HARD X-RAY FLARES FROM THE SUN*

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Abstract

A review of solar flare hard X-rays is presented. Various features of these flares have been considered to pinpoint the location of the source of emission and the nature of the emission of these flares. It is shown that the arguments for the location of the source in the dense chromosphere and against it are finely balanced, so that nothing conclusive may be said about the location of the source. Similarly, arguments for and against the non-thermal nature of the emission do not allow any definite conclusion at the present moment, though a belief persists that the hard X-ray emission is nonthermal in nature. Theories of non-thermal X-ray emission are briefly considered and it has been suggested that a combination of emission mechanisms may be needed to explain the complete energy spectrum of hard X-rays.

A solar flare is the most dramatic manifestation of of solar activity. A big flare may release as much as 10^{31} —10^{32} ergs of energy in a short time of about 10^{3} sec. The bulk of this energy is in the form of optical and corpuscular emissions. The rest is spread over the various regions of the electromagnetic spectrum whose emission is enhanced by several orders of magnitude over their quiet-time level. Certain emissions, such as hard X-rays and γ-rays, are seen only at the time of a flare; their quiet-time levels are too low to be detected. Moreover, hard X-rays, as well as some other emissions, appear in the form of short, sharp bursts.

It is commonly believed that the energy of a flare comes from the partial annihilation of magnetic fields of active regions where the flares take place. This belief stems from the following reasons : (1) the flares take place in regions where the magnetic fields reverse their polarity, (2) rearrangement of lines of force occurs as a result of a flare, and (3) there is no other source known which could deliver the required amounts of energy at the required rate. A reduction of magnetic field strength, say, from 300 gauss to 250 gauss can release as much energy per unit volume as is required for a big flare. The actual process of transfer of energy from the magnetic field to the particles of the solar atmoshphere is, however, not completely known at the present moment. Though this is an important problem, we shall not be considering it here; we merely assume that such a transfer does take place.

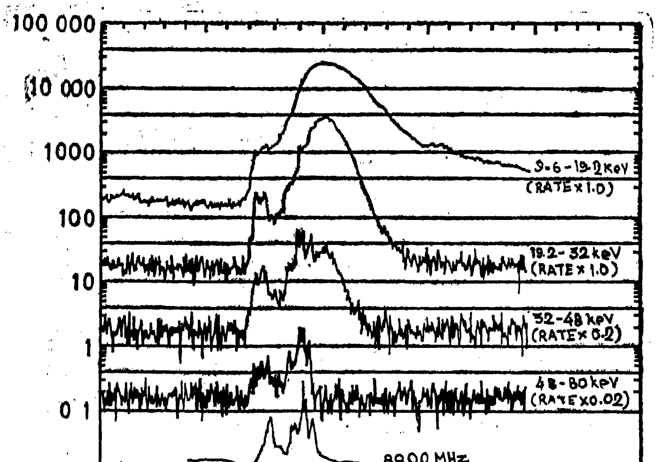

Fig. 1: A hard X-ray burst recorded in various energy bands. Maximum is seen to shift to earlier times as one goes to higher energies. Notice the rapid intensity fluctuations. The lowermost plot is the impulsive microwave burst at 8,800 MHz (Zirin *et. al.* 1971)

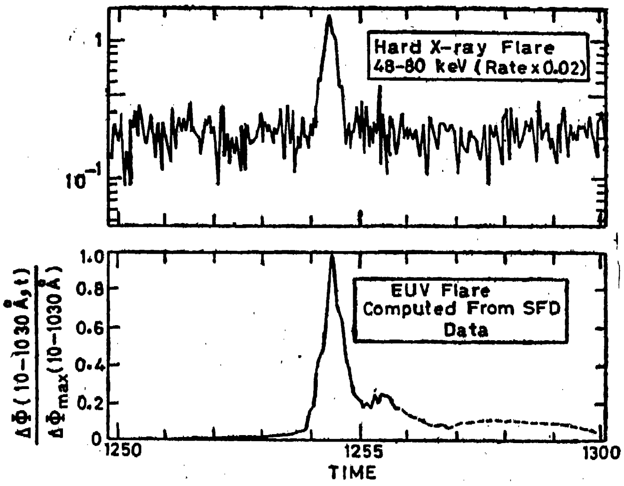

Fig. 2: Intensity-time profile for 48-80 kev X-rays and the EUV flux enhancement computed from SFD data for the flare of May 24, 1968 (Kane and Donnelly 1971).

