THEORETICAL MOTIVATION FOR HIGH SPATIAL RESOLUTION, HARD X-RAY OBSERVATIONS DURING SOLAR FLARES

(Invited)

A. Gordon Emslie

Department of Physics, UAH, Huntsville, Alabana 35899, U.S.A.

ABSTRACT

We review the important role played by hard X-ray radiation as a diagnostic of impulsive phase energy transport mechanisms. It is argued that the sub-arc second resolution offered by an instrument such as the Pinhole/Occulter Facility (P/OF) can greatly increase our understanding of such mechanisms.

I. INTRODUCTION

For nearly three decades, observations of solar flares in hard X rays (photon energy $\epsilon \gtrsim$ 10 keV) have been vigorously pursued, in an attempt to understand the true nature of the impulsive phase of this astrophysical enigma. Although the total amount of energy emitted in hard X rays is a negligible ($\lesssim 10^{-5}$) fraction of the flare energy budget, this radiation is an extremely valuable diagnostic of the population of high energy electrons which produce the hard X rays, and, according to some models, these electrons constitute a dominant fraction of the energy released in the flare. Indeed, since the upper solar atmosphere is optically thin to all short-wavelength (< optical) radiation, electrons must constitute the dominant form of energy transport there, and so the importance of high quality diagnostic hard X-ray observations becomes obvious.

It is generally accepted that solar flare hard X rays are produced by bremsstrahlung interaction of high energy electrons with ambient protons (see, however, Emslie and Brown, 1985). To investigate this farther, toward the ultimate goal of understanding the mechanisms that give rise to a solar flare, we must evaluate the characteristics of the high energy electron population through interpretation of its bremsstrahlung signature. This involves an investigation of the temporal, spectral, spatial, and polarization signatures of the hard X-ray radiation. Spectral information has been available since the earliest observations (Peterson and Winckler, 1959), with ever-increasing precision as higher resolution detectors with larger and larger detecting areas have been developed (Lin et al., 1981). The excellent statistics available from recent large detectors such as the Hard X-Ray Burst Spectrometer (HXRBS) onboard the Solar Maximum Mission (SMM) satellite have allowed studies of fine temporal structure ($\tau \approx 10$ ms) in flares to be made (Kiplinger et al., 1983). Polarization measurements are relatively sparse, yet have provided definite results (see Tramiel et al., 1984, and references therein) to be compared with model predictions.

One of the major problems of interpreting the above mentioned data has been the lack of spatial information on the source. This means that data represent a convolution over a wide extent of possible physical regimes, and it is extremely difficult, if not impossible, to deconvolve this spatial information. By way of an example, consider a model in which the (nonthermal) electrons responsible for the bremsstrahlung radiation are injected at the apex of a magnetic loop and spiral about guiding magnetic field lines. The degree of curvature and torsion in the field line geometry will affect the predicted hard X-ray polarization from the entire source. Indeed, for a suitably inhomogeneous magnetic field, one expects the target-averaged electron velocity distribution to be nearly isotropic, leading to a near-zero observed polarization; however, over sufficiently localized regions of the source quite high polarization can result (see Leach et al., 1985). Similar problems exist in the interpretation of bremsstrahlung spectra in terms of a continuous injection thick target model (Brown, 1971): the physical processes operating on the electrons within the source volume can have as much of an effect on the emitted bremsstrahlung spectrum as does the electron spectrum at injection (Brown and MacKinnon, 1985). With spatial resolution these effects can be decoupled and the injected spectrum (with its associated constraints on the primary energy release process) better determined. It is thus clear that spatial resolution of hard X rays is essential for a better understanding of conditions in the impulsive phase of flares.

Imaging of solar flare hard X rays has so far been accomplished in three distinct ways. The Hard X-Ray Imaging Spectrometer (HXIS) on SMM observed solar hard X rays through multiple layers of collimator holes, with a large number of proportional counters (one per collimator channel) to record the data. This instrument yielded images of regions on the Sun in six energy bands spanning the range of 3.5 to 30 keV, with spatial resolution down to 8 arc s. The Solar X-Ray Telescope (SXT) onboard the Japanese Hinotori satellite used a rotating double-grid modulation collimator (see Makishima, 1982) to image the entire solar disk with a spatial resolution of order 10 arc s. Finally, use of stereoscopic views of behind-the-limb flaring regions (from different spacecraft) has yielded crude imaging in the form of a measure of the fraction of X-ray photons emitted above the occulting photospheric limb (Kane et al., 1979).

