within the main flare region, where footpoints A and B were observed in the early flare phase. Figure 2.2.4 shows a light curve of the hard X-ray emission of the event, in which two hard X-ray peaks, P1 and P2, have been defined. P1 corresponds to the time when the footpoints were observed, while P2 (more gradual and softer) shows a single source in the hard X-ray (16-30 keV) images which is located between the two footpoints, coinciding with the locus of maximum emission in the soft X-ray images. An approximate estimate of the flare volume V ≈ 2.3 × 10^{43} cm^3 can be obtained, leading to densities n(P1) ≈ 5 × 10^{10} cm^{-3} and n(P2) ≈ 10^{11} cm^{-3} of the loop plasma during each peak (the density increase is presumably due to chromospheric evaporation). These densities are a lower limit, since a filling factor ≈ 1 is assumed (see Wolfson et al. (1983) for a critical discussion). The expected spatial distribution of hard X-rays

![Figure 2.2.3](chart.png)
Figure 2.2.4 Hard X-ray emission light curves of the November 5, 1980 event. In the 22-30 keV lightcurve the two peaks are marked with P1 and P2 and correspond to the the points that the spatial distribution of hard X-rays has been computed.

X-rays can be calculated under simplified assumptions (cf. Brown and McClymont, 1976; Machado et al., 1985) of the predominance of Coulomb losses and parallel injection of electrons along field lines. We should note that this is the most favorable case for footprint prediction, since it neglects any effect (like e.g., pitch angle distribution, Leach and Petrosian, 1981) that could increase beam stopping.

Machado et al. (1985) calculated the intensity distribution of hard X-rays using idealized loop models. They analyzed three different models for the energy release (see Figure 2.2.5a). Case A represents a situation in which the acceleration site is located at the boundary between two pixels, presumably at the loop’s apex, and the beam strength is symmetrical towards both sides. In case B it has been assumed that the acceleration region is at the middle of a pixel, and the beam is predominantly towards one side of the loop. Finally, in case C, the acceleration site is also located at the middle of a pixel, but beam strengths towards both sides are equal. The boxes shown in Figure 2.2.5a represent the pix-

<table>
<thead>
<tr>
<th></th>
<th>22.6</th>
<th>14.6</th>
<th>62.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.1</td>
<td>35.3</td>
<td>42.5</td>
</tr>
<tr>
<td>CASE A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.6</td>
<td>18.2</td>
<td>60.2</td>
</tr>
<tr>
<td>CASE B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|       | 51.3 | 12.5 | 36.2 |
|       |      |      |      |
| CASE A|      |      |      |

|       | 50.2 | 21.8 | 27.9 |
|       |      |      |      |
| CASE C|      |      |      |

|       | 65.0 | 26.1 | 32.2 |
|       |      |      |      |
| CASE C|      |      |      |

Figure 2.2.5 (a) The three cases of convolution discussed in the text. The cross marks the place where particle acceleration is presumed to occur and the arrows the predominant direction of beam injection. The shaded area in the third pixel is the chromospheric footprint, which is assumed to be smaller than a HXIS 8” × 8” pixel and is shifted in location across the “footprint pixel”. Note that in cases B and C, due to its spatial overlap with its neighbor to the right, a fourth pixel should contain part of the footprint emission. (b) Result of the intensity distribution of hard X-rays in percentage of the total emission. Cases A, B and C correspond to those shown in Figure 2.2.1. The “footprint pixel” contains the total of the emission which should be spread in two (see cases B and C of Figure 2.2.1). Note the strong changes that can be expected by changing the location of the acceleration source and/or the footprint location. In particular case A of P1 shows a large change in the brightness of the pixel located to the left of the footprint, and case C of P2 the increase in brightness of the loop source.
els from the HXIS instrument, the total emission over half of a loop length assumed to cover two HXIS 8" pixels and the third pixel from the left is the "footpoint pixel". The "footpoint pixel" shows the emission of the chromospheric part of the hard X-ray distribution. In Figure 2.2.5b Machado et al. displayed the percentage of the total emission for all three cases using a photon energy $\epsilon = 19$ keV. These idealized calculations clearly show a transition from footpoint to predominantly single structure in the hard X-ray distribution of P1 and P2. We also present in Figure 2.2.5b the results obtained from the convolution of the unconvolved distribution (c.f. earlier comments and Svetska et al., 1983). The general result here is that the convolution tends to decrease the footpoint/loop brightness ratio, a result consistent with the observations reported by Duijveman et al. (1982), Hoyng et al. (1981) and Machado et al. (1982). The Machado et al. results tend to reinforce the conclusions about the reality of hard X-ray footpoints, and provide a warning against the direct interpretation of single hard X-ray sources as indicative of regions heated by a mechanism different from the one leading to acceleration (cf. Implications of footpoint to single source transition in type B flares).

Another important aspect to take into account is the heating effect of beam particles along the loop, due to Coulomb collisions with the ambient plasma. Calculations of energy deposition rate as a function of column density, $N$ (cm$^{-2}$), have been performed by many authors (Brown, 1972, 1973; Lin and Hudson, 1976; Emslie, 1978, 1980, 1983), generally in connection with chromospheric heating calculations. Machado et al. (1985) have been able to show that in the cases of high-density flare loops (like e.g., the July 14, 1980 event described by Duijveman and Hoyng, 1983) single sources are not only likely to appear because of particle stopping within the loop and high efficiency in the nonthermal bremsstrahlung production, but also because their localized heating causes an increase in the thermal contribution to the hard X-ray output below 25 keV (note also that if the heating is very large it invalidates the condition $E > E_b$ of the thick target approximation, where $E$ is the particle’s energy and $E_b$ the mean thermal energy of the particles in the target). It is also worth noting that these single source (type A or C) flares often show less “spiky” time profiles, which can result as a natural consequence of the fact that the temporal behavior is no longer exclusively related to time variations in the beam intensity but also to the conductive cooling timescale of the heated regions. A detailed analysis of this latter possibility has not yet been carried out. An alternative for the beam induced heating may also be related to the opposite case, i.e. low loop densities, which can lead to beam - plasma - return current instabilities and increase the beam losses due to non-collisional effects, (Vlahos and Rowland (1984), Rowland and Vlahos (1984)). This is another field in which more work is needed before reaching definite conclusions.

Machado et al. concluded that, in spite of the instrumental limitations, the presence of footpoints in the hard X-ray images, seems to give support to the thick target interpretation of the bursts. MacKinnon et al. (1985) on the other hand, feel that no aspect of the images demands such an interpretation uniquely, and find that some aspects of the data are difficult to accommodate in any conventional (thick target or dissipative thermal) model.

There are several pieces of evidence that indicate that a substantial fraction of the low energy ($E < 30$ keV) impulsive emission in flares is not purely due to thick target bremsstrahlung. Machado (1983b) reached this conclusion by the analysis of the energy and particle content of a compact flare loop, where a pure thick target analysis was shown to be incompatible with the parameters derived from the soft X-ray plasma.

Brown et al. (1983b), from the analysis of stereoscopic observations, find that the detailed quantitative dependence of occultation ratio on height, energy and time are not compatible with the basic thick target model as the sole source of the hard X-rays. Either emission from thermal sources or from magnetically trapped electrons have to be invoked to explain the observations.

Finally, Machado and Lerner (1984) re-analyzed the observations of a limb flare of April 13, 1980, which showed a bright X-ray (16-30 keV) source at the boundary between two distinct magnetic structures (see Machado et al., 1983). They find that the spatial distribution in intensity and spectral behavior of the hard X-rays is incompatible with a pure nonthermal interpretation. They conclude that a large fraction ($> 50\%$) of the emission in the 20 keV range is due to thermal bremsstrahlung of plasma with temperatures $> 5 \times 10^6$K. The spatial distribution of the emission leads them to propose that the site of the maximum hard X-ray brightness is located where energy is released (at the region of interconnection between two field structures) both in the form of heating and particle acceleration.

2.2.2 Microwave Source Structure, Location and Development

Accelerated electrons produce microwave radiation through their interaction with the magnetic field. High resolution observations at cm-wavelengths have given important information about the magnetic structure of the flaring region. Observations at several frequencies can, in principle, provide valuable diagnostics of both the magnetic field and the distribution function of the energetic electrons as a function of time. However, so far there have been very few multi-frequency observations at high spatial resolution and consequently the discussion has been focused on the diagnosis of the magnetic field configuration.

Two dimensional images with the Very Large Array (VLA) radio telescope suggest that interacting magnetic loops
and magnetic field reconnection have important roles to play in solar flares. This can occur as a result of emergence of new flux interacting with pre-existing flux, or as a consequence of rearrangement and/or reactivation (e.g., twisting) of two or more systems of loops. Kundu (1981) illustrated this phenomenon with a set of 6 cm observations made with the VLA (spatial resolution ~ 2') that pertains to changes in the coronal magnetic field configurations that took place before the onset of an impulsive burst observed on 14 May 1980 (Kundu, 1981; Kundu et al., 1982; Velusamy and Kundu, 1982). The burst appeared as a gradual component on which was superimposed a strong impulsive phase (duration ~ 2 minutes) in coincidence with a hard X-ray burst. Soft X-ray emission (1.6-2.5 keV) was associated with the gradual 6 cm burst (before the impulsive burst), as is to be expected. There was a delay of hard X-ray emission (> 28 keV) relative to 6 cm emission. The most remarkable feature of the 6 cm burst source evolution was that an intense emission extending along the north-south neutral line, possible due to reconnections, appeared, just before the impulsive burst occurred, as opposed to the preflare and initial gradual emission being extended along an east-west neutral line. This north-south neutral line must be indicative of the appearance of a new system of loops. Ultimately the loop systems changed and developed into a quadrupole structure near the impulsive peak. This field configuration is reminiscent of flare models in which current sheet develops at the interface between two closed loops. The impulsive energy release must have occurred due to magnetic reconnection of the field lines connecting the two oppositely polarised bipolar regions (Kundu et al., 1982).

