ELECTRON-ELECTRON BREMSSTRAHLUNG EMISSION AND THE INFERENCE OF ELECTRON FLUX SPECTRA IN SOLAR FLARES

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ABSTRACT

Although both electron-ion and electron-electron bremsstrahlung contribute to the hard X-ray emission from solar flares, the latter is normally ignored. Such an omission is not justified at electron (and photon) energies above \( \sim 300 \) keV, and inclusion of the additional electron-electron bremsstrahlung in general makes the electron spectrum required to produce a given hard X-ray spectrum steeper at high energies. Unlike electron-ion bremsstrahlung, electron-electron bremsstrahlung cannot produce photons of all energies up to the electron energy involved. The maximum possible photon energy depends on the angle between the direction of the emitting electron and the emitted photon, and this suggests a diagnostic for an upper cutoff energy and/or for the degree of beaming of the accelerated electrons. We analyze the large event of 2005 January 17 and show that the upward break around 400 keV in the observed hard X-ray spectrum is naturally accounted for by the inclusion of electron-electron bremsstrahlung. Indeed, the mean source electron spectrum recovered through a regularized inversion of the hard X-ray spectrum, using a cross section that includes both electron-ion and electron-electron terms, has a relatively constant spectral index \( \delta \) over the range from electron kinetic energy \( E = 200 \) keV to \( E = 1 \) MeV. Such a spectrum is indicative of an acceleration mechanism without a characteristic energy or corresponding scale.

Subject headings: Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

The hard X-ray spectrum \( I(\epsilon) \) (photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at the Earth) from a solar flare is produced by bremsstrahlung of accelerated electrons, characterized (Brown et al. 2003) by a mean electron flux spectrum \( \Phi(E) \) (electrons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at the Sun), and related to \( I(\epsilon) \) through

\[
I(\epsilon) = \frac{1}{4\pi R^2} \tilde{n} V \int_{E_0}^{\infty} \Phi(E) Q(\epsilon, E) dE,
\]

where \( Q(\epsilon, E) \) is the bremsstrahlung cross section (cm\(^{2}\) keV\(^{-1}\)) differential in photon energy, \( R = 1 \) AU, and the mean target density \( \tilde{n} \) (cm\(^{-3}\)) is defined by \( \tilde{n} = V^{-1} \int n(r) dV \), where \( dV \) is a volume element. Bremsstrahlung in the energy range \( \gtrsim 10 \) keV is produced by energetic electrons interacting with both protons/ions and electrons (both free and bound in atoms); these contributions are summed to give the total differential bremsstrahlung cross section \( Q(\epsilon, E) \).

For electron energies \( \lesssim 300 \) keV, the contribution from electron-electron bremsstrahlung can be safely ignored (Haug 1975). However, for higher energies, this is no longer the case. Generally, for a given electron spectrum, the additional electron-electron bremsstrahlung yield acts to flatten (harden) the photon spectrum in this energy range (see, e.g., Haug 1975). Equivalently, the inclusion of electron-electron bremsstrahlung requires, for a given photon yield, a softer (steeper) electron spectrum than would be required for electron-ion bremsstrahlung alone.

The Ramatyr High-Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) has opened a new era in the study of hard X-ray spectra from solar flares. With the high-resolution, hard X-ray spectra made available by RHESSI, an investigation is now warranted into the form of the hard X-ray spectrum above \( \sim 300 \) keV, using a cross section that takes into account both electron-ion and electron-electron bremsstrahlung.

In this paper, we therefore study the effect of adding the electron-electron bremsstrahlung term to the mean electron spectrum corresponding to a given hard X-ray spectrum. In \( \S \) 2, we discuss the forms of the electron-ion and electron-electron cross sections, and we show that the presence of an upper limit to the photon energy in the electron-electron process can, in principle, provide evidence for a high-energy cutoff in the electron spectrum and/or evidence of strong anisotropy in the injected electron distribution. In \( \S \) 3, we discuss the sample event (on 2005 January 17) chosen for analysis. In \( \S \) 4, we present the form of the electron spectrum corresponding to the observed photon spectrum, using both forward-fitting (e.g., Holman et al. 2003) and regularization (Piana et al. 2003) techniques, in conjunction with a bremsstrahlung cross section that takes into account both electron-ion and electron-electron emission. In \( \S \) 5, we discuss the results obtained, and in particular we point out that certain features in the electron spectrum inferred using the electron-ion bremsstrahlung cross section are artifacts that can vanish when the full, correct cross section is employed.