As has been noted, the hard X-ray emission takes place in the form of sharp bursts (Fig. 1). These bursts are very well correlated in time with the bursts of EUV radiation (Fig. 2), flashes of Hα and white light whenever the later occur (Fig. 3), bursts of microwave radiation and type III bursts at metre wavelengths. As we shall see below, these correlations are important for the theory of the origin of hard X-rays.

The sharpness of the bursts increases as we go to higher energies. Moreover, the bursts occur irrespective

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of the importance of the flare. In some cases these bursts have been found to be quasi-periodic (Parks and Winckler 1969 ; Frost 1969) while in most cases no single periodicity has been found. It has been suggested that the whole X-ray emission may be regarded as consisting of individual bursts of varying amplitudes, each burst lasting from 2 to 20 sec and this time may be inherent to the acceleration mechanism of the electrons responsible for the emission. It is possible that the magnetic field annihilation process is interrupted quasi-periodically with time periods of 2—20 sec (Anderson and Mahoney 1974). It is also possible that the individual flashes come from locations which are unconnected. We would, of course, not be able to find it out since the spatial resolution of the present-day detectors is rather poor. In the EUV pictures of the Sun, however, one observes bright points in the coronal holes. A significant fraction of these bright points exhibits flaring phenomena and in large number of flaring events bright points separated by thousands of kilometres have been seen to flare simultaneously (Noyes et al. 1975).

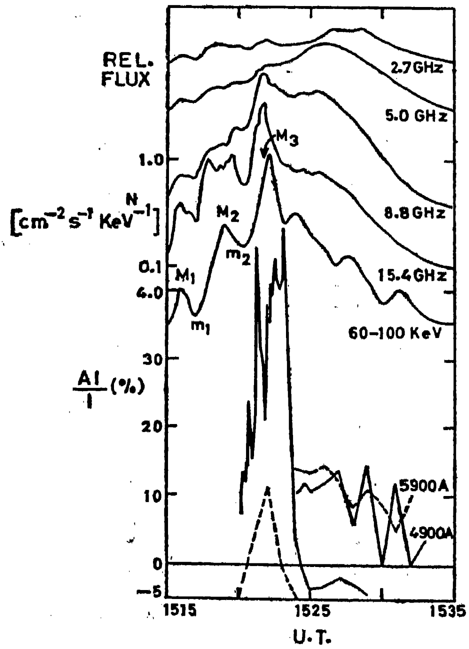

Fig. 3: Intensity-time profiles of hard X-rays and white light for the flare of August 7, 1972 (Rust and Hegwer 1975)

Before we can say anything about the processes which are likely to produce hard X-rays, we have to establish (i) the location of the source, and (ii) the nature of the emission. In the absence of high resolution instruments ($\lesssim 10''$) and correlated observations by two satellites, we can infer the location of the source only indirectly. The excellent correlation in time with the EUV bursts indicates that the hard X-ray source may be located low down in the chromosphere, since there are reasons to believe that the EUV bursts originate in the regions where $n_e \approx 10^{12}$ cm^{-3}. The correlation with Hα and white light emission would also suggest the source to be in the dense chromosphere. On the other hand, correlation with microwave bursts would suggest that the source may be somewhere in the lower corona since the microwave impulsive bursts are believed to come from this region via the synchrotron emission of energetic charged particles gyrating in the magnetic fields of the coronal active regions (Takakura 1972). It may, however, be noted that the correlations in all these cases may simply mean that the energy source is the same, rather than that the emissions are cospatial. Behind-the-limb flares can also be used to monitor the location of the source region.

The idea here is that the events taking place low in the chromosphere behind the limb should be occulted by the limb and their character should undergo a change vis-a-vis the events on the front side of the disk. On the other hand, if the events take place at high altitudes (10^4—10^5 km) or over extended regions in the solar atmosphere, their character would not be affected by the limb. The results of such studies are, however, not very definitive. Roy and Datlowe (1975) examined 37 behind-the-limb X-ray bursts (identified by the absence of any simultaneous flashes of Hα on the disk) from the OSO-7 data and compared their results with those of the disk events. They found that the proportion of the behind-the-limb events having hard X-ray components (2/3 approx.) is not significantly different from the proportion of such events on the disk. Moreover, the peak 20 kev flux for the events behind-the-limb was not different from that of events on the disk. From these observations it may be concluded that the hard X-ray emission takes place over extended regions. Mckenzie (1975), however, reached an opposite conclusion. He examined data for 9 behind-the-limb intense soft X-ray bursts which were likely candidates for the hard X-ray component. He found that none of these events had any appreciable hard X-ray component. Thereby he concluded that the hard-X-ray emission must be localized in the chromosphere and was therefore occulted by the limb. He did find a small hard X-ray emission component accompanying the soft X-ray events, for which he proposed trapping of energetic electrons at high altitudes. The possibility of the hard X-ray emission high in the corona has also been suggested in connection with the event of March 30, 1969 (Frost and Dennis 1971). Altogether, the position regarding the location of the source of hard X-rays is not clear.