A second burst observed by Kundu et al. 1984 on 24 June 1980, 19:57 UT provides a good example of interacting loops being involved in triggering the onset of a 6 cm impulsive flare associated with a hard X-ray burst. It also provides evidence of preflare polarization changes on time scales of a minute or so, which may be related to coronal magnetic field configurations responsible for triggering the burst. The 6 cm burst source is complex, consisting initially of two oppositely polarized bipolar sources separated E-W by ~ 1.5' arc. The first brightening occurs in one component at 19:57:10 UT, the western component being much weaker at this time. It then brightens up at 19:58:05 UT, just at the onset of the impulsive rise of the burst and is accompanied by changes in its polarization structure. It then decays and splits into two weak sources separated E-W by ~ 12" arc. The eastern component brightens up at 19:58:41 UT, accompanied by significant polarization changes, including reversal of polarization. A third component appears approximately midway between the eastern and western component at 19:58:45 UT during the peak of the associated hard X-ray burst. The appearance of this source is again associated with polarization changes, in particular the clear appearance of several bipolar loops; its location overlaps two opposite polarities implying that it might be situated near the top of a loop. During the peak of the associated hard X-ray burst (1980 June 24, 19:57:00 event), a third (perhaps another bipolar) loop appears in between the previous two sources. Kundu believes that we are dealing with interaction between multiple loop structures, resultant formation of current sheets and magnetic field reconnection, which is responsible for the acceleration of electrons.

Lantos, Pick and Kundu (1984) combined observations of three solar radiobursts obtained with the VLA at 6 cm wavelength and with Nancay Radioheliograph at 1.77m. A small change in the centimetric burst location by about 10" arc corresponds to a large change by about 0.5 R\(_{\odot}\) in the related metric location. The metric bursts occur successively at two different locations separated by about 3.10\(^3\) km. During the same period, an important change in the microwave burst source is observed. This may indicate the existence of discrete injection/acceleration regions and the presence of very divergent magnetic fields in agreement with the suggestions made by Kane et al. (1980).

The Westerbork Synthesis Radio Telescope (WSRT) was used by Alissandrakis and Kundu (1985) for solar observations at 6.16 cm with a spatial resolution as good as 3" and a time resolution of 10 sec. In spite of the limitations of one-dimensional fan-beam scans in total intensity (I) and circular polarization (V) of burst sources, several interesting features could be discovered in their structure.

Out of the 76 bursts observed, 57% consisted of two or more components in total intensity. An example of a burst with two components is shown in Figure 2.2.6a,b, where contours of 1-D brightness temperature as a function of position and time are plotted. In total intensity (I), the burst consists of two impulsive components, A and B, with their peaks separated by 26" and a total duration of about 4 minutes. The peaks are almost simultaneous with a possible delay of component B by no more than 5 sec with respect to component A. Component A is fairly symmetric with a width of 7" and a maximum 1-D brightness temperature of 6.5 \times 10^6K arc sec above the background; assuming a circular shape this value corresponds to a brightness temperature of about 10^7K. The other component is asymmetric with a width of 11" and an estimated brightness temperature of about 4 \times 10^6K. Alissandrakis and Kundu pointed out that near the maximum the two components appear to be connected by a bridge of low intensity emission. Such interconnections between burst components are the rule rather than the exception in their sample of bursts. In the example shown there is a definite extension of component B in the direction of component A. The circular polarization map shows that both components, as well as the bridge between them are polarized. Component A shows two peaks of opposite sense with the total intensity peak coinciding with the region of zero polarization; the degree of polarization at the V peaks is about 50%. The polarization of the other component is
A two component burst observed with the WSRT at 6.16 cm. (a) The contours of equal brightness temperature (integrated in the direction perpendicular to the resolution) as a function of one-dimensional position and time in Stokes parameters I and V. (b) The I map is $10^3$ K arcsec with a contour interval of $0.5 \times 10^3$ K arcsec, while the V map the lowest contour and the counter interval are $0.3 \times 10^3$ K arcsec. Dashed lines show negative (left handed) circular polarization (from Alissandrakis and Kundu, 1985).

Figure 2.2.6 A two component burst observed with the WSRT at 6.16 cm. (a) The contours of equal brightness temperature (integrated in the direction perpendicular to the resolution) as a function of one-dimensional position and time in Stokes parameters I and V. (b) The I map is $10^3$ K arcsec with a contour interval of $0.5 \times 10^3$ K arcsec, while the V map the lowest contour and the counter interval are $0.3 \times 10^3$ K arcsec. Dashed lines show negative (left handed) circular polarization (from Alissandrakis and Kundu, 1985).

uniform with a 40% maximum near the I maximum. The sense of polarization of component B is the same as that of the nearest V peak of component A, as well as that of the bridge; the latter is almost 100% polarized. Such a polarization structure of 6 cm burst sources is quite common.

If we assume that the sense of circular polarization corresponds to the polarity of the magnetic field, we can interpret the observations in terms of a small flaring loop, corresponding to component A and a larger loop connecting component A with component B. The large loop emits mainly at the footpoints with some emission from the rest of the loop which corresponds to the bridge; the emission from the top of the large loop is weak because it is located higher in the corona where the magnetic field is weak. This scenario is similar to the schematic model presented by Kundu and Shevaonkar (1985) for the impulsive onset of the microwave burst radiation as a result of two interesting loops. However, as pointed out by Alissandrakis and Preka-Papadema (1984) that the observed sense of circular polarization can be influenced by propagation effects in the corona outside of the flaring region, so that the polarization-inversion line does not necessarily coincide with the neutral line of the magnetic field. If polarization inversion does indeed take place, the observations can also be interpreted in terms of a single large loop connecting the two components and radiating predominantly at the footpoints.

Using the Nobeyama 17-GHz interferometer Nakajima et al., (1984a) observed on November 8, 1980 a microwave burst occurring at a site (Hale region 17255) $8 \times 10^3$ km remote from the primary flare site (Hale region 17244). The time profiles of the secondary microwave bursts are delayed relative to the primary bursts even in details. The overall time profiles of the secondary microwave bursts are peaked relative to those of the primary bursts by 11 or 25 secs. The velocity of a triggering agent inferred from this delay and the spatial separation is about $4 \times 10^3$ or $8 \times 10^4$ km s$^{-1}$ and therefore is probably due to fast electrons which were transferred from the primary site to the secondary site along a huge coronal loop. The SMM-HXIS data showed that a new X-ray loop was excited in the region adjacent to the secondary microwave source. The X-ray loop was associated with a faint, compact Hx brightening at its footpoints. The event occurred twice with a similar behavior within a time interval of $\sim 40$ min and therefore the occurrence of the correlated events is not random. The observations suggest that a new flare (a sympathetic flare) was triggered at the secondary site by an energetic electron stream from the primary site. Similar observations were first reported by Kundu, Rust and Bobrowsky (1982) for a flare observed on May 14, 1980, with practically the same conclusions.

Heights and sizes of microwave burst sources at 17 GHz were obtained as shown in Figure 2.2.7. The events were selected from those which were observed with the 17 GHz one-dimensional interferometer between October 1978 and February 1981. An additional selection condition is that the longitude of the associated Hx flare is $\geq 70^\circ$ and the peak flux density at 17 GHz is $\geq 50$ s.f.u. The heights were estimated on the assumption that the microwave sources were above the corresponding Hx flares. Both the heights and sizes of the impulsive bursts (12 events) are roughly correlated and range from about 10 to 20 arc sec above the photosphere with an average value of 13 arc sec ($10^4$ km). The long-
enduring bursts (2 events) are located higher (30 arc sec) and larger (35 arc sec) in size compared to those of the impulsive bursts. Although SMM-HXIS and HINOTORI-SXT hard X-ray imaging observations show in several cases that the hard X-ray component of the impulsive burst is located in the chromosphere (e.g., Duijveman, Hoyng, and Machado, 1982; Tsuneta et al., 1983), the observations reported by Nakajima et al., 1984a show that the microwave emission from the impulsive burst comes from the corona. The VLA observations have often shown a compact (very small compared to the distance between Hα kernels) source of the impulsive bursts located spatially between Hα kernels (Marsh and Hurford, 1980; Velusamy and Kundu, 1982; Hoyng et al., 1983). On the other hand, the observation reported above shows that the source size and height are roughly the same. The height observations of the long-enduring bursts confirm the results reported by Kosugi et al. (1983) and Kawabata et al. (1983).

2.2.3 Time Structures and Time Delays in Radio and Hard X-rays

2.2.3.1 Centimeter-Decimeter Millisecond Pulses and Electron Cyclotron Masering

Spikes of durations less than 100 ms are well known in the 200 – 3000 MHz radio band. At meter wavelengths some have been reported near the starting frequency of type III bursts (Benz et al., 1982), at decimeter wavelengths as a part of type IV events (Dröge, 1977) and at centimeter wavelengths superposed on a gradual event (Slottje, 1978). In an analysis of 600 short decimetric events (excluding type IV’s), Benz, Aschwanden and Wiehl (1984) have found 36 events consisting only of spikes. An example of the data is presented in the Figure 2.2.8 together with a hard X-ray time profile and a blow-up of some single spikes. A detailed analysis (Benz, 1984) shows that the groups of spikes are always associated with groups of metric type III bursts. The spikes tend to occur in the early phase of the type III groups and predominantly in the rising phase of hard X-rays. The half-power duration of the spikes is less than 100 ms, the time resolution of the instrument used. The spectrum of the spikes has been recorded and the typical half-power widths are 3-10 MHz at 500 MHz, i.e. about 1% of the center frequency. This puts a severe constraint on the spectral width of the radio emission and therefore on the generating mechanism. The most plausible interpretation is emission at the electron cyclotron frequency or harmonic (e.g., upper hybrid wave emission or cyclotron maser). Even then, the requirement on the homogeneity of the source is formidable: assuming a locally homogeneous corona with a magnetic field scale length of 10,000 km, the source size in the direction of the field gradient must be equal to or less than 100 km. This is less than the upper limit of the size imposed by time variation. Assuming this dimension for the lateral extent of the source, the lower limit of brightness temperature is up to 10¹⁰K. Provided that the emission is radiated close to the plasma frequency, the source density amounts to about 3 × 10⁶ cm⁻³. The spikes have peak fluxes of up to 800 sfu and are circularly polarized. The polarization ranges from 25-100%. The sense of polarization is righthanded, opposite to most type III bursts occurring at lower frequencies at the same time.

