SOLAR FLARES: THE IMPULSIVE PHASE

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Abstract. Only during the previous solar cycle have systematic observations begun to be made with the sensitivity and time resolution, and the continuous coverage required to catch the impulsive phase and measure the rapid variations present in many wavelength ranges. Observations in X-rays, gamma-rays, UV, Hα, and radio wavelengths all reveal rapid variations during the impulsive phase and have contributed to our understanding of the different phenomena involved. Results have been obtained from several spacecraft, from rocket and balloon flights, and from ground-based observations. These are reviewed in the context of a simple single loop flare model with a view to showing what results are consistent with this model and what the major problems are in our understanding of the impulsive phase. New instrumentation planned for observations during the present Cycle 22 will provide a concerted attack on the impulsive phase as part of the Max '91 program.

1. Introduction

The terms 'impulsive' and 'gradual' were originally proposed by Covington and Harvey (1958) to describe two broad classes of microwave bursts. Kane (1969) first recognized the two components in energetic X-ray bursts. Today, the terms are used to describe the different phases of flares as observed in many wavelength ranges. Unfortunately, there is often confusion with this terminology since what appears impulsive in one wavelength range, e.g., hard X-rays, may appear gradual in another wavelength range, e.g., soft X-rays. Nevertheless, the distinction between the two phases is important since it is assumed that during the impulsive phase energy is being released 'impulsively', i.e., on time-scales of seconds or less, whereas during the gradual phase either energy is being released more gradually on time-scales of minutes to tens of minutes or no energy is being released at all.

The usual assumption is that solar flares result from the release of free energy in coronal magnetic fields either through reconnection or some other form of magnetic dissipation. The impulsive and gradual phases must then be interpreted as resulting from different energy release processes, different modes of magnetic dissipation, or different magnetic configurations. In many cases, though not all, the gradual phase is thought to result from the slow decay of the energy released during the impulsive phase with no new energy release being required. This idea that all the energy of a solar flare is released during the impulsive phase may explain why, as pointed out by Sturrock *et al.* (1984), it has often been 'implicitly assumed that to explain the impulsive phase is to explain the complete flare'. This idea may be true for many smaller flares where the impulsive phase appears as the dominant feature but for other flares, particularly the larger ones,

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gradually varying hard X-ray and microwave emissions lasting as long as an hour or more indicate clearly that energy continues to be fed into the flare long after any impulsive phase is over.

Further indications that the impulsive phase is not the complete story of flare energy release are the observations of coronal mass ejections (CMEs) lifting off *before* the impulsive phase of the presumably associated flare (Simnett and Harrison, 1985; Harrison *et al.*, 1985; Harrison, 1986). Kahler *et al.* (1988) also report that filament eruptions begin before the onset of the impulsive phase and evolve smoothly through the flare. Thus, we must conclude from these observations that in those cases, the impulsive flare was a consequence of the associated filament eruption or CME rather than that the eruption or the CME was a consequence of the flare. This places a completely new light on the significance of the impulsive phase for those events. It must be remembered that the total kinetic energy associated with the mass motion of a CME can be considerably larger than the total energy released during the associated flare.

In spite of this new understanding of the relation between the different aspects of the energy release phenomena, it is still true that 'the principal theoretical flare problem is that of sufficiently rapid primary energy release' (Brown, Smith, and Spicer, 1981). Hard X-rays are observed with such intensities that, given the standard interpretation of them as collisional bremsstrahlung from high-energy electrons in the flare plasma, energy release rates as high as 10^{30} ergs s^{-1} are required to accelerate the emitting electrons during the impulsive phase. Simpler considerations of the $\gtrsim 10^{32}$ ergs released in the biggest flares in a characteristic flare duration time of $\sim 10^3$ s show that sustained energy release rates of at least 10^{29} erg s^{-1} are required. Such energy release rates are extremely challenging theoretically given the magnetic field strengths and configurations believed to exist in the corona. It is for this reason that increasing emphasis is being placed on observations of the impulsive phase in many different wavelength ranges. This paper constitutes a review of the more recent observations of impulsive phase phenomena at all wavelengths where evidence of such phenomena is found. It is hoped that this review will be valuable to theoreticians, who will see what observations are available to compare with their model predictions, and to observers, who can use it as a basis for comparing with observations from the much improved instrumentation planned for the next maximum in solar activity during Cycle 22.

In order to provide a common basis for discussing the observations in different wavelength ranges, we present in the next section a simple flare model that is consistent with many impulsive phase observations. This model also serves to show where in the solar atmosphere the different emissions may originate and how they may be related to one another and to the various phenomena of the impulsive phase. We have broken down the paper into three sections – energy release, energy transport, and energy loss – and show how the observations in different energy ranges provide information on these processes. The following sections contain discussions of observations in hard X-rays and γ-rays, microwaves and other radio waves, soft X-rays, UV and EUV wavelengths, and Hα. Finally, a brief discussion is given of what to expect from the planned Max '91 program of new observations during the current cycle of solar activity.

2. A Simple Flare Model

It has been known since Skylab observations showed the ubiquity of magnetic loops in the solar atmosphere that such loops must play a dominant role in the flare process. Consequently, it is not surprising that the possible flare model illustrated in Figure 1 (Dennis *et al.*, 1986; Gurman, 1987) is based on a magnetic loop extending into the corona. While a single loop is shown in the figure, much more complicated field geometries involving arcades of loops are usually present in all but the simplest of flares. Indeed, the most intense impulsive flares tend to occur in magnetically complex regions (Švestka, 1976).

