HARD X-RAY BREMSSTRAHLUNG PRODUCTION IN SOLAR FLARES BY HIGH-ENERGY PROTON BEAMS

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ABSTRACT

We investigate the possibility that solar hard X-ray bremsstrahlung is produced by acceleration of stationary (thermal) protons, rather than vice versa as commonly assumed. We find that a beam of protons which involves 1836 (=m_p/m_e) times fewer particles, each having an energy 1836 times greater than that of the electrons in the equivalent electron beam model, has exactly the same bremsstrahlung yield for a given target, i.e., the mechanism has an energetic efficiency equal to that of conventional bremsstrahlung models. Allowance for the different degrees of target ionization appropriate to the two models (for conventional flare geometries) makes the proton beam model more efficient than the electron beam model, by a factor of order 3.

The model places less stringent constraints than a conventional electron beam model on the flare energy release mechanism. It is also consistent with observed hard X-ray burst spectra, intensities, and directivities. The altitude distribution of hard X-rays predicted by the model agrees with observations only if nonvertical injection of the protons is assumed. The model is inconsistent with γ-ray data in terms of conventional modeling.

Subject headings: radiation mechanisms — Sun: flares — Sun: X-rays

1. INTRODUCTION

Large solar flares are characterized by intense emission at hard X-ray (>10 keV) energies, and much effort has been devoted to studying this hard X-ray production, both observationally and theoretically (see, e.g., Brown and Smith 1980 for a review). The numerous detailed models hitherto proposed almost all share the central feature that the hard X-rays originate in collisional bremsstrahlung of fast electrons on near-stationary (thermal) protons, on the grounds that other emission mechanisms (e.g., gyrosynchrotron radiation or inverse Compton emission from relativistic electrons) are incompatible with data at other wavelengths (see, e.g., Brown and Smith 1980). However, the most popular model of non-thermal bremsstrahlung from a thick-target electron beam demands problematically high beam currents, with regard to both their acceleration and propagation.

It has recently been realized, through simultaneous observations of large flares in both hard X-rays and γ-rays, that the impulsive phase of a flare accelerates fast protons cotemporously with hard X-ray emission (e.g., Bai et al. 1983). These protons have individual energies from a few MeV up to some GeV, and their total energy can constitute a significant fraction of the energy released in the flare (e.g., Ramaty 1985). The acceleration of such protons can result in hard X-ray bremsstrahlung by a number of processes.

First, proton beam currents can, under certain laboratory conditions, filament through electrothermal instabilities to produce intense localized heating of plasma electrons to sufficient temperatures for emission of thermal hard X-ray bremsstrahlung (Haines and Marsh 1982). Simnett (1985) has speculated that this mechanism may produce the hard X-rays in flares, but he did not check whether the thermal plasma emission measure produced is compatible with observed burst intensities. More significantly, the growth of the electrothermal instability discussed by Haines and Marsh (1982) depends critically on the boundary conditions imposed: for a constant electric field E the ohmic heating term scales (for classical resistivity) like T^{-3/2} and is thus destabilizing, while for a constant current J, the ohmic heating scales as T^{-3/2} and is therefore stabilizing. The former condition is more closely approximated under laboratory conditions (and possibly in the particle acceleration region of flares; see Spicer 1977), while the latter is probably a better representation of the flare plasma outside the acceleration region itself (see, e.g., Knight and Sturrock 1977). We therefore do not necessarily expect the Haines and Marsh (1982) mechanism to operate extensively in flares and shall not pursue Simnett’s hypothesis further here.

Second, near head-on collisions of fast protons with ambient electrons can generate high-energy, bremsstrahlung-producing, electrons (cf. Elliot 1964). We find, however (see Appendix), that the hard X-ray yield from this process is much less than that from the process next to be discussed.