These data have traditionally been interpreted (see Hoyng et al., 1981; Brown et al., 1981) in terms of two distinct hard X-ray production models: the so-called "thermal" and "nonthermal" models. We refer the reader to numerous articles (e.g., Emslie and Rust, 1980; Brown and Smith, 1980; Emslie, 1983) for a description of these two canonical models and the physical differences between them. However, it is becoming increasingly obvious to modelers that neither of these simple models is really appropriate to actual flare conditions, with a suitable hybrid being employed frequently (e.g., Emslie and Vlahos, 1980). We therefore see that what is really required is a knowledge of the relative proportions of electrons with velocities much greater than the ambient thermal velocity ("nonthermal" electrons) to those with velocities of order of the thermal velocity. In fact, this article seems to be an appropriate place to lay this historical "thermal versus nonthermal" distinction to rest, and to turn our attention to the real unknown of the energetic electron problem – the electron phase-space distribution function $f^*(\underset{\sim}{r}, \underset{\sim}{v})$ and its evolution with time. Knowledge of $f^*(\underset{\sim}{r}, \underset{\sim}{v}, t)$ (electrons cm^{-3} $(cm\ s^{-1})^{-3}$) gives us not only the requirements on the acceleration region ($\underset{\sim}{r} = \underset{\sim}{0}$), but also the physics of the interaction of the energetic electrons with the ambient solar atmosphere. In the next section we will show how spatially resolved hard X-ray images can give us *direct* information on $f^*(\underset{\sim}{r}, \underset{\sim}{v}, t)$ and its derivatives, and so address both of these two areas of investigation. We will also discuss (Section III) theoretical and observational evidence that the behavior of $f^*(\underset{\sim}{r}, \underset{\sim}{v}, t)$ is at present poorly understood. In Section IV we summarize these results and look toward the P/OF as the logical next step in solar flare hard X-ray studies.

II. DETERMINATION OF THE ELECTRON PHASE SPACE DISTRIBUTION FUNCTION THROUGH SPATIALLY RESOLVED MEASUREMENTS OF HARD X-RAYS

Consider the observation of hard X rays from a "pixel" of a bremsstrahlung source. Let the volume of this pixel be V, the distribution of target protons within the source be $n_p(\underset{\sim}{r})$, and the phase-space density of the bremsstahlung-emitting electrons be $f^*(\underset{\sim}{r}, \underset{\sim}{v}, t)$. For simplicity, we will here consider only the total X-ray yield from the pixel, and not its directionality or polarization properties. It is thus sufficient to work with the four-dimensional phase-space function $f(\underset{\sim}{r},E,t)$ (electrons cm^{-3} erg^{-1}, where $E = 1/2\ m\ |\underset{\sim}{v}|^2$) and the isotropic non-relativistic Bethe-Heitler cross-section $Q_B(\epsilon,E)$ for calculations of the bremsstrahlung yield. With these simplifying assumptions, the flux of hard X-rays observed at the Earth will be

$$I(\epsilon,t + \Delta t) = \frac{1}{4\pi R^2} \int_{E=\epsilon}^{\infty} \left(\int_V f(\underset{\sim}{r},E,t) n_p(\underset{\sim}{r}) d^3 \underset{\sim}{r} \right) v(E)\ Q_B(\epsilon,E)\ dE \text{ photons cm}^{-2}\ s^{-1}\ erg^{-1}\ , \quad (1)$$

where Δt is the light travel time from Sun to Earth and R = 1 AU. Following Brown (1971) we write

$$n_o = \frac{1}{V} \int_V n_p(\underset{\sim}{r})\ d^3 \underset{\sim}{r} \quad (2)$$

and

$$\overline{f}(E,t) = \frac{1}{n_o V} \int_V f(\underset{\sim}{r},E,t) n_p(\underset{\sim}{r}) d^3 \underset{\sim}{r} \quad (3)$$