The high brightness temperature of short duration (1-100 msec) spikes observed during the impulsive phase of some flares at microwave frequencies (~ 3 GHz) indicates that a coherent radiation mechanism is responsible. Coherent plasma radiation at the electron plasma frequency was originally suggested as the radiation mechanism (Slottje, 1978; Kuijpers, van der Post, and Slottje, 1981). Holman, Eichler and Kundu (1980) argued that electron cyclotron masering at frequencies just above the electron gyrofrequency or its second or third harmonic was a likely mechanism for the spike emission. As a third possibility, coherent emission at twice the upper hybrid frequency, has been suggested by Vlahos, Sharma and Papadopoulos (1983). Electron cyclotron masering has been the most highly studied of the three mechanisms. The mirroring of suprathermal electrons in a flaring loop naturally leads to a loss-cone particle distribution, which is unstable to electron cyclotron maser emission (Wu and Lee, 1979). The attractive features of this mechanism are that it is a linear process, not requiring wave-wave interactions, and the conditions for it to operate are essen-

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Figure 2.2.8 Top: Composed figure showing hard X-ray counts (> 30 keV, observed by HXRBS on board the Solar Maximum Mission) vs. time, of the double flare of August 31, 1980 and radio spectrogram registered by the analog spectrograph at Bleien (Zürich). The spectrogram shows type III bursts at low frequency having starting frequencies in correlation with the X-ray flux and spike activity above 300 MHz. Bottom: Blow-up of a small fraction of spectrogram produced from data of the digital spectrometer at Bleien (Zürich). The blow-up shows single spikes which are resolved in frequency (from Benz, 1984).
Finally the same as those required for an incoherent microwave source: trapped, mildly relativistic electrons (roughly the same number as required for the incoherent emission) with moderately high pitch angles. The masering occurs as long as the loss-cone distribution of the mirrored electrons is maintained. As shown by Melrose and Dulk (1982) and Sharma, Vlahos, and Papadopoulos (1982), the saturated level of the emission is sufficient to provide the observed high brightness temperatures. The emission must escape thermal cyclotron absorption at the next higher harmonic, however, and this requirement favors second harmonic emission, since emission at the fundamental will generally not be able to escape the second harmonic absorption layer. Growth of the first harmonic poses a problem for second harmonic emission however, since the first harmonic growth can saturate the maser before the second harmonic is able to grow significantly. Sharma et al. (1982) and Sharma and Vlahos (1984) have shown that the first harmonic, extraordinary mode growth will be suppressed by the ambient thermal plasma if \( \omega_c \geq 0.4 \Omega_e \), (\( \omega_c \) is the plasma frequency; \( \Omega_e \) is the gyrofrequency). The growth of the first harmonic ordinary mode is still large, however, so the conditions under which the second harmonic emission can grow and escape are still not entirely clear. Vlahos and Sharma (1984) analyzed the role of the filling of the loss-cone distribution and suggested that loss-cone driven electron cyclotron emission will be localized at the bottom of the corona and the emitted radiation will have a narrow bandwidth. This is in agreement with the observations reported above.

Finally, in a recent study Zaitsev, Stepanov and Sterlin (1985) suggested that the millisecond pulsations are due to a non-linear induced scattering of plasma waves by background plasma ions. They reduced the coupled non-linear system of equations, that describe the wave-particle interactions, to the well known Volterra equations which describe the "prey-prey" problem. The duration of the pulses (a few milliseconds) is used to determine the density of the energetic electrons that cause the radio emission.

### 2.2.3.2 Ultrafast Time Structure in Microwaves and Hard X-rays and their Time Delays

The use of antennas with large collecting areas has considerably improved the observation of solar bursts at centimeter and millimeter wavelengths with high sensitivity and time resolution (Kaufmann et al., 1975, 1982a; Butz et al., 1976; Tapping, 1983). The 45 ft. diameter radome-enclosed radio telescope, at Itapetinga, Brazil, operating at 22 GHz and 44 GHz, was extensively used during the period of SMM operation, providing high sensitivity (0.03 s.f.u. in single linear polarization) and high time resolution (1 ms) data; these data revealed new aspects of low level solar activity as well as fine time structures in larger bursts. In practically all the bursts studied with high sensitivity at mm-cm wavelengths, fine time structures (< 1 sec) were identified superimposed on the slower time structures (seconds). The repetition rate of the ultrafast structures appear to be higher, for higher mean fluxes of 22 GHz bursts (see Figure 2.2.9). Kaufmann et al. (1980a, 1980b) suggested a possible interpretation of this behavior in terms of a quasi-quantization in energy of the burst response to the energetic injections. A similar suggestion was made earlier from the statistical properties of a collection of X-ray bursts (~ 10 keV) (Kaufmann et al., 1978). A trend similar to that shown in Figure 2.2.9 was found independently at 10.6 GHz (Wiehl and Matzler, 1980) but for bursts with larger flux and timescales. Kaufmann et al. (1980a) showed that for a given burst flux level \( S \) at 22 GHz there is a minimum repetition rate of ultrafast structures \( R \), such as \( S \leq kR \), where \( k \) is a constant. One of the faster repetition rates was found at the peak of an intense spike-like burst (Figure 2.2.10) which was also observed in hard X-rays by SMM-HXRBS (Kaufmann et al., 1984). A striking example obtained simultaneously in microwaves and hard X-rays is the burst of November 4, 1981 at 1928 UT (Takakura et al., 1983b).

![Figure 2.2.9 Scatter 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 (from Kaufmann et al., 1980a).](image-url)
Figure 2.2.10 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 (from Kaufmann et al., 1984).

High sensitivity 10.6 GHz data for the same burst was obtained with the 45-m antenna at Algonquin Radio Observatory, (Tapping, private communication). The presence of a "ripple" is evident at all microwave frequencies and is very significant at 30-40 keV range (HINOTORI-HXM). The ripple relative amplitude (ΔS/S) is 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-cm vs hard X-ray association of superimposed ripples was obtained for the November 13, 1981, 1102 UT burst. The most important findings of such studies are: (a) the slow time structure (seconds) are often poorly correlated, or not correlated, between the four microwaves frequencies (7, 10.6, 22 and 44 GHz) and 30-40 keV X-rays; (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 the HINOTORI-HXM X-ray experiment.

The time structures in complex microwave bursts are frequently not correlated in time at various frequencies. Delays of peak emission at different microwave frequencies range from near coincidence to 3 sec, both toward higher and lower frequencies (Kaufmann et al., 1980a; 1982b). Delays toward lower frequencies only have been reported by Uralov and Nefed’ev (1976) and Wiehl et al. (1980). One long-lasting pulsating burst (quasi-period 0.15 sec) has shown a systematic delay of 300 ms for 44 GHz pulses relative to 22 GHz pulses (Zodi et al., 1984). It might be meaningful, however, to stress that 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. For relatively slower (and smoothed) time structures, the hard X-rays appear to occur 1-2 sec prior to microwave emission (Crannell et al., 1978).

There are several ways to interpret the time delays reported above, for example, convolution effects of multiple emitting kernels (Brown et al., 1980, 1983a; MacKinnon and Brown, 1984, see also discussion on Section 2.2.6.2) or the fact that microwave emitting source may move in a varying magnetic field (Costa and Kaufmann, 1983) are among the suggested candidates. For the large delays between the microwave and hard X-ray peaks (several seconds), it has been suggested that microwave emission originates from another population than the one that produces the X-rays (Tandberg-Hanssen et al., 1984). Finally, the long-enduring persistent quasi-periodic pulsations in bursts, presenting pseudo-delays at different microwave frequencies, might be a phenomenon of a different nature, and might be conceived as due to simple modulation of synchrotron emission by a varying magnetic field (Gaizauskas and Tapping, 1980; Zodi et al., 1984). Some bursts appear to be strictly coincident in time, at various microwave frequencies and X-ray energy ranges (to less than < 100 ms) (Kaufmann et al., 1984).

The impulsive phase X-ray and microwave emission, examined with high sensitivity and high time resolution put several constraints on the models of the bursting region. Among the new observations that require theoretical interpretations are the "ripple" structures, the trend of flux vs. repetition rates, and the possible quasi-quantized energetic injections. Sturrock et al. (1985) suggest that "elementary flare bursts" may arise from the energy release of an array of "elementary flux tubes", which are nearly "quantized" in flux. As a stochastic process of reconnection sets in, by mode interaction, explosive reconnection of magnetic islands may develop in each tube, accounting for the ultrafast time structures (or "ripple") with subsecond timescales.

2.2.3.3 Time Delays in Hard X-ray Bursts

Before the launch of SMM, energy-dependent delay of hard X-rays had been observed only from a small number of flares (Bai and Ramaty, 1979; Vilmer, Kane and Trottet, 1982; Hudson et al., 1980). Hard X-ray delay was first observed from the two intense flares observed on August 4 and 7, 1972 (Hoyng, Brown and van Beek, 1976; Bai and Ramaty, 1979), which happen to be the first gamma-ray line flares (Chupp et al., 1973). Hudson et al. (1980) analyzed a very intense gamma-ray line flare observed with the first High Energy Astronomical Observatory (HEAO-1), and reported a delay of the continuum above 1 MeV with respect to the X-ray continuum about 40 keV. Vilmer, Kane and Trottet (1982) studied the hard X-ray delays exhibited in a
flare observed with ISEE-3. The HXRBs experiment aboard SMM, which has a large area and good time resolution (71 cm$^2$ and 0.128 s in normal mode, respectively; cf. Orwig et al., 1980), is most suitable for studying energy-dependent delays of hard X-rays. In collaboration with the HXRBs group, Bai studied the delay of hard X-rays for many flares (Bai et al., 1983a; Bai and Dennis, 1985; Bai, Kiplinger and Dennis, 1985). A balloon-borne detector and the hard X-ray detector aboard HINORI also detected hard X-ray delays (Bai et al., 1983b; Ohki et al., 1983). The energy dependence of hard X-ray delays is not simple. In some flares the delay seems to increase smoothly with hard X-ray energy, but in others, it seems to show a sudden increase. For example, in the impulsive flares of June 27, 1980 (Bai et al., 1983b; Schwartz, 1984) and of February 26, 1981 (Bai and Dennis, 1985), the delay is negligibly small below a certain energy, and it suddenly increases above that energy. The energy at which a sudden increase occurs varies from burst to burst (Schwartz, 1984). In the August 4 and 7, 1972 flares, the delay increased gradually with increasing energy to about 5 s, and then for energies above $\sim 150$ keV it increased to $\sim 15$ s (Bai and Ramaty, 1979). In the flare of August 14, 1979 flare, the delay was about 10 $\pm$ 5 s for the energy channel 154-389 keV, but it increased to 32 $\pm$ 10 s for the next energy channel 389-874 keV (cf. Vilmer et al., 1982). (It is important to keep in mind that fast increases may also be the result of the fact that the energy channels are wider in higher energies). However, in other flares the delay seems to increase smoothly with hard X-ray energy (cf. Bai and Dennis, 1985). The energy-dependent delay of hard X-rays is equivalent to flattening of the hard X-ray spectrum. In flares with the delay increasing like a step function at a certain energy (such as the ones on June 27, 1980 and February 26, 1981), the spectral shape at low energies remains unchanged while the spectrum at high energies flattens as time progresses during the burst. If the delay is a smooth function of energy, the hard X-ray spectrum flattens with time both at low energies and high energies (Bai, Kiplinger and Dennis, 1985). Often single power law spectra give good fits to the data. The flares exhibiting hard X-ray delays form a small but significant fraction of the total number observed. Another important observational fact is that energy dependent hard X-ray delays have been mostly observed in flares which produced observable nuclear gamma-rays and/or energetic interplanetary protons (Bai and Ramaty, 1979; Hudson et al., 1980; Bai et al., 1983a, 1983b; Bai and Dennis, 1985; Ohki et al., 1983).