Third, the motion of fast protons through an ambient plasma generates nonthermal bremsstrahlung by collisionally accelerating plasma electrons, in exactly the same manner as fast electrons produce bremsstrahlung by scattering off stationary protons. The former process has been termed, somewhat confusingly, “inner bremsstrahlung” (for un-ionized targets; Hayakawa and Matsuoka 1964) and “inverse bremsstrahlung” (Boldt and Serlemitsos 1969, hereafter BS), although the relation to “normal” bremsstrahlung by a fast
electromagnetic field is simply due to a change in reference frame rather than the time reversal usually implied by the labeling "inverse." We here adopt the terminology "inverse bremsstrahlung," since the term "inner" appears to have even less correspondence with the actual physical situation involved.

BS were the first to propose that inverse bremsstrahlung could well be the source of solar hard X-rays. This, however, corresponded with the actual physical situation involved. (§ II) that the process of inverse bremsstrahlung has exactly the same energetic efficiency (photons emitted per erg of energy injected) as does normal bremsstrahlung (in the same target composition); further, the photon spectra bore the same relation to the electron or proton spectra involved in both models. The main difference between the two models is that, for inverse bremsstrahlung, the energy resides in a relatively small number of very energetic protons, whose total current is small compared to the electron current in the case of normal bremsstrahlung. Allowance for the fact that high-energy protons interact principally with deep, un-ionized atmospheric layers (reducing the Coulomb energy loss per photon emitted, compared to an ionized target, appropriate for "normal" bremsstrahlung), leads to the conclusion that a proton beam will be approximately 3 times more efficient energetically than an electron beam and involve a current only \( \sim 2 \times 10^{-4} \) times that of an equivalent (hard X-ray-producing) electron beam. The attractiveness of these features is discussed in § III, where we also discuss the compatibility of the model with other data, such as spatial structure and directivity of solar hard X-rays, and its chief problem, namely its incompatibility with observed \( \gamma \)-ray fluxes according to present interpretations of \( \gamma \)-ray data. Our conclusions are presented in § IV.

II. ENERGETICS OF NORMAL AND INVERSE BREMSSTRAHLUNG PROCESSES IN A THICK TARGET

In a thick target (Brown 1971), the number of bremsstrahlung photons per unit photon energy \( \epsilon \) emitted during the lifetime of an average electron of initial energy \( E_{0,e} \) is

\[
v_{\epsilon}(\epsilon, E_{0,e}) = \frac{4 \pi R^2}{\epsilon} \int F_{0,e}(\epsilon, E_{0,e}) \nu_{\epsilon}(\epsilon, E_{0,e}) dE_{0,e}.
\]

where \( Q_{\epsilon}(\epsilon, E_{0,e}) \) is the bremsstrahlung cross-section differential in \( \epsilon \), \( n \) is the local plasma density (protons + hydrogen atoms), \( v_{\epsilon} \) and \( E_{\epsilon} \) are the instantaneous velocity and energy of the electron, and \( t \) is time. For Coulomb collisions (see Emslie 1978),

\[
\frac{dE_{\epsilon}}{dt} = -\frac{K \gamma}{E_{\epsilon}} m_{e} v_{\epsilon},
\]

where \( K = 2 \pi e^2 \), \( e \) being the electronic charge (esu). The quantity \( \gamma = x \Lambda + (1 - x) \Lambda' \), where \( x \) is the degree of ionization of the target and \( \Lambda, \Lambda' \) are Coulomb logarithms, defined in equations (8) and (12) of Emslie (1978). Equation (1) thus becomes

\[
v_{\epsilon}(\epsilon, E_{0,e}) = \frac{1}{K \gamma} \int F_{0,e}(\epsilon, E_{0,e}) \nu_{\epsilon}(\epsilon, E_{0,e}) dE_{0,e}.
\]

If we now consider the continuous injection of a flux of electrons, with differential energy spectrum \( F_{0,e}(E_{0,e}) \text{cm}^{-2} \text{s}^{-1} \text{ergs}^{-1} \), then the total bremsstrahlung yield (photons \text{cm}^{-2} \text{s}^{-1} \text{ergs}^{-1} \text{from the target, measured at the Earth, will be}

\[
I_{\gamma}(\epsilon) = \frac{A}{4 \pi R^2} \int F_{0,e}(\epsilon, E_{0,e}) \nu_{\epsilon}(\epsilon, E_{0,e}) dE_{0,e}
\]

\[
= \frac{A}{4 \pi R^2 K \gamma} \int_{\epsilon}^{E_{0,e}} E_{\epsilon} Q_{\epsilon}(\epsilon, E_{\epsilon}) dE_{\epsilon} dE_{0,e},
\]

where \( A \) is the flare area and \( R = 1.5 \times 10^{13} \text{cm} = 1 \text{AU} \).