According to this simple model, free magnetic energy in the current-carrying loop is

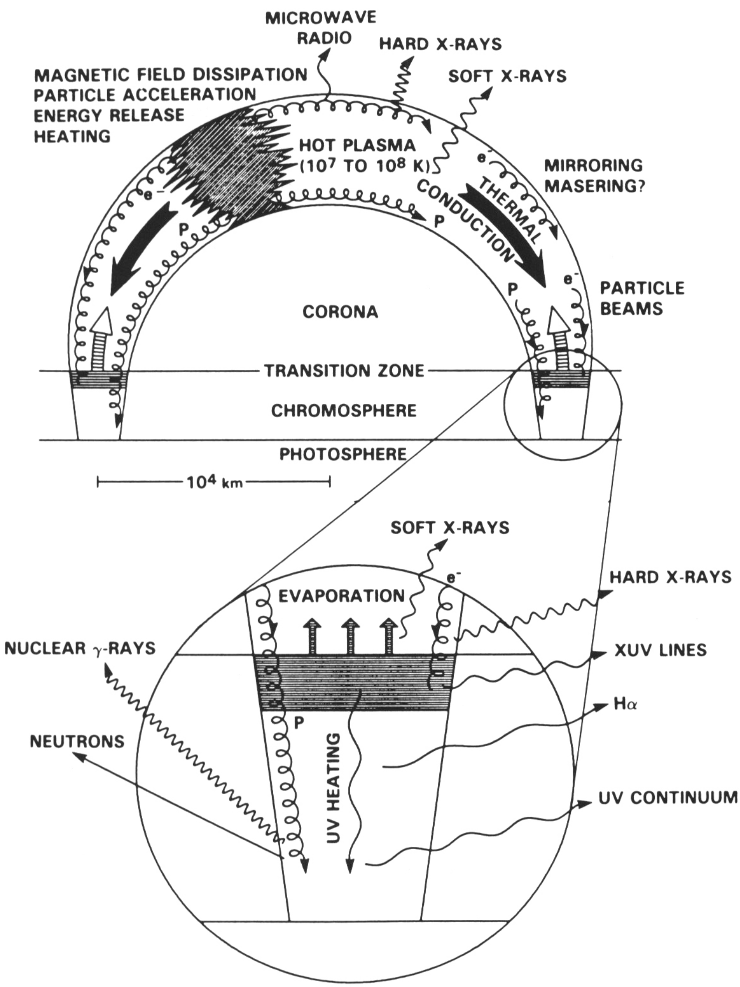

Fig. 1. Schematic diagram of a simple flare showing some of the physical processes that are believed to occur and where in the solar atmosphere different emissions are thought to originate.

dissipated by some ill-defined mechanism probably in the coronal part of the loop. As a result of this dissipation, the coronal plasma is heated, possibly to temperatures in excess of 10^8 K, and electrons and protons are impulsively accelerated to high energies. The division of the released energy between the heated plasma and the accelerated particles is still largely unknown and the subject of great controversy. The accelerated particles propagate along the magnetic field lines and interact with the ambient gas in the legs of the loop, with the most energetic ones penetrating to the loop footpoints in the chromosphere.

As indicated in the figure, a variety of observable emissions are produced from the different parts of the loop. From the point of view of understanding the particle acceleration process and, hence, the energy release process itself, the hard X-rays, γ-rays, radio waves, and neutrons are the most important emissions. The hard X-ray and γ-ray continuum is believed to be electron-ion bremsstrahlung, the γ-ray lines and neutrons result from nuclear interactions, the microwaves are most probably gryro-synchrotron emission, and the longer wavelength radio emission is plasma wave emission of various types. All of these emissions are produced before the accelerated particles lose their energy to the ambient atmosphere, and, consequently, they contain the greatest amount of information available about how the particles were accelerated. Increasing emphasis has been placed on observing these emissions with ever greater temporal, spectral, and spatial resolution (plus polarization measurements where possible) to extract this information. This push for greater resolution will continue during the maximum of Cycle 22, for we are still not close to the resolutions required in many of these wavelength ranges to extract the available information.

3. Energy Release

We assume, as illustrated in Figure 1, that the impulsive energy release takes place in the coronal part of the magnetic loop or loops. The evidence for this location of the release site is not overwhelming but it almost certainly lies above the photosphere since no sudden change in the photosphere below the flaring region is observed (Kahler *et al.*, 1980). Currently, there is no direct way to determine the magnetic field strength and configuration in the corona – only the photospheric and chromospheric fields are measured from the Zeeman splitting of emission lines from various partially-ionized atoms generally at temperatures much less than 10^6 K. These photospheric fields can be extrapolated into the corona assuming either a potential field or a 'force-free' field.

Observations show that a flare is most likely to occur in an active region where the magnetic shear is the greatest (Hagyard, Moore, and Emslie, 1984), thus implying that there is considerable twist in the magnetic field lines of the loop. Moore, Hagyard, and Davis (1987) show that a flare will occur in 1000 G fields if a critical shear angle of 80–85° is exceeded for a distance of $> 10\,000$ km along the polarity inversion line. It may well be that the flare energy is derived from the dissipation of the poloidal component of the field in the loop produced by a current along the loop. At present such theories are speculative because of the limitations of the magnetic field measurements and there is little hope in the foreseeable future of being able to directly measure the coronal magnetic fields in a flaring region with anything like the accuracy required to detect the reduction in free energy expected during a typical impulsive flare. Indeed today the uncertainty in measurements of the total magnetic energy in an active region is generally greater than or of the same order as the energy released in the flare. Thus, while definite before-to-after magnetic changes have been detected in a few flares (e.g., Moore *et al.*, 1984), in no case has it been shown that the observed change quantitatively accounts for the flare energy (Moore, 1988).

In spite of this limitation, changes in the magnetic field can be seen in observations of filaments of chromospheric material that reside in and trace out sheared magnetic fields over magnetic inversion lines. During a flare these filaments are seen to expand and untwist indicating a decrease in the magnetic energy (e.g., Kurokawa *et al.*, 1987; Moore, 1988). Moore (1988) has shown that for three eruptive events the decrease in magnetic energy of 10^{30}–10^{32} ergs is of the same order as the total energy released in the flare and/or coronal mass ejections. This provides strong support for the idea that the flare energy comes from the magnetic field, at least for this particular kind of flare involving a filament eruption.