2. FORM OF THE BREMSSTRAHLUNG CROSS SECTION AND THE RELATION BETWEEN ELECTRON AND PHOTON SPECTRA

The cross section for electron-ion bremsstrahlung scales as \( Z^2 \), where \( Z \) is the atomic number of the ion. Furthermore, in consideration of electron-electron bremsstrahlung, the possible binding of target electrons to their host ions in a neutral or partially ionized

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medium is not significant (E. Haug 2005, private communication). Hence, in a quasi-neutral target of particles with atomic number $Z$, the bremsstrahlung cross section per atom for emission of a photon of energy $\epsilon$ by an electron of energy $E$ is in general equal to

$$Q(\epsilon, E) = Z^2 Q_{e-p}(\epsilon, E) + Z Q_{e-e}(\epsilon, E),$$  \hspace{0.5cm} (2)$$

where $Q_{e-p}(\epsilon, E)$ and $Q_{e-e}(\epsilon, E)$ are the cross sections for bremsstrahlung in electron-proton, and electron-electron collisions, respectively.

The (fully relativistic) form of $Q_{e-p}(\epsilon, E)$, averaged over solid angle in the ion rest frame (which, to a high degree of accuracy, is the same as the observer frame), was given by Koch & Motz (1959). The form of $Q_{e-e}(\epsilon, E)$, averaged over solid angle in the rest frame of the target electron was given by Haug (1998),\(^6\) while the solid angle averaged form in the zero-momentum (center of mass) frame was given by Haug (1989). Neither of these latter formulae are strictly appropriate to the case of an electron beam incident on a warm plasma; the target electrons, unlike the ions, have a velocity that may be comparable to the velocity of the electrons in the impinging beam, so that a range of injected-particle/target-particle relative velocities exist for a given injected electron energy. However, as verified through numerical simulation, for low electron energies (from \(\sim 10 \text{ to } \sim 200 \text{ keV}\)), the form of $F(E)$ corresponding to a given hard X-ray spectrum, inferred using the cross section (eq. 2), does not differ, within statistical uncertainties in the photon flux, from the form of $F(E)$ obtained using the electron-ion cross section alone. Hence, only at electron energies \(\gtrsim 200 \text{ keV}\) is the inclusion of the electron-electron bremsstrahlung term necessary, and for such energies the velocity of the target particles is relatively insignificant. The target particle rest frame is, therefore, a better approximation to the observer frame than is the zero-momentum frame. Hence, use of the electron-electron cross section in the target particle rest frame is more appropriate, and will be used here.

For electron-ion bremsstrahlung at nonrelativistic energies, the photon spectrum produced by a power-law spectrum of electrons $F(E) \sim E^{-\delta}$ is close to a power-law form $I(\epsilon) \sim \epsilon^{-\gamma}$, with $\gamma \sim \delta + 1$ (e.g., Brown 1971). As the photon energy increases, relativistic terms in the cross section become more important, and the photon spectrum flattens somewhat. For electron-electron bremsstrahlung, a power law $F(E) \sim E^{-\delta}$ also produces a power law $I(\epsilon) \sim \epsilon^{-\gamma}$, but with a significantly flatter $\gamma \approx \delta$ (Haug 1989). Thus, as photon energy increases, both the effect of relativistic terms in the electron-ion cross section, and the increasing importance of the electron-electron bremsstrahlung contribution, lead to a flattening of the photon spectrum $I(\epsilon)$ produced by a given $F(E)$. While many previous analyses (e.g., Piana et al. 2003) of the relation between the hard X-ray spectrum $I(\epsilon)$ and the responsible electron spectrum $F(E)$ have utilized the fully relativistic form of the electron-ion cross section, they have generally ignored the effect of the electron-electron bremsstrahlung contribution. Here, we examine quantitatively the point that, if the additional contribution due to electron-electron bremsstrahlung is included, the $F(E)$ form required to produce a given $I(\epsilon)$ is steeper than would be required if only electron-ion bremsstrahlung were involved.

