Energy Deposition in White Light Flares with TRACE and RHESSI

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Abstract. In Fletcher et al. (2007) we investigated the white light (WL) continuum during solar flares and its relationship to energy deposition by electron beams. In 9 flare events, spanning GOES classifications from C4.8 to M9.1, we have high cadence TRACE WL and RHESSI hard X-ray observations, and compare the WL radiative power output with that provided by flare electrons. Under the thick–target model assumptions, we find that the electron beam must extend down to 15–20 keV, and the energy input to the chromosphere should occur within the collisional stopping depth of these electrons - approximately $2 \times 10^{-4} \text{ g cm}^{-2}$. In this short paper, we discuss some ideas on flare WL emission, summarise the results of the Fletcher et al. (2007) study and discuss their implications for chromospheric heating and white light flare emission.

1. Introduction

The earliest recorded flare observations were of white light flares (WLFs), yet the physical mechanism for the generation of this broadband emission remains unknown. The fact that WLFs can outshine the surrounding photosphere (and in fact in some large flares are observable against the entire visible photosphere, e.g., Woods et al. 2004) demonstrates that they involve colossal energy deposition. Direct imaging shows that this deposition occurs in very small surface patches. The problem of generating the WL continuum enhancement is intimately related to the problem of heating around the chromospheric temperature minimum region during flares, as inferred from observations of flare line emission (Machado & Linsky 1975).

An excellent overview of possible modes of WL generation during flares was presented by Metcalf et al. (1990). We concentrate here on WL generation mechanisms involving particle beams. The earliest such theories (e.g., Najita & Orrall 1970) held that WL emission was caused by direct excitation of the photosphere by beams of electrons or protons from the corona, which led to heating and ionization. Both processes would increase the white-light yield, through an increase in the blackbody intensity and in the H\textsuperscript{−} opacity. However, to penetrate to the photosphere, electrons of hundreds of keV are required (Aboudarham & Henoux 1986a estimate 350 keV), which - given that we know from hard X-ray observations that electrons have a roughly power-law distribution in energy - requires orders of magnitude more energy at tens of keV energy. This is not energetically feasible. The proton penetration energy to the photosphere is on the
order of 15 MeV. However, to have a reasonable energy budget for the flare, and explain the WL emission, one would require all protons to be at $\approx 10^{-20}$ MeV (Machado et al. 1978), inconsistent with inferences from $\gamma$-ray observations.

Brown (1973) studied the effect of localised heat input by electron beams, finding significant temperature increases in relatively narrow layers of the solar chromosphere. Machado & Linsky (1975) point out that Brown’s analytic results are similar, in terms of temperature as a function of column depth, to their semi-empirical modeling, especially when correction for Brown’s over-estimate of radiative losses is made. However models relying solely on beam heating are unable to provide the temperature minimum region enhancement. Machado & Linsky (1975) and Machado et al. (1978) comment that excitation by an electron beam cannot, for reasonable beam energies, produce the upper-photospheric temperature increase, deduced from spectral line observations of the Ca II lines, of $\approx 100$ K at mass column densities down to about 0.3 g cm$^{-2}$.

The effect of collisional over-ionization in the context of WLFs was first discussed by Hudson (1972), who investigated the free-bound continuum generated following direct collisional ionization of the deep chromosphere by electron beams. Later models of WL generation, known as “chromospheric backwarming” models, studied the radiative heating and excitation of deep layers by the free-bound Balmer-Paschen continuum (e.g., Aboudarham & Henoux 1987, Aboudarham & Henoux 1989). Since the temperature minimum region of the deep chromosphere produces the ultraviolet continuum, it should also absorb and be heated by these wavelengths. Other backwarming models have invoked optically thin ultraviolet lines (Machado et al. 1978), extreme UV (Emslie & Machado 1979) or soft X-rays (Somov & Syrovatskii 1974, Machado 1978), which produces photoionization of heavy elements and enhancement of H$^-$ emission. But to be effective, such models require very compact ($\approx 100$ km) and intense sources, within a few hundred kilometers of the temperature minimum region (e.g., Emslie & Machado 1979, Metcalf et al. 1990). Conceivably, observations in the 1550 Å filter of TRACE could help assess whether this is reasonable; at the time of these earlier studies it was considered to be unlikely.