There is hope that future microwave observations made with high spatial resolution at many frequencies can provide a means of determining magnetic field strengths in the corona and transition zone (Kundu and Lang, 1985; Holman, 1986). Webb *et al.* (1987), for example, have been, 'able to deduce or place constraints on the magnetic field strengths within, and their variations along', six coronal loops using microwave observations at 1.45 GHz (20 cm) and 4.9 GHz (6 cm) together with photospheric magnetograms and soft X-ray images and the dipole loop models of Holman and Kundu (1985). Holman (1986) has pointed out that the present determinations of coronal magnetic field strengths are ambiguous since there are two, or possibly three, different contributions to the observed microwave emission, thermal bremsstrahlung (free-free), thermal gyroresonance (cyclotron) emission, and possibly non-thermal gyrosynchrotron emission. The magnitude of each of these contributions must be determined before the observations can be unambiguously interpreted.

The contribution from free-free emission can be determined if simultaneous soft X-ray images are available to provide measures of the electron temperature and emission measure. The gyroresonance emission depends on the magnetic field strength and electron temperature but it can be present at several possible harmonics of the electron gyrofrequency. Holman and Kundu (1985) have computed the expected thermal gyroresonance emission for two-dimensional dipole loop models, the simplest non-trivial configuration that might be expected, and these predictions can be used as a basis for comparing with observations. They show that, in order for future observations to provide unambiguous magnetic field information useful in determining the preflare conditions of a loop, the microwave maps must be made with high spatial resolution and at many closely spaced frequencies. Coordinated EUV and/or soft X-ray images should be obtained to determine the temperature and emission measure distributions so that the thermal bremsstrahlung contribution can be determined and the thermal gyroresonance temperature dependence computed.

Measurements of the magnetic field topology during an impulsive flare are also difficult to obtain but for different reasons. Although one type of emission, gyro-synchrotron emission, dominates at this time, the fluctuations are much more rapid and short time-resolution observations at many different frequencies are desirable. Consequently, the 3–10 s capability of the VLA at only one or two frequencies becomes a serious limiting factor. Hoyng *et al.* (1983), Dulk and Dennis (1982), and Schmahl, Kundu, and Dennis (1985) have combined VLA snapshot maps at 2 and/or 6 cm with single-frequency flux measurements and hard X-ray observations to determine a magnetic field strength of ~ 550 G in the flaring region. No mapping of the field was possible, however, although Hoyng *et al.* were able to show a bending of the field lines by $\gtrsim 80°$ over a distance of 3″ suggesting the top of a magnetic loop, albeit a considerably smaller loop than the one suggested by the X-ray images.

The closest we have come to observing the energy release process may be by observing the decimetric radio spikes present during some impulsive flares. Benz (1985) showed that events are observed between 100 and 1000 MHz with ~ 10 000 spikes suggesting that the energy release process was fragmented with each spike resulting from an energy release of 10^{26} ergs within 0.05 s.

Significant metric and decimetric radio emission is usually observed during the impulsive phase, often in the form of type III bursts. These bursts are narrow band and drift rapidly with time generally towards lower frequencies. They are interpreted as resulting from an electron beam passing upwards through the corona with the radio emission produced at the leading front of the beam where it is unstable to the production of Langmuir waves that subsequently couple into electromagnetic waves at the local plasma frequency or its harmonic. The bursts are generally observed at frequencies of $\lesssim 500$ MHz corresponding to densities of $\lesssim 10^9$ cm^{-3} and altitudes of $\gtrsim 10^5$ km although they have now been seen at frequencies as high as 5 GHz (Benz, private communication). Comparisons between type III and hard X-ray bursts show poor correlations with isolated type IIIs – only 3% are correlated with hard X-rays – but good correlation with groups of type IIIs (Kane, 1981) especially those with type V continuum (Stewart, 1978). The correlation becomes even better for type IIIs with high starting frequencies (Benz, Bernold, and Dennis, 1983) presumably because a beam that produces such a burst is denser and hence becomes unstable earlier along its trajectory from the acceleration site (Benz, 1987). The denser the beam, the bigger the hard X-ray flux it or its downward directed counterpart produces.

Some type III bursts are observed to extend to the vicinity of the Earth. *In situ* measurements of the source electrons have verified the electron beam origin and have established that the number of electrons required to generate a type III burst is several orders of magnitude smaller than the number required to generate a detectable flux of X-rays with current instrumentation.

4. Energy Transport

At least five possible forms have been proposed for the energy transport from the energy release site in the corona to the region of energy dissipation in the lower corona and chromosphere at the loop footpoints. They are as follows with the X-ray production mechanism shown in brackets:

– Thermal plasma with a temperature $T \geq 10^8$ K (thermal bremsstrahlung X-rays).

– Fast electrons with energies ≥ 20 keV (thick-target bremsstrahlung X-rays).

– Relativistic electrons (X-rays by inverse Compton interactions).

– Protons with energies ≤ 1 MeV (fast electrons produced at footpoints by ill-defined mechanism produce bremsstrahlung X-rays).

– Protons with energies > 1 MeV (inverse bremsstrahlung X-rays).

The first two possibilities in this list constitute the well-known thermal and thick-target models, respectively. In the thermal model (Brown, Melrose, and Spicer, 1979; Smith and Lilliequist, 1979; Batchelor *et al.*, 1985), the energy release goes to impulsively heat the plasma near the release site to a temperature of $\geq 10^8$ K. This plasma is temporarily confined behind ion-acoustic conduction fronts that form in the loop and move at the ion sound speed (10^8–10^9 cm s^{-1}) down the legs of the loop to the footpoints taking ~ 20 s for a 30000 km long loop if the density is 10^{10} cm^{-3}. In the thick-target model, electrons are accelerated high in a magnetic loop and propagate along the guiding field lines, producing X-ray bremsstrahlung and atmospheric heating as they proceed. The higher energy electrons lose most of their energy in the higher density regions of the lower corona and upper chromosphere. This thick-target model has been the most successful in explaining the largest fraction of the observations during the impulsive flares but still cannot be considered as proven.

