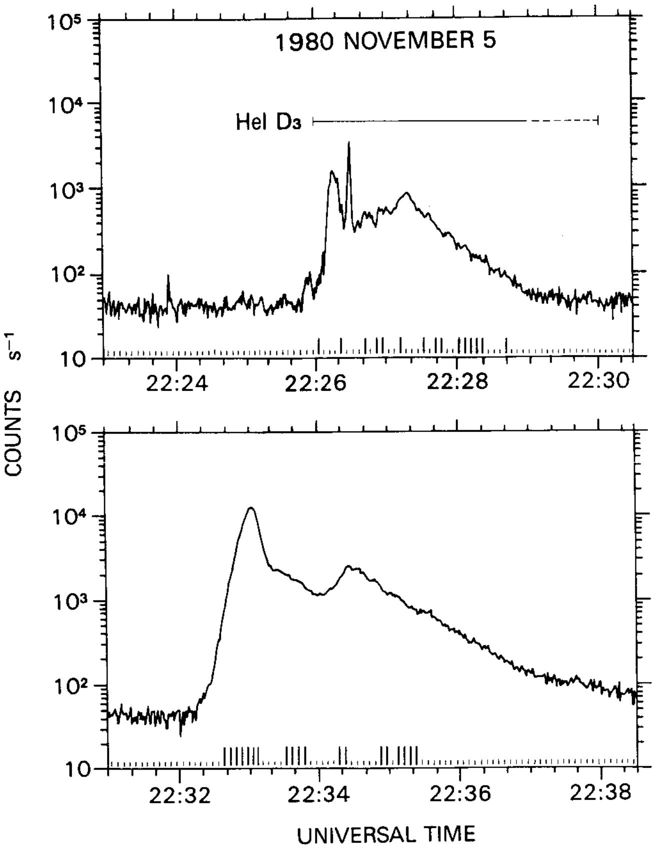

Figure 5A.14 The hard X-ray time profiles of the two flares on 1980 November 5 on a logarithmic scale with the times of the HeI D_3 observations also indicated. The short, evenly spaced, vertical lines just above the horizontal axis indicate when D_3 images were taken every 5 s on film at the Big Bear Solar Observatory. The longer vertical lines indicate the images which show obvious new or enhanced flare points in D_3. The entire impulsive phase is characterized by the presence of D_3 although not all new flare points are spatially resolved. The detection of these resolvable new points, however, is confirming evidence that energy is continuously released throughout the impulsive phase, not just during the rise.

terpreted as a small, low-lying loop with a strong horizontal field. From the optical data, Hoyng *et al.* concluded that the magnetic field rearranged itself over a small area in the center of the active region during the first flare and that a major rearrangement of the magnetic field took place during the second flare on a much larger spatial scale. During the final hard X-ray spike at 22:27:20 UT and on the decay of the first flare [Figure 5A.16(c)], the hard X-rays came almost exclusively from position T, although there is still a resolved bright point at lower energies from B.

At the onset of the second flare [Figure 5A.16(d)], the 16 to 22 keV X-rays came initially from region A and from a point to the south of B, at the position of the end of the bright Hα strand S1 seen in the first flare [Figure 5A.15(b)]. After the onset, the hard X-ray intensity continued the rapid rise and the bright points switched to position B and to a remote point at the eastern end of the filament [Figure 5A.17(a)]. Within 10 to 15 s, this remote emission had died away leaving a bright point at A [Figure 5A.16(e)]. During the final hard X-ray peak at 22:34:30 UT (Figure 5A.12), the hard X-rays were once more concentrated near T [Figure 5A.16(f)]. The appearance of the sequential hard X-ray brightenings from a number of distinct, and in one case widely separated, points suggests that there is a hierarchy of magnetic loops involved. The distant emission shown in Figure 5A.17(a), over 7×10^4 km away from the main flare site, is from the end of a structure which becomes completely filled with hot, X-ray emitting plasma during the decay of the flare [Figure 5A.17(b]. Bright points corresponding to A, T, and the initial hard X-ray bright point south of B are clearly resolved.

An estimate of the density of the soft-X-ray-emitting plasma is available during the decay of the second flare when FCS was operating in a spectral scanning mode. The measured Ne IX intercombination-to-forbidden-line ratio is density sensitive and indicates a maximum density of 1.5×10^{12} cm^{-3} at the time of the peak in the soft X-ray emission.

The Ca XIX and Fe XXV resonance line profiles observed with BCS during the impulsive phase of the second flare show broadening and extended blue wings visible for 30 s, beginning at the time of the peak hard X-ray flux. The blue shifts correspond to velocities between 200 and 500 km s^{-1}, and the line widths indicate that the turbulent velocities reached values of 100-200 km s^{-1}.

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APPENDIX 5B. A REVIEW OF IMPULSIVE PHASE PHENOMENA

C. de Jager

5B.0 Introduction

In this appendix we present a brief review of impulsive phase phenomena in support of the models used in this chapter to compute the energies of the different components of the flares under study. A more complete review is given in Chapter 2 of this Workshop proceedings.

We begin with the observational characteristics of the impulsive phase, followed by the evidence for multi-thermal or non-thermal phenomena. The significance of time delays between hard X-rays and microwaves is discussed in terms of electron beams and Alfven waves, two-step acceleration, and secondary bursts at large distances from the primary source. Observations indicating the occurrence of chromo-

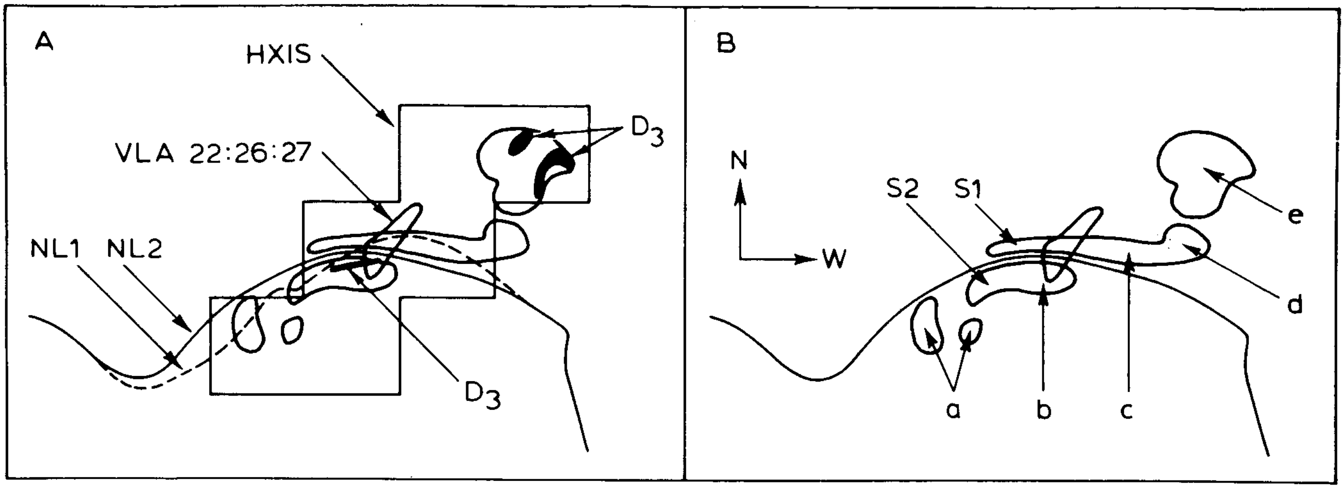

Figure 5A.15 Composite line drawings indicating the locations of the various flare components: the Hα flare kernels labelled 'a' through 'e' and the strands labelled S1 and S2; two possible positions for the neutral line, the one labelled NL1 being the measured location and the other labelled NL2 being a possible actual location that is everywhere within 2.5 arcsec of NL1; the VLA source at the time indicated; the outline of the six 8 × 8 arcsec HXIS pixels containing the points marked A, T, and B in Figure 5A.16(b); and the HeI D_3 emission patches (the one south of the neutral line being very weak).