Let us now consider the nature of the source, the the information about which may be provided by (i) the distribution of hard X-ray bursts in solar longitude, and by (ii) the presence, or absence, of polarization in them. Several workers (Ohki 1969; Pinter 1969; Phillips 1973; Datlowe *et al.* 1974; Pizzichini *et al.* 1974) have undertaken the study of hard X-ray bursts in relation to the solar longitude. The results have been conflicting. This is not surprising, since there are many factors which may complicate matters. Some of these are (1) the impulsiveness of the bursts, (2) the sensitivity thresholds of the detectors, and (3) the spectral hardness of the bursts. The expected anisotropy in any flare model is rather small, whereas the range of the burst intensities is rather large. Since no detector can cover the whole of this range, selection effects are inevitable. For statistical analysis of sufficient accuray, one should have a large sample, the spread in whose intensities ($\backsim 1/\sqrt{N}$) is reasonably small. Further, such a sample should be available for each longitude (or a small range of longitudes). Even then, whether the results would tell us anything worthwhile is debatable. The reason is that there are many factors (e.g., back-scattering, details in the spectrum and pitch angle distribution of the source electrons) whose contribution to the anisotropy of emission is uncertain. It must be borne in mind here that in studies of this type, as well as of the behind-the-limb events, identification of hard X-ray flares may also pose some problems, since some prolific hard X-ray emitting flares are known to be poor emitters of Hα , the usual identifier of a flare.

The message that we get from the polarization studies is also not clear at the present moment. Firstly, only a few attempts have been made to measure polarization. Secondly, the energy at which the measurements have been made is at the borderline between the soft and the hard X-rays. Thirdly, the results derived from these measurements (Tindo et al. 1972; Nakada et al. 1974) are apparently mutually conflicting. What is needed is the measurement of polarization at high energies with the laboratory calibrated instruments.

Let us now see if we can say anything unambiguous about the thermal or the nonthermal nature of the emission. The main arguments advnced in favour of a nonthermal interpretation are (1) short rise and decay times of the bursts, (2) the occurrence of hard X-ray bursts before H α maximum (the time lag is $\sim$ 0.05-3 min), (3) close temporal association between the hard X-ray bursts on the one hand and impulsive microwave bursts and type III bursts on the other, (4) rapid intensity variations in the hard X-ray bursts, and (5) the observed power-law energy spectrum of the emission and the source electrons (see below, however). None fo these arguments are, of course, conclusive. Thermal models with elaborate temperature distributions can be built which satisfy some of these criteria. It has been shown, for example, that a certain temperature distribution in the emitting region may give out thermal emission with a spectrum resembling a power-law spectrum (Chubb 1970). Again, the observed break in the simple power-law specturm of hard X-rays in the region of 60-100 kev is characteristic more of a thermal emission than that of a non-thermal emission, unless one assumes a corresponding break in the power-law spectrum of the source electrons themselves. Further, the observed softening of the bursts towards the end seems more consistent with a thermal interpretation (a plasma heated and then cooled) than a nonthermal one. But the argument that clinches the issue in favour of the nonthermal interpretation is that the termperature of the plasma required for thermal emission of hard X-rays are $\gtrsim 10^{8}$ K, and at these tempertures, the mean free path of the electrons is larger than the scale height of the emitting region, and therefore the electrons are more likely to escape the region rather than undergo binary collisions necessary for the establishment of a Maxwellian velocity distribution. Avoiding the problem of thermal relaxation by using high densities lands one into the problem of excessively high energy requirement. Total energy needed to sustain the plasma at $\sim 10^{8}$ K, against heat losses due to the particle streaming is prohibitively large for $n_e \gtrsim 10^{9}$ cm^{-3} (Kahler 1971a,b). If we have plasma turbulence in the region, then the wave particle interactions will restrict the heat loss and the thermal interpretation may then become more appealing.