It is also important to note that while the electron-ion cross section is finite for all $\epsilon < E$, the “laboratory frame” cross section for electron-electron bremsstrahlung vanishes above a maximum photon energy, due to the necessarily finite energy carried by the recoiling target electron. Quantitatively (Haug 1975),

$$\epsilon_{\text{max}} = \frac{E}{E + 2 - \sqrt{E(E + 2) \cos \theta}},$$ \hspace{0.5cm} (3)$$

where $E$ is the electron kinetic energy in the laboratory frame (in units of the electron rest mass $mc^2$), and $\theta$ is the angle between the incoming electron and the outgoing photon trajectories. For highly nonrelativistic electrons ($E \ll 1$), $\epsilon_{\text{max}} \to E/2$ for all values of $\theta$. Only for highly relativistic electrons ($E \gg 1$) and $\theta = 0$ (a singular case) does $\epsilon_{\text{max}} \to E$; for all other situations, $\epsilon_{\text{max}}$ is less than $E$, and approaches zero as $E \to \infty$ (Fig. 1).

This result has important implications for the form of the photon spectrum produced by electron-electron bremsstrahlung. If the electron spectrum $F(E)$ has a maximum energy $E_{\text{max}}$, then, while electron-ion bremsstrahlung will generate photons at all energies up to $E_{\text{max}}$, electron-electron bremsstrahlung will produce no photons at all in the range $\epsilon_{\text{max}} < \epsilon < E_{\text{max}}$. The entire spectrum above $\epsilon_{\text{max}}$ will therefore be produced completely by electron-ion bremsstrahlung; the flattening of the photon spectrum associated with the electron-electron contribution disappears, and the relationship between $I(\epsilon)$ and $F(E)$ reverts to the form appropriate to electron-ion bremsstrahlung alone.

Note also that the maximum photon energy $\epsilon_{\text{max}}$ depends significantly on the viewing angle $\theta$. Hence, if the injected electron distribution is highly beamed, the strong angular dependence of the maximum photon energy produced permits a determination of the direction of the beam. For example, for $E_{\text{max}} = 1 \text{ MeV}$ and $\theta = 120^\circ$, Figure 1 shows that $\epsilon_{\text{max}}/E \simeq 0.2$, so that there should be evidence for a transition in the photon spectrum around 200 keV. Figure 2 shows the effect of such a 1 MeV upper energy cutoff on the total (electron-ion and electron-electron) photon spectrum $I(\epsilon)$ and on its local spectral index $\gamma = -d \log I(\epsilon)/d \log \epsilon$ for various values of $\theta$. For $\theta = 120^\circ$, there is indeed an abrupt step in $\gamma$ at $\sim 200 \text{ keV}$; this step moves toward larger energies as $\theta$ is reduced.

Kontar et al. (2004) and Brown et al. (2006) have shown that, for electron-ion bremsstrahlung, the presence of an upper cutoff energy $E_{\text{max}}$ in the electron spectrum $F(E)$ may be deduced from

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\(^6\) Note that in the formula for $H(\epsilon, k, x)$ for the case $k > \frac{1}{2}$ (Haug 1998, p. 347), the term $(x + s)$ on line 3 of the equation should be replaced by $(x + s/w + s)$ (E. Haug 2005, private communication).
the overall shape of the photon spectrum $I(\epsilon)$, even at energies $\epsilon$ that lie wholly below $E_{\text{max}}$ (this is because the lack of electrons with $E > E_{\text{max}}$ has a measurable effect on the photon spectrum at lower energies). An accurate assessment of $E_{\text{max}}$ by this technique requires accurate measurements of $I(\epsilon)$ out to energies $\epsilon \leq E_{\text{max}}$. However, the spectral break produced by the “switching off” of electron-electron bremsstrahlung at high values of $\epsilon$ can occur at energies $\epsilon$ substantially less than $E_{\text{max}}$ (Fig. 2), where, especially for steep spectra, photon statistics may be much better. However, it should be noted that due to the fairly strong dependence of $E_{\text{max}}/E$, and hence the location of the spectral break point, on $\theta$ (Figs. 1 and 2), the inferred value of $E_{\text{max}}$ depends significantly on the value of $\theta$, and may indeed be masked if a range of $\theta$ values (i.e., a beam distributed widely in solid angle) is involved.

