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CLASSIFICATION OF SOLAR FLARES

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CSSA-ASTRO-88-20
NOVEMBER 1988

CENTER FOR SPACE SCIENCE AND ASTROPHYSICS
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Stanford, California

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1. INTRODUCTION

Solar flares exhibit diverse phenomena: they cause electromagnetic radiations ranging from kilometric radio waves to tens of MeV gamma rays, and accelerate energetic particles interacting in the solar atmosphere as well as those escaping into interplanetary space. They are also associated with shock waves which sometimes propagate to several A.U. and ejections of magneto-plasma configurations into interplanetary space. It has been controversial whether there is only one class of solar flares or many classes of flares. According to one school of thought, flares are basically the same and must intrinsically involve all flare phenomena, the relative strengths of which vary from flare to flare. During very energetic flares all flare phenomena are strong enough to be detected, but during less energetic flares many flare phenomena are too weak to be detected although they take place. (See Kahler (77) concerning the "big-flare syndrome.") According to the other school of thought, there are different classes of flares, and some flare phenomena take place during one class of flares and not during other classes of flares. In this view, additional physical processes take place during flares exhibiting complex flare phenomena. It is important to determine which view is closer to reality.

The problem with classifications in general is that objects or phenomena do not fall into neatly arranged boxes. There are always exceptions, and some objects fall in the gray areas. (See ref. 1, for a summary of a discussion on solar flare classification.) However, a good classification scheme can serve useful purposes by organizing seemingly bewildering phenomena or objects. A good classification scheme should be closely related to the physical processes involved, and it is desirable that the names of different classes should indicate important characteristics of the classes (70). Our aim is to base a classification of flares related to energy release processes, including the important process of particle acceleration.

Through observational data collected during the last solar cycle, especially those made by the *Solar Maximum Mission* (*SMM*) (131) and the Japanese *Hinotori* Satellite (174), we now have a more complete understanding of what is going on in solar flares, so that this is a good opportunity to review the thoughts of solar physicists on flare classification schemes. Because the physics of solar flares is such a diverse field, we confine the scope of our paper to observations and theoretical ideas directly related to flare classification. Hence, many important papers that have contributed to our general understanding of solar flares will perforce not be discussed.

Since we are trying to understand the differences between different classes of flares, we will not dwell much on the primary (sometimes called the "first-phase") acceleration process, which is responsible for nonthermal electrons with energies up to a few hundred keV, but we will instead concentrate on those additional processes which distinguish various class of flares, emphasizing high-energy phenomena and interplanetary phenomena involving energetic particles. Energetic particles play important roles in the development of flares; not only do they transport energy from the energy release site to the lower atmosphere and cause almost all the detectable radiations, but some of them escape into interplanetary space to influence the near-earth space environment. Gamma-ray emission from solar flares has been reviewed by Chupp (34), Hudson (73), and Ramaty & Murphy (144); and hard X-ray emission, by Dennis (46).

Although we shall frequently refer to radio emission in discussing the observational properties of flares, it will not be possible to consider theoretical aspects of flare radio emission. However, comprehensive reviews of radio emission have already been published in *the Annual Review of Astronomy and Astrophysics* (50, 193, 194). For more recent reviews on radio emissions from solar flares, see refs. 102 & 120. Melrose & Dulk (120) and Trottet (178), in particular, discuss particle acceleration in terms of radio-burst observations. A recent monograph (119) also deals with solar radio bursts. Coronal mass ejections (CMEs), as will be shown, are well associated with a certain class of flares. For reviews of CMEs, see refs. 69, 80, & 188. For other aspects of flares, see the *SMM* Workshop monograph (103). This paper is organized as follows. First

We organize the paper as follows. In Section 2 we discuss the historical background before the *SMM* (Solar Maximum Mission) launch. ~~launch. In Section 3~~ Next we discuss the recent developments made by observations with *SMM*, *Hinotori*, and other contemporary satellites and ground-based observatories. Based on these observations ~~discussed in Sections 2 and 3, in Section 4~~ we classify solar flares into the following five classes: *thermal hard X-ray flares, nonthermal hard X-ray flares, impulsive gamma-ray/proton flares, gradual gamma-ray/proton flares, and quiescent filament-eruption flares.*

In Section 4 we also discuss the roles of filament eruptions in flare development. ~~In Section 5 we~~ discuss theoretical ideas related to processes occurring in different classes of flares. Closing remarks are given in Section 6.

2. HISTORICAL BACKGROUND

2.1 Proton Flares and Radio Bursts

Long before soft and hard X-rays and gamma rays from solar flares were observed, energetic protons accelerated by flares had been detected. As early as in 1946, protons above 1 GeV were detected from their ground level effects (GLE) (56a), and subsequently protons with energy of order 10 MeV were detected from the resulting "polar cap absorption" (PCA) events (189). Solar flares which cause PCAs are called "proton flares," and flares which cause ground level effects are often called "GLE events" or "cosmic-ray flares." However, the term "proton flares" in general refers to both groups.

Ellison *et al* (54) first noticed that cosmic-ray flares are typically two-ribbon flares, with two large Hα ribbons that slowly drift apart. Later studies have shown that the same is true for the majority of proton flares (7). In the meantime, radio astronomers have found that nearly all proton flares are associated with type IV metric bursts, and claimed that type IV emission is the most reliable indicator of proton acceleration by the parent flare (194). Type IV bursts are almost always preceded by type II bursts. (See Pick (138) for emission mechanisms for type IV.) According to Wild *et al* (194), type II radio bursts, which are narrow-band meter-wave emission, the frequency of which slowly drifts to lower frequencies, are due to energetic electrons accelerated by shock waves propagating in the corona.

It has been proposed (194) that the same shocks also accelerate energetic protons arriving at Earth.

As indicated above, some researchers have for some time considered that proton flares may differ from most flares, and may involve additional physical processes. On the other hand, McCracken & Rao (118) have expressed the view that it is only a matter of detector sensitivity whether or not we detect energetic interplanetary (IP) protons, implying that flares producing energetic IP protons do *not* comprise a unique class of flares. With the advent of energetic particle detectors aboard spacecraft, many flares have been found to accelerate protons detectable in the neighborhood of the Earth, so that the characteristics of proton flares could be studied in more detail. Lin (103a) showed that the majority of proton events were associated with type II and type IV radio bursts. Svestka & Fritzova (170) even suggested that almost all flares producing type II bursts were proton flares. However, later studies (9, 78) have shown that only a small fraction of flares with type II radio bursts are associated with proton events although the majority of proton events are associated with type II and type IV radio bursts. By studying solar-flare soft X-rays and energetic particles with detectors aboard the same satellites, Sarris & Shawhan (151) found that soft X-ray decay times of proton flares, ranging from about 80 to 100 min, are longer than those of electron flares (with high-energy electrons but without high-energy protons), and that the ratios between rise and decay times of proton flares are smaller than those of electron flares. This has been confirmed by many other studies (e.g., 76, 128), and Kahler (76) called flares with slowly decaying soft X-ray emission "long decay events" (LDEs). Sturrock (161) proposed that the slow separation of the Hα ribbons of a two-ribbon flare and the associated long-lasting soft X-ray emission may be attributed to the progressive reconnection of the oppositely directed field lines of an open field configuration. Sturrock considered that an initially closed flux tube may be slowly opened by the same stress that drives the solar wind. Kopp & Pneuman (99) later considered a similar model, proposing that an erupting prominence would lead to an opening of the overlying flux system. However, neither of these articles discussed the location or mechanism of proton acceleration.

2.2 Skylab Observations

The next important contribution to flare classification came from *Skylab* observations. Analyzing *Skylab* soft X-ray images (2-60 A) of flares observed near the solar limb, Pallavicini *et al* (132) proposed that there are two classes of flares---compact and extended. Extended flares do exhibit a large array of distinct characteristics: large and diffuse soft X-ray sources (with volumes in the range 10^{28}–10^{29} cm^3), high soft X-ray sources (heights of order 5×10^9 cm), long enduring soft X-ray emission (with e-folding times of hours), low energy density (10–10^2 erg cm^{-3} as compared with 10^2–10^3 erg cm^{-3} for compact flares), association with type II and type IV radio bursts, and association with prominence eruption and white light coronal transients (now often called CMEs). Although Pallavicini *et al* did not study energetic IP protons, one can see that many of the above-mentioned properties of extended flares are also the properties of proton flares, with some important new additions.

In view of the foregoing, it is natural that, by the end of the *Skylab* Workshop, the majority of solar-flare physicists obtained the following view: solar flares consist of two classes---simple, compact flares, for which the flare energy is released mainly during a "first phase"; and complex, extended flares, for which additional energy release and acceleration take place during a "second phase." The second-phase acceleration energizes protons to high energies and electrons to relativistic energies, possibly via shocks propagating in the corona (42, 152, 168, 194). Evidence for continuous energy release by Kopp-Pneuman-Sturrock type reconnection after the first phase of extended flares is that the top is the brightest part of a loop (110, 132) and the decay time is much longer than the cooling time (110). Svestka's (169) review paper, though written comparatively recently, maintained basically this pre-*SMM* view, by dividing flares into confined flares and dynamic flares.

2.3 First and Second Phases

Wild *et al* (194) used the terms "first phase" and "second phase" of particle acceleration. Analyzing the hard X-ray (>10 keV) observations by the *Fifth Orbiting Geophysical Observatory*, Kane (90) reported the discovery of impulsive and slow components of hard X-rays. The impulsive component is due to bremsstrahlung of nonthermal electrons while the slow component is thermal X-rays. Since then, the terms "impulsive phase" and "gradual phase" have been widely used. The term "impulsive phase" has often been used as a synonym for "first phase." However, the term "impulsive phase" has become ambiguous because the hard X-ray emission of some flares shows gradual behavior. Some people use the term to refer to the whole period of hard X-ray emission, and others use it to refer only to the period in which the hard X-ray flux changes impulsively. Therefore, in describing observational characteristics, we will use the term "first phase" instead of "impulsive phase." (When we come to propose a theoretically based terminology, we will introduce other terms.) First-phase phenomena include acceleration of nonthermal electrons in the first phase, and direct consequences of this acceleration such as hard X-ray and microwave emission and chromospheric responses.

Frost and Dennis (61) and Hudson *et al* (75) interpreted gradual hard X-rays as resulting from electrons accelerated during the second phase. However, Kahler (79) and Tsuneta *et al* (182) have shown that the source height of the gradual hard X-ray emission is well below the location of the type II producing shock. We also regard the gradual hard X-ray emission as a first-phase phenomenon, for the reasons discussed in the following sections.

Type II and type IV radio bursts start several minutes later than the start of hard X-ray emission; therefore, in short-duration flares type II and type IV bursts start after the hard X-ray emission decayed completely. However, in long-duration flares type II and type IV bursts start while hard X-ray emission is still in progress. Thus, first-phase and second-phase phenomena are not cleanly separated in time, but there are indications that first-phase and second-phase phenomena are separated in space, the latter occurring in the high corona.

2.4 Nuclear Gamma-Rays

Energetic protons and heavy ions interacting in the solar atmosphere produce excited nuclei, which are in turn promptly de-excited to produce gamma-ray lines. The lines at 4.4 MeV and 6.1 MeV, due to excited ^{12}C and ^{16}O, are the two most prominent nuclear lines. Nuclear interactions also produce neutrons, which are thermalized in the solar atmosphere and combine with protons to produce deuterons and the 2.2 MeV gamma-ray line. Pions produced by nuclear interactions decay to muons, which in turn decay to electrons or positrons. Positrons are also produced by the β-decay of radioactive nuclei produced by nuclear interactions. Positrons annihilate with electrons to produce 511-keV gamma-rays. The 2.2 MeV line is delayed with respect to nuclear gamma rays because neutrons take time to be captured. The 0.511 MeV line is also delayed because positrons from energetic pions take time to slow down and annihilate, and because radioactive nuclei have finite half-life times for β-decay. For the above reasons, we can learn about high-energy protons and ions by studying gamma-rays originating from nuclear interactions (143, 144). In particular, the time profiles of a nuclear line or gamma-rays in the 4–7 MeV band (where nuclear gamma-rays are dominant over the bremsstrahlung continuum) can tell us when protons and heavy ions are accelerated.

On the basis of observations of energetic IP protons, it was expected that solar flares would emit detectable nuclear gamma-rays (108), and it was expected that such gamma-rays would be detected after the first phase. Before the launch of *SMM,* solar nuclear gamma-rays had been observed by means of the *Seventh Orbiting Solar Observatory* (*OSO 7*) (35), the *First High Energy Astronomical Observatory* (*HEAO 1*) (74), and the *Third High Energy Astronomical Observatory* (*HEAO 3*) (141). Such observations showed that nuclear gamma rays are emitted nearly contemporaneously with hard X-rays with some delays of tens of seconds. Such delays were interpreted as evidence for the "second-phase" acceleration of protons (16, 74).

3. RECENT DEVELOPMENTS

3.1 SMM Results

One of the main achievements of *SMM* has been the detection of nuclear gamma rays from many flares---45 flares up to January 1985 (ref. 39)---far more than the modest pre-launch expectation of the GRS group. Figures 1 and 2 show time profiles of hard X-rays and 4-7 MeV gamma-rays for two flares detected with GRS. Observations such as these run counter to the traditional notion of two phases of acceleration. It is now clear that protons and relativistic electrons are accelerated during the first phase before the start of a type II radio burst. Furthermore, for impulsive flares such as that of 1980 June 7, protons must be accelerated promptly with time scales of a second or so. Although some observations before *SMM* showed that nuclear gamma rays are produced during the first phase, contemporaneously with hard X rays, the GRS detection of nuclear gamma-rays from many flares made solar physicists come to terms with this fact. The delay of nuclear gamma-rays with respect to hard X-rays can be seen in these figures, and it ranges from less than 2 s up to 100 s (34, 199).

The detection of nuclear gamma rays during the first phase raises the following two questions. Since it is known that the first phase can accelerate protons to high energies, do we need a second phase of acceleration? (32, 58, 59, 141). And are protons accelerated during all flares or only during some classes of flares? These two questions are discussed in this section in reverse order.

Characteristics of Gamma-Ray Line Flares

In addition to the impulsive behavior of nuclear gamma-ray time profiles and very short delays of gamma-rays with respect to hard X-rays, the GRS group (34, 57, 184) found a good correlation between gamma-ray continuum fluences >270 keV and excess 4-8 MeV fluences (excess over the power-law continuum). From these discoveries, the GRS group at New Hampshire (32, 58, 184) proposed that a single, primary acceleration may be responsible not only for low-energy electrons (<200 keV), but also for relativistic electrons and energetic ions. It is implicit in this view that, as far as acceleration is concerned, there is only one class of flares.

In a dissenting opinion, Bai (8) proposed at a meeting at La Jolla in 1981 that, in addition to the classical second-phase acceleration (42, 194), an additional process energizes protons to gamma-ray-producing energies and electrons to relativistic energies during the first phase. Bai & Ramaty (17) had initially proposed such an acceleration, which they termed "second-step acceleration," for the further acceleration of electrons during the first phase.

It is implicit in this view that gamma-ray-producing flares differ from other flares in that an additional acceleration process operates during the first phase. In order to test this hypothesis, Bai *et al* (13) and Bai & Dennis (12) compared gamma-ray line (GRL) flares (which emit detectable nuclear gamma rays) with flares having peak HXRBS rates $>10^4$ counts s^{-1} but without detectable nuclear gamma rays. Because the comparison group has peak HXRBS rates as large as those of GRL flares, we may regard the comparison group as "non-GRL flares" or "gamma-ray poor flares." They found the following results:

(1) GRL flares have flatter hard X-ray spectra (the average spectral index being 3.5).