Let us now consider the inverse bremsstrahlung process. Here protons of energy \( E_{p} \) (velocity \( v_{p} \)) are incident on the stationary electrons of the plasma. As viewed from the center-of-mass frame (essentially comoving with the proton), the electron has energy \( E = (m_{p}/m_{e}) E_{p} \), and so the cross section for photon emission at energy \( \epsilon \) is \( \Omega(\epsilon, (m_{p}/m_{e}) E_{p}) \). The expression for the bremsstrahlung yield of an average proton with initial energy \( E_{0,p} \) is therefore (cf. eq. [3])

\[
v_{\epsilon}(\epsilon, E_{0,p}) = \frac{4 \pi R^2}{\epsilon} \int_{(m_{p}/m_{e}) E_{p}}^{E_{0,p}} \Omega(\epsilon, (m_{p}/m_{e}) E_{p}) dE_{p}.
\]

Using the formula for proton energy loss

\[
\frac{dE_{p}}{dt} = -\frac{K \gamma}{E_{p}} m_{p} v_{p}
\]

(Emslie 1978; note that the Coulomb logarithms \( \Lambda \) and \( \Lambda' \) are not appreciably changed from the electron case), we find that

\[
v_{\epsilon}(\epsilon, E_{0,p}) = \frac{1}{K \gamma} \int_{(m_{p}/m_{e}) E_{p}}^{E_{0,p}} E_{p} \Omega(\epsilon, E_{p}) dE_{p}.
\]

Changing variables to \( E_{p}' = (m_{p}/m_{e}) E_{p} \), we have

\[
v_{\epsilon}(\epsilon, E_{0,p}) = \frac{(m_{p}/m_{e})}{K \gamma} \int_{E_{0,p}'}^{E_{0,p}} E_{p}' \Omega(\epsilon, E_{p}') dE_{p}'.
\]

so that, for a continuous injection of protons at a rate \( F_{0,p}(E_{0,p}) \text{cm}^{-2} \text{s}^{-1} \text{ergs}^{-1} \), we obtain, analogously to equation (4),

\[
I_{\gamma}(\epsilon) = \frac{A (m_{p}/m_{e})}{4 \pi R^2 K \gamma} \int_{E_{0,p}'}^{E_{0,p}} E_{p}' \Omega(\epsilon, E_{p}') dE_{p}' dE_{0,p}'.
\]

Equations (4) and (9) show that if we consider the injection of protons and electrons at equal rates and with similar spectra, but with the proton injection energies \( E_{0,p} \) equal to \( m_{p}/m_{e} \) times the electron injection energies \( E_{0,e} \), then the bremsstrahlung yield from a proton is exactly \( m_{p}/m_{e} \) times as large as that from the corresponding electron and the bremsstrahlung spectral shape is identical. Physically this follows from the increased stopping distance of the proton in the thick target: the stopping column density (along the trajectory of the particle) for electrons is \( N_{e} = E_{e}^{2}/2K \), while for protons it is \( N_{p} = E_{p}^{2}/(2m_{p}/m_{e}) K = (m_{p}/m_{e}) E_{p}^{2}/2K \) (Emslie 1978). Therefore, if we consider (for single particles) the bremsstrahlung yield (photons \text{ergs}^{-1} \text{per erg of injected energy}

\[
\eta = \frac{\nu_{\epsilon}}{E_{0,e}} - \frac{v_{\epsilon}}{E_{0,p}} - \frac{v_{p}}{E_{0,p}}
\]