3. DATA ANALYSIS

In selecting suitable events for analysis, we searched for a clear identification of high-energy photons in the flare light curve, and specifically a count rate high enough to provide good count statistics in energy channels above 300 keV. Quasi-logarithmic energy binning was used in order to enhance the signal-to-noise ratio in each energy channel, and the time bins were chosen equal to RHESSI’s rotation period (as given for the time of the flare), to ensure that there is no differential modulation of the light curve from varying aspects of the imaging grids.

The data were corrected for the following effects: decimation, detector energy response, detector live time, attenuator transmission, imaging grid transmission, and pulse pile-up. These steps were performed using standard software incorporating the most up-to-date information on the instrumental calibration (Schwartz et al. 2002). The background was then subtracted using the SPEX package to interpolate between two background time intervals, one before, and one after the flare. Data from detectors 2 and 7 were not used, because their energy resolution is significantly poorer than for the other detectors (Smith et al. 2002).

Figure 3 shows the photon spectrum for the time interval 09:43:16—09:44:24 UT (the time of approximate peak flux) for the 2005 January 17 (GOES class X3.8) event. This event, which produced several strong gamma-ray lines, was previously studied by Kontar & Brown (2006), who concluded that the pitch angle distribution for electrons up to $\sim 300$ keV is close to isotropic.

We focus attention on the highest energy spectrum ($\epsilon > 200$ keV) in this paper.

This event was located at position ($x = 380''$, $y = 320''$) on the solar disk, corresponding to a heliocentric angle $\sim 30''$. Consequently, the assumption of a downward-directed electron beam leads to angles $\theta$ between the beam direction and the observer in the second quadrant; this enhances the possibility of observing the spectral features noted in § 2 associated with the upper limit to electron-electron bremsstrahlung emission (see Figs. 1 and 2).

4. DETERMINATION OF THE MEAN SOURCE ELECTRON SPECTRUM

Before attempting to determine the form of the mean source electron spectrum responsible for the observed hard X-ray/ gamma-ray continuum, it is first necessary to subtract the emission from strong gamma-ray spectral lines. In the energy range under consideration, the two most significant ranges for which this subtraction is necessary are (483–512) keV and (829–882) keV. The corrected spectrum is presented in Figure 3. The first of these corresponds to the electron-positron annihilation line at 511 keV and its associated positronium continuum at lower energies; the second corresponds to a variety of strong emission lines from
27Al, 54Cr, and 56Fe (see Table 1 in Ramaty et al. 1979; Table 1 in Kozlovsky et al. 2002). These lines were removed by replacing the data in these ranges with a smooth interpolation of the continuum spectrum on either side of each feature.

The residual photon spectra then represent principally bremsstrahlung continuum, with an emissivity given by equation (1). (Since our focus is on the highest energy emission \([\epsilon > 200 \, \text{keV}]\), the effect of photospheric Compton back-scatter of primary photons [albedo] should be insignificant [Bai & Ramaty 1978; Kontar et al. 2006].) These continuum spectra were then used to determine the mean electron flux spectrum \(F(\epsilon)\) in the source, using two different, well-established methodologies for the solution of equation (1).

4.1. Forward Fit

Here we follow the procedure of Holman et al. (2003), and assume that the mean electron spectrum is the sum of a low-energy Maxwellian, plus a broken power law of the form

\[
F(\epsilon) = \begin{cases} 
\frac{A E^{-\delta_1}}{E_{\text{brk}}^{\delta_1}} & \epsilon < E_{\text{brk}}, \\
\frac{A E_{\text{brk}}^{-\delta_2}}{E_{\text{brk}}^{\delta_2}} & \epsilon \geq E_{\text{brk}}.
\end{cases}
\]

Because the Maxwellian part of \(F(\epsilon)\) (with a characteristic temperature \(T \approx 3 \, \text{keV}\)) is utterly insignificant at energies \(\epsilon \gtrsim 200 \, \text{keV}\), it is not necessary to consider this component in our analysis.