spheric evaporation, coronal explosions, and thermal conduction fronts are reviewed briefly, followed by the gamma ray and neutron results. Finally, a preferred flare scenario and energy source are presented involving the interactions in a complex of magnetic loops with the consequent reconnection and electron acceleration.

5B.1 Observational Characteristics of the Impulsive Phase

5B.1.1 Main Characteristics

The main characteristic of the impulsive phase is the impulsive release of energy on timescales of less than or about 10 s. This is demonstrated best by intensity-time plots in hard X-rays and microwaves. These show a number of bursts (Figures 5A.2, 4, 7, 10, and 12), often with considerable time structure down to greater than or about 30 ms (Kiplinger *et al.*, 1984, Dennis *et al.*, 1984). The individual complex bursts are rarely shorter than 10 s or longer than 100 s. The more complex and long-lasting bursts are associated with complex Hα flares, particularly two-ribbon flares (Dwivedi *et al.*, 1984). There is no strict energy range for impulsive bursts: sometimes flares show impulsive characteristics only at energies above >40 keV (Tsuneta *et al.*, 1984a), but usually impulsive X-ray bursts are also seen at lower energies (Tanaka *et al.*, 1984). When the X-rays are imaged, impulsive bursts can sometimes be located in certain pixels at energies as low as 5 keV (de Jager and Boelee 1984; de Jager *et al.*, 1984).

The impulsive nature of flares has been detected in other emissions besides hard X-rays and microwaves. Peaks in the emission of the transition zone lines, O V at 1371 Å, C IV at 1548 Å, and Si IV at 1402 Å have been observed with UVSP to coincide to within 1 s with peaks in the hard X-ray emission (Woodgate *et al.*, 1983, Poland *et al.*, 1984, Tandberg-Hanssen *et al.*, 1983, Cheng *et al.*, 1984, Dennis *et al.*, 1984). Observations with UVSP in the EUV continuum have shown temporal structure coincident with similar structure in the hard X-ray emission to better than 0.25 s (Woodgate 1984). Coincident structure is also sometimes seen in Hα (Acton *et al.*, 1982, Gunkler *et al.*, 1984, Kampfer and Magun 1984). The coincidence of hard X-ray bursts with the appearance of emission kernels in HeI D_3 has been observed for the two flares of 1980 November 5 (see Figures 5A.14). At the other end of the spectrum, the hard X-ray bursts are closely correlated with gamma-ray bursts, the two kinds sometimes occurring simultaneously to within 2 s (Chupp and Forrest 1983).

5B.1.2 Spatial Investigations

The picture given above can be amplified by spatial investigations. At the time of the impulsive hard X-ray bursts, the source of radiation is restricted to small areas, in some cases situated in pairs with components on either side of the magnetic inversion line (Duijveman *et al.*, 1982). These 'footpoints' are clearly visible in medium/hard X-ray images (16-30 keV) but they can also be discerned in images taken at lower energies, particularly if care is taken in background subtraction. However, MacKinnon *et al.* (1984) have shown for the same flares analysed by Duijveman *et al.* that only ~ 10% of the hard X-rays within the HXIS fine field of view actually come from the footpoints. Thus, the observations