(2) A large fraction (75%) of GRL flares produce either type II or type IV radio bursts or both whereas only a small fraction (30%) of the comparison group do so.

(3) The hard X-ray spectra of some GRL flares harden as a spike burst progresses, whereas the majority of flares show a soft-hard-soft behavior.

Bai (9) has confirmed these findings by more detailed statistical analyses. Cliver *et al* (40) also have confirmed that GRL flares are well associated with type II and type IV bursts by studying a larger sample of GRL flares that had been observed with GRS up to January 1985.

The progressive hardening of hard X-ray spectra observed in GRL flares is shown in Figures 3 and 4. Such spectral hardening is equivalent to a delay of high-energy hard X-ray time profiles with respect to lower energy hard X-rays (12). Such delays or spectral hardening can be due to the fact that the energy loss time of energetic electrons trapped in a coronal loop increases with increasing energy (17, 186). Inclusion of the precipitation of electrons from a hypothetical trap to the chromosphere does not change this proper.y, although it shortens the delay times (112, 150). Even if the trap interpretation is correct, GRL flares are still different in that such delays are observed in almost all cases in GRL flares. The second-step acceleration (8, 9, 12, 14, 119a, 126) was invoked to explain not only the delays but also the acceleration of relativistic electrons and gamma-ray-producing protons.

Second Phase Acceleration

Now we address the question whether there is a second phase of acceleration. One of the puzzling results of *SMM* was that there is a very poor correlation between the number of energetic protons deduced from nuclear gamma-ray observations and the number of energetic protons estimated from IP observations (37, 39, 135, 187). Some flares that produced large fluxes of IP protons produced hardly any nuclear gamma rays; on the other hand, some other flares with large gamma-ray counts produced only small fluxes of IP protons. The following two possibilities were proposed: (1) The same acceleration mechanism accelerates both gamma-ray-producing protons and energetic IP protons, but the escape rate varies from flare to flare. (2) There are two acceleration mechanisms for protons, one for protons that are mostly confined in the solar atmosphere and produce gamma rays, and the other for protons that mostly escape into IP space. In retrospect, considering that impulsive GRL flares did not exhibit the characteristics of proton flares that were well known before *SMM*, it seems easy to opt for the second possibility. But this was not so obvious at the time: one of the reasons may be that the first well publicized gradual GRL flare was that of 1981 April 27, which did not produce a noticeable change to the high background flux of IP energetic protons due to a big event 3 days earlier. Bai (8) advanced the second possibility, and Bai *et al* (15) subsequently proposed that there are two classes of gamma-ray/proton (GR/P) flares---impulsive and gradual. (Here GR/P flares refer to flares which produce nuclear gamma-rays and/or energetic IP protons. GRL flares refer specifically to flares for which nuclear gamma rays are detected, so that GRL flares are a subset of GR/P flares.) According to Bai *et al* (15), in gradual GR/P flares, additional (second-phase) acceleration produces energetic protons which mostly escape into IP space, whereas in impulsive GR/P flares only a "second-step" mechanism is operative. This proposal has been further supported by a later, more detailed, study by Bai (9). By studying the properties of flares producing energetic IP particles, Cane *et al* (23) also have classified IP particle events into impulsive and long-duration events, based on the duration of the associated soft X-ray emission.

Bai (9) studied 17 GRL flares (both impulsive and gradual) observed with GRS in 1980 and 1981, and, in addition, 23 "HXRBS gradual flares" selected on the basis of HXRBS observations in the interval 1980 through 1982. If the total hard X-ray duration of a flare is longer than 10 min and the duration of the strongest hard X-ray spike burst is longer than 1.5 min, the HXRBS flare was regarded as a gradual flare (Figs. 2 & 4). Although the selection of these gradual flares was based solely on the characteristics of hard X-ray emission (i.e. on "first-phase" characteristics), they were found to exhibit a large set of characteristics (16 are listed in Table 6 of ref. 9; see Table 1), and many of these characteristics are also the known characteristics of extended (or proton) flares.

Out of these 23 HXRBS gradual flares, the nine flares with the largest peak HXRBS counting rates were found to emit detectable nuclear gamma rays. Therefore, it seems reasonable to infer that other gradual flares also emitted nuclear gamma rays but that this emission level is below the GRS threshold. The large majority of the HXRBS gradual flares west of E20°, which is the region well connected to Earth by magnetic field lines, turned out to produce detectable energetic IP protons.

In view of the evidence that these HXRBS gradual flares must have produced nuclear gamma rays as well as energetic IP protons, they were called "gradual GR/P flares." Compared with gradual GR/P flares, impulsive GR/P flares do not exhibit characteristics pertaining to phenomena occurring in the high corona and IP medium, with the exception that they may produce type II and type IV radio bursts. In fact, the majority of impulsive GR/P flares produced metric type II bursts, but none of them was found to produce kilometric type II bursts, which are indicative of IP shocks (26). Also it was found that the estimated ratio between the number of energetic IP protons and the number of gamma-ray-producing protons is small (<<1) for impulsive GR/P flares while it is relatively large (>1) for gradual GR/P flares. For these reasons, it was concluded that energetic IP protons from gradual GR/P flares are mostly produced in open magnetic field configurations in the high corona, possibly by shocks in that region. It is proposed that, in impulsive GR/P flares as well as gradual GR/P flares, protons are accelerated during the first phase (or hard X-ray phase) in closed magnetic loops by the second-step mechanism, and only a small fraction of the energetic protons escape into IP space.

Bai's studies (9, 12) have led to the following conclusions that are relevant to the problem of flare classification: (1) Gradual GR/P flares are sufficiently distinct to be selected solely on the basis of the characteristics of their hard X-ray emission (a first-phase phenomenon). (2) Gradual and impulsive GR/P flares share some common characteristics, in addition to nuclear gamma-ray emission. In addition these studies throw light on the relationship between gamma-ray-producing protons and energetic IP protons.

Cane *et al* (23) have studied 67 solar particle events detected with *IMP 8* and *ISEE 3* (the *Third International Sun-Earth Explorer*, now *International Cometary Explorer*) in the period from 1978 September to 1983 December. (Although this study draws heavily from results obtained with other satellites, it is discussed in this section because it is related to *SMM* results.) These events were divided into two groups---impulsive events and long-duration events. Flare-associated events were considered impulsive if the *1–8 A X-ray duration* (not the duration of proton flux enhancement) is less than 1 hour at the 10 % level of the peak; otherwise, they were considered to be long-duration events. These two groups were found to be distinct in many respects; in particular, the long-duration events have exactly the same characteristics as extended flares (proton flares, or gradual GR/P flares). This study also found several new and interesting points. (1) The parent flares of impulsive events are mainly in the Western hemisphere, which is well connected to Earth by magnetic field lines, whereas a considerable fraction of the parent flares of long-duration events are in the Eastern hemisphere. (2) The decay times of proton and electron fluxes are short (<10 hr) for impulsive events, whereas the decay times of long-duration events are long. (3) The proton fluxes of long-duration events are, on the average, much larger than those of impulsive events. However, the electron fluxes of both groups are similar.

From these findings, we can draw the following inferences: (1) In long-duration events, protons are accelerated mainly by shock waves propagating in large volumes of the corona (cf. 18, 115). (2) In impulsive events, protons and electrons are accelerated in closed loops during the first phase of flares, and only small fractions of these particles escape along open magnetic field lines near the flare site. (3) The shocks accelerating protons in long-duration events are not efficient in accelerating relativistic electrons, so that long-duration events are "electron-poor." Evenson *et al's* (56) finding that GRL flares are "electron-rich" is applicable only to impulsive GRL flares, since the GRL flares in Evenson's study all happen to be impulsive (9, 23). In this connection, we recall the result of Sarris & Shawhan (151) that proton events are associated with long-duration soft X-ray emissions and electron events are associated with short-duration soft X-ray emissions.

In a recent paper, Cliver *et al* (39) have compared the number of energetic protons deduced from gamma ray observations with that deduced from IP observations, for flares observed in the period from February 1980 through January 1985, and arrived at essentially the same conclusion as Bai (9) and Cane *et al* (23). We have mentioned that energetic protons accelerated during the second phase mostly escape into IP space and do not produce substantial gamma rays. However, Chupp *et al* (31) and Ramaty *et al* (145) have found that the gamma-rays showing gradual variations after 11:43.5 UT of the 1982 June 3 flare are due to protons with a flatter spectrum than the protons of the first phase, and Ramaty *et al* have proposed that if a small fraction (4%) of protons accelerated by the second-phase acceleration interacted at the Sun they could account for the observed gradual gamma rays.

We have mentioned that for impulsive GR/P flares the ratio of IP protons to gamma-ray-producing protons is small. In further detail, Hua & Lingenfelter (71) have found that for impulsive GR/P flares this ratio increases as the total number of energetic protons increases. However, this is based on a small number of flares.

In contrast to the interpretations of Bai (9), Cane *et al* (23) and Cliver *et al* (39), Zaitsev & Stepanov (201) have proposed that one mechanism accelerates both gamma-ray-producing protons and IP protons, and that the ratio between the plasma pressure and the magnetic pressure, $\beta = 8\pi P/B^2$, determines the escape rate. If $\beta<<1$, energetic protons are mostly confined in the flare loops and produce gamma rays. If, on the other hand, $\beta>\beta_*=0.3\sim1.0$, the hot plasma and high-energy protons escape from the loops by means of the flute instability. Lin & Hudson (105) have proposed an idea similar to that of Zaitsev & Stepanov (201).

The above interpretation is implausible from the following consideration. We would expect an impulsive GR/P flare to have a high plasma pressure because it involves a large energy deposition by energetic electrons in a short time interval in a small volume. In a gradual GR/P flare, on the other hand, energetic electrons deposit their energy more slowly in a larger volume. Furthermore, many gradual GR/P flares are quite weak in hard X-ray emission, implying that they involve little heating by energetic electrons (9, 38). In support of this view, we may note that Pallavicini *et al* (132) found that gradual (or extended) flares have lower energy densities than impulsive flares.

Kocharov (98) has proposed that the density of the ion interaction region is low ($10^{10} - 10^{11}$ cm^{-3}) for gradual GRL flares and high ($10^{12} - 10^{13}$ cm^{-3}) for impulsive GRL flares. He proposed that the long lifetimes of ions interacting in the low-density medium of gradual flares leads to higher escape probability. However, IP observations of energetic protons from gradual events are consistent with protons being accelerated in a large volume for a long time (23, 115).

3.2 *Hinotori Results*

The *Hinotori* satellite, which was in operation from February 1981 to October 1982, led to important advances in our understanding of flare classification. *SMM* failed to obtain X-ray images of gradual flares (except for imaging a diffuse soft X-ray source long after the main flare of 1980 May 21 (44)), partly because its Hard X-ray Imaging Spectrometer (HXIS) ceased to operate in November 1980 and was not rendered operational at the time of the Space Shuttle repair mission of April 1984. *Hinotori*, on the other hand, made soft and hard X-ray images of many gradual GR/P flares (129, 173, 181, 182). Although soft X-ray images of gradual GR/P flares had been obtained by *Skylab,* and although there had been some indication, from hard X-ray observations of over-the-limb flares (61, 72, 75, 94, 149), that hard X-ray sources extend to great heights, *Hinotori* results directly showed for the first time that the hard X-ray sources of gradual GR/P flares are located high above the photosphere ($h>10^9$ cm). *Hinotori* also made valuable gamma-ray observations (197, 198, 200), supplementing those obtained by means of the *SMM* gamma-ray detector.

Mainly relying on *Hinotori* observations of soft and hard X-ray images and spectra, Tanaka (175, 176) and Tsuneta (180) classified flares into three types. According to Tanaka (176), these are as follows.

Type A (Hot Thermal Flares): These flares are effective in producing a superhot component of $T=(3 \text{ to } 4)\times10^7$ K that emits hard X-rays in the range $E<40$ keV and strong FeXXVI lines. The HXR time profile shows a gradual rise and fall similar to the SXR profile and the HXR source is compact (<5000 km). The spectrum above 40 keV is soft (effective power-law index γ=7–9). Radio emission is weak.

Type B (Impulsive Flares): These show typical impulsive HXR bursts consisting of rapidly varying spikes, emitted from the low corona including the loop footpoints. The spectral index is in the range γ=3–7. The later phase of some flares evolves to a more gradual time profile with a softer spectrum (γ=5–8) and to a more compact source structure located at a higher altitude.

Type C (Gradual Hard Flares): These flares show a long-lived (>30 min) burst with a broad peak or peaks showing no impulsive variation. The source is located high in the corona (h>40000 km) and can be identified with large extended loops. The spectrum is very hard, well characterized by a power-law (γ=2.5–4), and shows systematic hardening with time. Microwave emission is very strong.

Hinotori made unique contributions to flare classification, including the imaging of hard X-ray sources, the identification of type A flares as another class, and a detailed study of the superhot component (~3.5×10^7 K) initially identified by Lin *et al* (106). One may argue that during the first phase of all flares heating and acceleration of nonthermal electrons take place simultaneously, and that it is only a matter of degree whether heating is more efficient than acceleration or *vice versa*. However, it is important to find out what parameters determine the outcome. *Hinotori* made an important contribution in this regard.

3.3 Other Results

Cliver *et al* (36) have studied the properties of gradual hard X-ray bursts (GHBs). They selected flares for which the FWHM durations of 2.8 GHz radio bursts (as measured at Ottawa and Penticton) exceed 10 minutes and studied their properties in hard X-rays, microwaves, and other aspects. Their events seem in some respects to be different from the gradual GR/P flares of Bai, although they are similar in other respects. (Three of the ten events in Cliver *et al* are in Bai's (9) list of gradual GR/P flares.) Except for two cases, all GHBs were preceded by impulsive bursts by about 30 minutes. Nevertheless, these GHBs show flattening of their hard X-ray spectra, "microwave-richness," and association with CMEs. Kai *et al* (89), working with their 17 GHz microwave data, have studied gradual bursts occurring 10 to 30 minutes after impulsive bursts, and they also found that the hard X-ray spectra of these delayed gradual bursts flatten with time.

4. A NEW CLASSIFICATION SCHEME

The new observations discussed in the preceding sections enable us to identify the following four classes of flares: *thermal hard X-ray flares, nonthermal hard X-ray flares, impulsive GR/P flares, and gradual GR/P flares*. The *Hinotori* group (175, 176, 180) first proposed thermal hard X-ray flares as a separate class. Bai and his co-workers (9, 12, 13) first proposed that GRL flares should be considered as a distinct class. In addition to the above four classes, flares resulting from quiescent filament eruptions are regarded as constituting their own class, as shown in Section 4.5. We discuss the properties and relative frequencies of these five classes of flares:

- *thermal hard X-ray flares*
- *nonthermal hard X-ray flares*
- *impulsive GR/P flares*
- *gradual GR/P flares*
- *quiescent filament-eruption flares*

4.1 Thermal Hard X-ray Flares

As shown Figure 5, for these flares, the hard X-ray emission below 40 keV is dominated by thermal bremsstrahlung due to plasmas with a temperature of order 30 million degrees. At high energies (>40 keV), hard X-ray time profiles reveal impulsive variations. For thermal hard X-ray flares, there is no clear cut separation between the impulsive component and the gradual thermal component (176). The impulsive component is embedded in the gradual thermal component. The light curve of 30 keV hard X-rays is similar to that of 5 keV X-rays, and both are considered to be thermal bremsstrahlung, although from plasmas of different temperatures. The hard X-ray spectrum above 40 keV is very steep with spectral indices γ=7–9. Microwave emission is weak because of the paucity of high-energy electrons. To date, none of the flares of this class has been known to emit type II or type IV radio bursts, nor do they show any other second-phase activity.