The other three possibilities given above involving relativistic electrons or protons of different energies have met with limited success in explaining the observations of impulsive flares. However, there are several scientists working to better understand the implications of these models and to make predictions that can be tested against observations. It is fair to say that none of these models can, as yet, be definitively ruled out.

Models involving relativistic electrons require much less total electron energy (Brown, 1976) than the other models but are perhaps the least successful in explaining the observations. The hard X-rays are produced from the relativistic electrons as synchrotron or inverse Compton radiation but the required electron energies are very high, > 1 GeV for synchrotron and > 10 MeV for inverse Compton radiation. Electrons with such high energies and in sufficient numbers to produce the observed X-ray fluxes are not consistent with microwave burst intensities nor are they detected in interplanetary space (Brown, Smith, and Spicer, 1981).

Models involving protons as the primary accelerated particles have seen a resurgence of interest recently in attempts to explain some apparent difficulties with the thick-target bremsstrahlung model. In particular, Simnett (1986) has proposed that the bulk of the energy in the impulsive phase is initially transferred to protons with energies between

100 keV and 1 MeV. Martens (1988) has developed a model for the generation of proton beams in two-ribbon flares. In this model neutral beams are generated by direct electric field acceleration making protons with typical energies of 200 keV the main carriers of the beam energy. Henoux *et al.* (1988) have recently presented observations of Hα linear polarization in a flare as evidence for the existence of the atmospheric bombardment by deka-keV protons. Their suggestion that impact linear polarization of chromospheric lines can be used as a diagnostic of deka-keV protons opens up the possibility for detecting these enigmatic protons and determining if they do in fact play a dominant role during impulsive flares. Previously, the best hope for detecting these protons was through the predicted red-shifted component of the Lα line resulting from the decay of excited hydrogen atoms produced in charge exchange interactions between the protons and the ambient plasma (Orrall and Zirker, 1976).

Heristchi (1986) has argued that bremsstrahlung by fast protons ($E_p \gg 1$ MeV) on stationary electrons may be the origin of hard X-ray emission in flares. However, as pointed out by Emslie and Brown (1985), such a model, while energetically feasible, requires a number of fast protons which is three orders of magnitude higher than that required to produce the observed gamma-ray fluxes by nuclear reactions (e.g., Ramaty and Murphy, 1987). Heristchi (private communication) has countered this claim by pointing out that the following factors not considered by Emslie and Brown may in fact remove this discrepancy:

(i) a factor of two decrease in the number of protons required because of the lower energy loss rates, and hence greater bremsstrahlung efficiency, in the near-neutral deeper layers of the atmosphere where the protons mostly interact;

(ii) an uncertainty of a factor of ~ 8 in the extrapolation of the proton spectrum from the 60 MeV or so responsible for emission of 30 keV hard X-rays (the lower limit of the SMM HXRBS energy range) to the 20 MeV responsible for γ-ray emission;

(iii) a general confusion of up to a factor of 6 in the quantitative ratio between particle and photon energy contents in a thick-target model (cf. discrepancies between Brown (1971); Hoyng, Brown, and van Beek (1976); and Emslie, Phillips and Dennis (1986)); and

(iv) a factor that could be as large as 10 resulting from a high degree of directivity of the emitted bremsstrahlung, producing a given photon yield for a smaller flux of protons than in a calculation assuming isotropic emission.

If these factors are all taken together, *and in the same direction*, they can remove the discrepancy between hard X-ray and gamma-ray yields by reducing the number of 20 MeV protons required to a value much less than that used by Emslie and Brown (1985). However, Emslie (private communication) points out that factor (ii) could work the other way, i.e., there could equally well be a spectral steepening below 60 MeV; factor (iii) is probably not an issue any more since early errors and misprints have now been corrected (e.g., Emslie, Phillips, and Dennis, 1986); and factor (iv) depends on the position and orientation of the flaring loop on the Sun. Therefore, the consistency claimed by Heristchi seems to be extremely unlikely at best.

An equally serious problem of this model is the large numbers of pions and neutrons that would be produced in nuclear interactions of the high-energy protons required to produce the observed γ-ray continuum up to ~ 10 MeV. The electron/positron and γ-ray decay products of the pions should result in far more γ-rays in the 10 to 100 MeV range than are observed with the Gamma-Ray Spectrometer on SMM (Forrest, private communication). The neutron fluxes would also be higher than those observed. Thus, although this model is intriguing and it is being further refined by Heristchi (private communication), it seems to be beset with several problems that make it inconsistent with the γ-ray and neutron observations.

5. The Energy Loss Region

In this section we focus on the energetic particles as they enter the higher density footpoints of the lower corona and the chromosphere. Here, some small fraction of their energy goes into radiation while the rest is lost to collisions heating the cooler ambient plasma which in turn yields its own radiation signatures. In this section we examine observations not only of that immediate radiation from the energetic particles, but also that resulting from heating and collisional excitations.

First, we describe the hard X-ray and microwave radiation produced by the energetic electrons, citing observations describing its spectral, temporal, and spatial morphology. We note whether these measurements support a thick-target beam interpretation or some thermal or trap model. Then we look at the implications of the γ-rays produced by energetic ions colliding with the solar atmosphere. Next, we describe the UV, soft X-rays, and Hα emanating from the apparent footpoint products of the energy input associated with the fast electrons. While considerable qualitative support exists for the general picture of particle acceleration and transport within loops, it must be emphasized that all of the observations are subject to varying interpretation due to the uncertainties in many important parameters and unavoidable integrations over space, time, and energy.