Figure 2.2.11a shows a smoothed plot of the 60-120 keV and 120-235 keV rates observed by the UC Berkeley balloon experiment during the impulsive phase of the 27 June 1980 flare (Schwartz, 1984). The smoothed rate during each 0.128 sec interval is computed by averaging the rates over the surrounding bins using a Gaussian weighting function with a 0.5 sec FWHM for the 60-120 keV rate and with a

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intense and longest duration bursts, D and F, the longest delay is for the > 235 keV rate with only a smaller delay for the 120-235 keV rate (Bai et al., 1983b). The lack of significant delays between the 22-33 keV and 60-120 keV channels makes it unlikely that the large delays at higher energies can be explained purely by simultaneous injection at all energies followed by energy-dependent decay due to collisional energy loss (see bottom of Table 2.2.2). Figure 2.2.12, shows five spectra which were accumulated over the intervals marked in Figure 2.2.11. The evolution is similar over both bursts. The double power law becomes a single a power law although the counting rate sensitivity is not enough to observe the hardening in detail. There are two important aspects of the spectral evolution which may provide important clues to the acceleration process. First, the power law exponent at low energies (≤ 70 keV) does not change throughout the acceleration. Secondly, the spectrum at high energies hardens up to the point where the power law exponent is the same as at low energies, but not harder. It is not clear whether the spectral hardening occurs because the break in the spectrum has moved to very high (≥ 200 keV) energies or whether the entire high energy portion has hardened to form a single power law at all energies.

### 2.2.3.4 Hard X-ray Microflares

The U.C. Berkeley balloon flight of June 27, 1980 was the first to observe the Sun with high energy resolution (≤ 1 keV) and sensitivity (50 cm$^2$ germanium plus 300 cm$^2$ scintillation detectors, both well collimated and actively shielded for low background) in the energy range ≥ 20 keV (Lin et al., 1984). They discovered the phenomenon of solar hard X-ray microflares which have peak fluxes ~ 10-100 times less than in normal flares. These bursts occurred about once every five minutes through the 141 minutes of solar observations. Although they are associated with small increases in soft X-rays, their spectra are best fit by power laws which can extend up to ≥ 70 keV. These microflares are thus probably nonthermal in origin. The integral number of events varies roughly inversely with the X-ray intensity (Figure 2.2.13), so that many more bursts may be occurring with peak fluxes below their sensitivity. The rate of energy released in these microflares may be significant compared

![Figure 2.2.12 Five spectra accumulated over the intervals marked in Figure 2.2.11 (from Schwartz, 1984).](image-url)
longer timescale at much lower rate. The stored electrons, however, would radiate via bremsstrahlung. The high sensitivity of the UC Berkeley balloon hard X-ray measurements made on June 27, 1980 permit the study of the pre- and post-impulsive phase nonthermal emissions of a large flare (Figure 2.2.15) in great detail (Schwartz, 1984). Using the high sensitivity of the X-ray detectors: upper limits have been set to the preflare flux during 1600 – 1610 UT. The three sigma upper limit to the flux at 20 keV is $8.3 \times 10^{-4}$ (cm$^{-2}$ sec keV)$^{-1}$. This gives an upper limit to the power law emission measure (Hudson, Canfield and Kane, 1978), $N_{\text{e}} = n_{\text{e}} < 2.4 \times 10^{39}$ cm$^{-3}$, where $N_{\text{e}}$ is the average number of electrons above 20 keV at any instant of time in a region with an ion density $n_{\text{i}}$. Conceivably, the electrons could be stored very high in the corona where the density could be as low as $1 \times 10^{9}$ cm$^{-3}$. This would give a 50 hour collisional lifetime for a 20 keV electron. Thus, up to $2 \times 10^{35}$ electrons could have remained undetected. This is about the number of fast electrons in the small early burst at 1616:00 UT and it represents less than 1% of the total accelerated electron population (see Figure 2.2.15). Schwartz (1984) concluded that while it is possible that a stored electron population could have triggered one of the early small bursts, the vast majority of the flare electrons could not have been stored in the corona but must be energized during the impulsive phase. The question is if there is any acceleration in the post-impulsive phase. In Figure 2.2.15 one can see that at ~1617:30 UT the > 60 keV X-ray flux falls to < 1% of peak intensity. Also, the 22-33 keV rate, mostly from the super-hot component, is falling more slowly. Of great interest for this discussion on electron acceleration is the series of impulsive bursts occurring during 1617:30 – 1630 UT and most clearly seen in the 30-60 keV rate. These post-impulsive phase bursts are similar to the impulsive phase bursts but have a peak intensity of about 0.5% of the largest impulsive phase peak. All the bursts contain fast spikes which rise and fall in 4-10 seconds. The spectral index $\gamma$, uncertain due to the large low energy continuum rates, is obtained by comparison with the count rates during the impulsive phase. These values are consistent with a nonthermal spectrum, similar to the bursts in the impulsive phase. Certainly, this continual bursting is evidence of electron acceleration throughout the post-impulsive phase, as proposed by Klein et al. (1983).

### 2.2.4 Microwave-Rich Flares

Figure 2.2.16 is a correlation diagram between HXRBS peak count rates and peak microwave fluxes; each point in this figure represents the peak HXRBS count rate and the peak flux density of 9 GHz microwaves for a particular flare. The frequency 9 GHz is chosen because for the majority of flares the microwave emission peaks near 9 GHz and because it is in a frequency range well observed world wide. As can be seen, there is a positive correlation between peak
Figure 2.2.14 The four largest hard X-ray microflares are shown here at 1.024 sec resolution (from Lin et al., 1983).

Figure 2.2.15 The hard X-ray burst observed by the scintillation detector. The low decay in the 22-23 keV channel lasts till \(\geq 16:31\) UT. This is due to the super-hot component. The small bursts of non-thermal emission occur till 16:31 UT (from Schwartz, 1984).
Figure 2.2.16 Correlation diagram between peak count rates measured by HXRBS and peak flux densities of 9 GHz microwaves for 1980 through 1981. Although there is quite a lot of scatter, there seems to be a positive correlation between these quantities. The median value of MRIs is about 1 (0.85 to be precise). The three straight diagonal lines indicate constant values of MRI, 1/4, 1 and 4. The large dots indicate GRL flares. Note that the HXRBS peak rates of the GRL flares are > 5000 cts/s (from Bai, Kiplinger, and Dennis, 1985).

Hard X-ray counts rates and peak microwave flux densities (cf. Kane, 1973), consistent with our understanding that both hard X-rays and microwaves are produced by energetic electrons of the same origin. Bai, Kiplinger, and Dennis (1985) defined the "microwave-richness index" (MRI) for each flare as follows:

$$MRI = \frac{\text{peak flux density of 9 GHz microwaves (sfu)}}{\text{HXRBS peak count rate (cts/s)}} \times 10$$

Here the multiplication by 10 is to make the median value of MRI about 1. The diagonal straight lines in Figure 2.2.16 represent constant values of MRI. The line for MRI = 1 divides the population into roughly equal numbers. As can be seen from this figure, there is large scatter: MRI varies more than an order of magnitude (from less than 1/4 to more than 4). Bai, Kiplinger, Dennis (1985) studied the characteristics of the "microwave-rich flares" (with MRI > 4). They noticed that among the gamma-ray line flares studied by Bai and Dennis (1985) gradual gamma-ray line flares exhibit large delays of hard X-rays and large values of MRI. They studied 17 microwave-rich flares (12 flares in Figure 2.2.16 plus 5 microwave-rich flares observed in 1982), and found that these flares share many common characteristics. (1) Large values of MRI (> 4). This was the selection criterion. (2) Long durations of hard X-ray bursts. Microwave rich flares last several minutes, as opposed to the ordinary flares that usually last less than 1 minute. (3) Large H-alpha area. Except for one microwave-rich flare observed at the limb, all belong to H-alpha importance class 1 or higher, and 13 out of 17 belong to H-alpha class 2 or 3. (4) Long delay times (> 10s) of high-energy hard X-rays with respect to low-energy hard X-rays. In a given burst the delay time increases with hard X-ray energy. Such delays are equivalent to hardening of the X-ray spectrum with time during the burst (see Figure 2.2.17). (5) Long delay times (10 - 300s) of microwave time profiles with respect to low-energy hard X-ray time profiles. (6) Flat hard X-ray spectra. The average of the power-law spectral indices is 3.5. (Compare with 3.36, which is the value for the gamma-ray line flares studied by Bai and Dennis (1985)). (7) Association with type II and IV radio bursts. All of them produced type II or type IV bursts or both. Seven of the 13 microwave-rich flares have HXRBS peak count rates between 1000 and 5000 cts/s. Considering that the largest HXRBS count rates are of the order of 10^3 cts/s (Dennis et al., 1983), the above count rates are moderate. (8) Emission of nuclear gamma-rays. Only six of the 17 microwave-rich flares produced observable nuclear gamma-rays, but it is interesting to note that all the microwave-rich flares which did not produce observable nuclear gamma-rays have HXRBS peak rates < 4000 cts/s. None of the gamma-ray line flares observed during 1980 through 1981 have HXRBS peak rates < 4000 cts/s (Bai and Dennis, 1985). Therefore, the failure to observe nuclear gamma-rays from the microwave-rich flares with low HXRBS count rates are most likely to be due to the threshold effect of GRS. Another interesting point is that the microwave-rich flares share all the characteristics of gamma-ray line flares. Detailed discussions on the correlation of microwave rich flares and gamma-ray line flares, as well as a possible scenario for their interpretation can be found in Bai and Dennis (1985).