(the average value of f in the pixel, weighted with respect to n_p). Equation (1) then becomes

$$I(\epsilon,t + \Delta t) = \frac{n_o V}{4\pi R^2} \int_{E=\epsilon}^{\infty} \overline{f}(E,t) v(E) Q_B(\epsilon,E) dE\ . \quad (4)$$

The formula may be straightforwardly inverted, as in Brown (1971), to give f(E,t) in terms of $I(\epsilon,t+\Delta t)$; we refer the reader to Equation (7) of Brown (1971) for the essential result. Here we wish to emphasize that *no assumptions regarding the origin of evolution of the electron distribution function* $f(\underset{\sim}{r},E,t)$ have been made and that, if the pixel size is made sufficiently small that the averaging processes given by Equations (2) and (3) are redundant, then $f(\underset{\sim}{r},E,t)$ can be *explicitly determined* from hard X-ray observations alone (with the proviso that the number of protons $n_o V$ in the pixel must also be known). Thus hard X-ray observations of sufficiently good angular resolution allow us to trace the evolution of $f(\underset{\sim}{r},E,t)$ throughout the source, fulfilling the dual scientific objectives of (a) determining the "injected" electron distribution $f(\underset{\sim}{0},E,t)$, and (b) providing an evolutionary scenario for f throughout the target, against which to test theoretical transport models.

By way of illustration, let us calculate the predicted evolution of $f^*(\underset{\sim}{r}, \underset{\sim}{v},t)$ in a model in which nonthermal electrons ($E \gg kT_e$, where k is Boltzmann's constant and T_e the ambient electron temperature) interact with a background plasma of uniform density n_o by purely collisional processes. Let us further adopt a vertical geometry, so that $f^*(\underset{\sim}{r}, \underset{\sim}{v},t)$ may be replaced by g(z,E,t), where z is height in the source, and let us also assume a steady-state over timescales of interest, so that the t-dependence of g need not be considered explicitly. The bremsstrahlung yield from a pixel of height Δz centered on z then becomes

$$I(z,\epsilon) = \frac{n_o A \Delta z}{4\pi R^2} \int_{\epsilon}^{\infty} g(z,E) v(E) Q_B(\epsilon,E) dE \ , \tag{5}$$

where A is the area of the vertical column imaged. Equation (5) can easily be inverted to give g(z,E) in the manner of Brown (1971). By continuity of electron flux, however, we know that

$$g(z_1,E_1) v_1(E_1)\, \mu_1(E_1) = g(z_2,E_2) v_2(E_2)\, \mu_2(E_2) \ , \tag{6}$$

where z_1 and z_2 are different heights in the source and μ_1, μ_2 are the cosines of the pitch angles to the (vertical) guiding field lines, taken here to be single-valued functions of the respective energies E_1, E_2 (see below). In a purely collisional analysis, we have (Brown, 1972; Emslie, 1978)

$$\left.\begin{aligned} E_1 &= E_2 \left(1 + \frac{3K\Delta N}{\mu_2 E_2^2}\right)^{1/3} \\ \mu_1 &= \mu_2 \left(1 + \frac{3K\Delta N}{\mu_2 E_2^2}\right)^{1/3} \end{aligned}\right\} \ , \tag{7}$$

where $K = 2\pi e^4 \Lambda$, e being the electronic charge (e.s.u) and Λ the Coulomb logarithm, and $\Delta N = n_o(z_2 - z_1)$ is the intervening particle column density between the two levels. Substituting formula (7) into Equation (6) gives

$$g(z_2,E_2) = \left(1 + \frac{3K\Delta N}{\mu_2 E_2^2}\right)^{1/2} g\left[z_1, E_2 \left(1 + \frac{3K\Delta N}{\mu_2 E_2^2}\right)^{1/3}\right] . \tag{8}$$