5.1. Energetic particle radiation signatures

The most direct way to study the energetic particle populations is from the radiation produced as they move through the solar atmosphere. Bremsstrahlung X-rays are produced by the fast electrons, most from ~ 10 to 100 keV but ranging to above 10 MeV. Despite the fact that the photon production cross-section is quite broad, simplifying assumptions allow one to relate the X-ray spectrum and the injected and instantaneous electron distributions (Brown, 1971). The overlying solar atmosphere is transparent to this radiation but detection is limited to space-borne photon-counting instruments with event energy obtained by pulse-height analysis. Imaging can only be achieved using some variant of a masking technique. Fast electrons also produce microwaves by gyro-synchrotron emission as they move along the magnetic field. Even though there is significant absorption in high field regions at lower frequency, the opacity drops well below unity at the higher frequencies. The spectrum produced depends on the magnetic field strength, harmonic number, and direction. Consequently, compared to the hard

X-ray spectrum, it is more difficult to relate it directly to the spectrum of source electrons. The great advantage of microwaves is that they can be imaged interferometrically on the ground in both left and right circular polarization from <1 GHZ to over 20 GHZ. Both line and continuum γ-ray emission are produced as the energetic protons and other ions (10–30 MeV) move through the solar atmosphere. Spectroscopic measurements reveal the composition and spectra of these energetic ions.

5.2. Hard X-rays from fast electrons

In the thick-target model, the energetic electrons stream through the low density corona and lose most of their energy in Coulomb collisions in the higher density plasma at the footpoints. The effective range of the electrons, computed by integrating the expression given by Trubnikov (1965) for the energy loss rate in a cool medium, is $(E/20\ \mathrm{keV})^2 \times 7.7 \times 10^{19}\ \mathrm{cm}^{-2}$. Consequently, most deka-keV electrons are stopped by a column depth of about $10^{20}\ \mathrm{cm}^{-2}$, i.e., most of the loop length for coronal densities of 10^9–$10^{10}\ \mathrm{cm}^{-3}$. Also, since the ratio of bremsstrahlung to collisional loss is about 1 in 10^5, most of the energy flux does not appear in the form of hard X-rays but instead heats the ambient medium. While the actual electron-ion bremsstrahlung X-rays are not energetically important, they provide the most direct and most easily interpretable information on the fast electrons, and these are energetically important.

5.3. Evidence for footpoint emission

The most direct evidence that the impulsive hard X-rays are produced at the footpoints of loops was provided by the Hard X-ray Imaging Spectrometer (HXIS) on SMM when it revealed widely separated bright patches in 16–30 keV images during impulsive flares on 10 April, 21 May, and 5 November, 1980 (Duijveman, Hoyng, and Machado, 1982). The Solar X-ray Telescope (SXT) on Hinotori also showed double sources during some impulsive flares (Ohki *et al.*, 1983). For other flares (Kane, 1983) stereoscopic measurements obtained from spacecraft off the Earth–Sun line have shown that 95% of the emission at 150 keV comes from a height of less than 2500 km above the photosphere, i.e., consistent with a footpoint source.

5.4. Spectra

A balloon-borne high-resolution spectrometer (Lin *et al.*, 1981; Lin and Schwartz, 1987) has revealed the details of the 15–200 keV photon spectrum for a moderately large flare (GOES class M6). Earlier measurements had shown that the spectrum was consistent with a power-law from 20–70 keV and steepened at higher energies. Such a 'broken' power-law spectrum is also consistent with the spectrum expected from a thermal distribution of electrons. Also, it had been noted that for individual spikes within a flare, the spectrum would harden to the peak and then soften again on the fall. It also seemed that the largest flares were also the hardest. The high-resolution spectra, on the other hand (Lin and Schwartz, 1987), were not consistent with an isothermal shape on either short (2 s) or long (30 s) time-scales. The spectra show an evolving double power-law form suggestive of the dc electric field acceleration seen in the lower

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magnetosphere during aurorae. It was also shown that the soft-hard-soft spectral evolution was most pronounced at energies above 30 keV. Furthermore, there was a clearly thermal hard X-ray component which first appeared near the peak of the event, but it was not impulsive and dominated the emission as the power-law tail diminished. Lin *et al.* (1981) named this the super-hot component, at 30–35 million K some 10–15 million K higher than the normal soft X-ray emitting plasma commonly seen during this and other flares; its emission measure was about 10% of the emission measure of the 20 million K plasma. This super-hot component has not been recognized previously because of the much poorer energy resolution of earlier hard X-ray spectrometers but it is probably present in most flares.

5.5. Time structures in hard x-rays

Important information is revealed about the energy release process and interaction region by the rise, decay, and delay times of hard X-ray bursts. Flare light curves consist of single bursts or a series of bursts with widths typically ranging from seconds to tens of seconds, although faster structures are sometimes superimposed on a slower profile. Hard X-ray flares also cover >4 orders of magnitude in peak flux ranging from microflares (Lin *et al.*, 1984), detected down to the limits of sensitivity, and up to giant events which can saturate all available detectors.

Commonly observed rise times of a fraction to several seconds are thought to indicate the time development of the acceleration process. Individual spikes in microflares (Lin *et al.*, 1984; Simnett and Dennis, 1987) may actually show the fundamental units of impulsive energy release (Parker, 1988). However, some extremely rapid rise times of 10's of milliseconds are thought to be characteristic of the electron propagation times (Kiplinger *et al.*, 1983; Lu and Petrosian, 1988).