2.2.5 Decimetric-Metric Observations and Comparison with X-ray Observations

Previous studies have already shown that type III bursts and soft X-ray X-rays are often observed several minutes prior to the occurrence of the flare itself (Kane et al., 1974). Evidence for hard X-rays observed before the flash phase was also reported by Kane and Pick (1976). A systematic study, using more sensitive spectrometers, was carried out by Benz et al. (1983b); they listed 45 major events observed by the HXRBS experiment aboard SMM. For most of these events, metric type III bursts and decimetric pulsation were

Provided by the NASA Astrophysics Data System
Figure 2.2.17 Spectral evolution of hard X-ray emission from the 1981 May 13 flare. The top panel shows the hard X-ray flux at 100 keV, and the middle panel shows the observed spectral evolution (with dots) together with a spectral evolution calculated using a perfect-trap model. In the last panel the spectral evolutions were obtained by using various values for the ambient density. In order to get a reasonable fit to the data, the ambient density should be as low as $5 \times 10^8 \text{ cm}^{-3}$. However, this density is incompatible with other observations as mentioned in the text. Tsuneta et al. (1984) found that the images of the hard X-ray source and the soft X-ray source are almost the same. These authors also deduced from the emission measure and the size of the soft X-ray source that the density of the flare loop is $3 \times 10^{10} \text{ cm}^{-3}$. As the density increases, the spectral index change will be less and less, approaching the steady state case. For $n = 3 \times 10^{10} \text{ cm}^{-3}$, the resultant spectral index evolution is hardly different from a straight line, which is for the steady state case. Before the hard X-ray peak the spectral index is larger than the steady state case and after the peak it is smaller, but near the peak the spectral index is similar to that of the steady state case independent of the density (from Bai and Dennis, 1985).
observed preceding the hard X-ray emission. In 7 of the 45 flares, significant hard X-ray fluxes were observed before the rapid general exponential increase. This phase in the flare development was called “preflash phase”. It usually lasts for about one minute. These observations give evidence for electron acceleration before the impulsive phase (see also Section 2.2.3.5).

It is commonly believed that electrons responsible for type III bursts and hard X-ray emission have a common origin (Kane, 1972, 1981a) since their temporal evolution is well correlated. Simultaneous observations of X-ray and radio emission with a time resolution of less than 1 sec have shed new light on our understanding of the electron acceleration process. The main conclusions can be summarized as follows: (a) Some hard X-rays peaks are well correlated with type III bursts and show delays of the order of or shorter than one second (Kane, Pick and Raoul, 1980; Benz et al., 1983b). The type III source may consist of several elementary components widely separated (by more than 100,000 kms) which radiates quasi-simultaneously or successively. This implies that the acceleration/injection region covers a wide range of magnetic fields (Mercier, 1975; Raoul and Pick, 1980). (b) Kane and Raoul (1981) reported an increase in the starting frequency of type III bursts during the development of the impulsive phase. This variation is correlated with an increase in the hard X-ray flux. As the type III bursts radiation is emitted at the local plasma frequency, the starting frequency corresponds to the density at the point where the electron beams become unstable. Thus this fast variation of the starting frequency may be explained either by a real variation of the electron density in the source (downward shift or compression of the injection/acceleration site) or to a variation in the distance from the acceleration site, travelled by the electron beam before it becomes unstable (Kane et al., 1982). A systematic study was carried out by Raoul et al. (1985) to determine if the presence of an increase in the starting frequency of type III bursts influences the probability of their correlation with hard X-ray bursts. A total of 55 type III groups were selected which had been observed with the Nancay Radiospectrograph (Dumas et al., 1982) in the frequency range 450 – 150 MHz, and with the ISEE-3 X-ray spectrometer. Of the 55 events, 32 cases, (58%) were associated with X-ray emission. In this sample, 28 events (52%) showed an increase in the starting frequency. 75% of these events were associated with X-ray emission, resulting in significant improvement of the correlation. Conversely, 75% of the X-ray associated events show an increase in the starting frequency. Thus, an increase in starting frequency seems to be a significant factor that improves the association between type III burst groups and X-ray bursts. (c) However, Raoul et al. (1985) pointed out that among these 55 events, 15 events were associated with type V continuum visible in the frequency range 450 – 150 MHz with a typical duration of about one minute or less. All these events have an X-ray response. Thus, the presence of a type V continuum at frequencies > 150 MHz appears to be a decisive factor in increasing the correlation between X-rays and type III bursts.

Raoul et al. (1985) also suggested that type III/V events have a consistently large X-ray response. Stewart (1978) first reported that among a list of X-ray associated radio bursts, 80% contained a type V burst. They performed a detailed data analysis for meter events which have an X-ray response. Their main findings are: (a) Pure type III bursts groups are not associated with intense X-ray emission. The hard X-ray bursts associated with these events have fluxes < 1 photon cm⁻² sec⁻¹ keV⁻¹ at about 30 keV and are not detectable above 100 keV. The corresponding radio burst source is often multiple. The X-ray response around 30 keV closely follows the starting frequency evolution. (b) When a radio event is associated with strong X-ray emission (> 1 photon cm⁻² sec⁻¹ keV⁻¹ at 30 keV and detectable above 100 keV), a continuum emission (type V) in the range 450 – 150 MHz appears along with the type III groups. The type evolution of these events is illustrated in Figures 2.2.18 and 2.2.19, and may be described as follows: The first part of the event, “preflash phase”, contains only type III (or U) bursts coming from locations (A). Then a new source “B” (see Figure 2.2.19) appears at the time of the fast increase in the X-ray emission. This is also coincident with an increase in the radio starting frequency. At that time, one of the pre-existing type III burst sources (A`) becomes predominant. Sources B and A` have similar sizes (2' – 3' arc at 169 MHz), and they fluctuate simultaneously within short time delays of less than one second. Thus both sources contribute to the spiky and smooth parts of the radio emission identified as type III and type V bursts, respectively. There is an overall correlation between the radio flux and X-ray fluctuations, although there is no correlation on short timescales. When the rapid radio fluctuations are no longer present, both X-ray and radio fluxes decrease sharply and the X-ray emission appears at energies below 30 keV. The total X-ray flux and radio flux decrease rather smoothly, the source B being usually the predominant one. The duration of the type V burst increases with increasing wavelength. Similarly the duration of the X-ray emission increases with decreasing energy.

The results described above have implications on the geometry of the magnetic field structure at the site of injection of electrons. The presence of sources A` and B, which fluctuate quasi-simultaneously, implies that the electrons are quasi-simultaneously injected into two structures (or two unresolved groups of structures). According to Raoul et al. (1985) most flares that are associated with a small hard X-ray emission correspond to an electron injection/acceleration site that covers several diverging magnetic flux tubes. The fact that during the impulsive increase of the hard X-ray flux, the radio emission is reinforced in one pre-existing location and appears quasi-simultaneously in a new location, suggests
that at the injection site the two magnetic structures interact. At that time the energy that is released in the interaction region increases sharply. Another possible interpretation was given by Sprangle and Vlahos (1983) and is discussed in Section 2.4.6.

Rust et al. (1980), Benz et al. (1983b), Aschwanden et al. (1985) and Dennis et al. (1984) have also studied the correlation of hard X-rays with decimetric radiation, which originates at lower altitudes. Their results on decimetric type III bursts reinforced many of the conclusions reported for metric bursts. Aschwanden et al. (1985) have found decimetric type III bursts to be associated with hard X-ray events in 45% of the cases. The association rate increases with the number of bursts per group, duration, bandwidth and maximum frequency of the group. Some single bursts (but not all) are correlated with hard X-ray spikes. In some cases the difference in time of maximum between type III and hard X-rays is a few tenths of a second, which may be significant. This may imply that ordinary cross-field drifts or diffusion from closed to open field lines are too slow. The acceleration of the electrons by intense electromagnetic waves, as proposed by Sprangle and Vlahos (1983) seems to be a likely interpretation (see Section 2.4.6 for details). These bursts occur at frequencies of 300 MHz to > 1 GHz, corresponding to densities \( \geq 3 \times 10^9 \text{ cm}^{-3} \) (Benz et al., 1983b).

Strong et al. (1984) investigated a double impulsive flare in radio, soft and hard X-ray emissions. The decimetric radio emission of both events contains U bursts. In several cases they have harmonic structure. From the total duration and extent in frequency of the U bursts the geometry of the loop guiding the electron beam can be calculated. The average length of these loops is 94,000 km and 157,000 km, and the average height 24,000 km and 45,000 km in the two flares respectively. The U bursts are sometimes correlated in time with hard X-rays spikes (Figure 2.2.2). If the elongated soft X-ray source is interpreted as a loop, its projected size is only 30,000 km. Post-flare soft X-ray loops have been found in the second flare with footpoints separated by 115,000 km. The presence of loops of different sizes is also evident in the microwave spectrum which shows evidence for 3 peaks.

Figure 2.2.18 Type III/V bursts on 1981 July 29, observed with the Nancay Radiospectrograph (Dumas et al., 1982) and the associated hard X-ray burst observed with the SMM-HXRBS experiment. Evolution of the X-ray emission compared to the evolution of the radio event. (From Raoul et al., 1984).