we find that

\[
\eta = \frac{v_{\epsilon}}{E_{0,e}} - \frac{(m_{p}/m_{e}) v_{p}}{E_{0,p}} = \frac{v_{\epsilon}}{E_{0,e}} - \frac{v_{p}}{E_{0,p}}.
\]
i.e., the bremsstrahlung efficiencies \( \eta \) are energetically the same in both processes (the protons required for a prescribed bremsstrahlung yield are only \( m_p/m_e \) times as numerous than electrons, but each has \( m_p/m_e \) times the energy of the equivalent bremsstrahlung-producing electron). It follows that for any bremsstrahlung-producing ensemble of electrons, the same X-ray yield will result from an ensemble of protons with an energy spectrum of identical shape, involving fewer \( (m_p/m_e) \) times particles, each of which has more \( (m_p/m_e) \) times energy. While keeping the injected energy the same as in a normal bremsstrahlung model, the inverse bremsstrahlung mechanism does reduce the injected particle current by a factor of \( m_p/m_e \).

Note that the above analysis assumes the electrons and protons to interact with targets which are identical (i.e., of the same ionization level). However, according to conventional assumptions regarding particle beams in solar flares, these beams are accelerated in the corona and are injected downward toward the chromosphere. Since protons have a much larger range than electrons of the same velocity (and so the same bremsstrahlung-producing capability), they will undergo most of their collisions much deeper in the atmosphere. Quantitatively, the vertical column densities \( N \) (particles cm\(^{-2}\)) required to stop the particles are given by (Emslie 1978)

\[
N_p = \frac{E_{0_p}}{2K\gamma(m_p/m_e)} = m_p \frac{E_{0_p}}{m_e 2K\gamma} \approx 3.5 \times 10^{22} \left( \frac{E_{0_p}}{10 \text{ keV}} \right)^2 \text{cm}^{-2} \quad (12a)
\]

and

\[
N_e = \frac{E_{0_e}}{3K\gamma} \approx 1.3 \times 10^{19} \left( \frac{E_{0_e}}{10 \text{ keV}} \right)^2 \text{cm}^{-2} \quad (12b)
\]

where the latter differs by a factor of \( \frac{1}{3} \) from the stopping distance along the particle trajectory due to scattering of electrons. In both equations (12a) and (12b) a value of \( \gamma = 20 \) was used; actual \( \gamma \)'s will be within a factor of 2 of this for all possible degrees of ionization of the target.

Most solar hard X-rays are emitted at energies \( E \geq 10 \text{ keV} \) and, due to the characteristic steepness of the spectra, are produced by electrons in the energy range \( E_{0_e} \approx 10-30 \text{ keV} \) or protons in the energy range \( E_{0_p} \approx 20-60 \text{ MeV} \) (i.e., \( E_{0_e} \approx 10-30 \text{ keV} \) also). For these values, we find \( N_p \approx 1.3 \times 10^{16} \) and \( N_e \approx 3.5 \times 10^{22} \times 3.5 \times 10^{23} \text{ cm}^{-2} \). Under conventional assumptions regarding flare morphology, where the energy release occurs high in a coronal loop, with the energetic particles transporting the energy downward, we find that these two \( N \) values correspond to significant levels of target ionization. The \( N_p \) values lie in the ionized \((x \approx 1)\) upper chromosphere, both in empirical flare model atmospheres (Machado et al. 1980) and in theoretical ones (e.g., Ricchiuzia and Canfield 1983). The \( N_e \) values fall in the deep chromosphere or below, where hydrogen ionization levels are very low \((x \approx 0)\). Thus in equation (4) \( \gamma \) can be replaced by \( \Lambda \), while in equation (9) it should be replaced by \( \Lambda' \), which is \( \approx \Lambda/3 \) for the typical parameters involved (Brown 1973; Emslie 1978).

(Insertion of this correction in eqs. [12a] and [12b] further increases \( N_p \) relative to \( N_e \), and so strengthens this conclusion.) Thus we see that for normal thick target beam geometries the inverse bremsstrahlung yield (9) is enhanced over the normal bremsstrahlung yield (4) by a factor of order 3 (for equal injected energies, i.e., \( \eta_e \approx 3\eta_p \) (cf. eq. [11]).)