For an energetic electron either precipitating into the lower corona or becoming trapped in a low-density loop, the ambient electron density, n, seen along its trajectory sets an upper limit to the burst decay time τ_ε (there may be additional loss times). Kiplinger *et al.* (1983) show that

$$\tau_\varepsilon < \left(\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t}\right)^{-1} = 2 \times 10^8 E^{3/2} n^{-1}\ \mathrm{s} = 1.8\left(\frac{E}{20}\right)^{3/2} n_{10}^{-1}\ \mathrm{s}\,,$$

where n_{10} is the density in units of $10^{10}\ \mathrm{cm}^{-3}$. The soft-hard-soft spectral evolution typical of most flares suggests that the decay is governed by changes in electron injection/acceleration rather than by trapping of the electrons. Trapping in a low-density loop would result in the progressive hardening of the X-ray spectrum and this is sometimes observed, especially in the large, gradual bursts. The fact that many high-energy impulsive bursts decay within a few seconds supports the idea that the electrons *are* precipitating into the higher densities of the low corona and chromosphere.

During most bursts, X-rays peak simultaneously at all energies but increasing delays have been seen in the peak times at progressively higher energy X-rays for a number of flares (Bai *et al.*, 1983a; Bai and Dennis, 1985; Ohki *et al.*, 1983; Schwartz, 1984;

or see Vlahos *et al.*, 1986). There are two competing explanations for this phenomenon. The first is that the low-density traps which could produce slow decays could also produce progressive delays for electrons injected simultaneously at all energies (Bai and Ramaty, 1979; Vilmer, Kane, and Trottet, 1982). The second is a second-step acceleration process where energetic particles above some threshold are further accelerated by an energy-dependent process (see Bai *et al.*, 1983b). This is believed related to the fact that energy-dependent hard X-ray delays have been mostly observed in flares which produced observable nuclear γ-rays and/or energetic interplanetary protons (Bai and Ramaty, 1979; Bai *et al.*, 1983a, b; Bai and Dennis, 1985; Ohki *et al.*, 1983). Also a trap model really requires a progression of delays but Schwartz (1984) showed that for good statistical data, there was an absence of any delays at low energies.

5.6. Directivity of Hard X-rays

Any directivity of the hard X-ray flux could be a key diagnostic of the energetic electron population because bremsstrahlung is emitted preferentially in the direction of the incident electron (Henoux, 1975; Langer and Petrosian, 1977). A good measure of directivity could be made using identical instruments with good sensitivity above several hundred keV (necessary because Compton backscatter is expected to wash out the effect at lower energies) placed 90° apart relative to the Sun. To date this has not been possible but two recent studies (Vestrand *et al.*, 1987; Kane *et al.*, 1988) have attempted to measure it using existing sets of less than ideal data. A set of 39 joint ISEE-3 and PVO observations, with angular separations ranging from 1 to 66 degrees, does not indicate any systematic directivity (Kane *et al.*, 1988). In contrast, Vestrand *et al.* (1987) have made a statistical study of the >300 keV flux observed by a single instrument, GRS, where they find convincing evidence of spectral hardening for flares closer to the limb. However, there are problems with both studies – the first must be accurately inter-calibrated and has a small sample of ideal events while the second is prone to selection effects. A much clearer case for directivity can be made for very high energy electron bremsstrahlung. Above 10 MeV, GRS has observed continuum photon emission primarily from flares near the solar limb (Vestrand *et al.*, 1987). These γ-rays are believed to be from ultra-relativistic electrons emitting close to their footpoint turnaround and hence mostly moving parallel to the surface. Their bremsstrahlung is highly beamed in the direction of electron motion thus explaining these results.

The energetic electrons also emit gyro-synchrotron microwave radiation in addition to hard X-rays. Using the peak fluxes as a function of energy for a sample of ~ 400 events, Kosugi, Dennis, and Kai (1988) determined that for impulsive flares the best correlation was obtained between X-rays ≤ 80 keV and the 17 GHZ microwaves. Assuming then that both emissions come from the same population, they concluded that ~ 20 GHZ flux comes from ≤ 200 keV electrons streaming through a ~ 900 G field in a layer $3–10 \times 10^3$ km thick. Few electrons are reflected and trapped in the loop and 'the thermal model is incompatible with the observations'. However, many other studies show the microwaves originating near the top of the loop (Leach and Petrosian, 1983) even for flares with footpoint hard X-rays.

5.7. Gamma rays from energetic particles

Gamma-ray lines were first detected during the great flares of August 1972 (Chupp *et al.*, 1973; Chupp, Forest, and Suri, 1975). Since the launch of SMM, GRS has detected line emission in many flares and a far greater understanding of the morphology of these events has been obtained (Chupp, 1984). Although it has not yet been possible to fly the appropriate detectors to directly image the MeV photons, we at least know that the majority of energetic ions move towards the Sun and not into space because the outgoing particle flux of events detected on interplanetary spacecraft is usually only $\leq 1\%$ of that necessary to produce the observed γ-rays (Murphy and Ramaty, 1984).

One of the more important results from the last maximum is that for some events the peaks of the γ-ray emission are coincident (± 1 s) with the hard X-ray peaks (Chupp, 1984). From earlier observations (Chupp *et al.*, 1973; Chupp, Forrest, and Suri, 1975), it had been thought that additional time, at least 10's of seconds, was required to accelerate ions up to the 10's of MeV necessary to produce γ-ray line emission. The best example of coincident peaks were found for energy bands from 40 keV to 25 MeV for the flare of 1982 February 8 (Chupp, 1984). Also, fast decay times imply that the energy loss region must be of high density precluding the trapping of the bulk of the ions high in the corona (Share *et al.*, 1983; Ramaty and Murphy, 1984; Murphy and Ramaty, 1984).

The spectroscopic analysis of the γ-ray lines is expected to yield rich results when these measurements can be obtained during the coming maximum using liquid nitrogen cooled germanium detectors. To date the only high-resolution results were serendipitous HEAO-3 measurements of 2.223 MeV photons which leaked through a thick CsI anti-coincidence shield (Prince *et al.*, 1982). This is a narrow line resulting from the capture of neutrons on hydrogen. From other flares it has been learned that this line is suppressed for limb events relative to disc flares (Murphy and Ramaty, 1984) showing that the photons must be produced in the photosphere as the result of a downward directed energetic particle flux.