2. Chromospheric Backwarming

Following a detailed study of 5 solar flares Metcalf et al. (1990) concluded that chromospheric backwarming by Balmer-Paschen continuum was the most likely WL generation mechanism. The Balmer-Paschen models require excitation at a depth with sufficient neutral hydrogen to provide the Balmer-Paschen emissivity. In Aboudarham & Henoux (1986b) and Aboudarham & Henoux (1989) the effect of collisional ionization only becomes significant at column masses above a few times $10^{-3}$ g cm$^{-2}$, or column depths of a few times $10^{21}$ cm$^{-2}$; the bulk of the Paschen continuum is also generated at such values. A study of a TRACE and Yohkoh Hard X-ray Telescope event by Metcalf et al. (2003) concluded that sufficient energy existed in electrons above 20 keV to generate the Balmer-Palmer continuum required to explain the backwarming, and also that the beam ionization leading to the enhanced continuum and ultimately the WL emission was formed at an electron density of about $9 \times 10^{12}$ cm$^{-3}$. In a semi-empirical flare model atmosphere, such as that of Machado et al. (1980), 20 keV
electrons can readily penetrate to such densities but this is not true of pre-flare atmospheres, in which the bulk of the electrons would be stopped in targets of insufficient optical depth to produce the required UV continuum. So the question of whether chromospheric backwarming can indeed produce the WL enhancement depends on the model used for the chromospheric density distribution. As the WL enhancement (like the HXR enhancement) is an impulsive-phase phenomenon, there is justification for using quiet sun models, such as the Model “C” of Vernazza et al. (1981), rather than the flare models of Machado et al. (1980), since these latter are based primarily on spectral observations made after the Hα flare maximum. This is most certainly also after the flare impulsive phase, once the atmosphere has had time to respond dynamically to the flare energy input. WL and HXR emission is an impulsive-phase phenomenon.

3. Summary of the TRACE White Light and RHESSI Flare Study

In our recent study (Fletcher et al. 2007) we used joint RHESSI and TRACE white light observations to investigate the energetics of WLF production. The RHESSI hard-X-ray and TRACE WL sources correlate well in space (within pointing errors) and time (with peaks coinciding within the $\approx 10$ s time cadence). Examples of the HXR and WL co-alignment are shown in Fig. 1, and of time profiles in Fig. 2. The interested reader is referred to the full Journal paper for more detail.

By calculating the WL luminosity and comparing it with the energy content of the electron beam implied by the HXR emission, we can arrive at an
Figure 2. The light curves corresponding to the flares in Fig. 1. Black shows the RHESSI 25-50 keV light curve, and grey the TRACE WL light curve. The horizontal black bars show the times during which the RHESSI thin attenuator is in. TRACE WL includes a strong UV response; when this is subtracted (see Metcalf et al. 2007 in prep.) the “true” WL peaks map extremely well onto the HXR peaks.

upper limit for the energy down to which the beam must extend to balance the WL luminosity. Since we do not have any substantial WL spectral information we can only do this approximately. However, the TRACE observation sequence interleaves broadband WL emission with images taken through the 1700 Å filter, so we do have a filter ratio value. We proceeded under two different assumptions: firstly that the WL (and 1700 Å) enhancement is increased blackbody radiation due to photospheric heating; secondly that the emission is Balmer-Paschen continuum emission but not at an increased temperature (c.f. Metcalf et al. 2003), rather at the photospheric colour temperature of 5300 K. We are confident that the first assumption provides an upper limit to the WL power, since we use an increased temperature of 25,000 K, commensurate with the observed ratio of 1700 Å to broadband WL emission. The second assumption provides a lower limit, since by taking a temperature of 5300 K we are neglecting the enhanced UV component.

The electron beam power can be calculated by invoking the collisional thick-target model Brown (1971), in which an electron beam radiates HXR radiation as it decelerates (and heats) in the dense chromospheric plasma. The collisional thick-target model provides the link between the observed properties of the HXR photon spectrum and the parameters of the parent electron spectrum. The beam power can be deduced straightforwardly knowing the slope of the HXR spectrum in its power-law regime, the intensity, and assuming a “cut-off” electron energy, below which there are no more beam electrons.

The result of this study can be summarised as follows: The lower limit to the WL enhancement implies that the HXR and WL power budgets are compatible, but that the parent electron spectrum must extend to 15-20 keV to provide the required power. In Table 1 we give the white-light luminosity assuming the Balmer-Paschen model (lower limit); the photon spectral index; the electron
beam cut-off energy \((E_c)\) required to match the power budgets for each flare – see below.