We have cited the power-law spectra of the source electrons and the hard X-ray emission as an argument in favour of the nonthermal interpretation. But doubts have lately arisen whether the spectra derived from observations have any meanig at all (Craig and Brown 1976). Take first the derivation of electron spectrum. The observed flux of radiation is given by

$$I\ (\varepsilon,t) = \frac{nV}{4\pi R^{2}} \int_{\varepsilon}^{\infty} F\ (E,t)\ Q\ (\varepsilon,E)\ dE\ , \qquad (1)$$

where nV is the total number of emitting particles, R the Sun-Earch distance, F(E,t) the electron energy spectrum and Q (ε,E) the production cross section of photons of energy ε. Now what we have are the observations of X-ray emission at a few energies (or in a few enrgy bands). Usually one fits a power-law spectrum to these observations (a procedure based on the belief that X-rays are nonthermal, but otherwise completely arbitrary), and then uses this power law to get F(E) after feeding in (1) the appropriate expression for Q (ε, E). In some cases (1) can be solved analytically, but in most cases it cannot be, since Q (ε, E) has to be interpolated numerically. The appropriate procedure in such cases is to use the emission flux data as it is, without fitting it to a power law. That means that I (ϵ) is replaced by a discrete set $I(\epsilon_i) = I_i$. F(E) then must likewise be replaced by a discrete set $F_j = F(E_j)\Delta E_j$. The equation (1) then becomes

$$\sum Q_{ij}\ F_j = I_i\ , \qquad (2)$$

or in matrix notation

$$\left[Q\right] \left\{F\right\} = \left\{I\right\} \qquad (3)$$

or

$$\left\{F\right\} = \left[Q^{-1}\right] \left\{I\right\}. \qquad (4)$$

This equation is unstable in the sense that small errors in $\{I\}$ may be magnified many times due to large entries in $[Q^{-1}]$ resulting in large errors in $\{F\}$. (This statement is correct if bremsstrahlung is the X-ray production process. In the case of other processes, such as inverse Compton process, the statement needs to be verified.) In some cases the errors are so large that the result is rendered meaningless. It is important to point out that improvement in spectral resolution does not alleviate the severity of ill-conditioning of (4). What is needed for the correct determination of the electron energy distribution is a large number of observational points, i.e. the large dynamic range of the detector system. If one has grounds to believe that the X-ray spectrum is a power-law spectrum, then the procedure may be legitimate, but what is not true is the supposition that because a power law for F(E) yields a good fit to I (ϵ), the power law is the true electron spectrum. These remarks also apply to the cosmic X-ray spectrum determination.

Even if we grant that the electrons have a power-law pectrum, it is not necessary that the hard X-ray spectrums will also be of the power-law form. There are two main reasons for this :

(i) X-ray photons which propagate downwards from the place they are produced are Compton scattered by the solar atmospheric electrons. At low energies ($\lesssim$ 15 kev) many of these albedo photons are photoelectrically absorbed. At high energies, the albedo contribution is diminished because of the relativistic anisotropy of Compton scattered photons and by the increasing loss of the photons in scattering. The backscattering thus results in the distortion of of the X-ray spectrum , which in the hard X-ray range, amount to as much as 30 per cent (Santangelo *et al.* 1973). The backscattering also produces a steepening in the X-ray spectrum in the region of 40 kev.

(ii) The model dependent factors affect in complex ways the intensity and spectrum of hard X-rays. For example, if the energy loss time of the electrons is small (thick target) then the instantaneous electron energy distribution may be different from that at injection and this may cause deviation from the power-law as well as a change in the power-law exponent of the X-radiation (Brown 1971). Similar effects may be produced by the inhomogeneities in n_e and F, or anisotropies of the assumed X-ray production cross-section.

In fact, there are so many factors and their contribution so uncertain that not much can be said about the nature of the X-ray spectrum.

Thus we find ourselves in a strange situation. Although there are a large number of observations of hard X-ray bursts, little can be said with any certainty about the nature of the hard X-ray emission, or about the nature of the source of emission, or about the physical processes which may be responsible for the production of the emission. Still, the belief prevalent among solar physicists is that the hard X-ray bursts are nonthermal. Before we discuss the nonthermal processes of X-ray production, we show in Fig. 4 a simple-minded model of a flare which has been constructed keeping in view the optical observations. From the neutral point X, where the field merging takes place and the particles are accelerated, the energetic particles may move upward as well as downward. The former may produce microwave bursts in the lower corona and later, type III bursts in the higher layer. The downward moving particles may excite hard X-ray bursts and indirectly, by depositing energy in the lower chromosphere through collisions, the EUV bursts. This sequence takes care of the various temporal associations. Flare models on these lines have been proposed by Wild *et al.* 1963, Tandon *et al.* 1968 and Takakura 1972, among others.