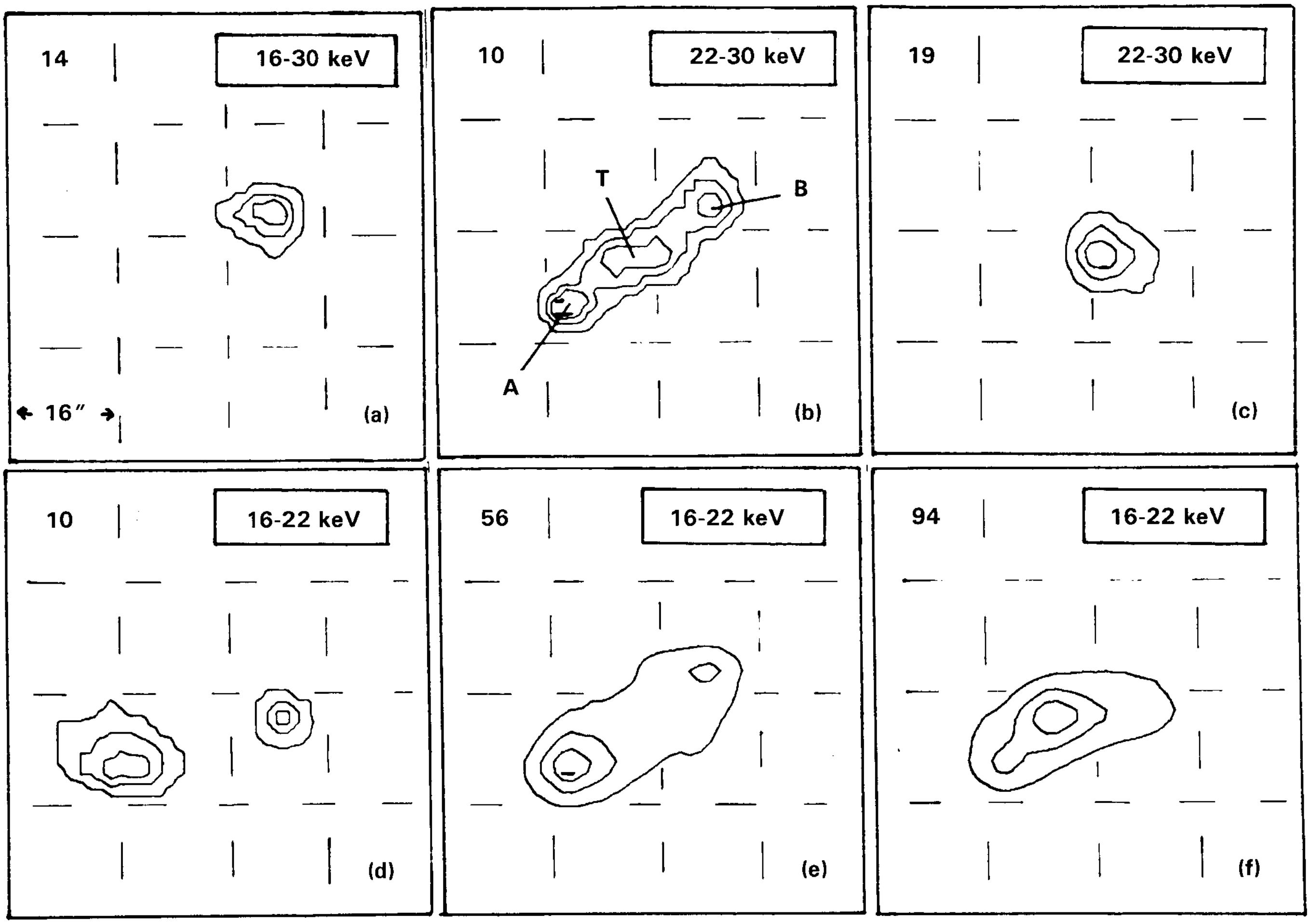

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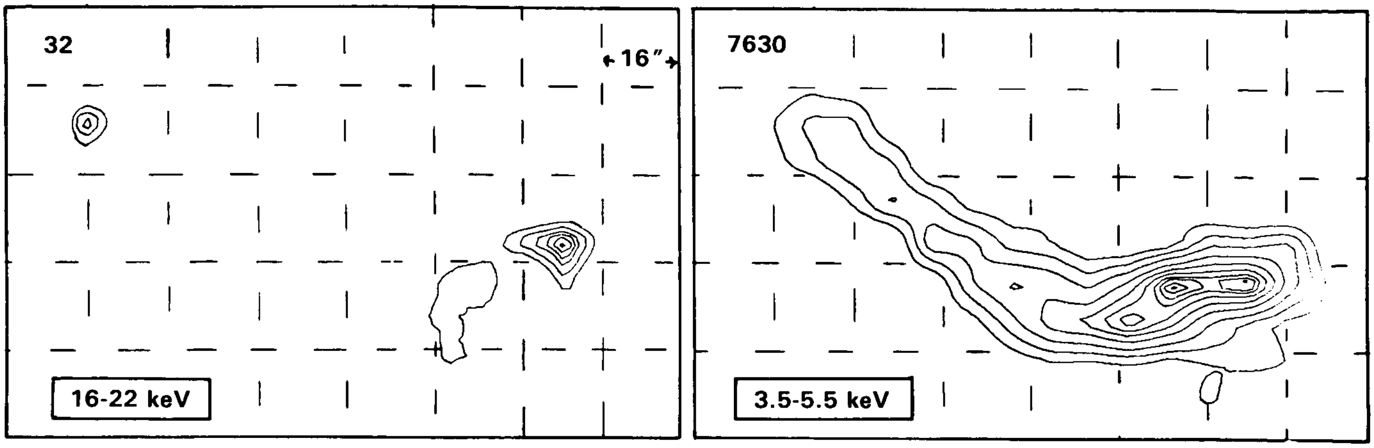
Figure 5A.16 HXIS contour maps of the hard X-ray flux at the following times during the flares on 1980 November 5: (a) 22:26:11 - 22:26:19 UT (start of first flare), (b) 22:26:11 - 22:26:37 UT (first two peaks of first flare), (c) 22:26:39 - 22:27:30 UT (third peak of first flare), (d) 22:32:34 - 22:32:47 UT (start of second flare), (e) 22:33:12 - 22:33:25 UT (decay of first peak of second flare), (f) 22:34:26 - 22:34:39 UT (second peak of second flare). The number in the top left hand corner of each map is the highest number of counts per pixel in the image. Points marked A, B, and T in (b) are believed to be the footpoints and the top, respectively, of a magnetic loop; they are discussed in the text.

of two bright areas in the 16 to 30 keV X-ray images does not necessarily mean that the major source is electron beams interacting in the thick target at the footpoints.

Similar bright compact sources or 'kernels' are also observed in UV line emissions such as O IV (1401 Å) and Si IV (1402 Å) (Cheng *et al.*, 1984, Tandberg-Hanssen *et al.*, 1983, 1984). Images taken in optical lines such as Hα and Mg I (Cheng *et al.*, 1984) show that such kernels generally coincide with the location of the X-ray footpoints. These observations are inconsistent with a flare model in which hard X-rays are produced at the top of a loop, followed by the formation of a thermal conduction front propagating downward to the footpoints (Woodgate *et al.*, 1983).

There is much evidence that the impulsive emissions are concentrated in the low coronal regions, the transition region, and even in the chromosphere. Kane *et al.* (1982) found that sources with photon energies of greater than or about 100 keV are located at altitudes of less than or about 2500 km. In addition, HXIS observations of the X-ray emission of the limb flares of 1980 April 30 (de Jager *et al.*, 1983) and 1980 November 18 (Simnett and Strong 1984) show that the X-ray sources are located at low altitudes during the impulsive phase. For the flare of 1980 November 1 at 19:15 UT, images in the Fe XXI line show that at least during the first minute of the impulsive phase, the hot plasma component (10^7K) was confined to the feet of the flare arch (Tandberg-Hanssen *et al.*, 1984).



(a) 22:32:53-22:33:07 UT

(b) 22:39:24-22:42:27 UT

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Figure 5A.17 HXIS contour maps of the second flare on 1980 November 5. (a) Map in hard X-rays at the time of the main impulsive spike, showing the two bright patches A and B on the right (west) and the third bright area in the top left (northeast) corner. (b) Map in soft X-rays during the decay of the second flare. The number in the top left-hand corner of each map is the highest number of counts per pixel in the image.

5B.1.3 Multi-thermal and/or Non-thermal Phenomena

During the first part of the impulsive phase, i.e., during a period of typically 1 min but sometimes longer (see Figure 5A.4), there are clear indications of the occurrence of multi-thermal or non-thermal phenomena. The temperature parameters derived from ratios of counts in different HXIS energy bands at that time have different values; this clearly suggests a multi-thermal or non-thermal situation. Thermalization is restored towards the end of the impulsive phase when all X-ray energy band ratios yield the same temperature values in the majority of flares (de Jager, 1985b). Bely-Dubau *et al.* (1984) found that they could not fit the combined BCS, HXIS, and HXRBS line and continuum spectral data with a purely thermal DEM model during the impulsive phase of the flare on 1980 June 29 at 18:22 UT. The deviations from such a model can be matched by assuming an additional component to the X-ray spectrum, as expected from a power-law distribution of electrons. MacNeice *et al.* (1985) also find for a flare on 1980 November 12 that the ratio of the flux in the Fe XXV line measured with the FCS to the continuum emission measured with HXIS is inconsistent with a thermal model. They conclude that there must be a significant non-thermal continuum contribution to the footpoint emission recorded by HXIS, even in the lowest channels from 3.5 to 8 keV.

The same situation is valid for the relative values of the electron temperature (derived from spectral fits to continuum observations) and the ion temperature (derived from Doppler widths of spectral lines). These also differ considerably in the first part of the impulsive phase and equalize later, usually also within 1 or 2 min. The Doppler temperatures are higher than the electron temperatures (Antonucci *et al.*, 1984). Figure 5B.1 illustrates the similarity between these two different indicators of non-thermal and multi-thermal phenomena.