Figure 2.2.19 Top: Evolution of the radio flux from sources A, A’ (solid line) and B (broken line) see text. Bottom: Evolution of X-ray spectral index and hard X-ray emission. (From Raoul et al., 1984).
Figure 2.2.20 Correlation between U-bursts and hard X-ray spikes in the August 31, 1980, 1251 UT flare. Data from radio spectrometer at Bleien (Zürich) and HXRS on SMM. Left: U-bursts are outlines in the upper part and compared with the X-ray count rate in the lower part. Right: Details of left figure showing correlation of X-ray spikes with rising part of U-bursts (from Strong et al., 1984).
indicating sources with widely different magnetic field strengths. Apparently energetic particles have immediate access to small (soft X-ray) loops and large (U burst, post-flare) loops suggesting that the acceleration site is at the boundary or interface between the two loop systems.

The decimetric emission of flares can be divided into radiations which generally occur during the impulsive phase and the type IV emission generally observed after the impulsive phase. The impulsive phase bursts are found to vary considerably in shape (Wiehl et al., 1985). A large fraction can be interpreted as due to type III-like beam instabilities. The bursts may have some unexpected forms, however, such as narrow bandwidth ($\Delta \nu / \nu \leq 0.2$), called blips by Benz et al. (1983a) or very high drift velocities (an example is shown in Figure 2.2.21). These deviations from the normal shape are probably caused by the disturbed properties of the ambient plasma.

Figure 2.2.21 Top: Dynamic spectrogram of type III-like decimetric emission with very high drift rate, observed on May 19, 1980 with the analog spectrometer at Bleien (Zürich). Enhanced emission is bright, horizontal lines are terrestrial interference, and vertical lines are minute marks. Bottom: Hard X-ray count rate as observed at energies $> 30$ keV by HXRBS on SSM.

All decimetric bursts during the impulsive phase do not appear to be explained by particle beams. About 25% of all cases are in this category and they are strongly associated with hard X-rays (70%). These bursts have been divided into 4 classes by Wiehl et al. (1985). 1) Diffuse patches of emission probably originate from trapped particles either by synchrotron or loss-cone radiation. 2) Grass-like chains of small spikes resemble elements of metric type II bursts. They may be caused by shock waves. 3) Nonperiodic broadband pulsations with pre-flash hard X-ray emission. The decimetric emission in these cases precedes both hard X-ray and Hα emission, as shown by Benz et al. (1983b) from a study of 3 flares. However, a more general study of 45 such events (Aschwanden et al., 1985) has shown that pulsations usually start after the hard X-rays and end before them. Most important, pulsations and hard X-rays do not seem to correlate closely. Durations of single elements are between 20 and 100 ms. The elements are of similar bandwidth (several 100 MHz) and have about the same low-frequency end. 4) Spikes of short ($< 100$ ms), narrowbanded (3-10 MHz) emission occur in large groups. They are associated with shorter and more impulsive hard X-ray bursts than the average. They tend to occur in the early impulsive phase (Benz, 1985). The single elements are scattered in a chaotic manner between $\sim 400$ and $> 1000$ MHz (corresponding to densities of 0.3 $- 1 \times 10^{10}$ cm$^{-3}$). Their circular polarization can be between 25 – 40%. They probably are similar to the microwave spikes observed at 2.6 GHz by Slottje (1978), probably also produced by the electron cyclotron maserings.

2.2.6. Discussion of Models for X-ray and Microwave Emission

Information about the accelerated electrons are obtained through models which depend on parameters such as local ambient density, temperature and magnetic field which are poorly known. Three major problems face us in our interpretation of the observations:

- what is the relative role of thermal and nonthermal electrons in producing X-rays at different energies?
- does nonthermal production of hard X-rays arise from beams of electrons (thick-target model) or from a trapped population of electrons or from a combination of both.
- do the observations imply a single or a two step acceleration process?

We discuss below several attempts to model the energy release and answer some of the questions posed above.

2.2.6.1 Trap Plus Precipitation vs Two Step Acceleration Models

The two competing interpretations of the energy-dependent hard X-rays are trap plus precipitation models (Kane, 1974; Melrose and Brown, 1976; Bai and Ramaty, 1979; Vilmer et al., 1982; MacKinnon et al., 1983; Ryan, 1985) and second-step acceleration models (Bai and Ramaty, 1979; Bai, 1982; Bai et al., 1983a, 1983b; Bai and Dennis, 1985). Interestingly, the first paper that analyzed hard X-ray delays (Bai and Ramaty, 1979) invoked both interpretations, the trap model for small delays below 150 keV, and second-step acceleration for large delays (15 s) above 150 keV. Bai and Ramaty (1979) and Vilmer et al. (1982) used a pure trap
model, and MacKinnon et al. (1983), Trottet and Vilmer (1983), and Ryan (1985) considered the effect of precipitation. MacKinnon et al. (1983) reported that, in the weak diffusion limit, precipitation does not change the essential nature of the trap model. A detailed discussion of trap models is given later in this Section.

We emphasize first that the second-step acceleration is different from the conventional “second-phase” acceleration proposed by Wild, Smerd and Weiss (1963), since the delay between the two steps is tens seconds and not tens of minutes.

Bai and Dennis (1985), who have studied many flares exhibiting hard X-ray delays, note the following points favoring the second-step acceleration interpretation. (1) In impulsive flares which exhibit hard X-ray delays, the delay time as a function of hard X-ray energy is quite different from what is expected from the collisional trap plus precipitation models. Instead of increasing gradually with energy, the delay time exhibits a sudden increase at high energies. (2) In very gradual flares such as the ones observed on April 26 and May 13, 1981, the ambient density deduced with the trap model is of the order of $10^8$ cm$^{-3}$ (see Figure 2.2.17). This is too low to explain the observed emission measure of soft X-rays (assuming of course, that the hard and soft X-ray emitting regions are coincident). Actually, the density deduced for the May 13 flare from the observed emission measure and volume is $3 \times 10^{10}$ cm$^{-3}$ (Tsuneta et al., 1984a). The above argument does not exclude the possibility of trapping of energetic electrons in a huge loop, (this was proposed by Tsuneta et al., 1984a), but it proves that trapping is not the primary cause of large hard X-ray delays (or spectral flattening with time) observed in these gradual flares. (3) The association between hard X-ray delay and proton acceleration (see Section 2.3), is naturally explained by the second-step acceleration model. In Fermi type acceleration, stochastic acceleration by a fluctuating magnetic field, or shock acceleration, there exist threshold energies (or injection energies) for both electrons and protons above which the acceleration can overcome the Coulomb energy loss (e.g., Ginzburg and Syrovatskii, 1964; Sturrock, 1974; Ramaty, 1979). Therefore, when these kinds of acceleration mechanism accelerate protons to gamma-ray producing energies, they will also accelerate electrons with energies greater than the injection energy to higher energies. On the other hand, in trap models it is hard to see the connection between proton acceleration and trap electrons. (4) The total bremsstrahlung fluence above 270 keV is roughly proportional to the 4-8 MeV fluence (see Chupp 1982 and Figure 2.3.4). On the other hand, when the 4-8 MeV fluence is compared with the hard X-ray fluence above 30 keV, the correlation is very poor (Bai and Dennis, 1985). Actually many flares with large fluences in $> 30$ keV hard X-rays did not produce observable nuclear gamma-rays. With the second-step acceleration, this is easily explained. In the second-step acceleration model, both high energy electrons and gamma-ray producing protons are accelerated by the second step, hence we expect a good correlation between hard X-rays $> 270$ keV and 4-8 MeV fluences. On the other hand, the fluence of low-energy hard X-rays ($> 30$ keV), which is due to electrons accelerated by the first-step mechanism, is not expected to correlate well with the gamma-ray fluence, which is due to the second-step mechanism. (5) In trap models the photon spectrum is somewhat steeper at the beginning of the burst than in a thick-target beam model, and it gradually flattens to be about the same as the thick-target model near the peak. On the other hand, if the second-step acceleration is operating, the photon spectrum at the peak of the burst is expected to be flatter because of additional acceleration at high energies. Consistent with the second-step model, the photon spectrum measured at the peak of the burst is flatter on the average for gamma-ray line flares than for non-gamma-ray line flares, which do not in general show hard X-ray delays. The site of the second-step acceleration is proposed to be the corona instead of the chromosphere (Bai and Ramaty, 1979; Bai et al., 1983b); therefore, in this model at least, high energy electrons are assumed to be trapped in the corona. Hence, it is possible that in many flares hard X-ray delay is partly due to trapping and partly due to the second-step acceleration, as proposed by Bai and Ramaty (1979). It is usually difficult to determine their relative importance unless we know the ambient density of the flare loop (trap region). For the May 13, 1981 flare the ambient density is deduced to be $3 \times 10^{10}$ cm$^{-3}$ (Tsuneta et al., 1984), and for this density the hard X-ray delay is much smaller than the observed one. For the gradual flare of April 26, 1981, the same is true (Bai, Kiplinger and Dennis, 1985).

Let us now summarize the recent progress made on models that invoke trap and precipitation. Vilmer et al. (1982) applied the trap model to explain observations of high-energy X-ray delays, and McKinnon et al. (1983) considered the effect of precipitation on the trap model. Trottet and Vilmer (1983) have also studied the case where the precipitation from the trap is in the strong diffusion limit (e.g., wave-particle interaction). The basic ingredients of the model are: (1) a trap of uniform density $n_o$, (2) a continuous injection of nonthermal electrons in the trap, with constant spectral index $\gamma$, during a finite time $t_o$, (3) a time dependent injection function having a maximum at $t_o/2$, (4) energy losses entirely due to electron-electron collisions, (5) precipitation from the trap gives rise to a thick target component, either in the weak diffusion limit (Coulomb collisions) or in the strong diffusion limit (wave-particle interaction). The computed X-ray time profiles depend then on $t_o$, $n_o$ and the precipitation process considered. In the weak diffusion limit, although hard X-ray emission starts simultaneously at all energies, the higher energy channels reach their maxima later than the lower ones. For given $t_o$ and $\gamma$ such delays are a function of $n_o$. Figure 2.2.22a shows that $\Delta t(E) = t_{max}$
the loss-cone angle and the characteristic length of the trap). The X-ray time profile depends on two characteristic times, the energy loss time $t(E)$, which increases with $E$, and the precipitation time $t_0$ which decreases with $E$. When $t_0$ is larger than $t_E$ (large scale loops or small $\alpha_0$), $\Delta t(E)$ increases with energy, but does not exceed a few seconds. When $t_0$ is of the order of or smaller than $t_E$, Figure 2.2.22a shows that $\Delta t(E)$ is very small, approximately constant with $E$ and weakly dependent on $n_0$. In this last situation no observable delays are expected. On the contrary $I_{\text{trap}}/I_{\text{prec}}$ is strongly dependent on the energy $E$ ($I_{\text{trap}}/I_{\text{prec}}$ decreases when $E$ increases) and decreases when $\alpha_0/L$ increases. The hardness of the hard X-ray spectrum remains approximately constant with time. Moreover for the same injection function and trap density, the X-ray spectrum is somewhat harder than in the weak diffusion regime before the maximum (Trottet and Vilmer, 1983).