4.2 Nonthermal Hard X-ray Flares

Among intense flares (peak HXRBS rates > 1000 counts s^{-1}), the majority belongs to this class. Flares of this class show impulsive variations with time scales ranging from 0.1 to 30 s and intermediate hard X-ray spectral index (γ=3.5–6). Figure 6 shows the light curves and the spectral evolution of hard X-ray emission.

Energy is released impulsively during the first phase in both impulsive acceleration of electrons and in-situ heating of the plasma in the loop. According to the thick-target model (2, 20, 104, 105), during the first phase, the chromosphere is suddenly heated by the precipitating electrons to coronal temperatures. The following evidence supports the idea that this model is basically correct for this class of flares. (1) UV and optical radiation show good timing coincidence with hard X-rays (55, 92, 195). (2) The estimated energy content of nonthermal electrons is quite well correlated with that of thermal plasmas (46, 159), although uncertainties are large. (3) The suddenly-heated uprising plasma ("chromospheric evaporation") that radiates blueshifted X-ray lines seems to account for the increase of the emission measure. The turbulence and the blueshifted component subside at the end of the first phase (5). (4) For some flares the light curve of soft X-rays resembles the integral of hard X-ray or microwave emission (43, 46, 127, 174; Fig. 6a). (5) Although the directivity of low-energy (30 keV) electrons is hard to observe, high-energy electrons (>300 keV) may be directional (11, 48, 137, 185). (6) The momentum carried by the uprising plasma is balanced by the downward-moving cool plasma radiating redshifted Hα radiation (202). (7) There is a good correlation between hard X-ray spikes and type III emission (146).

During the first phase of nonthermal hard X-ray flares, electrons are accelerated up to several hundred keV, but the efficiency of high-energy electron acceleration is low, resulting in rather steep hard X-ray spectra. Flares of this class do not accelerate protons to gamma-ray-producing energies in any appreciable quantities. For this class of flares, energy release occurs mainly during the first phase. Although we cannot rule out the possibility of additional energy release during the decay phase of this class of flares, there is no compelling evidence for it (196). After the first phase the thermal plasma cools by radiation and conduction. The increase of emission measure in this gradual decay phase is due to evaporation caused by conduction. The turbulent motions of the plasma observed in the first phase subside during the decay phase (5, 6). For some of the flares of this class, type II and type IV radio bursts are observed. Traditionally, such radio bursts were regarded as second-phase phenomena. However, no other second-phase phenomena are observed during this class of flares.

4.3 Impulsive GR/P flares

Impulsive GR/P flares are very similar to nonthermal hard X-ray flares. During the first phase of this class of flares, however, an additional process takes place and promptly accelerates electrons up to relativistic energies and protons to gamma-ray-producing energies. We do not know what is the mechanism for this "second-step acceleration," but there is no shortage of candidates. Various mechanisms involving shocks have also been proposed, such as shock drift acceleration, shock-resonant acceleration, and others (30, 45, 53, 130). Under suitable conditions these mechanisms seem to be able to accelerate very rapidly. However, they are hard pressed to accelerate electrons to 20 MeV in a few seconds, as some observations require (91, 148).

Hard X-ray spectra are relatively flat because of the second-step acceleration of relativistic electrons. Figure 3 shows the time profile and the spectral evolution of the hard X-ray emission of the impulsive GR/P flare on 1981 February 26. During the majority of impulsive GR/P flares, type II and type IV radio bursts are observed, but seldom are IP shocks produced. Only small fractions (10^{-3}–10^{-2}) of electrons and protons accelerated in the first phase escape into IP space, so that they can be detected near the Earth. The fluxes of IP particles from this class of flares rise and decay rapidly, with a characteristic time of a few hours. Kane *et al* (91) have shown that relativistic electrons detected with *ISEE 3* (now *ICE*) on 1982 August 14 were accelerated during the first phase of the flare at 0509 UT, which produced gamma-rays above 2 MeV. (Cane *et al* (23) proposed the same for energetic IP protons coming from this flare.) Therefore, impulsive flares producing relativistic electrons detected in IP space (23, 56, 151) are thought to emit nuclear gamma-rays as well as bremsstrahlung by relativistic electrons.

Since impulsive GR/P flares are well associated with type II and type IV radio bursts, the second-step acceleration and type II and type IV radio bursts must somehow be related. Initially it was proposed (14) that shock waves propagating in the flare loop might act as a second-step acceleration mechanism and produce type II bursts when they propagate to the high corona. However, a close investigation of the timing of type II bursts and hard X-ray emission makes it difficult to maintain this view (40).

4.4 Gradual GR/P Flares

Gradual GR/P flares (Fig. 2& 4) show a large array of characteristics, and therefore these flares were recognized as a separate class from quite early on (54, 132, 194). These flares have been called *two-ribbon flares, proton flares, extended flares, long-decay events, gradual flares, etc.*, depending on the method of observation. Associations between various characteristics of gradual GR/P flares have been studied by many researchers. Instead of going into details of such studies, we present the results in Table 1. In the left column, 19 characteristics of gradual GR/P flares are listed. In the top row numbers 1 to 19 are assigned corresponding to the 19 characteristics in the first column. The reading of this table is explained in the following example. We see letters "B" and "M" at the location of the 18th row and 17th column. This means that according to studies by ref. 23 and 86 (see the reference code in Notes to Table 1), the majority of flares with characteristic (18) (production of IP protons) exhibit characteristic (17) (CMEs). This table is not diagonally symmetric: for example, the majority of flares with type II bursts are not proton flares, even though the majority of proton flares produce type II bursts.

All of the 19 characteristics are not present in all gradual GR/P flares. It is difficult to determine which characteristics are most commonly present and which characteristics are most rarely present, because some of the characteristics are difficult to observe or require instruments aboard spacecraft to be detected. Gradual GR/P flares are all two-ribbon flares. However, two-ribbon flares which do not exhibit other characteristics of gradual GR/P flares are quite common, and some two-ribbon flares show very weak hard X-ray emission (52).

Type II and type IV radio bursts also are quite common. Many flares which are not gradual GR/P flares have been found to emit type II and type IV radio bursts. In particular, type II radio emission is a poor indicator of gradual GR/P flares. Only 30% of type II bursts are associated with type IV bursts (25). Therefore, it is evident that some shocks responsible for energetic electrons producing type II bursts do not accelerate protons efficiently. Maxwell & Dryer (116) proposed that shocks causing only type II bursts might be blast-wave shocks while shocks which accelerate protons and heavy ions are piston-driven shocks. Kahler (78) and Bai (9) concur with this proposal.

All gradual flares do not produce energetic IP protons; and therefore, production of IP protons should not be regarded as a necessary condition for a gradual GR/P flare. For example, the GRL flare of 1981 May 13 have all the characteristics of gradual GR/P flares including IP shocks although there is no data on CME (9). However, this GRL flare, with intense soft X-ray emission (GOES class X1; 4 hour duration at the 10% level of the peak), failed to produce a noticeable change to the background of the energetic IP proton flux due to a gradual GR/P flare on May 10. (The two preceding gradual flares on May 8 and May 10 produced large fluxes of energetic IP protons although they were M8 and M1, respectively, in GOES class.) Filament eruptions are also not observed from all gradual GR/P flares. (However, see Section 4.6.)

In the 1960s, type IV emission was regarded as the best indicator of gradual GR/P flares (194). At the present time, long-duration soft X-ray emission seems to be a better indicator of gradual GR/P flares, perhaps due to the availability of continuous soft X-ray observation. However, the distribution of the duration of soft X-ray emission is continuous, and a dichotomy is not obvious. Certain hard X-ray characteristics (long-duration >10 min, gradual variation with spike burst durations longer than 1.5 min, spectral hardening) seem to be an even better indicator of gradual GR/P flares. Long-lasting, gradual microwave emission is also a good indicator of such flares. In forecasting energetic protons arriving at the Earth from solar flares, characteristics appearing in hard X-ray emission and microwave emission are more useful because one can identify a gradual GR/P flare in the early phase.

Even though gradual GR/P flares show a large set of characteristics and they can indeed be identified on the basis of hard X-ray characteristics alone, one nevertheless finds that, if the time scale of a gradual GR/P flare is reduced by a factor of 5 to 10, the characteristics of hard X-ray emission phase are not distinguishable from that of an impulsive GR/P flare (9).

Almost all *gradual GR/P flares* show impulsive behavior in the beginning of their hard X-ray emission and gradual behavior later on. None of them is found to show impulsive behavior *after* the gradual hard X-ray emission. At least two gradual GR/P flares (1981 May 8 and 13) do not show impulsive behavior at all.

After the hard X-ray phase of gradual GR/P flares, the soft X-ray flux begins to decrease gradually with decay times ranging up to hours (Fig. 7). It is thought that reconnection of open magnetic field lines is the source of continued energy input (4, 28, 99, 123, 161). In gradual GR/P flares, full-fledged second-phase phenomena occur in the high corona, including second-phase particle acceleration and generation of shocks.

Hinotori observations (129, 173, 181) show that for gradual GR/P flares soft (5–10 keV) and hard (16–38 keV) X-ray sources are both high (1~4x10^9 cm) and almost cospatial. Observations of Kane *et al*, on the other hand, show that the bulk of 150 keV emission is from below 2.5×10^8 cm from the photosphere. However, hard X-ray observations from limb-occulted flares (72, 75) show that energetic electrons accelerated during gradual GR/P flares can reach to great heights (up to 10^{10} cm). Such electrons can reach to even greater heights (4×10^{10} cm) and radiate meter-wave continuum (35a, 89, 97). Therefore, we can infer that high-energy electrons of gradual GR/P flares are accelerated in loops with great heights ($1\text{–}4 \times 10^9$ cm), and then some of them precipitate to the chromosphere while some escape into loops of greater heights and into IP space.

4.5 Quiescent Filament Eruption Flares

Although eruptions of quiescent filaments do not lead to impulsive flare activity, they often lead to the development of pairs of faint Hα ribbons, together with IP shocks and energetic IP protons and heavy ions (22, 81). Dwivedi *et al* (52) have found that two-ribbon flares without hard X-ray emission are due to eruptions of filaments at the outskirts of active regions. Because such events cause Hα brightening, gradual-rise-and-fall of microwaves, and soft X-ray emission, they should be considered to be flares. According to Dodson & Hedeman (49), during the 1956–67 period 83 "spotless flares" with Hα class >1 were observed in plages without big sunspots, and the majority of them were related to activation of quiescent filaments. However, only a small fraction of them produced energetic IP particles. Such flares resulting from quiescent filament eruptions constitute an additional class. It is thought that an eruption of a quiescent filament can produce IP shocks and energetic IP protons only when it is fast enough.

Table 2 summarizes the characterisitics of different classes of flares.

4.6 Roles of Erupting Filaments in Flares

From the early days, it was known that filament activity is closely related to the occurrence of flares (95, 203). Studying 297 flares with Hα class 1 or higher, Martin & Ramsey (114) showed that 53% of these flares were associated with some kind of filament activity such as rapid darkening, expansion or apparent outward motion, breakup into more than one segment, transition to emission, ejection of at least one segment, complete disappearance or point of minimum visibility, and appearance of absorption in a new location. In particular, it has been noted that erupting filaments (or eruptive prominences seen at the limb) are associated with two-ribbon flares or extended flares (7, 132). There are many well-documented cases, particularly well-known cases being the 1972 August 7 flare (204) and the 1973 July 29 flare (122, 123). However, some gradual flares do not show a filament eruption. For example, the filament of the gradual GR/P flare on 1981 April 10 did not erupt but remained intact, although a post-flare loop system developed later (F. Tang 1984, private communication). There is no extensive statistical study of what fraction of extended flares or gradual flares are associated with filament eruption.

Not only gradual GR/P flares but also some impulsive flares are associated with erupting filaments. Kahler *et al* (84) have studied filament eruptions in four impulsive flares. They have found that the eruptive motion commences before the onset of the flare and its acceleration evolves smoothly through the first phase. However, it is often reported that the eruptive motion shows a rapid acceleration near the flare onset times (114). It is not clear why flares associated with erupting filaments are sometimes gradual and other times impulsive.

A large fraction of CMEs are associated with flares, filament eruptions, or both (125, 191). Among such CMEs with solar association, 66% of *SMM* CMEs and 78% of *Skylab* CMEs are found to be associated with either eruptions of active-region filaments (in such cases flares occur) or eruptions of quiescent filaments (191).

Summarizing the above results, we would suggest that all gradual GR/P flares are associated with eruptions of magnetic fields. An Hα filament eruption occurs only when the material in the magnetic field configuration is cool (See ref. 168, p. 216); therefore, during some gradual GR/P flares, if field configurations which erupt contain hot material, no Hα filament eruption is observed. Tang (177) has shown that in some two-ribbon flares only the top layer of the filament erupts while the bottom layer remains intact. What follows an eruption of a filament may be determined by the properties of the surrounding medium (10, 111). If the overlying magnetic field is strong enough, the filament is prevented from fully erupting, in which case an impulsive flare is produced. If the magnetic field strength of the overlying arcade is weak, the filament erupts, distending the overlying field lines and leading to reconnection and gradual GR/P flares (4, 99, 167). If the field of the overlying magnetic loop (or arcade) is very weak and its plasma density is low, as in the case of a quiescent filament, an eruption of the filament does not cause energetic flare activity but merely causes two faint Hα ribbons, and weak X-ray and/or microwave emission. However, such filament eruptions can lead to CMEs, IP shocks, and/or energetic IP particles.

4.7 Relative Frequencies of Different Classes of Flares

What are the relative frequencies of different classes of flares? No one has done any systematic study on this, but the question is important enough to convey whatever meager understanding on this is available in the literature.

From a correlation diagram between the spectral index and the peak HXRBS rate (9, 46), we find that during the period from 1980 February to 1980 January only 13 out of 126 HXRBS flares with peak rates greater than 1000 counts s^{-1} have power-law spectral index greater than 6.5. These flares have weak microwave emission compared to their hard X-ray fluxes, and none of them are associated with type II or type IV bursts. Granting that all these flares are thermal hard X-ray flares, we find that thermal hard X-ray flares are rare among intense hard X-ray flares. We do not have any information on less intense hard X-ray flares. In agreement with this, Kosugi *et al* (100) identify only 3 flares as thermal hard X-ray flares, among about 400 flares commonly detected by HXRBS and the 17 GHz radiometer at Nobeyama, Japan.

It is difficult to estimate what fraction of flares belong to the impulsive GR/P flares, because the detection of nuclear gamma-rays and energetic IP particles is limited by the detector threshold. Among 42 very intense hard X-ray flares with HXRBS peak rates $>10^4$ counts s^{-1} observed during 1980 and 1981, nine flares (21%) turned out to be impulsive GR/P flares (9). Among less intense hard X-ray flares, judging from hard X-ray spectral indices, the fraction seems to be smaller. Short-duration soft X-ray flares producing energetic protons or relativistic electrons detected in IP space (23) are impulsive GR/P flares. Among 31 such events (Table 1B of ref. 23), thirteen flares were observed by HXRBS during their peak of hard X-ray emission. Only two of these 13 flares have peak HXRBS rates less than 5000 counts s^{-1}. Again the detection of relativistic electrons is subjected to the threshold, but we do not expect a large fraction of flares with peak HXRBS rates <5000 counts s^{-1} to be impulsive GR/P flares.