Additional evidence is provided by observations of the time variation of the Hα line profile. The energy output of a flare in that line ($|\Delta\lambda| < 5$ Å) has a time dependence similar to that of hard X-rays (Figure 5B.2; Canfield and Gunkler 1985). The enhanced Hα emission of the flare of 1980 May 7 is due to increased emission in the wings of the line and agrees with theoretical line profiles calculated assuming bombardment of a thick target by energetic electron beams. These Hα observations therefore support the idea that the impulsive burst begins with a non-thermal event, i.e., the bombardment of the transition layer and/or the chromosphere by beams of energetic electrons.

This scenario is also supported by the X-ray imaging observations, as shown for the first time by Duijveman *et al.* (1982) for the flare of 1980 November 5 and later for that of 1980 May 9 at 07:10 UT by Machado (1983). Machado showed that the acceleration takes place during the early part of the impulsive hard X-ray event. One should note, however that a substantial amount of the emission at lower energies (less than or about 10 keV) is of thermal origin at that time. Also, HXRBS and HXIS observations show that only 10% of the total hard X-ray emission originates in the footpoints;

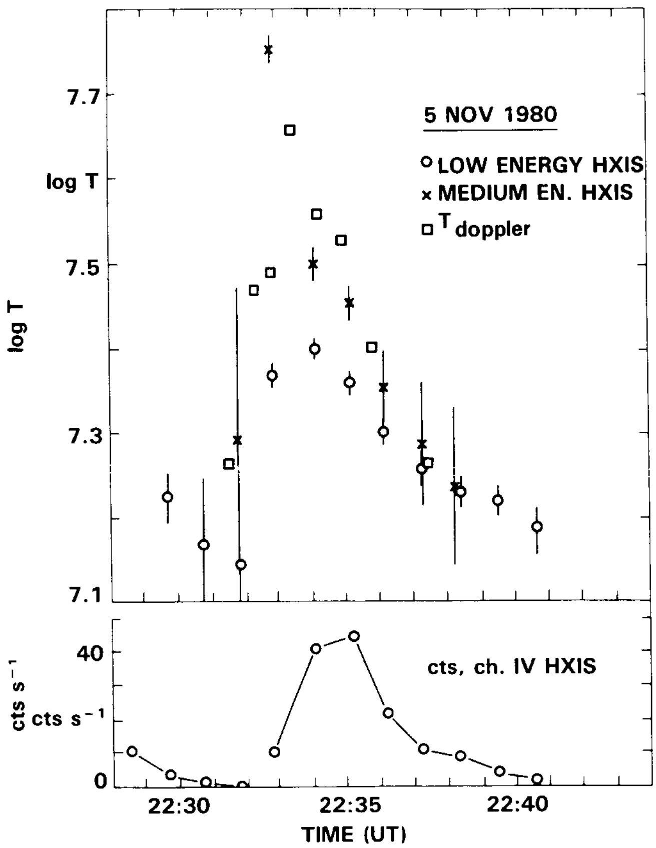

Figure 5B.1 Non-thermal or multi-thermal phenomena at the onset of the impulsive phase of the flare on 1980 April 8. 'Temperature' measurements from different HXIS energy band ratios show a similar behavior to the Doppler and electron temperatures measured at the same time with BCS (de Jager 1958b).

the rest comes from a larger area with a scale size of $\approx 10^4$ km (MacKinnon *et al.*, 1984).

We therefore infer from the observed impulsive phenomena that an instability occurs "somewhere" in the solar atmosphere, followed by electron acceleration and footpoint bombardment by beams of energetic electrons. The location and nature of that instability is still unknown.

5B.1.4 Impulsive-Phase Microwave Bursts

Information on the origin of the non-thermal phenomena occurring during the onset of hard X-ray bursts can be obtained from the observation of impulsive microwave bursts. The peak fluxes of hard X-ray bursts F_X and of the corresponding microwave bursts F_μ are well correlated over three orders of magnitude in F_X and F_μ according to the relation $F_\mu \propto F_X^b$ (Kai *et al.*, 1985). The scatter about this relation is much less than an order of magnitude. This correlation is remarkable at first sight because the microwave bursts are caused by gyrosynchrotron emission at high harmonics (10-100) of the gyrofrequency. Thus, the microwaves are mainly emitted by electrons with energies of the order of hundreds of keV, much higher than the tens of keV required to produce the hard X-ray bursts. However, the additional observation that the time variations of the microwave and hard X-bursts are very similar shows that both kinds of electrons must have the same origin, and the observed time variations must be caused by variations in the acceleration or injection of the electrons.

It is also very significant that the microwave sources are located at higher altitudes than the X-ray sources (Kane *et al.*, 1983), in a medium with electron densities $n_e \approx 6 \times 10^8$ cm^{-3} (Enome 1983). This supports the suggestion that the source of the microwaves consists of high energy electrons trapped in elevated parts of the pre-flare loops (Hoyng *et al.*, 1981, Marsh and Hurford 1982, Gary and Tang 1984), in contrast to the hard X-rays, which come from the feet of the loops. A possible confirmation of this model can be made from observations of the flare of 1980 May 28 at 17:47 UT, for which Gary and Tang (1985) found that the number of electrons responsible for the microwave emission is equal to that causing the hard X-ray bursts. The flare was a single spike in both hard X-rays and microwaves, and this facilitated the interpretation. Such equality was not found in previous comparisons because the thick-target model was adopted for the radio emission as well as for the X-ray emission. It now seems that the microwaves come from electrons near the top of the magnetic loops and so the thick-target model is not appropriate for the microwaves.

The model elaborated above is supplemented by data on size, magnetic field, and location of the microwave sources. The sizes are of the order of arc seconds. Spatially resolved images of microwave emission in the frequency range 5 - 15 MHz (Marsh and Hurford 1982) show that the sources are usually located near the magnetic inversion line and between Hα brightenings. These sources have diameters of 2 - 5 arcsec at 15 GHz and 10 - 15 arcsec at 5 GHz.

The emission properties demand a magnetic field B of the order 200–600 G. For the flare of 1980 June 29, $B \approx 220$ G. A model was proposed that consisted of a hot kernel with an electron temperature of $\approx 10^9$K surrounded by a 'cooler' gas of 10^8 K (Dulk and Dennis 1982). The flare of 1980 March 29 at 09:18 UT emitted a hard X-ray burst of only 10 s duration and a simultaneous microwave burst, the latter observed in the frequency range from 0.9 to 10.4 GHz. The hard X-ray emission spectrum can be represented as thermal bremsstrahlung from a plasma with a temperature of $\approx 5 \times 10^8$K, whereas the radio emission has been interpreted as gyrosynchrotron radiation from a loop with a magnetic field of 120 G (Batchelor *et al.*, 1984).

Summarizing this section, we conclude that the impulsive microwave bursts are caused by greater than or about 100 keV electrons emitting gyrosynchrotron radiation in a source at higher altitude than those emitting hard X-rays.