The energetic protons will "drag" ambient electrons along with them, in an attempt to restore charge and current neutrality, much as does the reverse current in the electron beam case (see, e.g., Knight and Sturrock 1977). Since the total beam current is much smaller than in the electron beam case, the ohmic heating due to this "return current" may be safely neglected. On the other hand, in the electron beam model, ohmic losses of the return current in passing through the resistive ambient plasma can reduce the bremsstrahlung efficiency of the electron beam (Emslie 1980). In such cases the proton beam model gains a further energetic advantage.

It might be argued that the "return current" in the proton beam model is in fact constituted by a relatively small number of high-velocity electrons (comparable to the number density and velocity of the driving proton beam), rather than a slow diffusion of all the ambient electrons in the vicinity of the beam. These high-velocity electrons, being tied to the high-momentum protons, would have their ranges increased to \( m_p/m_e \) times their "free" values and so would produce a bremsstrahlung yield comparable to that from the inverse bremsstrahlung process. However, the energy loss from the protons in sustaining this electron return current, and the corresponding reduction in proton range, exactly cancels this effect, so that the energetic efficiency of the inverse bremsstrahlung process is unaffected by return current considerations.

## III. Discussion

The analysis in § II shows that a beam of \( \geq 20 \text{ MeV} \) protons could produce solar hard X-ray bursts utilizing a proton energy flux in this range of only \( \frac{1}{2} \) of that required by the conventional thick target \( \geq 10 \text{ keV} \) electron beam interpretation. This result has important theoretical ramifications, such as the following:

a) Energy Supply.—The thick target electron energy flux required for hard X-ray bursts is typically a substantial fraction of the impulsive phase flare power (Hoeyng, Brown, and van Beek 1976; Lin and Hudson 1976). This poses a severe constraint on the energetic efficiency required of the electron acceleration process associated with the the primary process of magnetic dissipation. For a proton beam the fraction of flare power going into acceleration required by the hard X-ray burst would be reduced from, say, 30% to only 10%. Further, such protons have energies much further out in the Maxwellian tail than the equivalent electrons. They are therefore less susceptible to collisional drag forces with ambient electrons. This, in addition to their relatively small number (see [c] below) places less stringent constraints on flare energy release mechanisms to accelerate the required particles.

b) Impulsive Phase Heating Mechanism.—If hard X-ray bursts are produced by proton beam bremsstrahlung, it follows, conversely from case (a), that to be consistent with burst intensities, only a small percentage of flare energy goes into the proton beam above 20 MeV. Therefore impulsive phase heating of the flare atmosphere could not be due to the hard X-ray-producing protons themselves but rather must be due to a greater flux of lower energy protons (in which case benefit [a] is lost) or an entirely different transport process.

c) Beam Current.—Because the protons each carry \( m_p/m_e \) times the energy of the electrons in an equivalent beam, the proton beam number flux is only about \( \frac{1}{2}(m_p/m_e) \approx 2 \times 10^{-4} \) of the thick target electron number flux, with the same reduction in beam current and current density (cf. Simnett 1984). This current is still \( \geq 10^9 \) times the Alfven-Lawson limit and so in
no way avoids the electrodynamic need for a return current (cf. Brown and Bingham 1984). However, unlike a thick target electron beam, it is just small enough to lie within the typical maximum current which can be accelerated directly by an induced electric field in the high-inductance flare plasma (Spicer 1982; Holman 1985), as opposed to stochastic acceleration processes (Benz 1977; Brown and Loran 1985).