Among HXRBS flares of 1980 and 1981, only 18 are regarded as gradual GR/P flares (9). Fourteen of them have HXRBS peaks >1000 counts s^{-1}; the remaining four, <1000 counts s^{-1} (9). Considering that 266 HXRBS flares of 1980 and 1981 have peak rates >1000 counts s^{-1}, it is clear that gradual GR/P flares are rare. Because the selection of gradual GR/P flares are based on time scales of hard X-ray emission, it does not suffer from any threshold effect among flares with HXRBS peak rates >300 counts s^{-1}. Figure 8 shows the relative frequencies and dynamic ranges of impulsive and gradual GR/P flares for 1980 and 1981. Impulsive GR/P flares shown in this figure are identified from nuclear gamma-ray emission detected by GRS. Hence, the identification of impulsive GR/P flares is *limited by the GRS threshold effect*. However, as mentioned earlier, the fraction of impulsive GR/P flares is expected to decrease with decreasing HXRBS peak rates.

The frequency of quiescent filament-eruption flares is not well known; the six reported by Cane *et al* (22) for the 1978–1984 period are the ones associated with IP shocks. Dodson & Hedeman (49) reported 83 "spotless flares" with Hα class >1 for the 1956–67 period. Since the majority of these spotless flares are associated with quiescent filament-eruptions, we can form an idea about the frequency of this class of flares. Among intense hard X-ray flares with peak HXRBS rates >1000 counts s^{-1}, the majority belongs to *nonthermal hard X-ray flares*. It is possible that we will end up subdividing this class of flares as we learn more on flares.

5. THEORETICAL INTERPRETATION

We now face the question of trying to offer a theoretical interpretation of the fact that flares may be divided into distinct classes, adopting for our purposes the five classes proposed in the previous section. From a theoretical point of view, we need to understand what it is that flares from different classes have in common, and what it is that distinguishes flares in one class from flares in another class.

We propose to address these questions in two ways. First, we will try to understand the primary energy release processes that can occur in flares, and give a little attention to some secondary energy conversion processes also. Second, we will try to decide which of these processes play a role in various classes of flares.

5.1 Energy Release Processes

It is generally agreed that the energy released in a flare is initially embodied in the magnetic field of the active region in which the flare occurs. However, it is not possible to release the total energy of such a field configuration since the photosphere is sufficiently highly conducting and sufficiently massive that, on the time scale of a solar flare, magnetic field lines are effectively "frozen" into the photosphere. This means that the only magnetic-field re-arrangements that can occur as the result of a flare are those that leave the normal component of the magnetic field, B_n, unchanged.

The minimum-energy state of a magnetic field with prescribed values of the normal magnetic field at each point of a bounding surface is the current-free "potential" field, so called because it can be represented as the gradient of a scalar potential. A simple way to understand this is to consider the "thought experiment" of replacing the highly conducting corona by a medium with finite resistivity. Wherever there are currents, there would then be joule heating, so that the energy of the magnetic field would slowly decline. This decline will continue as long as there is a non-zero current density anywhere in the coronal region. Hence the field will end up in a state with zero current density everywhere in the corona (i.e., it will end up as a potential field), and that state will be the state of minimum energy.

These considerations lead to the useful concept of the "available energy" or "free energy" of the magnetic field configuration of an active region. This is the difference between the energy of the field and the energy of the potential field that has the same photospheric boundary condition, i.e. the same value of B_n at each point of the photosphere. The basic problem of solar flares is therefore to determine the various types of non-potential magnetic-field configurations that can exist in active regions, and to understand the processes that can lead to the release of some or all of the free energy of those configurations.

It was first proposed by Giovanelli (63, 64) that a flare represents an electromagnetic process of energy conversion. Dungey (51) was the first person to propose that magnetic "neutral points," where the field strength is zero but the current density is non-zero, are representative of configurations that can be unstable, and so lead to a catastrophic energy release. Sweet (171) first drew attention to the potential importance of current sheets, across which there is either a reversal of magnetic-field direction, or at least a sharp change in the direction. Parker (133) made a detailed analysis of the rate at which magnetic reconnection (the process that eliminates the current in a current sheet) might occur, and concluded that it is too slow to explain solar flares. However, Petschek (136) subsequently presented a new analysis, and argued that reconnection could occur at a rate approaching the rate at which an Alfven wave could propagate through the region.

At about the same time, Furth *et al* (62) published the first comprehensive analysis of resistive instabilities, including the "tearing mode" that can lead to reconnection of a current sheet. According to their linear theory, reconnection would occur in a time that is the geometric mean of the time it takes for magnetic field to diffuse (due to finite resistivity) across the current layer, and the time it takes for an Alfven wave to propagate across the layer. Whether or not that time is sufficiently short to explain a solar flare depends on the thickness of the current layer, which is an unknown and unobservable quantity. However, what appear to be reasonable values of this quantity do not lead to sufficiently rapid energy release to explain solar flares.

Since that time, the tearing mode process has been investigated by many individuals and groups, and certain modifications have been found to speed up the reconnection process. Spicer (158) pointed out that nonlinear mode-mode coupling could speed up the reconnection rate, and his argument has been supported by the study of numerical models by Carreras *et al* (29). Steinolfson & van Hoven (160) have incorporated radiative effects in a tearing mode model, and find that this too speeds up the reconnection rate. Sakai & Tajima and their collaborators (see, for instance, ref. 172) have shown that, after the tearing mode develops an array of current filaments in a current-sheet configuration, another process, which they call the "coalescence instability," will lead to the rapid merging of those current filaments to enhance and speed up the energy release process. It is interesting to note that this process is very similar to an early proposal by Gold & Hoyle (65), although they did not present a rigorous analysis of the coalescence process.

It is fair to say that the concept of magnetic reconnection has dominated theoretical investigation of solar flares over the past 25 years. Moreover, there has been the implicit assumption that the tearing-mode concept is equivalent to the reconnection concept. Alfven & Carlqvist (3) registered an early dissenting opinion, when they proposed that energy release might be due to a process that they called "current disruption." If a process were to occur in the corona that interrupted – or attempted to interrupt – the current of a current-carrying flux tube, for instance by a two-stream type of instability, the stored energy of the current-carrying magnetic field (the energy to be ascribed to the inductance of the system) would lead to the development of a large induced electric field that would tend to maintain the current. The proposal of Alfven & Carlqvist attracted some (see, for instance, ref. 157) but not great interest at that time, partly because it was presented in terms of circuit rather than plasma-physics concepts, and partly because they did not give a detailed comparison of their theory with observational data.

The situation has changed as the result of *SMM* experiments which, as we have seen, show that particle acceleration up to many MeV can occur on a time scale of only one or two seconds. Such rapid acceleration is difficult to understand on the basis of the tearing mode instability, since it is not that rapid, and since most of the energy released during that instability goes into mass motion and into joule-type heating, not into particle acceleration (192). The tearing mode is likely to produce a high level of MHD turbulence in the surrounding region, and this turbulence can lead to stochastic acceleration. Some authors have argued that this acceleration could be sufficiently rapid to explain the *SMM* results (see, for instance, ref. 142).

Various mechanisms involving shocks have also been proposed, such as shock drift acceleration, shock-resonant acceleration, and others (30, 45, 53, 130). Under suitable conditions these mechanisms seem to be able to accelerate very rapidly. However, such acceleration should affect electrons and protons quite differently, giving preferential acceleration to protons and comparatively little acceleration to electrons. This expectation does not square with the observational fact (91, 148) that, in GR/P flares, both electrons and protons are accelerated to high energies at the same time, and that electrons are rapidly accelerated to tens of MeV.

For these reasons, the concept of current interruption has recently been revived. Haerendel (66) has proposed that the ion acoustic instability (109) may play a key role, although, under some conditions, the electrostatic ion cyclotron instability (see, for instance, ref. 41) is more likely to occur. Whether or not the ion acoustic instability occurs depends on two factors: (a) the ratio of the electron drift velocity (due to the current) to the ion sound speed, and (b) the ratio of the electron temperature to the ion temperature. Both ratios must exceed unity by a small factor for the instability to occur. Sturrock (164, 165) has recently proposed that these conditions are likely to be met if we make the following assumption and argument. The assumption is there is no steady coronal heating, only a flare-like impulsive heating, so that most of the flux tubes in the corona are filled with cool gas at a temperature that could be as low as the chromospheric temperature or even the photospheric temperature. The argument is that if a flux tube suddenly expands (as the result of a filament eruption, for instance), the ions will tend to cool adiabatically, whereas the electrons will tend to remain at the same temperature as the boundary since electron thermal conductivity is much higher than ion thermal conductivity, and since heat exchange between the two species is quite slow. Hence a sudden expansion would suddenly decrease the ion sound speed and increase the ratio T_e/T_p. This argument offers an explanation of why a filament eruption should lead to the sudden acceleration that is known to occur in (and be responsible for) impulsive and gradual GR/P flares.

As we have pointed out in Section 4, in some flares there is such a close connection between the filament eruption and the flare itself that Kiepenenheuer (95) and, more recently, Moore (121) have argued that the two should be regarded as part and parcel of the overall flare phenomenon. S. F. Martin (1988, private communication) has expressed the view that most – but not all – flares show evidence of some kind of rapid mass motion. It seems likely that, in flares involving filament eruption or a similar process, the initiation and perhaps the driving process of the flare is a process that leads to the sudden motion of a massive structure, maybe just a sudden change in configuration or position of the structure, but maybe the complete eruption and ejection of the structure such as we witness when a filament erupts completely and is associated with a coronal mass ejection. Hence the most basic flare problem is perhaps not that of determining how and why energy is released during the impulsive phase, but that of understanding why sudden mass motions occur that are quickly followed by processes that lead to the visible and otherwise detectable manifestations of a flare.

In order to understand what dynamic – including magnetohydrodynamic – processes could affect filaments, we need to have an accepted model of the structure of a filament. Unfortunately, no detailed model has been presented and received wide acceptance. It is agreed that the cool hydrogen, that is visible (in Hα) as a dark feature on the disk or as a bright feature on the limb, must be supported in regions of a magnetic field where the field lines are essentially horizontal, and that an upwardly directed curvature of the field lines in those regions is favorable for long-term retention of the gas, as in the early Kippenhahn-Schluter (96) model. It is also agreed that filaments occur above polarity reversal lines, and that high-resolution Hα photographs (60) and vector-magnetograms by Hagyard *et al* (67) indicate that the magnetic field in or near a filament is almost parallel to the direction of the polarity reversal line. This has led to the concept that the magnetic field of a filament comprises a flux tube that runs above and parallel to the polarity reversal line (121). If this is an appropriate model, then the eruption of a filament may be interpreted as a purely MHD instability of such a magnetic flux tube that, in its initial state, is held in place by the stress of an array of overlying magnetic loops (139).

Such a scenario for the structure and instability of a model filament would explain the sudden disruption of a filament, but it offers no explanation of the associated heating, sometimes called "preflare heating" (183), that is detectable by its UV or soft X-ray radiation, or by Hα brightenings. An alternative is one depicted schematically in Figure 9a, in which a filament is taken to be a rope-like structure, made up of many intertwined magnetic "strands," and that most of these strands are tied to the photosphere at points along the length of the filament, rather than merely at the ends of the filament. Such a picture seems closer to the Hα appearance of filaments (60). It also helps understand the observational result of Tang (177) that, on some occasions, a part of a filament may erupt leaving the rest of the filament intact.

The balance of forces of such a model is somewhat similar to that of a large helium-filled balloon that is held close to the ground by many thin ropes. What may happen in such a situation is that two contiguous magnetic strands, that have opposite polarities where they meet the photosphere, may reconnect at a location such as that indicated in Figure 9a This would produce impulsive heating low in the atmosphere, so that it could explain the $H\alpha$ brightenings that occur shortly before a flare, in association with filament activation, and perhaps the small X-ray brightenings that are sometimes detected and referred to as "pre-heating" of the flare site (183). As the result of such a reconnection, two flux strands that tied the filament to the photosphere have been severed. This is like cutting two of the thin ropes holding down the helium balloon. This change puts more stress on the remaining strands. If the configuration is near a critical state, there can be a runaway process in which all the remaining strands are progressively severed (except that the filament must remain magnetically tied to the photosphere at its ends), and the filament lifts off, as indicated in Figure 9b, just as the balloon would lift off if the ropes were to break one after another (166).

Whether a filament merely erupts to a stable configuration at a higher level (somewhere in the corona) or is completely ejected from the Sun depends on the strength of the overlying field and the degree to which the erupting magnetic field is stressed. A highly twisted flux rope can have more magnetic energy than the energy of the corresponding open magnetic field with the same boundary conditions at its ends. If this is the case, we must expect the filament to expand indefinitely. It would then appear to be ejected completely from the Sun; this ejection is driven by its own magnetic energy. Moore (121) has recently applied such considerations to an analysis of the flare of 1972 August 7.

If a filament were to erupt as outlined above, one must expect that much of the magnetic energy that is being released would be converted into the kinetic energy of the moving filament material. Analysis of the energy budgets of certain flares (see, for instance, 27, 190) indicates that the kinetic energy of mass motion can indeed exceed the total energy emitted by the flare in the form of electromagnetic radiation of all types. However, the eruption of a filament has secondary effects that can lead to different types of energy conversion. One of these has already been mentioned: an erupting filament will lead to the sudden expansion of magnetic flux tubes in the neighborhood of the filament, and this can lead to a sudden increase in the electron-to-ion-temperature ratio, so precipitating the ion-acoustic or ion-cyclotron instability which leads to sudden particle acceleration.

Another important effect of filament eruption is that it may generate a shock wave that propagates through the corona. Such a shock wave can influence the chromosphere in such a way as to produce a Moreton wave (124). It can also accelerate electrons in such a way to produce a type II radio burst and an associated type IV radio burst (101). The shock wave may have the nature of a blast wave, caused by the sudden motion of the filament, or it may have the nature of a bow shock that runs ahead of the filament, if the filament moves sufficiently rapidly. In the latter case, the shock would persist as the plasmoid moves through interplanetary space, where it would be detectable by the generation of an interplanetary kilometric type II burst.

It is known that, as the result of MHD turbulence and particle scattering, shock waves can accelerate particles (ions preferentially) to high energies (see, for instance, 19). Hence it is likely that strong interplanetary particle events are due to shock acceleration, as was indeed suggested by Wild *et al* (194) many years ago. This is the conventional interpretation of "second-phase" acceleration.

We have referred earlier to another consequence of filament eruption that has important consequences for energy conversion. As has been pointed out by Kopp & Pneuman (99), Anzer & Pneuman (4), Sturrock *et al* (167), Cliver *et al* (36) and others, the eruption of a filament distorts and distends the overlying magnetic field configuration in such a way that we expect the overlying field to form a current sheet between the filament and the chromosphere (see Figure 9b) This magnetic-field topology is of the form proposed by Sturrock (161) as an explanation of two-ribbon flares. The interpretation is that the current sheet slowly reconnects and that the released energy, when thermalized, provides the energy content of the X-ray emitting flare plasma. The same heating process heats the upper layers of the chromosphere to high temperature (of order 10^7 K) so that it "evaporates" to fill the magnetic flux system with hot, dense, X-ray-emitting plasma. The various physical processes that take place at this stage are shown schematically in Figure 10, taken from Cliver *et al* (36).