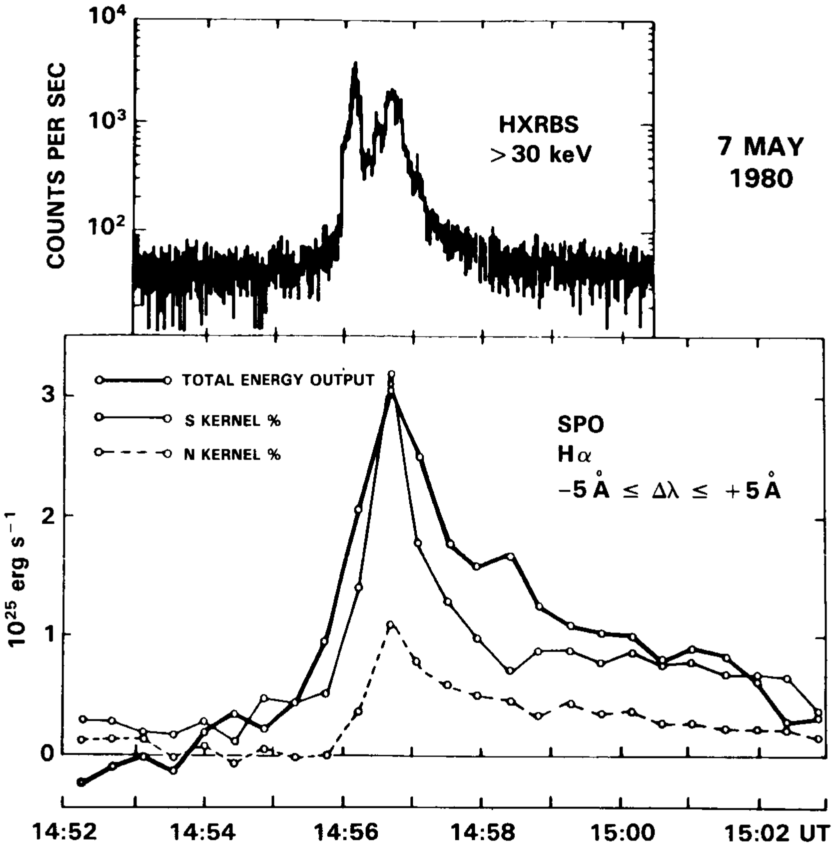

Figure 5B.2 Similarity between the hard X-ray response and the Hα output for the flare of 1980 May 7 (Canfield and Gunkler 1984). The hard X-ray data sum all counts at energies above 30 keV. The Hα data sum all power within 5 Å of pre-flare line center, subtracting the average value during a preflare reference period. For the Hα data, circles indicate values and times of observations. The heavy solid curve indicates the integrated Hα (± 5 Å) energy output (left scale). Percentage contributions of the south and north kernels are indicated by the light solid and dashed lines respectively (right scale).

These microwave sources are small, with dimensions of arc seconds, and are located above the magnetic inversion line; they occur in magnetic fields of a few hundred gauss.

5B.1.5 Simultaneity of Burst Emissions; Fine Structures; Acceleration Problems

Even when the sources of the bursts are separated by large distances, of up to 2×10^5 km (Kattenberg *et al.* 1983), the bursts may still occur simultaneously, to within 1 s. Short time delays are sometimes observed, however, between the microwave and hard X-ray bursts. On 1980 November 1 an X-ray burst occurred 6 ± 3 s before a microwave burst (Tandberg-Hanssen *et al.*, 1984). Nakajima *et al.* (1985) describe observations of "secondary microwave bursts" emitted by sources separated by 10^5 to 10^6 km from the primary source with time delays of 2-5 s. The evidence suggests that the secondary bursts were produced by electrons with energies of 10-100 keV, channeled from the primary source along huge coronal loops to the secondary location.

On 1980 June 7, flares were observed in which hard X-ray bursts preceded the microwave and gamma ray bursts by 1-2 s (Nakajima *et al.*, 1983) (see Figure 5B.3). These observations are consistent with the two-step acceleration model proposed by Bai and Ramaty (1979) and Bai (1982). In this model, 10 to 100 keV electrons that produce the hard X-ray bursts are accelerated first, while another population of ~ 100 keV electrons causes the first microwave bursts. Ions and electrons are both accelerated to $> 10^3$ keV a few seconds later, giving rise to gamma rays and delayed microwave emission.

Large time differences, of up to 5 s, between hard X-ray bursts (< 100 keV) and microwave and harder X-ray bursts

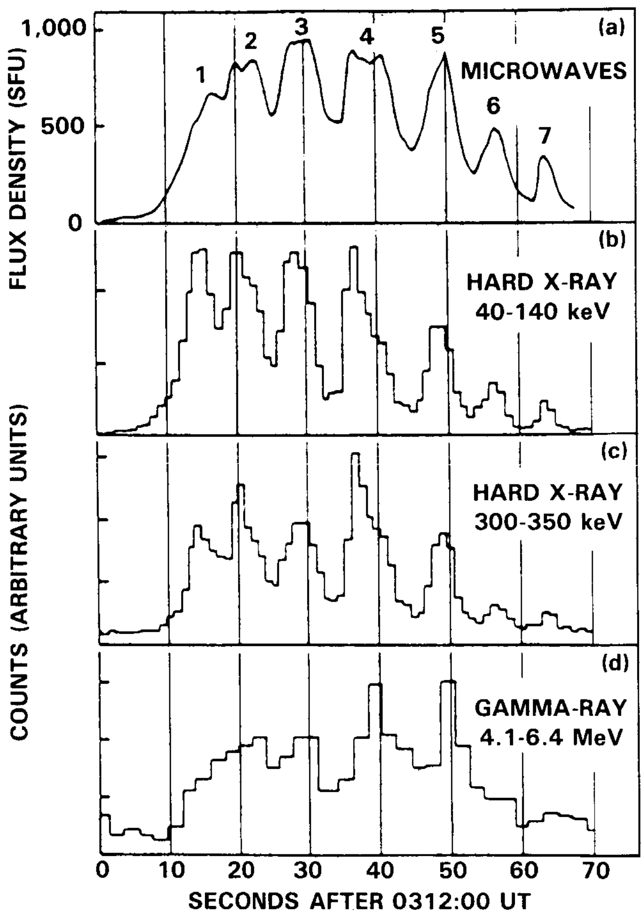

Figure 5B.3 Time profiles of the following emissions for the flare of 1980 June 7 at 03:12 UT from Nakajima *et al.* (1983): (a) 17 GHz microwaves, (b) 40 to 140 KeV X-rays, (c) 300 to 350 keV X-rays, and (d) 4.1 to 6.4 MeV gamma rays.

($>$100 keV) are ascribed to the time needed to build up a population of $>$100 keV electrons (Takakura *et al.*, 1983) and to path lengths. The latter aspect is dealt with easily on the basis of an Alfven wave travelling along a semicircular loop with a field B and an electron density n_e. An Alfven wave could travel between footpoints separated by the distances given in Table 5B.1 in a time of 4 s (chosen arbitrarily). Thus, most of the observed footpoint separations fit well with delay times of a few seconds, assuming that an Alfven wave is the connecting agent.