Table 1. TRACE and HXR flare parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>GOES</th>
<th>(P_{\text{WL}}/10^{24})</th>
<th>(\gamma)</th>
<th>(E_c) (keV)</th>
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<tr>
<td>2002-07-26</td>
<td>19:59:28</td>
<td>M1.0</td>
<td>12</td>
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<td>42</td>
<td>4.4</td>
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<tr>
<td>2002-10-05</td>
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<td>8.8</td>
<td>4.7</td>
<td>13.5</td>
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<tr>
<td>2002-11-12</td>
<td>18:15:49</td>
<td>C9.9</td>
<td>8.3</td>
<td>4.8</td>
<td>17.8</td>
</tr>
<tr>
<td>2002-06-12</td>
<td>01:22:59</td>
<td>M7.3</td>
<td>23</td>
<td>7.3</td>
<td>19.9</td>
</tr>
<tr>
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<td>33</td>
<td>5.9</td>
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<td>6.0</td>
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<tr>
<td>2004-07-22</td>
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<td>M9.1</td>
<td>140</td>
<td>5.6</td>
<td>15.7</td>
</tr>
<tr>
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<td>13:34:47</td>
<td>C4.8</td>
<td>32</td>
<td>4.3</td>
<td>15.0</td>
</tr>
</tbody>
</table>

\(a\) WL power assuming Balmer-Paschen at \(T = 5.3 \times 10^5\) K, in ergs s\(^{-1}\)

The electron beams are typically fairly steep power-laws (with index given by \(\gamma + 1\) in a fully-ionised thick target) so the majority of the beam energy resides in the lower energy part of the spectrum. So, if the beam is “injected” at the top of the chromosphere it cannot penetrate very deep, and the excitation that leads ultimately to the WL enhancement must also occur relatively high in the atmosphere. From Emslie (1978) we have (for electrons)

\[
\frac{dE}{dN} = -\frac{2\pi e^4}{\mu E} (x\Lambda + (1 - x)\Lambda')
\]  

(1)

where \(E\) is the electron energy, \(N\) the column depth, \(\mu\) the pitch-angle cosine of the beam electrons (which we take to be 1), \(e\) the electronic charge, \(\Lambda\) the Coulomb logarithm for charged-particle interactions, \(\Lambda’\) the effective Coulomb logarithm for electron-neutral interactions, and \(x\) the ionization fraction (see Emslie (1978) for details). This can be used to calculate the stopping depth of an electron in a target of arbitrary ionization fraction. Electrons at the values of \(E_c\) we find have a collisional stopping depth of \(\approx 10^{20}\) cm\(^{-2}\), or \(2 \times 10^{-4}\) g cm\(^{-2}\). Using a background VAL-C chromospheric model Vernazza et al. (1981), Fig. 3 compares this stopping depth with the model estimates from Aboudarham & Henoux (1987) for the depth at which the Balmer-Paschen continuum is produced, and of the backwarmed layer.

The penetration depth of those electrons in which the bulk of the beam energy resides is significantly smaller than that typically required by the UV radiative backwarming models.

4. Discussion

Clearly the vertical density structure of the pre-flare chromosphere in the region where the beam interacts is critical in this discussion, as it determines whether the Balmer-Paschen continuum can be excited in a region of sufficiently high density. We have adopted a non-flaring chromosphere since the
WL events that we observe are impulsive phase phenomena and the combination of the HXR time profiles and the motion of the WL and HXR sources from one spot to another during the flare suggest that an electron beam will enter essentially undisturbed chromosphere. However this should be studied in detail using lower-energy RHESSI channels to search for pre-flare activity, or TRACE UV to search for pre-flare chromospheric brightenings in the regions which are later illuminated by the WL and HXR emission.

Although we have not calculated them here, our observations of flare WL footpoint areas, combined with inferred beam parameters, lead us to extremely high electron beam numbers and number fluxes (on the order of $10^{19} \text{cm}^{-2} \text{s}^{-1}$) which are problematic for the collisional thick target model involving beams accelerated in the corona; firstly the total number of electrons required appears to be in excess of what the flaring corona can supply; secondly, even invoking the involvement of a large coronal volume still requires the electrons to be focused into a small number of tiny footpoints; thirdly, the beam density in the corona appears to be beyond what can be supported in a stable beam-return current system. Added to this, recent observations of disturbances in the photospheric magnetic field during flares (Sudol & Harvey 2005) and evidence that the electron distribution in the chromosphere is nearer isotropic than beam-like (Kontar & Brown 2007) leads us to suggest that perhaps now it is time
for theoretical models of chromospheric flare heating and particle acceleration to move away from ideas of coronal beams, and concentrate on chromospheric processes, involving large-scale disturbances to the magnetic field (akin to the auroral electron acceleration in the Earth’s magnetosphere/ionosphere system) - for example revisiting the work of Emslie & Sturrock (1982) on Joule dissipation of Alfvénic disturbances.

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