5.2 Phases of Flares

We can now attempt to use the above ideas concerning energy release for the elucidation of the similarities and differences of the classes of flares proposed in Section 4. We carry out this analysis by supposing that any flare involves one or more phases of energy release or conversion. We then attempt to understand each class of flares as involving certain phases, and we also try to understand each phase in terms of the energy-release mechanisms listed above. In the literature, the terms "first phase" and "second phase" have been widely used, and we followed the convention in Sections 2 through 4. However, we devise new terms, because these two phases are inadequate to describe all the energy release phases of solar flares. We first discuss flare phases.

Early Phase. We use this term to denote the phase of energy release that precedes the main phase. This phase of energy release may be subdivided into two sub-classes, as follows.

Early, Thermal, Phase. Since we choose to include filament behavior (where appropriate) in the overall flare event, this category of early phase would include filament activation and eruption and also processes that have been termed "pre-heating." We have proposed an interpretation of filament activation and eruption that incorporates the operation of reconnection in the lower atmosphere, and we suggest that heating due to this reconnection is the cause of "pre-heating."

Early, Nonthermal, Phase. It is well known that there are manifestations of nonthermal energy release shortly before the principal initiation of a flare, such as Type III radio emission (18a). The usual interpretation of a Type III radio burst is that it is caused by plasma oscillations in the coronal plasma that are excited by an electron beam with energy in the range 10 keV to 100 keV. This beam may be produced as a result of reconnection in a current sheet high in the solar corona.

Main Phase. We use this term to represent the principal phase of energy release in a flare. On the basis of Hα and hard X-ray observations, this phase is sometimes referred to as the "impulsive phase" or "flash phase." On the basis of observations of hard X-ray emission, that is indicative of electron accelerations, this phase is sometimes referred to as the "first phase." We feel that the term "first phase" is inappropriate since, as noted above, there is often an "early phase" that precedes the phase now under discussion. This class of energy release may be subdivided into two sub-classes, non-thermal and thermal.

Main, Nonthermal, Phase. This is used to describe the main phase of energy release when this phase involves particle acceleration, as would for instance be evident from the detection of hard X-ray emission.In most flares, we may select one of two sub-categories: **Main, Nonthermal, Impulsive**, or **Main, Nonthermal, Gradual**, depending upon the profile of the time-curve for hard X-ray emission, as discussed in Section 4. If the flare seems to involve a phase with the combined features of both the impulsive and gradual hard X-ray phases, then we simply use the term **Main, Nonthermal, Phase**.

Our proposed theoretical interpretation is that the main, nonthermal phase hinges on the operation of current interruption. The sudden onset of current interruption may be due to a sudden change in the plasma parameters (especially the ratio T_e/T_p) due to a sudden expansion, that may in turn be caused by a filament eruption. We propose that the main, nonthermal, impulsive phase involves energy release in a compact system of low-lying magnetic loops that are adjacent to, or perhaps part of, the magnetic-field structure associated with the filament. A main, nonthermal, gradual, phase is likely to originate in an extended flux system that suddenly expands, such as the magnetic field lines that overlie the filament and are stretched outward as the filament erupts.

Main, Thermal, Phase. This term is used to refer to the main phase of energy release operative in those flares for which the energy is converted primarily into a hot plasma that emits soft X-rays and some hard X-rays. In these flares, the time scale for energy release is longer than that of a typical impulsive phase. The main, thermal phase may be caused by reconnection in a current sheet, such as the sheet that we expect to form in an emerging-flux configuration (see, for instance, ref. 140).

The third main subdivision of flare energy-release phases is the **Late Phase,** that may in turn be subdivided into two categories

Late, Thermal, Phase. This term is used to describe for instance the late and long-lived phase of two-ribbon flares, while the ribbons are slowly drifting apart. As Moore *et al* (123) have shown, the X-ray emission during this phase sometimes seems to require continued energy input, rather than being due simply to the decay of the hot, dense flare plasma produced during the main phase. We ascribe this phase to reconnection of the extensive current sheet that forms below an erupting filament. The reason that this phase produces lower-energy radiation than the main, thermal, phase is that the magnetic field is weaker, being due to an extended flux system high in the corona rather than a compact flux system low in the corona.

Late, Nonthermal, Phase. This term is used to describe the operation of nonthermal processes late in the development of a flare, such as type II radio emission and "second-phase" particle acceleration. As described earlier, we ascribe this behavior to particle acceleration caused by a shock wave – either a blast wave or a bow shock – produced as the result of sudden mass motion (for instance, filament eruption). Martens (113) has proposed that a DC electric field developed in the reconnection phase of a two-ribbon flare can accelerate protons that produce nuclear gamma-rays. However, nuclear gamma-rays are emitted during the main phase long before the reconnection phase. Furthermore, impulsive GR/P flares which do not develop the reconnection phase emit nuclear gamma-rays. Therefore, we may regard such acceleration as late phase acceleration rather than main phase acceleration. Sometimes gradual hard X-ray emission is observed about 30 minutes after the main phase (36, 89), and this and stationary type IV radio bursts may be due to electrons accelerated during the reconnection.

5.3 Classes of Flares

We now turn to the five classes proposed in Section 4, and offer an interpretation of these classes in terms of the above proposed phases.

Thermal Hard X-Ray Flares. We attribute this class to the operation of the main, thermal, phase of energy release. We suppose that there is no filament eruption, and that this explains why the other phases do not occur.

Nonthermal Hard X-Ray Flares. In these flares, the dominant phase is the main, nonthermal, impulsive phase. There is little evidence of any other phase taking place, except in those events that produce type II and type IV bursts, that we attribute to a late, nonthermal, phase. It may be that all of these flares involve some kind of mass motion, but in most cases the only consequence is the main, nonthermal, impulsive phase. On the other hand, it may be that most of these flares involve a simple, more or less stable, magnetic geometry, and that the current interruption process occurs more or less spontaneously. For instance, it may be that the cooling phase of a coronal loop can lead to a situation in which the protons have cooled more rapidly than the electrons, so setting the stage for the ion-acoustic instability or the ion-cyclotron instability.

Impulsive GR/P Flares. These flares primarily involve the main, nonthermal, impulsive phase, that is, current interruption in a compact flux system. It is likely that these flare involve sudden mass motion and filament activation. Hence it is possible that the current-interruption process may be attributed to a sudden rearrangement of magnetic field caused by this mass motion. The "second-step" acceleration may be due either to the current-interruption process itself, or to stochastic acceleration caused by the turbulence resulting from the filament activation. We propose that for this class of flares the magnetic-field configuration is such that the overlying magnetic loops are not significantly distended, so that there is no main, nonthermal, gradual phase, and – of course – there is no late, thermal, phase since no extended current sheet is formed.

Gradual GR/P Flares. These flares involve several phases. They typically display an early, thermal, phase when a filament begins to erupt and when there is "preheating," as seen by X-ray and Hα emission. Such a flare will involve a main, nonthermal, gradual phase of energy release, perhaps in combination with a main, nonthermal, impulsive phase. As indicated earlier, we attribute the main, nonthermal phase to current interruption, a main, nonthermal impulsive, phase being produced in a compact flux system that suddenly expands, and a main, nonthermal, gradual, phase being produced in an extended flux system that suddenly expands, such as the magnetic field lines that overlie the filament and are stretched outward as the filament erupts. As these field lines begin to close under the erupting filament to form a current sheet, reconnection will occur that represents the late phase (thermal and nonthermal) of the flare.

If the filament eruption is sufficiently rapid, it will generate a shock wave that is responsible for a late, nonthermal, phase.

Quiescent Filament Eruption Flares. These appear to involve some of the phases of a gradual GR/P flare. There is an early, thermal, phase, when a filament is erupting, that may involve some weak Hα emission. It appears that a flare of this class does not exhibit a main phase (either nonthermal or thermal), but it does exhibit both the late, thermal, phase and the late, nonthermal, phase that we attribute to the slow reconnection of a newly formed current sheet and to shock waves generated by the eruption.

6. CLOSING REMARKS

The recent great advances in our observational knowledge of solar flares, due in large measure to the international program of space exploration, has had a dramatic effect on our understanding of solar flares. On the one hand, this great increase in our knowledge has made life more difficult for solar physicists, since a complex problem has become even more complicated, and since some new observations are clearly incompatible with some fondly held ideas. On occasion, we may even pine for the days in the early 1950s when theorists were challenged to explain only two facts in constructing a flare theory - the total energy of a flare, and the time scale of the impulsive phase!

On the other hand, solving the flare problem requires that we identify and understand the many physical processes that occur in flares. Since flares are intrinsically complicated, this clearly calls for more and better data, such as those we have obtained in recent years. We hope and expect that even more sophisticated equipment on rockets, balloons, and future space missions will yield even more detailed information about the many physical processes that occur in flares.

However, it would be wrong to give the impression that observational advances all stem from space experiments. Advanced new ground-based equipment is being planned, and will no doubt yield exciting new information when it is in operation. This includes both a new optical observatory and a new radio telescope in Japan, and a new vector magnetograph in the United States.

In the last two decades, our knowledge of solar physics has benefitted greatly from an explosive increase in our understanding of the plasma state, due primarily to the rapid development of theoretical plasma physics fostered by the fusion-reactor program. More recently, our knowledge of the plasma state has been greatly expanded by the advent of numerical simulation as a branch of science that supports both experimental and analytical studies.

Finally, it is becoming recognized, more clearly and more forcefully, that plasma processes that occur in the sun are likely to occur in other astronomical bodies also. Now much of solar physics can be regarded as part of the larger study of plasma astrophysics. It has long been agreed that flares occur on stars other than the sun, and that many of these flares are far more energetic than solar flares. It is also possible that gamma-ray bursts from sources in our galaxy may be due to flares in neutron-star magnetospheres. In addition, astrophysicists are now exploring the possibility that activity in galaxies and quasars may be caused by flare-like processes.

In view of all of these interconnections, it is to be hoped that increased understanding of solar flares will contribute not only to solar physics, but also in some measure to the wider field of astrophysics.

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Table 1. Characteristics of gradual GR/P flares and Associations between them

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Gradual HXR emission		AYZb	AYZ	A	ASZ	ASZ	ANZ	A
(2) Long duration HXR emission	AYZb		AEOZ	AEOZ	AEZ	AEOZ	AEOZ	AEO
(3) Hardening of HXR spectrum								
(4) Flat HXR spectrum								
(5) High HXR source								
(6) Gradual and long duration microwaves								
(7) Large microwave richness index								
(8) Delay of microwaves w.r.t. HXR emission								
(9) Nuclear gamma-ray emission								
(10) Spreading two Hα ribbons								
(11) Long-duration SXR emission (LDE)								
(12) Large soft X-ray Source								
(13) type II radio burst		Z						
(14) type IV radio burst								
(15) Active-region filament eruption								
(16) Interplanetary shocks								
(17) High speed CME								
(18) Energetic IP protons								
(19) Slow decay of the IP proton flux								

Notes
1. Reference code: A:9, B:23, C:24, D:25, E:36, F:40, G:54, H:76, I:78, J:82, K:83, L:85, M:86, N:88, O:89, P:97, Q:125, R:128, S:129, T:132, U:153, V:154, W:155, X:156, Y:175, Z:176, a:177a, b:180, c:191, d:194, e:151
2. Characteristics 1 through 9 are pertaining to the first (or main) phase phenomena.
3. Blanks do not necessarily mean lack of association. In many cases blanks mean lack of comprehensive study on association.

Table 1. (continuation)

	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
(1)	A	AZ	AZ	YZb	AP	A		A	A	A	
(2)	A	AEO	AZ		AEO	AEO		A	A	A	
(3)											
(4)											
(5)											
(6)											
(7)											
(8)											
(9)										F	
(10)											
(11)							U		H		B
(12)		T					T		T		
(13)											
(14)			C	D						I a	
(15)											
(16)									X	B	B
(17)			Wc		JL		Qc	VX		KM	
(18)		G	BHRe		d	d		B	BM		
(19)			B					B	B		

Table 2

Characteristics of Different Classes of Flares

	Thermal hard X-ray flares	Nonthermal hard X-ray flares	Impulsive GR/P flares	Gradual GR/P flares	Quiescent filament eruption flares
Hard X-ray light curves & spectrum	gradual & thermal <40 keV spiky & very steep >40 keV	spiky steep $<\delta>=4.5$	spiky flat $<\delta>=3.5$	gradual flat $<\delta>=3.5$	not observed
Hard X-ray spectral evolution	soft-hard-soft	soft-hard-soft	soft-hard-harder	soft-hard-harder	not known
Hard X-ray source	small low	small low	small low	large high (>10000km)	expected to be high
Nuclear gamma rays	no	no	yes	yes	no
Type II or IV	rare	rare	often	very often	rare
IP shocks	no	no	very rare	often	rare
IP particles	no	no	often (low flux)	very often (high flux)	rare
Soft X-ray duration	short	short	short	long	long
Microwave to hard X-ray flux ratio	small	normal	normal	large	not known

FIGURE CAPTIONS

Fig. 1 – Hard X-ray and gamma-ray time profiles of the 1980 June 7 flare. Gamma-rays in the 4.1–6.4 MeV range are emitted simultaneously with hard X-rays. Nevertheless the gamma-ray time profile shows a delay of about 2 s with respect to the hard X-ray time profiles. Type II radio burst started at 0313 UT and lasted until 0332. From Chupp (32).

Fig. 2 – Hard X-ray and gamma-ray time profiles of the 1981 April 27 flare. Gamma-rays in the 4.1–6.4 MeV interval are emitted while hard X-rays are emitted, but the gamma-ray time profile is delayed by about 1 minute. Type II radio burst started at 0812.8 UT and lasted until 0836.3 UT. The gamma-ray time profile is from Chupp (34), and the hard X-ray time profile is from HXRBS data.

Fig. 3 – HXRBS hard X-ray time profile and spectral evolution of the 1981 February 26 flare. This is an example of an impulsive GR/P flare. The spectrum hardens during the first spike burst (around 1424:45 UT) and the third spike burst (around 1425:55 UT), but it shows "soft-hard-soft" behavior during the second spike burst. From Bai & Dennis (12).

Fig. 4 – HXRBS hard X-ray time profile and spectral evolution of the 1982 December 7 flare. Panel (a) shows the total counts of HXRBS (32–559 keV). This flare, which emitted hard X-rays for 50 minutes, is an example of a gradual GR/P flare. The hard X-ray time profile is impulsive in the beginning but becomes gradual. A short-duration spike at 2352:30 is from a flare at another active region. From Bai (9).

Fig. 5 – HXRBS time profiles and spectral evolution of the thermal hard X-ray flare on 1980 December 2. The time profile of 29–58 keV is gradual with some contribution of spiky nonthermal component, but that of

58–132 keV is more spiky. For power-law fits, the spectral indices are large. For thermal fits, the temperature is about 6×10^7 K. Both pure power-law fits and pure thermal fits result in large chi-square values, which indicates that the X-rays might be combination of thermal and nonthermal emissions. (Courtesy of Larry Orwig)

Fig. 6 – (a) Soft and hard X-ray time profiles of the 1980 November 5 flare. The soft X-ray light curve behaves like the time integral of the hard X-ray count rate. (b) Time profiles and spectral evolution of a nonthermal hard X-ray flare on 1980 November 5. Notice the "soft-hard-soft" spectral behavior and the similarity of the UVSP (UV Spectrometer on *SMM*) counting rate of the Ov line to the hard X-ray time profiles. Both Figures 6a and 6b are from Dennis (46).