The value of μ_2 appropriate to E_2 follows from the global equivalents of (7), viz. (Brown, 1972; Emslie, 1978)

$$\left.\begin{aligned} E_2 &= E_o \left(1 - \frac{3KN}{\mu_o E_o^2}\right)^{1/3} \\ \mu_2 &= \mu_o \left(1 - \frac{3KN}{\mu_o E_o^2}\right)^{1/3} \end{aligned}\right\} \ , \tag{7a}$$

where N is the total column density between the injection point ($E = E_o$) and the pixel in question. For a given injection pitch angle cosine μ_o and prescribed pixel and energy E_2, the first relation of Equation (7a) gives implicitly the value of E_o; the second relation then gives $\mu_2(\mu_o,E_2,N)$ for substitution in Equation (8).

Equation (8) is a theoretical prediction for the behavior of g, given the ambient density $n_o(z)$ and the injection pitch angle μ_o of the electron beam. A corresponding, more complicated, result follows if the electrons are injected over a range of pitch angles μ_o. Either of these results can be compared with the forms of $g(z_2,E_2)$ and $g(z_1,E_1)$, deduced from inversion of Equation (5), in order to test whether a simple treatment of the beam dynamics in terms of collisional scattering in the presence of a uniform magnetic field and suitable $n_o(z)$ is indeed appropriate. Other effects, such as collective processes and a non-uniform magnetic field, will modify Equation (8) in a way that can in principle be determined empirically through spatially resolved X-ray observations and Equations (4) and (6). In the next section we will briefly outline the existing evidence, both theoretical and observational, which suggests that Equation (8) is indeed an over-simplification, and that new input from high spatial resolution hard X-ray observations is required to better define the true relationship between the forms of g(z,E) in different locations of the flare, and so the physics of electron transport in solar flare atmospheres.

III. EVIDENCE FOR NON-COLLISIONAL PROCESS AFFECTING ELECTRON TRANSPORT IN FLARES

In the additional presence of non-collisional processes the first of Equations (7) assumes the formal structure

$$E_1 = E_1(E_2, \Delta N; p_i) \quad , \tag{9}$$

where the p_i's are parameters of the electron distribution function and the ambient medium (e.g., temperature, electron/ion temperature ratio, magnetic field geometry, etc.). As pointed out in Section II, this relationship can in principle be determined through hard X-ray observations of sufficient quality at sufficiently high spatial resolution. However, there is already evidence to suggest that the collisional analysis leading to Equations (7) is inadequate and/or invalid. This evidence is both theoretical and observational.

Dealing first with the theoretical side, a purely collisional analysis assumes that (a) the magnetic field structure is uniform and that (b) collective effects can be ignored. Leach and Petrosian (1981) have analyzed the effect of a non-uniform magnetic field on the evolution of g(z,E) and we refer the reader to that paper for details. Collective effects can be subdivided into two classes: coordinate-space and velocity-space. The former (coordinate-space) collective effect is that of the beam-neutralizing reverse current, which causes the beam electrons to lose energy sufficient to drive this reverse current through the finite resistivity of the ambient plasma. The electrical potential difference which each electron must overcome is given by $V = \int \eta j dz$, where η is the resistivity and j the beam current; the corresponding energy loss is $\Delta E = e\int \eta j dz$. Thus, the energy loss rate required to drive the reverse current is $\dot{E} = e\eta j \mu v = e\eta_o j T_e^{-3/2} \mu v$. This loss rate differs from the collisional rate of $\dot{E} = K n_o v/E$ (Emslie, 1978) in three basic ways: (1) dependence on the properties of the electron: $\dot{E} \propto E^{1/2}$ for reverse current ohmic heating, but $\dot{E} \propto E^{-1/2}$ for collisional heating, (2) dependence on the properties of the background atmosphere: there is a *temperature* dependence of $\dot{E}$ in the reverse current case, replacing a *density* dependence in the collisional case, (3) dependence on the parameters of the overall beam: $\dot{E}$ depends on the total beam current j in the reverse current case, a dependence which is totally absent in the collisional case. We therefore expect that, for high beam fluxes for which reverse current ohmic heating can become an appreciable contributor to the energetics of the beam electrons (Emslie, 1980, 1985), Equation (7) will be substantially modified to the form

$$E_1 = E_1(E_2, \Delta N; j, T_e) \quad , \tag{9a}$$

and this new form should be evidenced by the evolution of hard X-ray spectrum from pixel to pixel in the source.