According to Trottet and Vilmer (1983), the main considerations that favor trap and precipitation models are as follows: (1) Hard X-ray imaging sometimes shows high and large X-ray sources, with power law spectra, suggesting a coronal thick target trap with continuous injection/acceleration of electrons (type C flares discussed in Section 2.2.1.1). (2) Some events exhibiting large delays (up to 1 min) have been successfully interpreted through trap and precipitation models (see Vilmer et al., 1982). The diversity of observed delays is easily explained by the variability of the trap density, injection time and nature of the scattering process. Certainly more work has to be done to describe more realistic situations, namely one has to develop time dependent models where the inhomogeneity of the ambient medium and the angular distribution of the energetic particles are taken into account. A first approach to this problem is to look for general time dependent solutions of the continuity equation. Vilmer et al. (1985) and Craig et al. (1985) have developed the mathematical framework that can be used for such a study. (3) The time lag between hard X-ray and $\gamma$-ray maxima is correlated with the $\gamma$-ray rise time.

Trottet and Vilmer (1983) have also argued that if a two step acceleration is at work some difficulties arise. Indeed Chupp (1983) has shown that the ratio of the prompt $\gamma$-ray line fluence in the 4-7 MeV band to the 2.23 MeV line fluence is approximately constant from one flare to another. According to Ramaty (1985), this requires a constant spectral shape for the ions. Moreover the total electron bremsstrahlung fluence above 270keV is roughly proportional to the 4-8 MeV excess fluence (Chupp et al., 1984b). This suggests that high energy electrons and ions are accelerated by the same process and that this process is common to all flares. Thus, if delays reflect a second step acceleration, they should be observed, without exceptions, for all flares producing $\gamma$-ray lines and X-rays above the few 100 keV. In fact some observations contradict such an interpretation. Let us illustrate this point by two examples reported by Rieger (1982).
First, reverse delays between X-ray and γ-rays are clearly observed for the October 14, 1981 flare (4-7 MeV and 10-25 MeV channels peak before the 80-140 keV and 300 keV channels). Second, the June 21, 1980 flare exhibits variable delays from one peak to another, the first peaks occurring even simultaneously in all channels. In summary Trottet and Vilmer argued that even if a two step acceleration process cannot be definitively ruled out, available observations of time delays may reflect the interaction between the accelerated particles and the ambient medium rather than the characteristics of the acceleration mechanism itself.

Ryan (1985) also considered independently the effects of particle trapping on the time profiles of hard X-rays and γ-rays. His results reinforce the work reported above. Ryan used three different models. The first is that of a closed trap with a finite density of matter within the trap providing the slowing down mechanism for the particles and the particle target for photon production. The two other models employ particle diffusion in a tenuous trap to allow particles to precipitate to denser regions of the solar atmosphere where they interact to produce the photons. The characteristics of all of these models are (1) to reduce the impulsiveness of the acceleration as it is seen in the high energy photons and (2) to produce delays in the maxima of the photon fluxes at various energies. These effects must be taken into account in searching for evidence of additional acceleration mechanisms. The constant density coronal trap which has been considered in the past for electrons below 200 keV can produce significant delays for electrons of energies > 0.5 MeV and larger effects still for γ-rays produced by ∼ 20 MeV protons. Particle densities of 10^{10} cm^{-3} can produce delays in the γ-rays of several tens of seconds. If particles are injected impulsively at one point in the loop, they diffuse toward both ends of the trap precipitating to the loss regions of high density. With this process, there is an intrinsic delay in the precipitation rate and thus the photon flux due to the finite time required for the particles to diffuse to both ends of the loop. The rise and decay times of this process are also proportional to the size of the trap. It should also be noted that the particle propagation effects in the observed photon flux for the constant density trap is also a function of the size of the trap. The study by Rosner et al. (1978) shows that the matter density in coronal non-flaring loops is inversely correlated with the length of the loop. Thus we have the situation where three mutually exclusive particle trap scenarios produce a reduced impulsiveness in the photon flux with respect to the particle acceleration or injection and the convolution of these effects with the acceleration profile produces a delay in the flux maxima with respect to the acceleration profile. In addition, the magnitude of these effects grow with the linear dimensions of the loop. The implications of this are that they complicate the search for and identification of a multi-step acceleration process and they limit the search for rapid fluctuations in photon flux, which is a signature or measure of the rapidity of the acceleration process.

2.2.6.2 Dissipative Thermal Model

We have emphasized in this section that heating and acceleration of the plasma tail occurs nearly simultaneously in flares. This poses a fundamental problem: How does the flare-energized (hot + tail) plasma expand along the field lines? Since the plasma outside the energy release region is at coronal temperatures (several million degrees Kelvin), the energized plasma interfaces with a “cold” ambient plasma. The steep temperature and/or density gradients accompanying the rapid energization may give rise to D.C. and stochastic electric fields which contain most of the electrons, but allow the fastest electrons in the tail of the distribution to escape. Brown, Melrose and Spicer (1979) suggested (following similar work by Manheimer (1977) in the pellet fusion plasma) that a return current, driven by the electrostatic potential at the interface, will set in and most probably will grow unstable, limiting the heat flux. This suggestion was followed by two extreme approaches: (1) Ignore the escaping electrons and use a fluid model to simulate the expansion of the hot plasma (see e.g., Smith and Harmony 1982 and references therein). (2) Describe qualitatively the hot plasma and concentrate on the escaping electrons (Vlahos and Papadopoulos, 1979 and Emslie and Vlahos, 1980). In the latter work it was also assumed that inside the energy release volume the tail was continuously replenished by sub-Dreicer electric fields. In reality both approaches were of a limited scope. The real problem is somewhere in between and we have to simulate the plasma below a critical velocity (which is unknown) as a fluid and as particles above it. In other words, the need for a multifluid or Vlasov type simulation is obvious. Such simulation is currently possible. It is worth mentioning that several qualitative suggestions, based on the dissipative thermal model, appeared in the last few years.

Brown et al. (1980) suggested that the energy release volume in a flaring loop may consist of many hot sources with lifetimes and sizes below the instrumental resolution. The overall hard X-ray burst emission is made up of a “convolution” of these “multiple kernels”. They investigated the effective (time-integrated) spectrum of hard X-rays from one such kernel, and showed that the majority of observed spectra could be explained by invoking a spread in the parameters characterizing the kernels. The hardest spectra are not, however, amenable to such an interpretation.

Smith (1985) suggested the following scenario for solar hard X-ray bursts which may explain the evolution of type B flares (cf. 2.2.1.1). At the beginning of the impulsive phase, we often see brightening of footpoints which indicates that a significant fraction of the energy released is going into accelerated electrons. This could occur due to fast tearing modes in a loop leading to electron acceleration via the modified two-stream instability (see Section 2.4). After these electrons evaporate a sufficient amount of chromospheric plasma, which then travels back up the loop, the electron plasma beta,
\( \beta \) rises sufficiently to cut off the modified two-stream instability and the footpoint behavior ceases. The emission is then dominated by the primarily thermal single source near the top of the loop. There may still be some small regions in the loop where \( \beta \) is sufficiently small to allow acceleration of electrons required by the microwave emission.

Holman, Kundu, and Papadopoulos (1982) have shown that streaming suprathermal electrons will be isotropized by self-generated electrostatic waves (the “anomalous doppler resonance” instability) if the electron gyrofrequency (\( \Omega_e \)) exceeds the plasma frequency (\( \omega_p \)) somewhere along the loop, and if the minimum velocity in the suprathermal electron distribution is well above the mean thermal electron velocity in the ambient plasma. The first condition (\( \Omega_e > \omega_p \)) may hold in most flare loops, and the second condition will hold as long as the accelerated electron distribution does not extend down to the thermal distribution, or if the accelerated electrons escape into a cooler plasma. Holman, Kundu and Papadopoulos also show that if the suprathermal electrons are also responsible for the observed hard X-ray emission, the scattering of the particles can also lead to breaks in the hard X-ray spectrum. These breaks result from wave damping preventing all of the suprathermal electrons from being scattered. An important conclusion is that the microwave source structure does not necessarily indicate the location of the particle acceleration region. Similar conclusions can be reached from considerations of the loop geometry and the directive of gyrosynchrotron emission (see Petrosian 1982).

Zaitsev and Stepanov (1983) showed that intense localized heating inside the energy release region may violate locally the condition that the plasma pressure is lower than the magnetic pressure, which in the past had permitted some numerical calculations of one-dimensional fluid models (e.g., Smith and Lilliequist, 1979). As a result, the magnetic field expands locally and setup a local magnetic trap, and \( B^2/8\pi \geq nkT_e \) and the magnetic field compresses the plasma again. This cycle repeats and sets in an oscillatory motion. Zaitsev's and Stepanov's results may explain the periodic pulsations observed in hard X-ray and microwave bursts.