Fig. 7 – Phases of a gradual GR/P flare. The soft X-ray fluxes decay very slowly. The *e-folding decay time of* the 1–8 A soft X-ray is about 20 minutes in the time interval from 0820 to 0857. The soft X-ray light curves decreased to the background levels more than 8 hours after the start of the flare. Two gaps in the hard X-ray data are due to satellite's nights. Compare with Fig. 2. (Courtesy of Larry Orwig)

Fig. 8 – Size distributions of different classes of flares. The vertical axis represents the number of flares in each bin of equal logarithmic interval. Panel (a) shows the size distribution of all flares with HXRBS count rates >1000 counts s^{-1} for 1980 and 1981(data from Ref. 47). Panel (b) shows the frequency of the *impulsive GR/P flares,* and (c) *gradual GR/P flares*. The identification of impulsive GR/P flares is limited by the GRS threshold. The majority of flares in panel (a) is thought to belong to nonthermal hard X-ray flare. Data from Bai (9).

Fig. 9 – This is a schematic representation of the magnetic-field configuration associated with a filament and its development during a filament eruption and flare. Figure 9a shows the pre-flare and pre-eruption filament configuration as an association of "magnetic strands" comprising a "magnetic rope" with multiple connections to the photosphere. Where strands with magnetic field of opposite polarity come into contact, reconnection can occur. This gives rise to energy release, and also to a partial disconnection of the filament magnetic field from the photosphere. Figure 9b shows the magnetic-field configuration that will develop if a "runaway" series of disconnections occur, leaving the flux system tied to the photosphere only at the two extremities. The new flux tube will tend to erupt (possibly expanding indefinitely into interplanetary space, if it is sufficiently stressed), distorting the overlying magnetic-field lines as shown to form an extended vertical current sheet.

Fig. 10 – This shows the processes that may occur in the vertical current sheet shown in Figure 9b as the result of progressive reconnection. From Cliver *et al* (35a, 36). Similar figures are found in Anzer & Pneuman (4) and Sturrock *et al* (167). Although this figure depicts that CMEs are driven by erupting filaments, there are contradictory observations (69, 80).

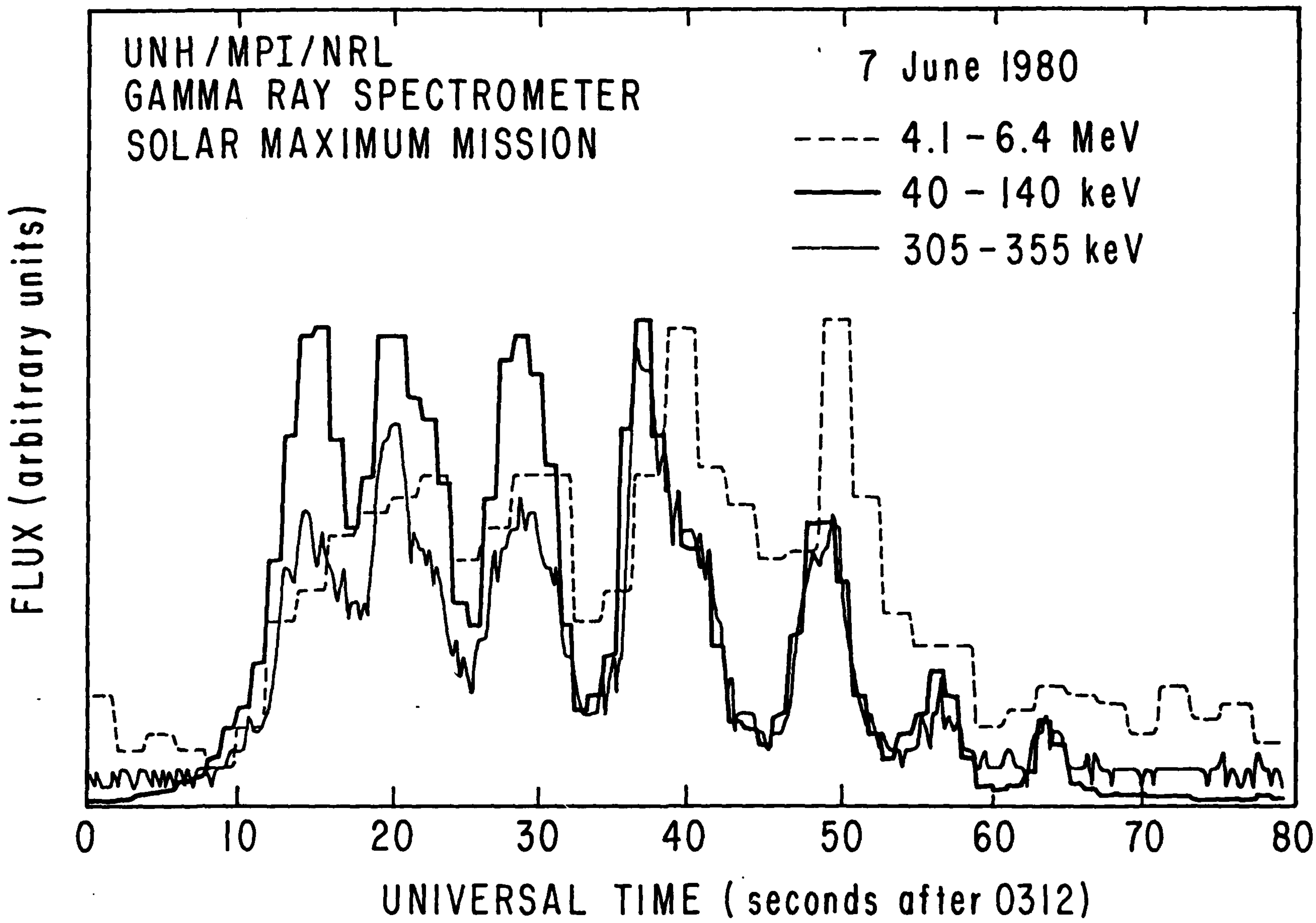

UNH / MPI / NRL
GAMMA RAY SPECTROMETER
SOLAR MAXIMUM MISSION
7 June 1980
4.1 - 6.4 MeV
40 - 140 keV
305 - 355 keV
FLUX (arbitrary units)
0
10
20
30
40
50
60
70
80
UNIVERSAL TIME (seconds after 0312)

Fig.1

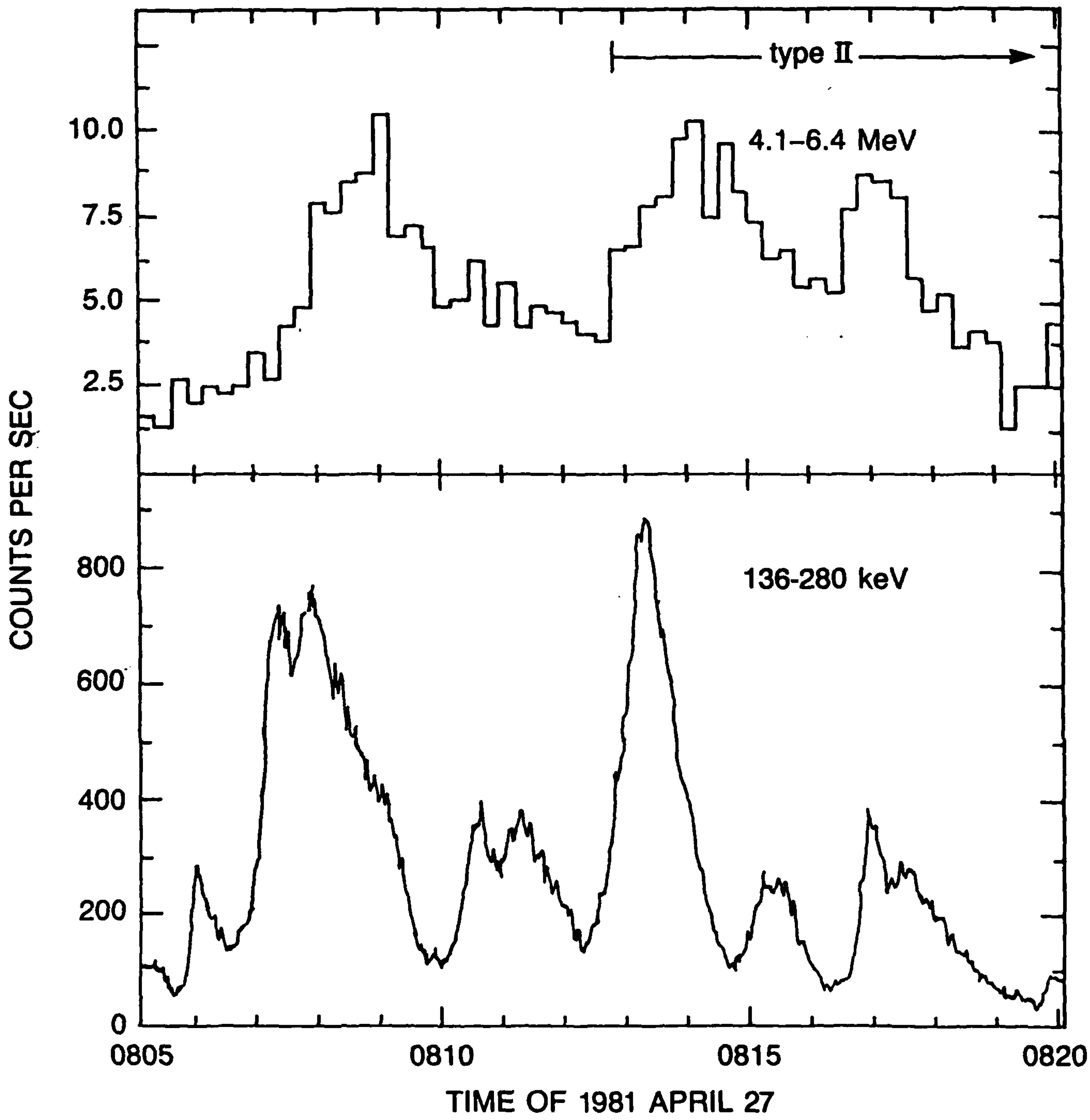

type II
10.0
7.5
5.0
2.5
4.1–6.4 MeV
COUNTS PER SEC
800
600
400
200
0
136-280 keV
0805
0810
0815
0820
TIME OF 1981 APRIL 27