Collective effects in velocity-space, as they apply to hard X-ray producing electron beams in flares, have only recently received attention. Emslie and Smith (1984) pointed out that, due to the inverse energy dependence of the collisional energy loss rate (see above), an injected flux of suprathermal electrons will develop a "hump" in velocity-space which moves to increasing energies with depth in the collisional target. For a sufficiently dense beam the hump eventually rises above the level of the background Maxwellian velocity distribution, creating an electron-electron two-stream unstable situation. Due to the great rapidity of microscopic collective plasma processes compared to the collisional lifetime of energetic electrons in plasmas of relevant densities, quasi-linear processes will effectively prevent this hump forming, so that instead a plateau of ever-increasing extent is formed as the electrons penetrate deeper into the target. The formula for the rate of change of the electron distribution function g is now a complicated function of g itself, and we must replace Equation (7) by

$$E_1 = E_1(E_2, \Delta N; g(z_2, E_2)) \quad , \qquad (9b)$$

the form of which has yet to be determined and represents work currently in progress (Emslie and McClements, 1985). It is possible that empirical determination of this form through spatially resolved hard X-ray measurements, as discussed in Section II, could increase our understanding of this collective process and how it operates.

We turn now briefly to the observational evidence for non-collisional processes affecting electron transport in flares. In an attempt to explain the stereoscopic data of Kane et al. (1979) in terms of a collisional model such as discussed above, Brown et al. (1983) found that the values of ΔN inferred from the "top pixel" (the unocculted part of the behind-the-limb flare, i.e., that part observed by both spacecraft – see Kane et al., 1979, for details) depended on the photon energy being observed – clearly an unphysical result pointing to the invalidity of the model (unless a suitably contrived energy-dependent pitch angle distribution of injected electrons was involved). Further, in an event discussed by Kane (1983; his Figure 7), the inferred value of the unocculted ΔN *rises* when determined using observations at one photon energy and *falls* when using observations at another. This is strongly indicative that a simple collisional model is inadequate.

IV. DISCUSSION AND CONCLUSIONS

We have seen in the previous two sections that our knowledge of electron energy transport in solar flares is at present quite possibly poorly understood, both from theoretical and observational standpoints, and how, in principle, hard X-ray observations with sufficiently fine spatial resolution can help to increase our understanding in this area.

Present hard X-ray imaging data, from both HXIS (SMM) and SXT (Hinotori), is not of a high enough quality to be of great aid in such an investigation. Indeed, there is great controversy over the basic interpretation of the images hitherto obtained. For example, Duijveman et al. (1982) claim to have observed the "footpoint" signature of precipitating nonthermal electrons in a flare on 5 November 1980. However, MacKinnon et al. (1985) claim that these "footpoints," although definitely representing real enhancements of emission in localized areas, may be simply due to the line of sight volume along a vertical column through the ends of a loop being greater than that along a similar column at the apex of the loop (see also Fennelly and Emslie, 1985). In addition, the "footpoint" spectra observed by HXIS are inconsistent with (lower than) the extrapolated Hard X-Ray Burst Spectrometer (HXRBS) spectra for the flare as a whole, implying that the "footpoint" emission is not the dominant component at HXIS energies. The need for statistically sound hard X-ray measurements at fine spatial evolution is therefore apparent, if only to unambiguously interpret the images obtained. For the analysis of Section II we need hard X-ray spectra spanning as wide a range of photon energies as possible, with spatial resolution of order 1 arc second or better. (The reason for a wide energy survey is because of the possibly different nature of energy loss processes operating in different electron energy ranges – see Section III.) As discussed elsewhere in this volume, the Pinhole/Occulter Facility (P/OF) is indeed capable of such measurements and therefore represents the logical next step in solar hard X-ray observation.

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