Batchelor et al. (1985) made a new analysis of the thermal flare model proposed by Brown, Melrose and Spicer (1979). They assumed that the model leads to the development of a quasi-Maxwellian electron distribution that explains both the impulsive hard X-rays and microwaves as opposed to our previous interpretation that allows a significant number of nonthermal electrons to escape from the thermal source. This implies that (a) the part of the microwave spectrum for which \( f < f_{\text{max}} \) consists of optically thick emission, so the source area, \( A_0 \), can be calculated from the Rayleigh-Jeans law, and (b) the plasma temperature can be measured from the hard X-ray spectrum by determining the best fit to a single-temperature thermal bremsstrahlung function. Using (a) and (b), Batchelor et al. (1984) calculated \( A_0 \) at the time of maximum hard X-ray flux. Assuming that the source was an arch, they estimated its half-length \( L_o = A_0^{1/3} \). The theoretical time scale of the burst would then be \( \tau_o = L_o/e_s \), where \( e_s = (kT_e/m_p)^{1/2} \) is the ion-sound speed, the speed of expansion of the source during the initial rise of impulsive emission. To test the prediction of the model, Batchelor et al. (1985) analyzed microwave observations made at the Bern Radio Observatory and hard X-ray observations obtained with the SMM-HXRBS experiment. The results are shown in Figure 2.2.23, which is a plot of log \( t_r \) vs log \( \tau_o \), where \( t_r \) is the measured rise time of the hard X-ray emission and \( \tau_o \) is computed from independent spectral parameters only. For 17 disk flares, the best fit relationship is found to be \( t_r = 0.51 \tau_o^{-0.5} \), which is within the statistical uncertainties of the predicted relationship, \( t_r = \tau_o \). Three limb flares lie to the left of the disk flares on the diagram, consistent with the interpretation that they were partially occulted by the solar limb, which would result in reduced values of \( L_o \) and \( \tau_o \) as observed. This result is in good agreement with the model, and is not explained by any other known flare models which have been considered. The main problem with Batchelor et al. model, however, is that the behavior of the energetic electrons was not properly considered.

### 2.2.7 Summary

We shall now return to the questions which we have posed in the introduction and which have guided our discussions during the workshops:

![Figure 2.2.23 Correlation diagram of \( t_r \) and \( \tau_o \). Solid lines indicate best fits by linear least-squares fitting. Dashed lines are boundaries of the expected positions of disk points if the sources are arches from 2 to 4 times as long as they are thick (from Batchelor et al., 1985).](image-url)
(1) What are the requirements for the coronal magnetic field structure in the vicinity of the energization source?

In the previous section we have shown a great deal of evidence suggesting that flares and strong particle acceleration do not generally occur in isolated magnetic structures (like an isolated flaring loop). Such evidence has been collected independently from soft and hard X-ray imaging observations, microwave imaging observations, and meter wave one dimensional imaging and decimetric observations. Simultaneous microwave/meter, microwave/X-ray and meter/X-ray observations have given support to the idea that during the impulsive phase several discrete injection/acceleration regions are present, connecting both open and closed field lines, the former associated in many cases with very divergent magnetic field lines. It is, of course, difficult to generalize the “small” sample of results presented in this section but we feel confident that in several cases (involving strong acceleration) the acceleration region must comprise a rather large volume encompassing regions of different topologies, as suggested schematically in Figure 2.2.24a and 2.2.24b. Such schematic models have been proposed earlier; however, the new wealth of space and ground based data obtained during the past solar maximum, provide strong observational support to such models.

(2) What is the height (above the photosphere) of the energization source?

A number of pieces of evidence in the past have placed the energization source in the low corona (microwave and decimetric burst observations). To this set we would like to add the observation on the starting frequency of type III burst and their correlation with hard X-ray bursts. We now believe that the acceleration source is in the low corona where the plasma density varies between $10^9$ and $10^{10}$ cm$^{-3}$. The acceleration may start at lower densities and “drift” to higher densities with a variable speed or it is stationary at the low corona and the region where the beam becomes unstable to plasma waves “drifts” towards higher densities with time.

(3) Does the energization start before and continue after the impulsive phase?

We have presented evidence indicating that both heating and acceleration have signatures before and after the impulsive flare. This is contrary to the well accepted scenario that slow heating starts before the impulsive phase, followed by intense acceleration during the flare and it ends up with a hot plasma that gradually cools off.

(4) Is there a transition between coronal heating and flares? What are the microflares?

High sensitivity hard X-ray detectors have dispelled the myth that the corona operates in two modes “heating” and “flaring”. We have presented evidence suggesting that microflares may be occurring all the time in the corona. In other words, the transition from “flaring” to “heating” may be more gradual than commonly perceived and depends strongly on the sensitivity of available instruments. The presence of nonthermal tails at all times, and microflares may be crucial requirements for the “coronal heating mechanisms”.

(5) Are there evidence for a purely thermal, purely non-thermal or a hybrid type of flare?

This is an open question and may have an “energy dependent” answer. Usually evidence for “purely thermal plasma” is provided by soft and lower energy hard X-ray bursts. However, gamma-rays and type III, IV and V bursts are not considered to be produced from a “purely thermal plasma”. At the other extreme, a “purely nonthermal flare” is also a myth. We have presented much evidence indicating that a “hot component” is always present in flares. Indeed, we have emphasized that accelerated electrons can quickly “thermalize” and turn in to a “hot plasma”. In summary we feel that a hybrid model is the best resolution to this dilemma and as we shall see later theoretically it is the easiest to explain.

(6) What are the time characteristics of the energization source?

There is strong evidence that the time profiles of flares at different wavelengths sometimes show sub-second or
even milli-second pulses. In several cases the pulses repeat
at regular or quasi-regular intervals. The brightness tem-
perature for each of these pulses is sometimes so high that a
coherent emission mechanism must be invoked. Delays be-
tween microwave and hard X-ray pulses have also been
reported. We believe that these fast pulses are evidence of
"micro-injection" similar to the ones discussed earlier and
a "flare" is composed of many micro-releases of energy.
The understanding of such fast pulsation is still relatively
poor.

(7) Is there any observational evidence for a two step ac-
celeration mechanism?

A few key observations have guided our past thinking
on particle acceleration in flares. One of them was the event
analyzed by Frost and Dennis (1971). In this event, the im-
pressive phase was followed by a type II burst, which im-
plies the presence of a shock, coinciding with the en-
hancement of relativistic particles. Thus the conclusion was
drawn that during the impulsive phase (or first phase from
the point of view acceleration) mildly relativistic electrons
where accelerated. This phase was followed several minutes
later by a second phase which coincided with the formation
of a shock that further accelerated ions and relativistic elec-
trons. During the SMM workshops no evidence was pre-
sented for such delays (of the order of tens of minutes)
between the acceleration of mildly relativistic and relativis-
tic electrons and ions. The delays between pulses in differ-
ent energy channels are of the order of seconds (10-50 secs).
Thus, we must refer to the two phase acceleration rather as
a "two step acceleration" (Bai and Ramaty, 1979) (two ac-
celeration mechanisms operating in close proximity, with one
being delayed from the other by 10-50 seconds). A novel
suggestion was also made during the workshop, namely that
we must search for one acceleration mechanism for parti-
cles of all energies and one possibly for heating. Such a
mechanism must result in no delays for the acceleration of
particles to higher energies. But then the question may be
asked: How does one create delays out of a synchronous ac-
celeration mechanism? The answer is by using a trapping
and precipitation model. The debate between these two ap-
proaches was not resolved during the workshops and the
arguments are presented in Section 2.2.6.

2.3 PHENOMENA ASSOCIATED WITH
IONS AND RELATIVISTIC
ELECTRONS IN SOLAR FLARES

Evidence for the acceleration of ions and relativistic elec-
trons in solar flares is obtained primarily from gamma-ray
line and continuum emissions and from neutron and charged-
particle observations. Gamma-ray lines and neutrons result
from nuclear interactions of accelerated protons and heav-
ier ions with the ambient solar atmosphere, while gamma-
ray continuum is due to electron bremsstrahlung and the
superposition of broad and unresolved narrow gamma-ray
lines.

In this section we present the gamma-ray and neutron ob-
servations and their implications and discuss the charged par-
ticle observations. We also examine the relationship between
the acceleration of ions and other flare phenomena.

2.3.1 Gamma-Ray Observations

Gamma-ray lines and continuum have been observed
from many flares. The first observations, carried out by de-
tectors on OSO-7 (Chupp et al., 1973), were followed by
observations on HEAO-1 (Hudson et al., 1980), HEAO-3
(Prince et al., 1982), SMM (Chupp et al., 1981) and
HINOTORI (Yoshimori et al., 1983). The gamma-ray spec-
trometer (GRS) on SMM, in particular, has provided a broad
base of data (e.g., Chupp 1984) which forms the basis of
much of the discussion in this Section. In addition, the hard
X-ray burst spectrometer (HXRBS) on SMM has provided
important data regarding the temporal and spectral behavior
of the X-ray continuum below ~0.3 MeV. We consider the
spectra of the observed gamma rays, the timing of the fluxes
in the various photon energy bands and the correlation of
the gamma-ray data with other flare manifestations.

2.3.1.1 Gamma-ray Spectra

An example of a gamma-ray spectrum, observed by GRS
from the April 27, 1981 limb flare, is given in Figure 2.3.1.
Here the distribution of the net detector counts (the differ-
ence between source and background counts) is shown as
a function of photon energy deposited in the detector, for
energies > 0.27 MeV, the GRS detection threshold. As can
be seen, this spectrum is a superposition of continuum emis-
ion, most likely due to electron bremsstrahlung, and nar-
row and broad lines resulting from ion interactions. The
narrow lines are due to proton and alpha-particle interactions
with the ambient medium, while the broad lines are from
the interactions of accelerated heavy particles with ambient
H and He. As indicated, the strongest narrow lines are at
6.13 MeV from 14O, at 4.44 MeV from 12C, at 2.31 MeV
from 14N, at 2.223 MeV from neutron capture on hydro-
gen, at 1.634 MeV from 20Ne, at 1.37 MeV from 24Mg, at
0.85 MeV from 56Fe and at 0.51 MeV from positron an-
nihilation. The 2.223 MeV line, normally very strong for
disk flares, is greatly suppressed in limb flares (Wang and
Ramaty, 1974). Theoretical nuclear gamma-ray line spec-
tra were calculated earlier by Ramaty, Kozlovsky and
Lingenfelter (1979).

Because the contribution of the nuclear lines to the total
emission below ~ 1 MeV is quite small, this component can
be separated from the bremsstrahlung by fitting a power-law
photon spectrum to the data below 1 MeV and then subtrac-
ting this power law from the data at higher energies.
However, this technique can only approximate the nuclear

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