Fig. 2

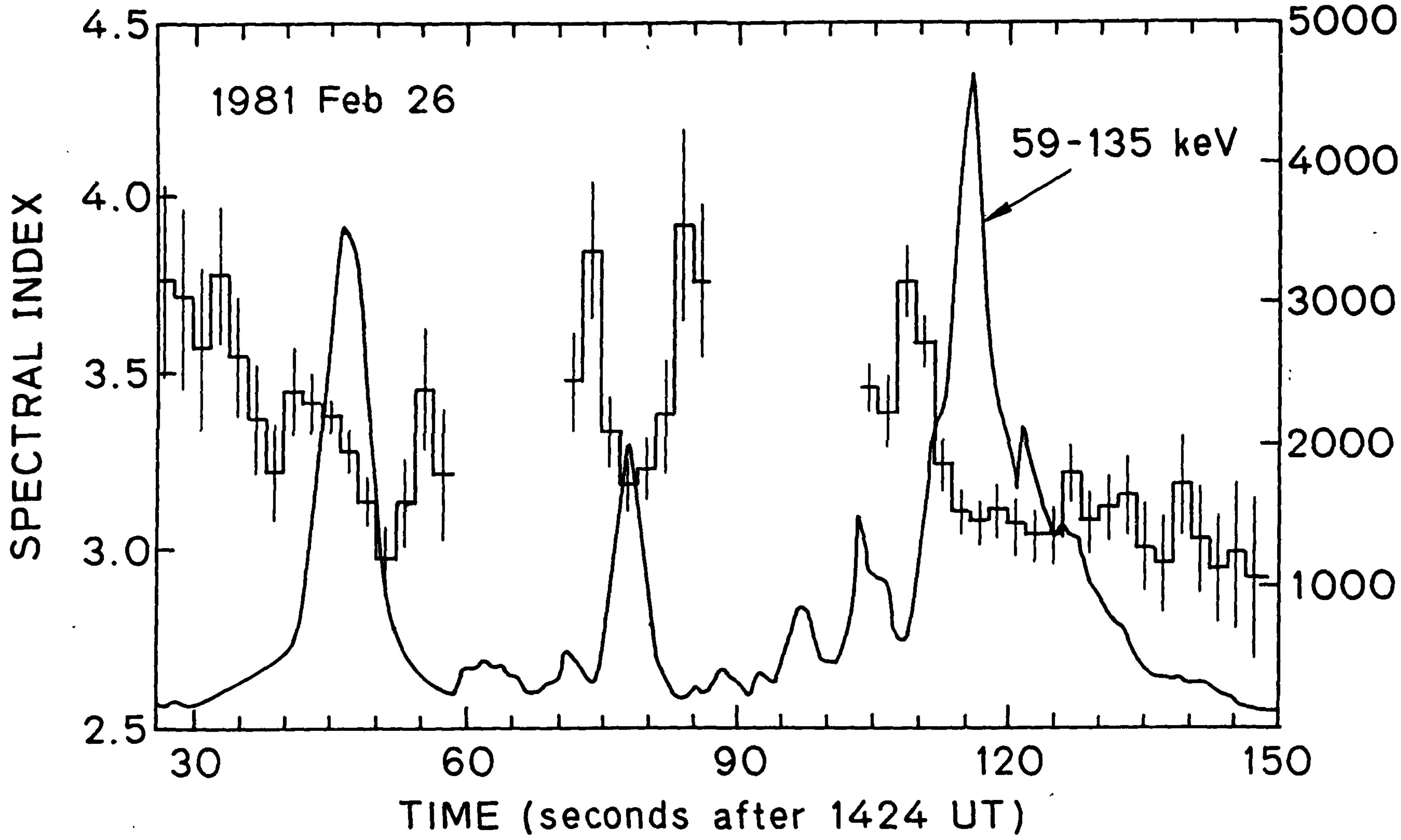
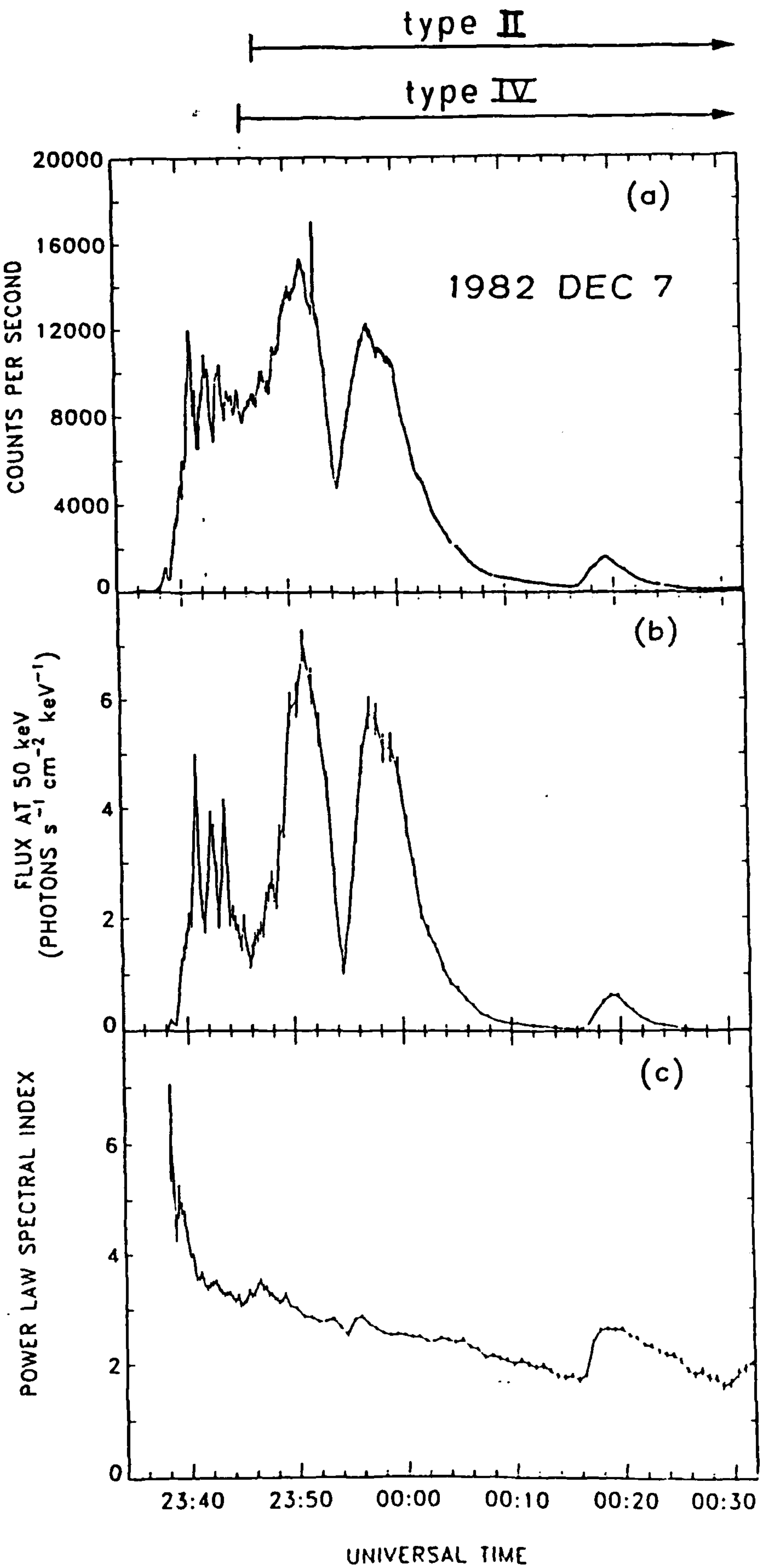
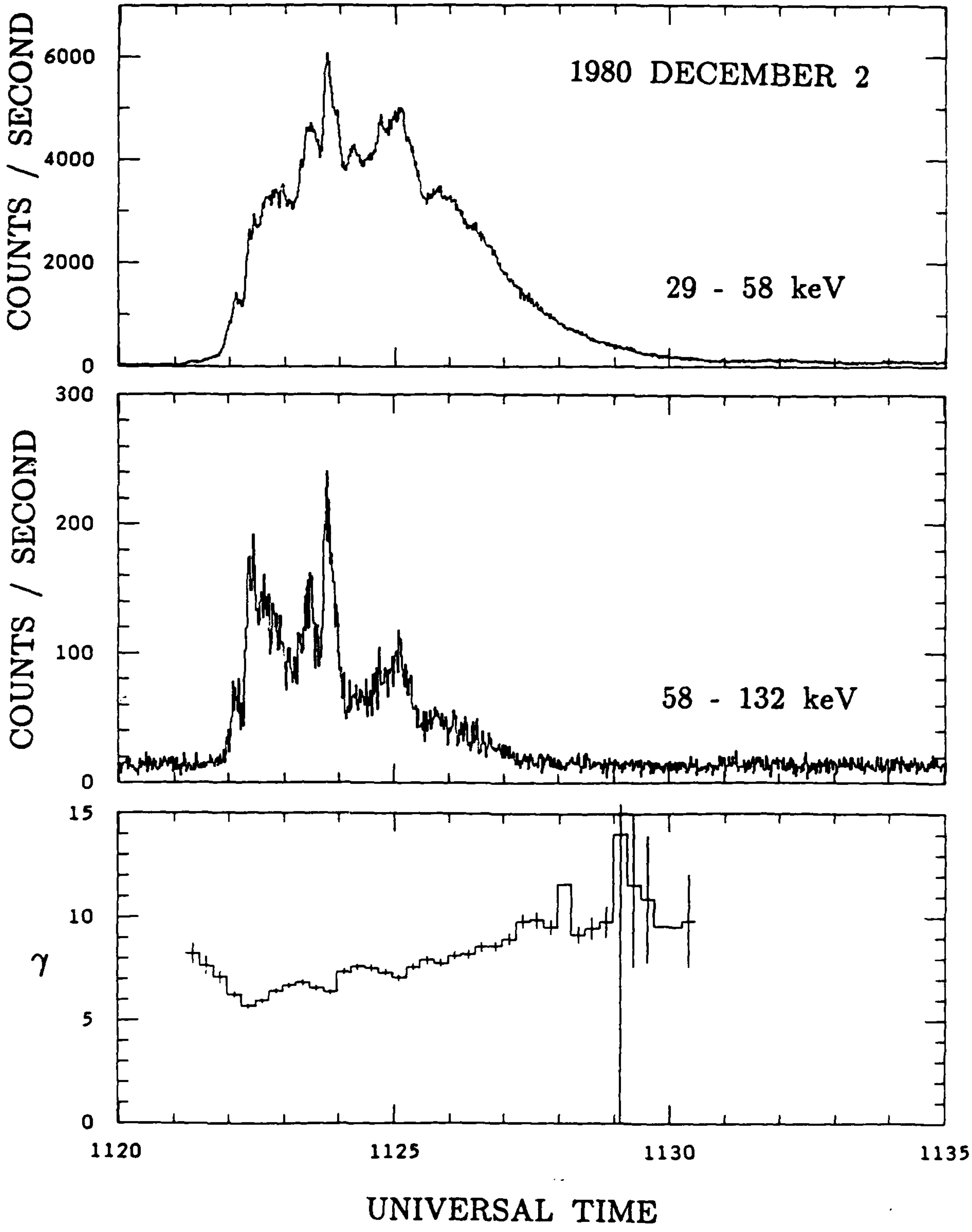

1981 Feb 26
59-135 keV
SPECTRAL INDEX
4.5
4.0
3.5
3.0
2.5
COUNTS/SEC
5000
4000
3000
2000
1000
30
60
90
120
150
TIME (seconds after 1424 UT)

Fig. 3



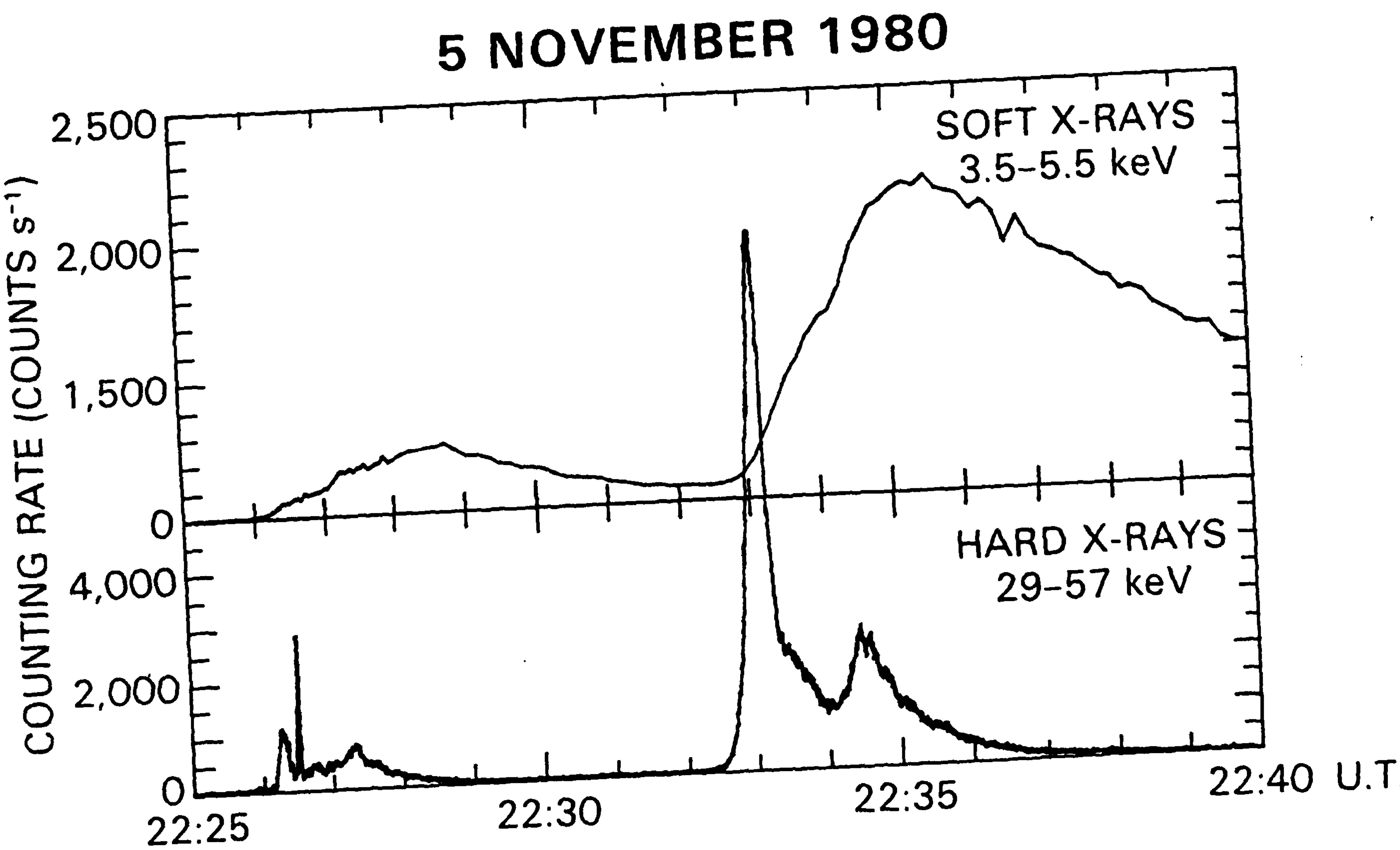
type II
type IV
20000
16000
12000
8000
4000
0
COUNTS PER SECOND
(a)
1982 DEC 7
(b)
FLUX AT 50 keV
(PHOTONS s^{-1} cm^{-2} keV^{-1})
6
4
2
0
(c)
POWER LAW SPECTRAL INDEX
23:40
23:50
00:00
00:10
00:20
00:30
UNIVERSAL TIME

Fig. 4



COUNTS / SECOND
6000
4000
2000
0
1980 DECEMBER 2
29 - 58 keV
300
200
100
0
58 - 132 keV
15
10
5
0
γ
1120
1125
1130
1135
UNIVERSAL TIME

Fig. 5



5 NOVEMBER 1980
SOFT X-RAYS
3.5–5.5 keV
HARD X-RAYS
29–57 keV
COUNTING RATE (COUNTS s⁻¹)
2,500
2,000
1,500
0
4,000
2,000
0
22:25
22:30
22:35
22:40 U.T.

Fig. 6a

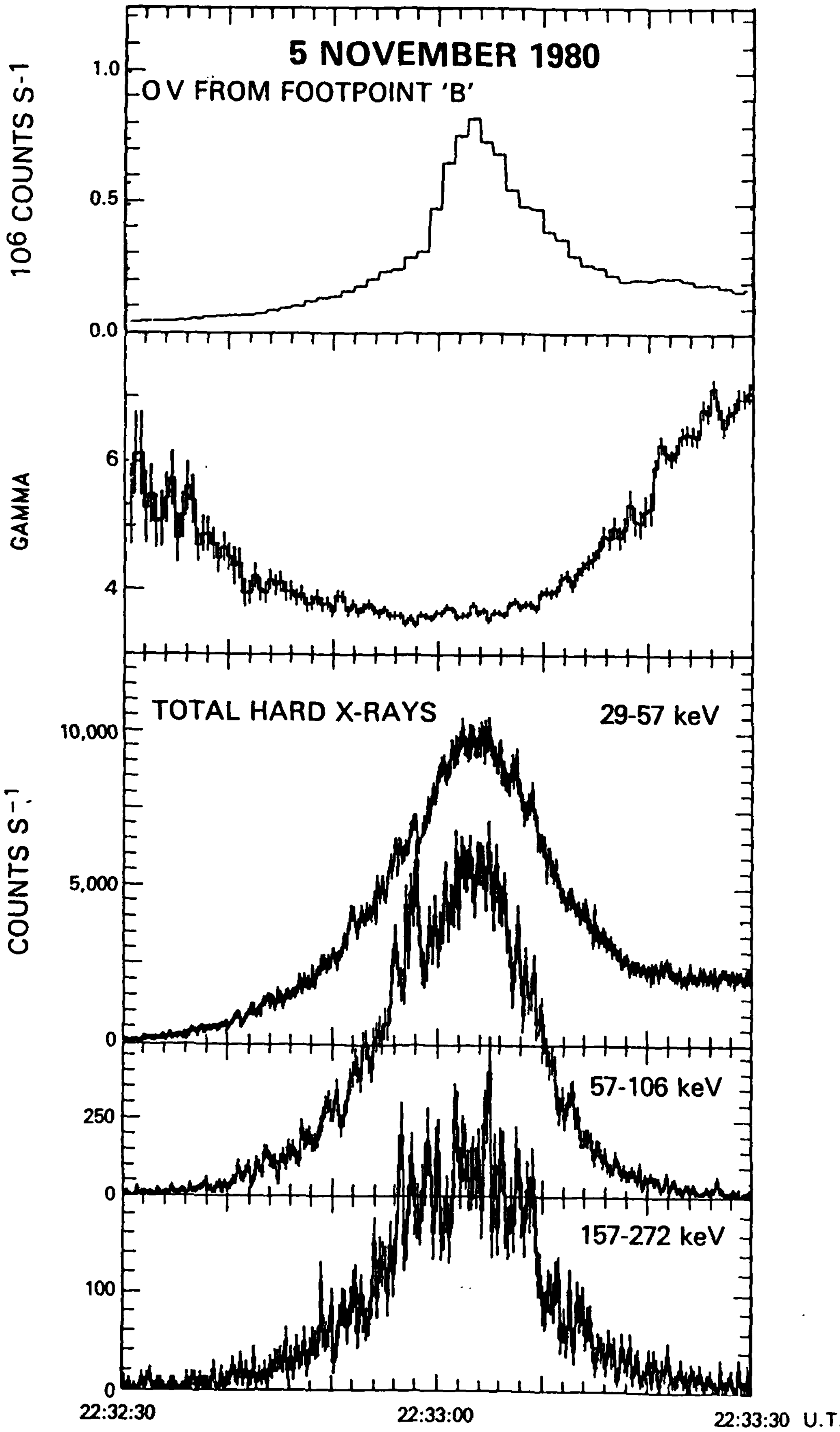

5 NOVEMBER 1980
O V FROM FOOTPOINT 'B'
10^6 COUNTS S-1
1.0
0.5
0.0
GAMMA
6
4
TOTAL HARD X-RAYS
29-57 keV
COUNTS S^-1
10,000
5,000
0
57-106 keV
250
0
157-272 keV
100
0
22:32:30
22:33:00
22:33:30 U.T.