Table 5B.1 Distances in 10^3 km travelled by an Alfven wave in 4 s

n_e(cm^{-3})	B = 30 G	B = 300 G	B = 1000 G
10^8	16	160	530
10^9	5.5	55	180
10^{10}	1.6	16	50

High time resolution observations at mm-microwaves show fine structures with characteristic timescales as short as 30 to 60 ms. A few bursts inspected in detail show some correlation with similar structures in hard X-ray bursts (Kaufmann *et al.*, 1980, Wiehl and Matzler 1980). Also, in these subsecond bursts, the microwave bursts are often delayed in time compared with the corresponding hard X-ray structures; delays may reach values up to ~ 0.4 s (Cornell *et al.*, 1984), but there is a case of a 1.5 s delay. The most acceptable explanation seems to be that the delayed bursts are from another population of energetic electrons ($\approx$ 100 keV) decoupled from, but accelerated nearly simultaneously with, the population that produced the hard X-rays (Tandberg-Hanssen *et al.*, 1984). Gary and Tang (1985), however, note that the major part of the delay may be caused by thc fact that the decay time for the microwave bursts can be considerably longer (because of the lower density) than that of the hard X-ray bursts.

These subsecond bursts are apparently a new class of bursts with characteristic times shorter by a factor of ten than the elementary flare bursts defined by de Jager and de Jonge (1978). The rate of energy release in the subsecond bursts is of the order of 10^{27}–10^{29} ergs s^{-1} (Kaufmann *et al.*, 1984), i.e., similar to that of longer bursts (Brown and Smith 1980). These subsecond bursts, as well as the elementary flare bursts, may be related to multiple energy injections. It remains to be investigated whether they are related to multithermal phenomena or to bursts in individual flare loops.

We conclude that information on the acceleration processes can be derived from a study of time differences between bursts in different energy ranges. Such studies show that acceleration of electrons to ~ 100 keV and of both electrons and ions to ~ 10^3 keV generally takes place in a time interval of less than a few seconds. It is not necessarily correct, though, to claim that all these particles are accelerated 'simultaneously', because clear time differences have been observed (Bai and Dennis 1985). Melrose (1983) has given evidence that secondary acceleration, assumed to occur stochastically by hydromagnetic turbulence, is responsible for the occurrence of high-energy particles (greater than or about 20 MeV per nucleon). The first step, pre-acceleration, should yield particles with energies up to ~ 100 keV per nucleon. It is ascribed to local heating of ions to ~ 10^9K or to acceleration by potential electric fields.

5B.1.6 Chromospheric Evaporation

The phenomenon of chromospheric evaporation (ablation) occurs during the early part of the impulsive phase. In high-resolution soft X-ray line spectra, the line profiles show evidence for high-speed plasma upflows with velocities up to 400 km s^{-1} and turbulent (non-thermal) mass motions of ~ 100 km s^{-1} (Antonucci *et al.*, 1982, 1984). Simultaneously, the Hα line profile is broadened and modified at the footpoints, consistent with the bombardment of electrons and

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or after several flares (Tanaka *et al.*, 1980, Farnik *et al.*, 1983).

5.7 ACKNOWLEDGEMENTS

We are grateful for contributions to this effort by E. Antonucci, H.M. Chang, U. Feldman, S. Graham, P. Hoyng, P. Kaufmann, M. Machado, D. Rust, and S. Walton. KTS and MEB acknowledge the support of NASA contract no. NAS5 23758 and the Lockheed Independent Research Program. The National Center for Atmospheric Research is sponsored by the National Science Foundation. RP, GP, and SS have been supported by the Italian Consiglio Nazionale delle Riceiche/Piamo Spaziale Nazionale and by the Italian Ministry of Education. STW would like to acknowledge support from NASA Grant (NAGW-9) and the SMM Guest Investigator Program. We are grateful to Drs. R.L. Moore and S.K. Antiochos for their careful reading of the manuscript and constructive criticisms as referees. We also thank Mrs. G. Wharen, Dr. Y. Strong and Dr. J.L.R. Saba for their help in preparing this chapter for publication.

Energetic solar neutrons with energies above 50 MeV have been detected with GRS after at least two flares on 1980 June 21 at 01:18 UT (Chupp *et al.*, 1982) and 1982 June 3 at 11:42 UT (Chupp *et al.*, 1983, Evenson *et al.*, 1983). In the case of the first flare, impulsive photon emission from 10 keV to >65 MeV lasting for $\sim$ 66 s was followed by a transient flux of 50-600 MeV neutrons incident over a 17-min period. These observations indicate the emission of 3×10^{28} neutrons sr^{-1} with energies of >50 MeV, requiring the rapid acceleration on a timescale of $<<60$ s of protons to GeV energies during the impulsive phase of the flare. Ramaty *et al.* (1983) have estimated for this flare that the total energy content in the protons and nuclei was 2.4×10^{30} ergs, with 75% of this energy residing in >1 MeV particles. In contrast, the energy content in electrons of energies greater than 0.3 MeV was only 5×10^{28} ergs.

The neutron flux observed after the second flare was an order of magnitude more intense but with a similar spectral shape. Prince *et al.* (1983) have used the measured flux in the 2.223 MeV gamma ray line to determine an upper limit of 3.9×10^{28} neutrons MeV^{-1} sr^{-1} on the flux below 20 MeV, which is the major source of this line. This indicates that the neutron spectrum must flatten at energies below $\sim$ 50 MeV.

5B.2 Summary and Scenario

The impulsive phase is a period during which hard X-ray bursts and microwave bursts occur nearly simultaneously, as well as bursts in other energy ranges (EUV, gamma). These emissions have a non-thermal character, but only for about 10^2 s, after which time thermalization is restored. During the impulsive phase, upward movements of plasma are also observed, indicating chromospheric evaporation (ablation) followed by convection. The thermal energy content of the flare increases steadily, reaching a maximum value at the end of the impulsive phase. Coronal explosions can also occur as a result of the large energy input in a small volume.

The flare model that results from these conclusions is that of a flare consisting of a system of loops. These loops may be interwoven and are often not resolved as loop complexes. Many observations show only a single or a few loops, but in other cases the observations can only be interpreted in terms of several or even many unresolved loops and therefore appearing as one. One such case is the flare of 1980 November 1, 19:15 UT (Tandberg-Hanssen *et al.*, 1984). Also, the fact that the so-called 'tongue' of a flare has a small filling factor (de Jager *et al.*, 1983, Woodgate *et al.*, 1983) suggests the existence of many unresolved magnetic structures or of many thin loops in a confined region.