Using the fundamental relation (eq. [1]), the cross section (eq. [2]), and an \(F(\epsilon)\) of the form in equation (4) permits us to obtain the photon spectrum \(I(\epsilon)\) for a given set of parameters \((A, E_{\text{brk}}, \delta_1, \delta_2)\). Comparison with the observed \(I(\epsilon)\) above \(\epsilon = 200 \, \text{keV}\) then permits determination of the best-fit values of \(A, E_{\text{brk}}, \delta_1,\) and \(\delta_2\). We performed such a forward fit for two forms of the bremsstrahlung cross section:

\[
Q_{\epsilon-E}(\epsilon, E) = Z^2 Q_{\epsilon-p}(\epsilon, E),
\]

(i.e., including electron-ion bremsstrahlung only) and

\[
Q_{\text{tot}}(\epsilon, E) = Z^2 Q_{\epsilon-p}(\epsilon, E) + ZQ_{\epsilon-e}(\epsilon, E),
\]

(which includes both electron-ion and electron-electron bremsstrahlung). Mean values \((Z) = 1.2\) and \((Z^2) = 1.44\) (representative of mean solar abundances) were assumed.

Using the cross section \(Q_{\text{tot}}(\epsilon, E)\), which represents only electron-ion bremsstrahlung, results in best-fit values \(\delta_1 = 3.4, \delta_2 = 2.9,\) and \(E_{\text{brk}} = 445 \, \text{keV}\). Using the more correct cross section \(Q_{\text{tot}}(\epsilon, E)\) (which incorporates both electron-ion and electron-electron terms) gives \(\delta_1 = 3.5, \delta_2 = 3.1,\) and \(E_{\text{brk}} = 431 \, \text{keV}\). The forms of both of these fits are shown in Figure 4. While inclusion of the electron-electron bremsstrahlung term results in little change to the form of \(F(\epsilon)\) at low energies, its inclusion does lead to the break energy moving downward from \(E \sim 450 \, \text{keV}\) to \(E \sim 430 \, \text{keV}\), and to the spectral index for the high-energy component steepening from \(\delta \approx 2.9\) to \(\delta \approx 3.1\) (\(\Delta \delta \approx 0.2\)). Such a steepening of \(F(\epsilon)\), and the energy above which it becomes significant, are in accordance with the expectations expressed in §1 and with earlier quantitative estimates based on the hardening of hard X-ray spectra (e.g., Vestrand 1988).

4.2. Regularized Inversion

Piana et al. (2003) have demonstrated how to construct smooth, regularized, forms for the mean electron flux spectrum \(F(\epsilon)\) from high-resolution RHESSI photon spectra \(I(\epsilon)\). The advantage of this method is that it is not necessary to assume an empirical form for \(F(\epsilon)\). In addition, as shown by Brown et al. (2006), this method is capable of accurately revealing the overall shape of the electron spectrum, and indicating the presence and approximate form of small-scale features of sufficient amplitude, if present.

Figure 5 shows the recovered \(F(\epsilon)\) solution for the same photon spectrum used in the forward-fit procedure of Figure 4. The results are presented in the form of a confidence strip, a set of different realizations of \(F(\epsilon)\), each curve corresponding to a different realization of the noisy data set \(I(\epsilon)\). Results using \(Q(\epsilon, E) = Q_{\epsilon-E}(\epsilon, E)\) (i.e., including only electron-ion bremsstrahlung) are shown as dashed lines; results using the full cross section \(Q_{\text{tot}}(\epsilon, E)\) (i.e., incorporating both electron-ion and electron-electron terms) are shown as solid lines.