In view of these theoretical advantages of the proton beam interpretation, it is essential to consider its compatibility with more complete flare hard X-ray data than just burst intensity and with other observational constraints. Here we discuss some of these briefly.

a) Altitude Distribution

Due to the much larger range of protons compared to their bremsstrahlung equivalent electrons (eqs. [12a]–[12b]), we expect that the hard X-ray emission created by inverse bremsstrahlung from a thick target electron beam will in general be concentrated considerably lower in the atmosphere than that created by normal bremsstrahlung from a thick target electron beam. The exact height differential will depend on the injected pitch angle distributions of both protons and electrons in the respective models, with larger pitch angle particles producing bremsstrahlung at smaller depths in the atmosphere. The height structure of hard X-ray sources has been observed spectroscopically by Kane et al. (1979, 1982) and modeled in terms of a thick target electron beam by Brown et al. (1983). Specifically, Brown et al. (1983) compared for several events the column density required above the occulting solar limb to produce the observed degree of hard X-ray burst occultation with the column density/height structure in spectroscopic (empirical) flare model atmospheres. They found that interpretation of the occultation data in terms of an electron beam injected with zero pitch angle to the guiding magnetic field lines (and with no increase in pitch angle due to convergence of these field lines) typically implied (vertical) column densities somewhat larger than spectroscopic models (cf. Brown et al. 1983; Fig. 2). For a proton beam interpretation, this discrepancy will be worse by a factor of at least $3 \times 10^3$; due to the lower proton collision rate, more material is needed above the occulting limb to match the unocculted X-ray flux there.

Such a large increase in the occultation values in $N(h)$ is certainly not consistent with any spectroscopic model. We thus conclude that the only two ways in which the proton beam model could be rendered compatible with the occultation data are if the protons indeed do have large pitch angles (either at injection or due to magnetic field variation; see Leach and Petrosian 1983 for discussion of these effects as they pertain to electron beams), so that their vertical range is much reduced; or if the inferred occultation heights in Kane et al. (1979, 1982) are systematically too low. (Because of the small density scale height $h \approx 150$ km at the low altitudes involved, the shift in $h$ required to produce an increase of 3000 times in the column density above the limb is only 1200 km.)

b) Directivity

One basic difficulty facing electron beam models with a substantial degree of beaming (anisotropy) at injection is the fact that they require large bremsstrahlung directivity at high energies, even when scattering, albedo, and magnetic field curvature are taken into account (Brown 1972; Leach and Petrosian 1983), predicting directivities of up to 5 at energies $\sim 150$ keV. At these energies, Kane et al. (1982) estimate from stereo data that the actual directivity is certainly less than 2. The large directivity predicted is substantially due to aberrational distortion of the basic dipole polar diagram of low-energy bremsstrahlung emission (Elwert and Haug 1970) by the high velocity of the emitting electrons (Elwert and Haug 1971). In the case of "inverse" bremsstrahlung due to a proton beam, the observer is at rest relative to the target electrons. Thus no aberrational effect will be present and the directivity can be much smaller (cf. Elwert and Haug 1970, Figs. 9–11). Note, however, that if a significant bremsstrahlung contribution comes from return current electrons accompanying the proton beam (cf. § II), this will have a substantial directivity, as in normal bremsstrahlung models, and so enhance the directivity of the combined radiation field.

c) $\gamma$-Ray Burst Intensity

Because of uncertainty and variability in the escape fraction, the number and spectra of protons in flares is not well defined by observations of interplanetary protons (e.g., van Hollebeeke, Ma Sung, and McDonald 1975). However, protons of energies high enough to produce hard X-rays by inverse bremsstrahlung are capable of revealing their presence by nuclear $\gamma$-ray line production as detailed by, e.g., Ramaty, Kozlovsky, and Lingenfelter (1975). If solar hard X-rays are indeed produced predominantly by inverse bremsstrahlung, then we would expect the ratio of $\gamma$-ray flux to hard X-ray flux to be largely event-independent (excluding effects due to spectral and optical depth [see, e.g., Ramaty 1984] variations). The relative absence of $\gamma$-ray events compared to hard X-ray ones shows this prediction is not satisfied by the data. Another way of testing the inverse bremsstrahlung hypothesis in a particular event is to compute the proton flux from the $\gamma$-ray data and calculate, using an inverse bremsstrahlung model, the corresponding flux in hard X-rays; this can then be compared with observations.