Another important result is that the nuclear line component may be present in all flares. Forrest (1983) has extrapolated the 270 keV to 1 MeV bremsstrahlung spectrum to the nuclear line range (4–8 MeV) for 65 flares and attributed any excess to nuclear processes. This excess was not always seen, but the absence may be attributed to the sensitivity in the nuclear range. The hypothesis of an omnipresent high energy ion acceleration is quite controversial as it covers only a small fraction of the observed hard X-ray flares (~ 1 in 100) due, at least in part, to the more difficult task of detecting higher energy γ-rays (falling spectrum and detection cross-section). In contrast, Bai and Dennis (1985) and Bai (1986) have determined that there are distinctive characteristics to γ-ray line producing flares.

5.8. UV–hard X-ray comparison

Several groups (Poland *et al.*, 1982; Machado, Duijveman, and Dennis, 1982) have found evidence for the cospatiality of the O v transition zone line and impulsive X-rays to the resolution of SMM HXIS and the UV Spectrometer Polarimeter (UVSP). A comparison of hard X-ray observations with coincident, high time resolution observations of hard X-ray, UV line and continuum emissions was reported by Orwig and Woodgate (1986). They found that in one flare on 1984 May 20, the UV continuum and hard X-ray emissions were simultaneous to within 0.1 s. A detailed cross-correlation analysis of the three emissions in another flare on 1985 April 24 showed that spiky features in the UV line and UV continuum emissions were simultaneous to within 0.1 s, but both UV emissions were delayed with respect to the corresponding hard X-ray features by up to 0.3 s. Cheng *et al.* (1988) have repeated the analysis for this event and present similar results for other events. These observations place strict limitations on the energy propagation times from the corona through the transition region to the lower chromosphere during the flare impulsive phase.

The simultaneity to within 0.3 s between the hard X-ray peaks and transition zone lines can be understood qualitatively in the thick-target model. However, attempts to quantify the expected O V flux have met with limited success (e.g., Poland *et al.*, 1984; Emslie and Nagai, 1985; Mariska and Poland, 1985).

The simultaneity between the hard X-rays and continuum, which is generally believed to originate from close to the temperature minium region, is much more difficult to understand at first sight. The high-energy electrons do not make it down to this low level in the chromosphere so that direct heating is not possible. Thermal conduction would take too long and is totally ineffective at these depths in any case (Emslie, Brown, and Machado, 1981). Furthermore, the extremely large energy deposition rates required at the temperature minimum region are unlikely to be attained by any canonical energy transport mechanism like accelerated particles or EUV heating (Machado and Mauas, 1987). Instead, Machado and Mauas (1987) have proposed that the source of the emission is Si II in the temperature minimum region created by photo-ionization due to line emission (mostly from the C IV resonance line at 1549 Å) from the transition region.

5.9. Iron $K\alpha$

Transient iron $K\alpha$ radiation is another possible diagnostic of electron beaming and/or the height of the hard X-ray production region (Tanaka, Watanabe, and Nitta, 1984; Emslie, Phillips, and Dennis, 1986). The radiation is produced after the removal of the K-shell electron either by photo-ionization (fluorescense) or by electron-impact. During a flare, there may be three sources of excitation: the soft X-ray plasma spectrum above 7.1 keV, the non-thermal X-rays above 7.1 keV, or an electron beam passing through the chromosphere. The efficiency of either fluorescence response depends upon the height of the X-ray source above the photosphere because of the difference in the solid angle subtended below.

Tanaka, Watanabe, and Nitta (1984) used the Hinotori instruments to measure the X-ray spectrum from 1.5 to > 100 keV during the 1981 July 28 flare. During the rise of the impulsive phase, before the soft X-ray plasma became too intense, the power-law spectrum extended to as low as 7 keV. Furthermore, they found that the fluorescence from the soft X-ray plasma could not account for all of the iron $K\alpha$ emission at that time.

However, the excess could be explained if height of the X-ray source is close to zero, or higher if there is an electron beam penetrating the chromosphere. Either of those cases is consistent with a footpoint source for the hard X-rays.

5.10. Soft X-rays

When the energy released in the corona reaches the cooler plasma near the footpoints, heating occurs resulting in a thermal plasma with a bulk temperature of 15–20 million K. The main increase in this hot plasma appears during the impulsive phase although it is usually detectable, albeit at a low level, for at least a minute before the beginning of the hard X-ray burst (see Priest *et al.*, 1986, for discussion). This may be a thermal precursor to the main energy release or the hard X-ray flux may be below the instrumental threshold level.

There are two principal observational requirements in soft X-rays which must be met by a successful model for the impulsive phase. The first is that the dynamic input of energy during the impulsive phase must be accounted for by a corresponding increase in the energy content of soft X-ray plasma. One of the early results (Neupert, 1968) of spaceborne instrumentation was that the smooth rise of the soft X-ray light curve resembled the integral of the impulsive hard X-ray light curve as is expected in the thick-target model. It is also expected to some degree in thermal conduction and joule heating models. The second point of agreement should be between the plasma dynamics revealed by spectroscopic line measurements and the consequences of a rapid energy input into a cooler stable region.

Although both hard X-rays and soft X-rays have been observed for thousands of flares, determining both the energy content of the initial fast electrons and the resultant soft X-ray emitting plasma is a process plagued with observational difficulties (Wu *et al.*, 1986). To obtain the fast electron spectrum, a power-law is normally fit to the hard X-ray spectrum and then the electron distribution is obtained from the fit parameters (Brown, 1971; Lin and Hudson, 1976). In a typical case, most of the electron energy is within ~ 10 keV of the low-energy cutoff, usually assumed to be ~ 20 keV, in a spectral region unresolvable by most hard X-ray detectors. The energy content of the soft X-ray plasma is also difficult to determine, since most measurements give only the temperature and emission measure while the filled volume (or density) must be otherwise estimated or guessed.