We now discuss briefly the nonthermal processes which may produce hard X-ray photons. The synchrotron radiation may clearly be ruled out because of the extreme conditions of magnetic field and/or particle energies it demands for the productions of X-rays. This leaves us with the following three processes :

1. Inner bremsstrahlung or bremsstrahlung associated with suprathermal protons;
2. inverse Compton scattering; and
3. nonthermal bremsstrahlung (thin and thick targets)

The first of these proceseses, namely, inner bremsstrahlung, is the radiation associated with the interaction between suprathermal protons and the electrons of the ambient plasma. This process was suggested as a possible hard X-ray production mechanism in the flares by Boldt and Serlemitsos (1969). Calculations show that the spectral exponent of the emitted radiation is the same as that of the suprathermal protons. The following two arguments go against this process being the source of hard X-rays in flares : (i) One does not know for sure if each hard X-ray flare is also a proton flare and whether spectral index of the emission agrees with the spectral index of protons; even if the exponents agree, there will always be doubt if the proton energy distribution in the interplanetary space (which is what is measured) can be identified with the proton energy distribution at source; propagation effects may introduce changes; and (ii) it has been argued that the protons are not accelerated in the first moments of a flare (Svestka and Fritzova-Svestka 1974).

Inverse Compton scattering is the process in which a low energy photon is scattered by a relativistic electron, the former walking away with its energy increased by several orders of magnitude. The process was suggested as a source of hard X-rays in flares by Shklovskii (1965) Zheleznyakov (1968) and Tandon et al. (1968). In this case, the spectral exponent α of the emitted radiation is related to the spectral exponent m of the electrons by the relation : $\alpha = (m-1)/2$.

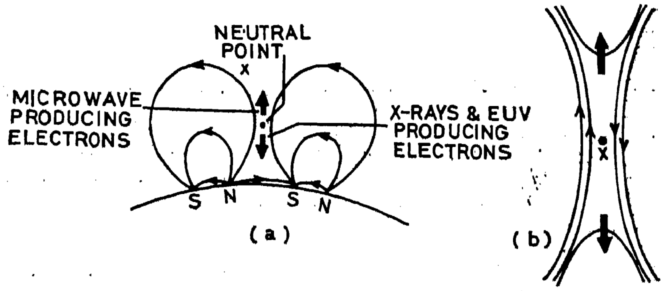

Fig. 4: Schematic model of a flare. The field merging takes place at the neutral point. The accelerated particles can move upwards and downwards from this point.

Nothermal bremsstrahlung, bremsstrahlung produced by a nonthermal distribution of electrons, has been suggested as the source of hard X-rays by Kane and Winckler (1968), Holt and Ramaty (1969), Zirin et al. (1971), among others. In this case, the following relations between α and m are obtained (Korchak 1971)

$$\alpha \simeq (m-1), \text{ relativistic electrons, thin target;}$$

$$\alpha \simeq m, \text{ nonrelativistic electrons, thin target.}$$

For a thick target, the bremsstrahlung spectrum is somewhat softer than for a thin target (Brown 1971). Moreover, the time profile of the resulting burst is governed by the rate at which the electrons are injected in source region, which in turn depends on the acceleration mechanism, about which very little is known at the moment.

The comparative study of the powers of the inverse Compton scattering and the nonthermal bremsstrahlung (Bhatia and Tandon 1973) shows that the former produces hard X-rays more efficiently at high electron energies and the latter process dominates at near relativistic energies and lower electron energies. Since the electron spectrum in a flare is expected to run from a few kev to a few tens of Mev, it is quite conceivable that both processes contribute to the production of hard X-ray bursts.

Note that recently Lee (1974) has observed a time correlated emission of hard X-ray and microwave bursts in a laboratory plasma discharge, which has a number of phenomenological similarities with solar flares. This indicates that some of the physical processes involved may be common to both the cases.

We have reviewed here the various features of the hard X-ray bursts. It is clear from the arguments for and against the various suggestions that, at the present moment, the picture is somewhat hazy. Nothing conclusive can be said either about the nature of the emission, or about the source electrons, or how these electrons might be accelerated. Belief, however, perisists and we subscribe to it, that the hard X-ray emission is nonthermal. This is because of the excellent correlation between the hard X-ray bursts and the impulsive microwave bursts. Even if we agree on the nonthermal nature of the emission, the question of the energy spectrum of the source electrons still remains to be answered. It is hoped that much of the haze will soon be lifted and we shall know where we stand.

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