A good event for this test is the large flare of 1972 August 4. Using $\gamma$-ray data from the OSO 7 satellite, Ramaty (1984) deduces that a time-integrated flux (or fluence) of $1.6 \times 10^{33}$ protons above 30 MeV was present in that event. If the hard X-rays in this event were emitted by inverse bremsstrahlung, this would imply a flux of hard X-rays with energies above 15 keV equivalent to that from $3(m_e/m_p) \times 1.6 \times 10^{33} = 10^{37}$ electrons with injection energies of 15 keV or greater. However, for the same event, Hoyng, Brown, and van Beek (1976) found that the observed hard X-ray yield corresponded to injection of $3.5 \times 10^{32}$ thick target electrons above 25 keV (or about $2 \times 10^{30} \times 15$ keV if the power-law spectrum extends that low). It follows that if the $\gamma$-ray modeling is correct, the inverse bremsstrahlung interpretation of hard X-ray bursts fails by about three orders of magnitude in this event.

A second example is that of the 1980 June 7 flare, for which the $\gamma$-ray data (Chupp 1982) are much superior to those of 1972. Analysis of the simultaneous SMM data in $\gamma$-rays and hard X-rays from this event has been carried out by Emslie (1983), who finds the total energy in electrons above 10 keV (from a thick target interpretation of the hard X-rays) to be $\sim 8.3 \times 10^{30}$ ergs and in protons above 20 MeV (from a thick target interpretation of the $\gamma$-rays) to be $3 \times 10^{32}$ ergs. Allowing again for the gain of 3 in inverse bremsstrahlung yield, this mechanism here falls short of requirements by a factor of $10^3$. 

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IV. CONCLUSIONS

"Inverse" bremsstrahlung from a 20 MeV or greater proton beam can be up to 3 times more efficient energetically than bremsstrahlung from a 10 keV electron beam in the production of hard X-rays. On first estimates the proton model appears to be more consistent than the electron model with data on hard X-ray burst directivity but less so in terms of spatial structure. The proton model is much less demanding (by factors of up to $10^4$) in terms of accelerated current and particle numbers. However, its predictions are entirely incompatible with observed γ-ray burst intensities unless the former can somehow be suppressed relative to the X-rays by two to three orders of magnitude. Since the protons involved in the two processes are in identical energy ranges, such a relative reduction cannot be achieved by invoking noncollisional energy losses which would suppress both emissions. Nevertheless, in view of the other advantages of the proton model, we would advocate a very thorough search for any factor hitherto overlooked which might modify the observed (as opposed to produced) hard X-ray or γ-ray fluxes.

Finally, it is appropriate to comment on the early claim by Boldt and Serlemitsos (1969) that inverse bremsstrahlung could explain hard X-ray burst intensities. At the time of that paper, the only proton data were from interplanetary measurements, and they based their conclusion on a typical value of $10^{28}$ ergs of protons above 20 MeV. They then claimed that this would yield $10^{24}$ ergs of photons above 20 keV by inverse bremsstrahlung in a neutral target and stated that this is compatible with hard X-ray data. There is here, however, a numerical error, since the Boldt and Serlemitsos analysis (their eq. [10], which we find to agree algebraically with our treatment) gives a photon energy yield of about $10^{-2}$ of the proton input, and not the $10^{-4}$ which they use. Furthermore, the correct proton energy content to use is that above 40 MeV (not 20 MeV), and this is a factor of 2 smaller for their spectrum. The remaining discrepancy of one to one-and-a-half orders of magnitude presumably lies in their use of proton and hard X-ray data not from a single flare and in the sensitivity of the hard X-ray energy content to the energy range observed.

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APPENDIX

BREMSSTRAHLUNG CONTRIBUTION OF KNOCK-ON ELECTRONS

One further source of bremsstrahlung from a proton beam is that from energetic knock-on electrons, produced by collisions of the beam protons with ambient electrons, as they collide with ambient protons during their thermalization. This process is the one invoked in the Elliot (1964) proton store model of flares for production of the hard X-ray burst. Here we show the knock-on contribution to be even smaller than that from "inverse" bremsstrahlung.