If the injection of energy into the transition region at the base of the loop exceeds an energy flux threshold defined by the peak of the radiative loss function and the pre-flare density (Fisher (1987) estimates a threshold $\gtrsim 10^{10}$ ergs cm^{-2} s^{-1}), the resultant heat cannot be radiated away fast enough leading to a rapid increase in temperature and volume. This process results in what is known as explosive chromospheric evaporation (Antonucci *et al.*, 1982; Antonucci and Dennis, 1983) and it may explain the blue-shifted emission lines observed in 80% of M and X disk flares detected with BCS. The blue-shifted component is absent in flares past 60 degrees in longitude as expected for upwardly directed flows.

5.11. Hα OBSERVATIONS

Of all the flare emissions, only in the optical Hα line does the current instrumentation permit high resolution images and spectra with a rapid sampling time (Acton *et al.*, 1982). The radiation comes from the lower chromosphere below the region where the UV and EUV are formed. While the path length to the optical source is almost the same as for the UV source, the column depth is increasing rapidly and this quickly attenuates an incident electron beam. With arc sec resolution, Hα images locate particle precipitation and energy loss with respect to other data such as vector magnetograms. Additionally, the radiative loss rate can reflect the rapid input and dissipation of energy just as seen in the EUV continuum.

The new generation of spectroheliogrammetry has spawned a concomitant effort to predict the spectra as a function of the energy release process. In particular, Canfield, Gunkler, and Ricchiazi (1984) have made predictions of the flare atmosphere under the condition of impulsive energy release to predict the Hα profile, which typically shows a central reversal. Additionally, only for high values of the energetic electron flux ($\gtrsim 10^{10}$ ergs cm^{-2} s^{-1} above 20 keV) are there broad non-gaussian wings in the Hα profile. Canfield and Gunkler (1985) have found evidence for such enhanced-wing signatures well correlated in space and time with hard X-ray emission during the compact solar flare of 7 May, 1980.

These observations provide strong support for the thick-target model although it is difficult to determine quantitatively the electron flux and spectrum required to produce the measured enhanced wings. As mentioned earlier, these high values of the energy flux are considered necessary to produce explosive chromospheric evaporation which gives rise to the upflowing plasma evidenced by the soft X-ray blue-shifts. Zarro *et al.* (1988) have seen redshifts in the Hα spectra indicating the corresponding plasma downflows into the cooler chromosphere. They have shown momentum balance to within the factor of two uncertainties of the measurements in both spectral ranges. Importantly, these spectral features are characteristic only of the impulsive phase with qualitatively different features observed during the following gradual phase of flares.

6. Conclusion

It is clear that as a result of the explosion of new data on impulsive phase phenomena obtained over the previous solar maximum, we now have a much clearer picture of a solar flare. Nevertheless, the fundamental longstanding problems remain unanswered. The thick-target loop model emphasized in this paper is consistent with much of the new data but it is clearly a great oversimplification. It does, however, serve to focus our thinking on the outstanding issues that elude our comprehension. These include the following principal flare problems:

(1) The rapid rate of energy release – as high as 10^{30} erg s^{-1} in some flares.

(2) The rapid acceleration of protons and electrons to relativistic energies in seconds or less.

(3) The number of particles accelerated exceeds the number initially in the coronal

loop. How is a sufficient number of particles transported from the higher density regions into the accelerator on the required time-scales?

(4) The electrical current associated with the electron beam would produce an unreasonably large magnetic field of $\gtrsim 10^9$ G unless it is divided into $\gtrsim 10^6$ filaments (Spicer and Sudan, 1984; Holman, 1985).

(5) The total energy in fast electrons appears to be larger than the thermal energy of the soft X-ray emitting plasma, especially for flares where the hard X-ray spectrum is measured to be a power law down to energies as low or lower than 10 keV (Kahler and Kreplin, 1971; Tanaka, Watanabe, and Nitta, 1984).

The new instrumentation planned for the current cycle of solar activity will have exciting new capabilities to address these and other issues in ways never before possible. As stated in the Max '91 report (Dennis and Canfield, 1988), "*The diagnostic power of this new instrumentation is qualitatively different from what was available during the previous solar cycle. It allows us to go deeper than the question of what a flare is; it allows us to gather spectra and images that are relevant to the question of what causes a flare to happen in the first place. We can seriously address not only the impulsive energy release with its attendant heating and particle acceleration, but also the magnetic and thermal environment that leads to it.*"

Currently planned instruments include the core space missions – the Japanese Solar-A spacecraft and the Gamma Ray Observatory (GRO) – and advanced instruments on high altitude balloons and rockets and at groundbased observatories. With this comprehensive Max '91 program of observations we can look forward to obtaining the following observations:

– Hard X-ray images with arc sec angular resolution that will, for the first time, fully resolve flaring magnetic loops and trace the evolution of the electron spectrum along the loops.

– Hard X-ray and γ-ray spectra with keV energy resolution to resolve, for the first time, γ-ray lines and determine their widths and shapes and also clearly separate the thermal and non-thermal components of the hard X-ray spectrum.

– Vector magnetograms with better spatial resolution and stability than previously possible to quantitatively measure, for the first time, the energy content of active regions before, during, and after a flare.

– Microwave imaging spectroscopy with arc sec angular resolution, subsecond time resolution, and better than 10% spectral resolution to exploit the microwave diagnostics of coronal magnetic fields, energetic electrons, and pre- and post-flare plasmas.

The Max '91 program is being developed to coordinate these and other observations in order to optimize the scientific return. Solar activity is rising at an unprecedented rate toward what may be an unexpectedly early and intense maximum in 1990. All indications are that the new observations will yield a prolific scientific bonanza; we stand expectantly and impatiently waiting for the show to begin.

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