Fig. 6b

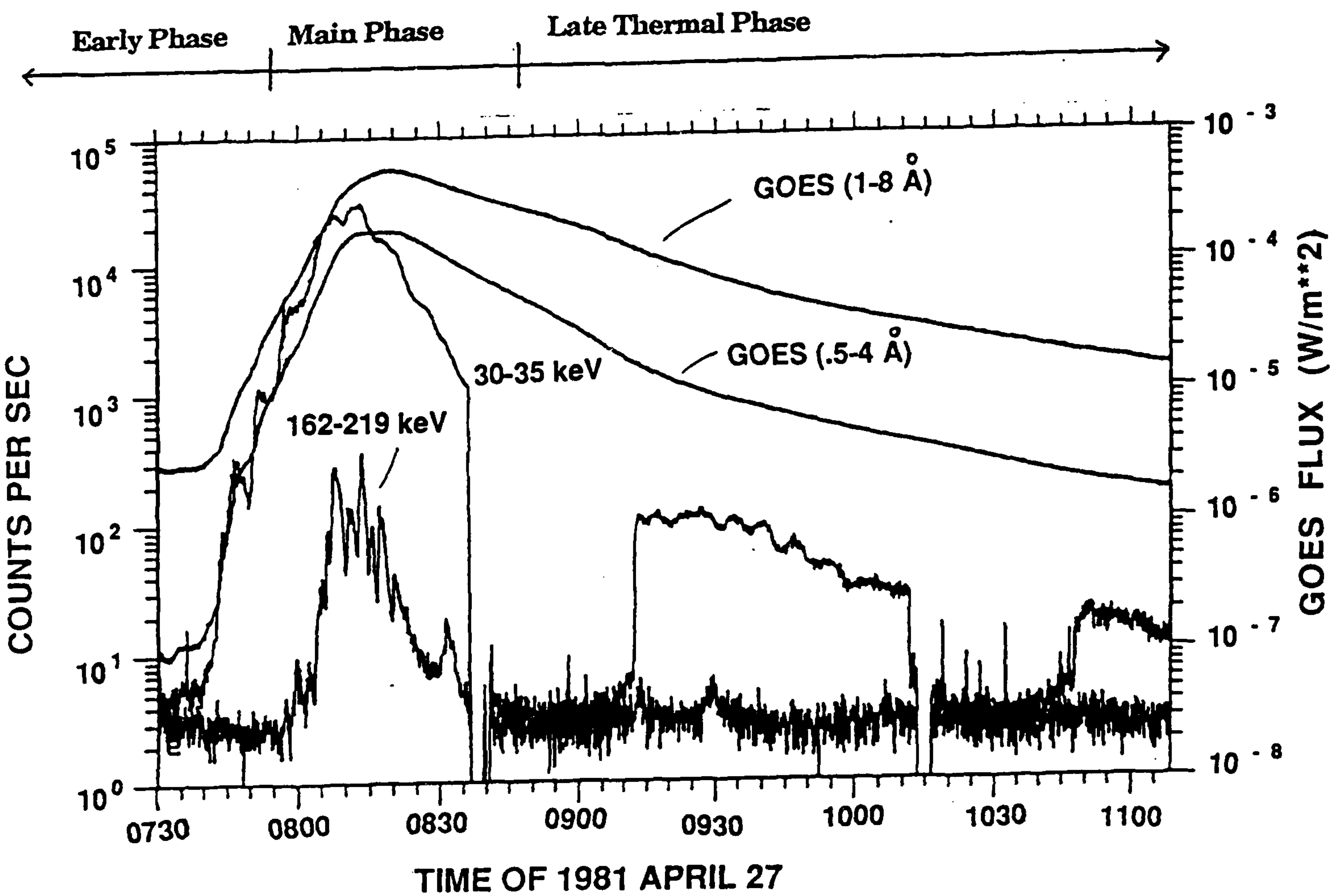

Early Phase
Main Phase
Late Thermal Phase
GOES (1-8 Å)
GOES (.5-4 Å)
30-35 keV
162-219 keV
COUNTS PER SEC
GOES FLUX (W/m**2)
0730
0800
0830
0900
0930
1000
1030
1100
TIME OF 1981 APRIL 27

Fig. 7

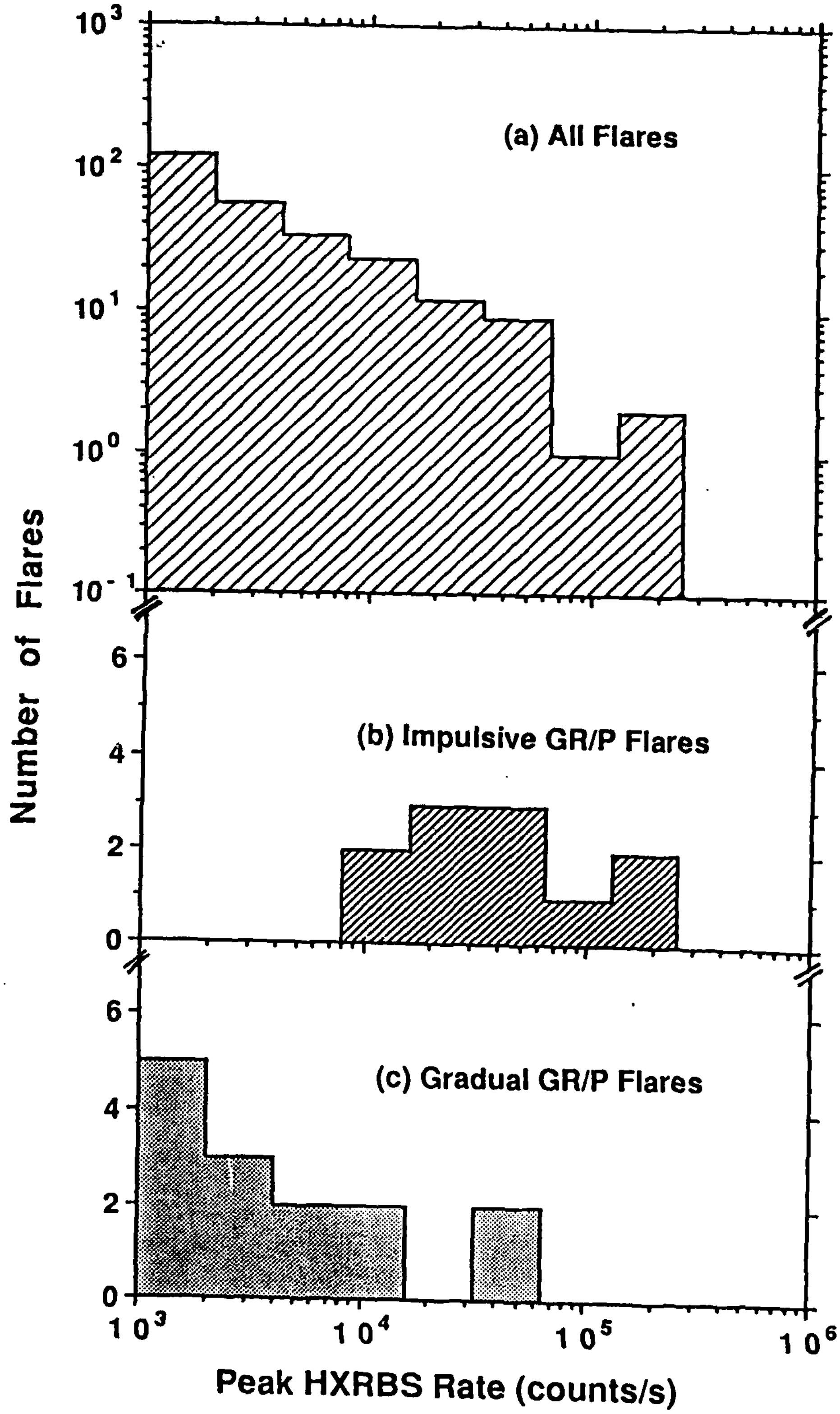

(a) All Flares
(b) Impulsive GR/P Flares
(c) Gradual GR/P Flares
Number of Flares
Peak HXRBS Rate (counts/s)
10^3
10^2
10^1
10^0
10^-1
6
4
2
0
10^3
10^4
10^5
10^6

Fig. 8

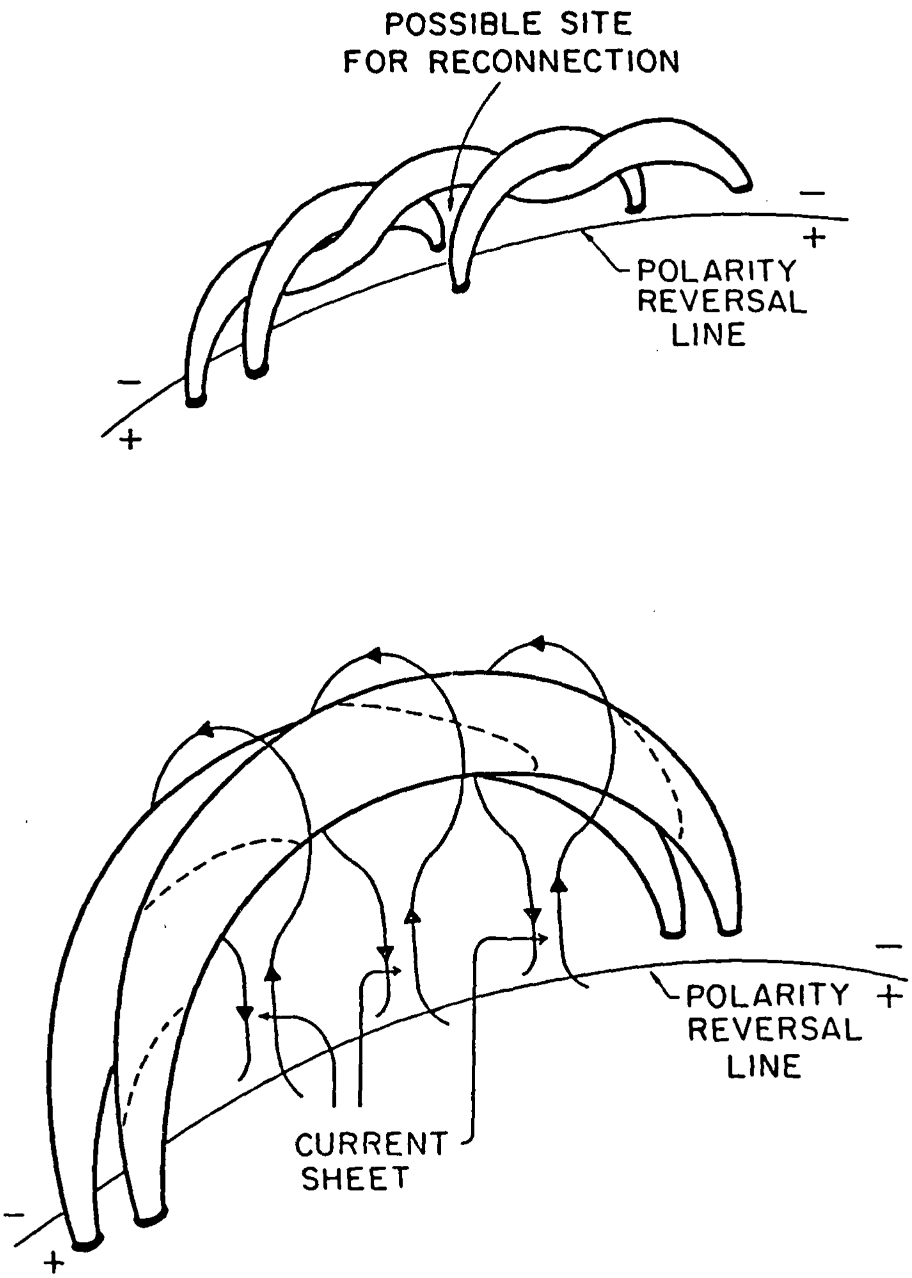

POSSIBLE SITE
FOR RECONNECTION
POLARITY
REVERSAL
LINE
POLARITY
REVERSAL
LINE
CURRENT
SHEET

Fig. 9

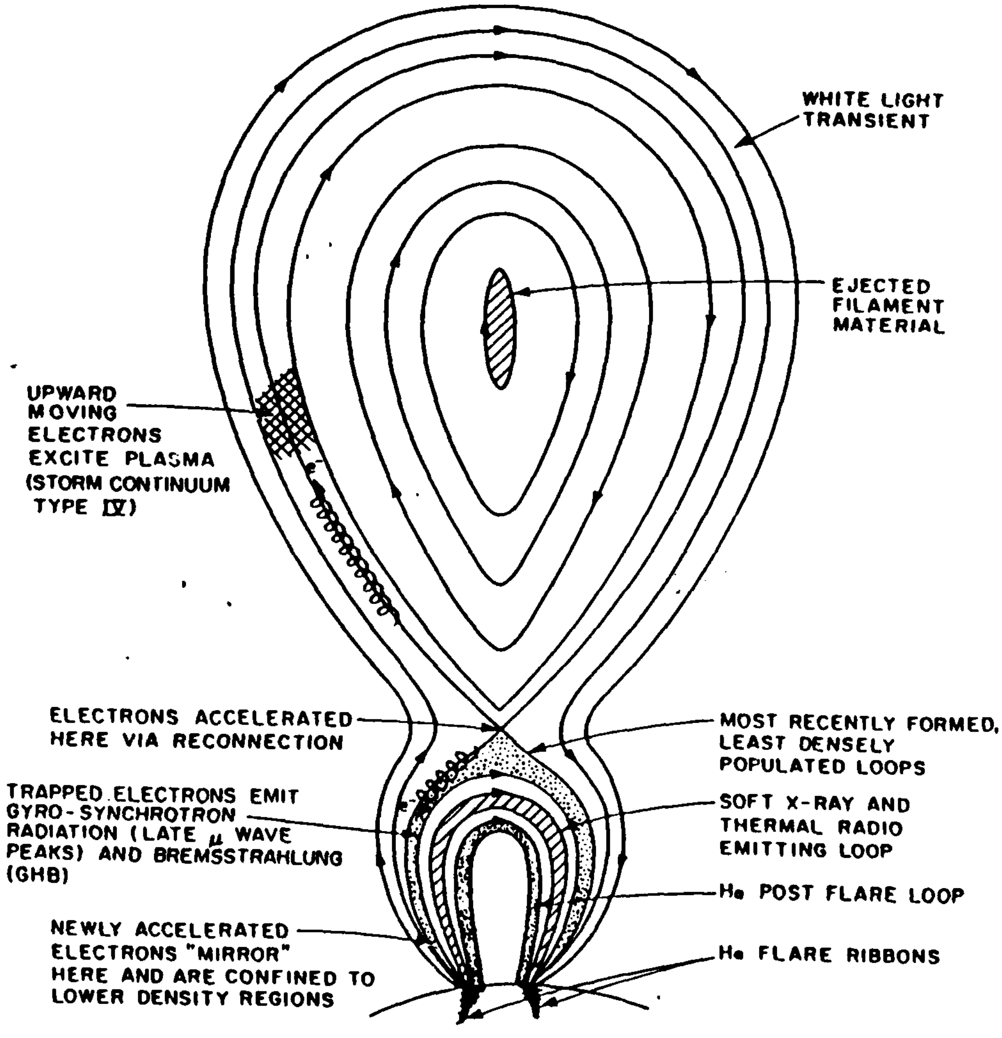

WHITE LIGHT TRANSIENT
EJECTED FILAMENT MATERIAL
UPWARD MOVING ELECTRONS EXCITE PLASMA (STORM CONTINUUM TYPE IV)
ELECTRONS ACCELERATED HERE VIA RECONNECTION
MOST RECENTLY FORMED, LEAST DENSELY POPULATED LOOPS
TRAPPED ELECTRONS EMIT GYRO-SYNCHROTRON RADIATION (LATE μ WAVE PEAKS) AND BREMSSTRAHLUNG (GHB)
SOFT X-RAY AND THERMAL RADIO EMITTING LOOP
Hα POST FLARE LOOP
NEWLY ACCELERATED ELECTRONS "MIRROR" HERE AND ARE CONFINED TO LOWER DENSITY REGIONS
Hα FLARE RIBBONS

Fig. 10