From the equations in Emslie (1978) it is easy to show that for impact parameter $b$, the collision of a proton of energy $E$ with a stationary electron results in a knock-on electron of energy

$$E_e = \frac{E}{m_p + \frac{m_e}{2m_e}(E_b/e^2)}.$$  

(A1)

If the maximum impact parameter is $b_0$, then the probability distribution of $b$ is $P(b) = bdb/b_0^2$. Thus the relative distribution of knock-on electrons over energy (fraction per unit $E_e$) is

$$f(E_e) = \frac{1}{b_0^2} \left| \frac{db}{dE_e} \right| = \frac{m_p}{m_e E_e^2} \frac{e^4}{2b_0^2} E_e \leq \frac{4m_e}{m_p} E_e$$

(A2)

(and zero for $E_e > E_{\text{max}} = 4(m_e/m_p)E$, where $E_{\text{max}}$ represents a head-on collision).

A proton of initial energy $E_0$ will therefore produce during its collisional thick target lifetime a number of knock-on electrons $N(E_e)$ per unit $E_e$ given by

$$N(E_e) = \int_{E_e/E_{\text{min}}}^{E_0} n\pi b_0^2 f(E_e) dE_e = \frac{1}{2\gamma E_e^2} \left( E_0 - \frac{m_p}{4m_e} E_e \right), \quad E_{\text{min}} \leq E_e \leq \frac{4m_e}{m_p} E_0,$$

(A3)

where we have used equation (6), $\gamma$ is the effective Coulomb logarithm as before, and $E_{\text{min}}$ is the value of $E_e$ corresponding to the maximum impact parameter.

The most relevant case to consider is the knock-on electron flux produced by a power-law distribution of protons injected into a thick target, i.e., an injection flux

$$F_{0,E} dE/(cm^{-2} s^{-1} ergs^{-1}) = (\delta - 1) \frac{F_1}{E_1} \left( \frac{E_0}{E_1} \right)^{-\delta}.$$  

(A4)
where $F_1$ is the total flux for $E_{0,p} \geq E_1$. The resulting production rate of knock-ons per unit $E_e$ is then, by equation (A3),

$$F_a(E_e) = \frac{1}{2\gamma E_e^2} \int_0^\infty F_{0,p}(E_{0,p}) \left( E_{0,p} - \frac{m_e}{4m_p} E_e \right) dE_{0,p}$$

$$= \frac{1}{2\gamma(\delta - 1)(\delta - 2)} \left\{ (\delta - 1) \left( \frac{m_e}{4m_p} \right) F_1 \left( \frac{E_e}{m_e/E_1} \right)^{\delta} \right\}.$$  \hspace{1cm} (A5)

It is clear that the term in braces in equation (A5) would represent a power-law flux of electrons (with index $\delta$) comprising $(m_e/4m_p)F_1$ knock-on electrons per second of $E_e \geq E_{e1} = (4m_e/m_p)E_1$, the actual number flux being a factor of $2\gamma(\delta - 1)(\delta - 2)$ smaller. The power going into these knock-on electrons is then

$$P_{e_1} = \frac{(\delta - 1)}{(\delta - 2)} E_{e_1} F_{e_1} = \frac{1}{2\gamma(\delta - 1)(\delta - 2)} P_1,$$  \hspace{1cm} (A6)

where $P_1$ is the proton power above $E_1$. For $\delta = 4$, $\gamma = 20$, this means that a beam of protons with energies above $E_1 = 9.2$ MeV produces a knock-on beam of electrons above $E_{e1} = 20$ keV with a power 120 times smaller than that of the proton beam. For the same $\delta$, the proton power above 9.2 MeV will be $4^{\delta-2} = 16$ times higher than the power among those protons above 37 MeV which produce “inverse” bremsstrahlung X-rays. The bremsstrahlung efficiency of the knock-on process for such a power-law proton beam will therefore be $120/16 = 7.5$ times lower than the efficiency of “inverse” bremsstrahlung.

REFERENCES