It is clear that the \(F(\epsilon)\) recovered using the full cross section (eq. [2]), including both electron-ion and electron-electron bremsstrahlung, is, for \(E \gtrsim 300 \, \text{keV}\), steeper (with a spectral index greater by \(~0.4\)) than the \(F(\epsilon)\) recovered assuming purely electron-ion emission. This result is consistent not only with the forward-fit results of the previous subsection, but also with the physical expectations enunciated in §1. Moreover, the dashed confidence strip
(corresponding to use of the electron-ion cross section alone) has an upward break near $E = 400$ keV (which can be verified visually by looking along, rather than at, the strip). Since a fully relativistic form for the cross section $Q_{\text{e-i}}(\epsilon, E)$ was used in constructing these solutions, such a break cannot be attributed to the growing importance of relativistic terms in the cross section. However, the true form of $F(\epsilon)$, as exhibited by the solid confidence strip, has a rather featureless power-law form over the energy range from 200–1000 keV. Consequently, use of the full cross section, including the electron-electron term that becomes important at energies $\geq 300$ keV, removes the need to account for the $\sim 400$ keV energy that characterizes the (unphysical) upward break in $F(\epsilon)$ that appears when only the partial (electron-ion) cross section is used in the analysis.

5. DISCUSSION AND CONCLUSIONS

As expected, recognition of the growing importance of electron-electron bremsstrahlung at high photon energies reduces, for a given hard X-ray spectrum, the number of high-energy electrons required to produce it; this leads to a steepening in the inferred mean source electron spectrum $\overline{\epsilon}(E)$ above $\sim 400$ keV. For the 2005 January 17 event studied, use of the electron-ion cross section alone leads, whether by forward-fitting or regularized inversion, to the inference of an upward break ($\Delta \gamma \sim 0.4$) in $F(\epsilon)$ at $E \sim 400$ keV (Fig. 5). However, when both electron-ion and electron-electron bremsstrahlung emission are considered, this break disappears, resulting in an $\overline{\epsilon}(E)$ that has a straightforward power-law form over the energy range from 100–1000 keV. Careful interpretation is therefore necessary when faced with apparent hard X-ray spectral changes in this energy range.

One process that can, for a sufficiently strong magnetic field, operate strongly in the few 100 keV range, and so affect this argument is gyrosynchrotron emission. However, the presence of this additional emission mechanism would cause the $\overline{\epsilon}(E)$ to bend downward at higher energies. The fact that, after inclusion of the electron-electron contribution, $\overline{\epsilon}(E)$ has no such bend puts an upper limit on the importance of gyrosynchrotron emission and so a (fairly generous) upper limit of $\sim 10$ kG on the strength of the ambient magnetic field.

Trottet et al. (1998) report very significant upward breaks ($\Delta \gamma \approx 1.2–2$; $E_{\text{brk}} \approx 400$ keV) in the hard X-ray spectrum for a series of intervals during an electron-dominated gamma-ray event on 1990 June 11. We agree with these authors that the inclusion of electron-electron bremsstrahlung cannot account for such breaks. However, Vestrand (1988) reports that “most flares show a break $\approx 0.5$” occurring at an energy “$\approx 300–400$ keV,” and a similar statement is made by Dennis (1985; however, he also reports a much larger spectral break $[\Delta \gamma \approx 2]$ in an event observed on 1980 June 4). Such modest ($\Delta \gamma \approx 0.5$) upward breaks at photon energies $\epsilon \approx 300–400$ keV are naturally accounted for by including the contribution from electron-electron bremsstrahlung; other considerations, such as energy-dependent anisotropy (Li 1995) or a separate emission/acceleration process (e.g., Heristchi 1986) are, in general, not required.

Only features common to all (or at least nearly all) realizations of $F(\epsilon)$ can be considered real. Using this criterion, one must concede that the recovered confidence strip (Fig. 5) is sufficiently wide that no firm evidence for a sudden change in the local spectral index $\gamma$ (cf. Fig. 2) can be claimed. Hence, the data do not provide compelling evidence for a narrow range of viewing angles $\theta$, i.e., for strong beaming of the accelerated electrons, or for an upper energy cutoff $E_{\text{max}}$ in the accelerated electron energy distribution. The former assessment is bolstered by Kontar & Brown’s (2006) finding, using a comparison of the brightness of the primary source with that of the photospherically back-scattered albedo patch (Kontar et al. 2006), that the electron distribution at energies $E \lessapprox 200$ keV in the 2005 January 17 event was also consistent with isotropy. The recovery of a single power-law electron spectrum also suggests an electron acceleration process absent any characteristic energy or corresponding scale.

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