Interaction between these loops on field lines that undergo violent motions and drastic changes of direction leads to magnetic reconnection (Moore *et al.*, 1984) with the acceleration of electrons and ions. The literature describes a few cases in which the interaction of loop-systems leading to the flare was seen quite clearly. The Queens' Flare (1980 April 30 at 20:20 UT; de Jager *et al.*, 1983) was a limb flare in which the interacting loops could be identified, and the site and time of the interaction was determined unambiguously. Another case is the disk flare of 1980 June 24 at 15:22 UT (Gunkler *et al.*, 1984). These observations show that the point of reconnection (probably identical to the site of particle acceleration) is normally not at the "top" of the loop. Mouradian *et al.* (1983) suggest the existence of 'elementary eruptive phenomena' consisting of two systems of loops, a cold ($T \approx 10^4$K) 'surging arch' and a hot 'flaring arch'. This concept is interesting, but it remains to be seen whether it applies to most of the observed flares.

Magnetic field reconnection leads to electron acceleration and the consequent emission of microwave bursts by gyrosynchrotron radiation and footpoint bombardment by the electron beams. The latter effect heats the chromospheric/transition layer part of the footpoint area, causes ablation (evaporation), convective ascent of heated gas, and coronal explosions.

5B.3 The Energy Source of Flares

Observations show the close connection between magnetic field twisting, energy build-up, and energy release of the solar magnetic field. Consequently, it is currently assumed that the shearing motion of footpoints of flux tubes is the origin of the solar flare energy (Wu and Hu 1982, Akasofu 1984). On the basis of this idea and the linear force-free magnetic field theory, Tanaka and Nakagawa (1973) studied some active regions and a bipolar sunspot. Yang and Chang (1981), and Yang *et al.* (1983) solved the first order force-free differential equations. From the observational data of penumbral filament twisting and their force-free field solution, they computed the energy excess, ΔM, of the force-free field at different times, where $\Delta M = M_f - M_p$, and M_f and M_p are the magnetic energies of the force-free and the potential fields, respectively. Comparing their results with solar flare data, they found that when ΔM was between 10^{28} and 5×10^{30} ergs, a subflare may occur; if $\Delta M \approx 10^{30}$-10^{31} ergs, medium sized flares can appear, whereas $\Delta M > 10^{32}$ ergs is the condition for the appearance of a large flare. The first quoted values are of the same order as those derived from the observations of the impulsive phase of the prime flares discussed in Section 5.2.

These considerations, applied to AR 2372 (Boulder number) in the period 1980 April 5 to 7 show how a self-consistent MHD model can be used to study the magnetic energy build-up in that region. It is found that almost all of the energy for the flare is stored in the magnetic field, the magnitude of the shearing motions being the crucial parameter (Wu *et al.*, 1984). It is therefore important that a reduction of the magnetic shear has been observed during

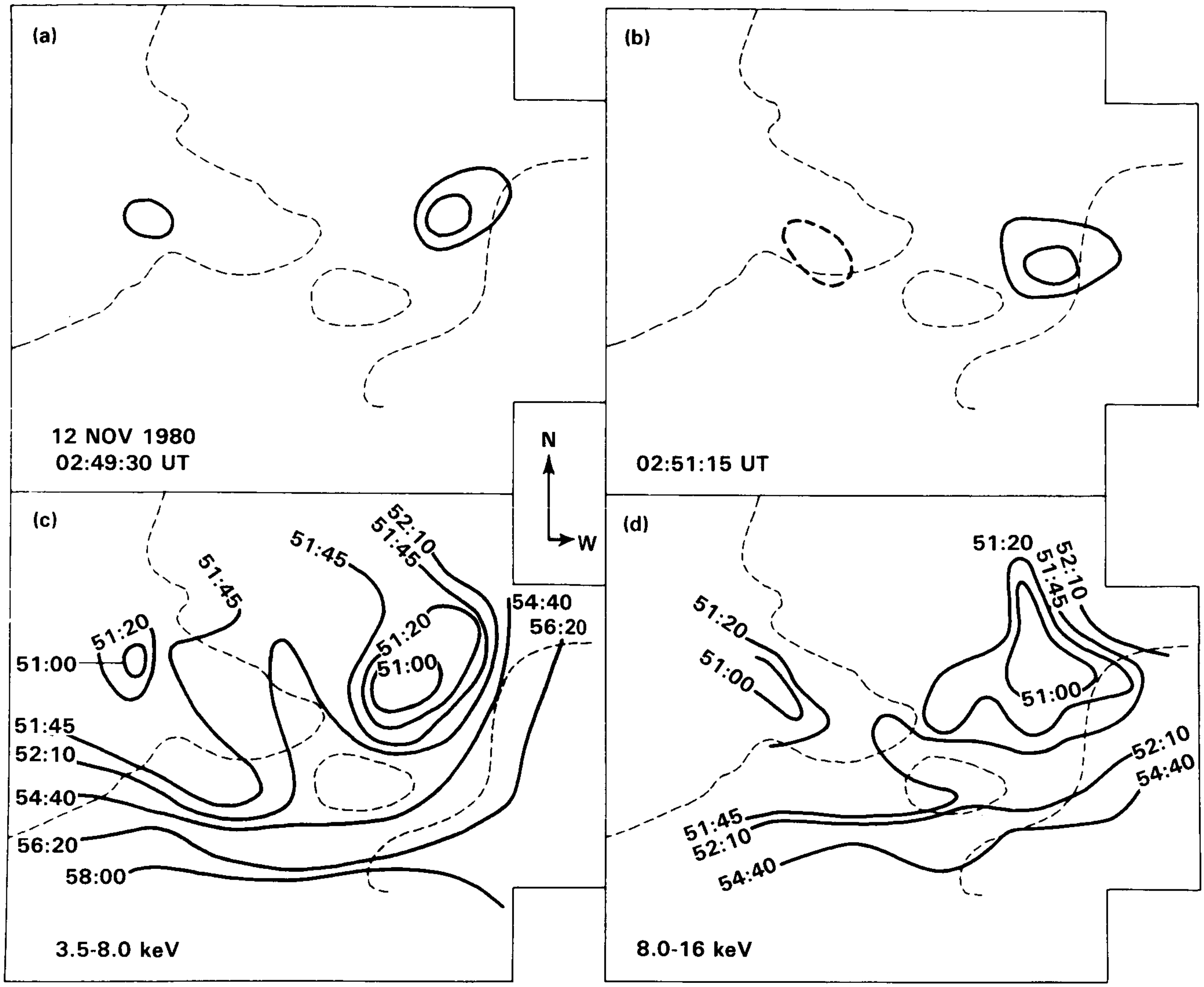

Figure 5B.5 Coronal explosion in the flare of 1980 November 12 at 02:50 UT from de Jager (1985a). (a) and (b) Location of hard X-ray footpoints at the times of the two main bursts of the impulsive phase. The dashed lines indicate the locations of magnetic inversion. (c) and (d) The explosion seen in soft (3.5 to 8.0 keV) and medium (8.0 to 16 keV) energy X-rays. The curves are labeled with the time in minutes and seconds after 02:00 UT.

and consequent convective motions, spreads out over a large area, with a strong lateral velocity component.

The energy of the coronal explosions is at least an order of magnitude smaller than the total thermal energy content of the flare at the time of the explosion (de Jager 1985a).

5B.1.9 Thermal Conduction Fronts

Evidence for thermal conduction fronts has been obtained in a few flares (Rust *et al.*, 1985). Their signature is the expansion of the X-ray emitting region along a loop with velocities between 800 and 1700 km s^{-1}. They differ from coronal explosions in that with conduction fronts the motions are directed along loops and the velocities remain high and virtually constant along the loop. The velocities are consistent with elementary considerations of thermal conduction with a heat flux of $\approx 10^{10}$ erg s^{-1} cm^{-2}. This corresponds to an energy release of 10^{28} erg s^{-1}.

5B.1.10 Gamma Rays and Neutrons from Flares

Observations of the gamma-ray and neutron flux and the analysis of their spectra offers a means of deriving the total kinetic energy W of the flare particles in the high-energy range (Ramaty 1982). Derived values for W(> 1 MeV) have an upper limit of 2.5×10^{30} ergs (for the flare of 1972 August 4), whereas the smallest reported value is 5×10^{28} ergs (1980 July 1).

chromospheric heating. These phenomena are restricted to the Hα kernels in the impulsive phase (Badalyan and Livshits 1982, Ichimoto and Kurokawa, 1984, Canfield and Gunkler 1984, Gunkler *et al.*, 1984).

5B.1.7 Convective Motions

Convective motions occur as a consequence of the heating of the evaporated gas. The observed velocities, ranging between 150 and 350 km s^{-1} are in agreement with theoretical views on convection in a coronal plasma (Fisher *et al.*, 1984, MacNeice *et al.*, 1984). An illustration of these phenomena is given in Figure 5B.4 for the flare of 1980 May 21 at 21:00 UT (Antonucci *et al.*, 1984). The total number of electrons involved is 3×10^{37}, and the number of chromospheric atoms is 7×10^{37} (Acton *et al.*, 1982). An energy flux of (3-10) $\times 10^{9}$ ergs cm^{-2} s^{-1} (MacNeice *et al.*, 1984, Fisher *et al.*, 1984) is needed, and the total energy that must be supplied to make the convection possible is (1-4) $\times 10^{30}$ ergs. The density of the upward moving plasma is $> 4 \times 10^{10}$ cm^{-3} (Antonucci *et al.*, 1984). For the Queens' flare (1980 April 30), 10^{37} electrons were involved and the densities of the convected plasma and of the footpoint kernel were 10^{11} cm^{-3} and 4.5×10^{11} cm^{-3}, respectively (de Jager *et al.*, 1983).

5B.1.8 Coronal Explosions

Coronal explosions have been detected in HXIS images of four flares (de Jager and Boelee 1984, de Jager *et al.*, 1984, de Jager 1985a). They were discovered by noting for each pixel in the flaring area the time t_m at which maximum intensity is reached. The earliest t_m values are found in small areas (10^8 km^2) near the flare footpoints. From there, the t_m-isochrones, being the lines of equal time of intensity maximum in the flare, spread out laterally over the flaring area with velocities that are initially of the order of a few hundred to more than 10^3 km s^{-1}, but that decrease rapidly in the course of a few minutes (Figure 5B.5). In the same way as there are generally two footpoints, there are also two 'sources' (i.e. areas where t_m is earliest), although it is not yet certain that the 'sources' are identical to the footpoints. From each 'source' the isochrones spread out as a wave-like feature. The two waves, from the two sources, may meet each other and merge after a few minutes.

These waves are not thermal or conduction fronts as can easily be ascertained: the variation of temperature in the various flare-pixels is not correlated with that of the intensity in these pixels. Since the t_m-isochrones connect points where maximum intensity is reached for any pixel, they connect points of maximum emission measure and, assuming the volume V not to vary too rapidly, the t_m-isochrones thus connect points where the density n_e is maximum in the various pixels. Therefore, a coronal explosion is a density wave, which may be identified with a shock wave, either hydro-

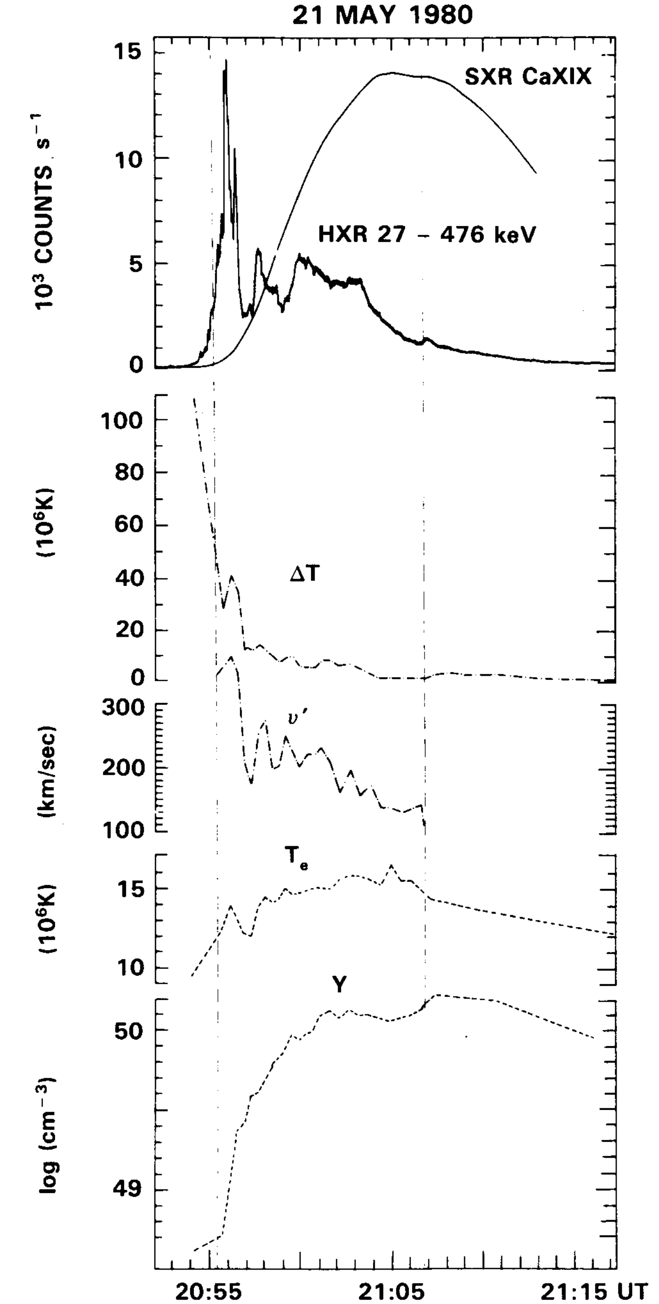

Figure 5B.4 Time variation of parameters characterizing the chromospheric evaporation for the 1980 May 21 flare from Antonucci *et al.* (1984). The following derived quantities are plotted as a function of time with the Ca XIX and hard X-ray rates shown for reference: the temperature difference ΔT between the ion and the electron temperatures, the upward velocity component v', the electron temperature T_e, and the Ca XIX emission measure Y.

dynamical or magneto-hydroynamical. The most likely explanation is that the explosion is the manifestation of gas that, after having emerged from the flare footpoint by ablation

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