FLARE ELECTRON ENERGY BUDGETS – WHAT IS RHESSI TELLING US?

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ABSTRACT

We address the idea that energetic particles may play a key role in the dissipation and transport of energy in flares. After three decades of predictions of spatial, spectral and temporal distributions of hard X- and γ-rays, the various models can now be quantitatively tested against RHESSI high resolution spectral imaging data. It is shown that RHESSI results for a number of HXR flares are in very good agreement with predictions of the basic thick target model (Brown 1971) regarding source height as a function of energy and of global HXR spectrum. A single power-law injection spectrum and purely collisional transport (no wave generation) fit well the decrease of source peak height with increasing energy for very plausible chromospheric density structures. When the target ionisation drop across the transition one is included, the global HXR spectrum agrees well with observed ‘knee’ spectra without any feature added to a scale-less power-law electron injection spectrum. This result favours statistically distributed, as opposed to single large scale, E-field acceleration. Whether energetic electron beams actually dominate flare energy transport still depends on accurate inference of the low energy thermal/nonthermal spectral transition though RHESSI results to date support the idea. The ion energy budget is also briefly mentioned.

Key words :Hard X-Rays; electron; flare; acceleration

INTRODUCTION

Quantitative testing of the long-standing idea that non-thermal electrons play a central role in flare energy budget requires the most accurate possible inference of the electron distribution function f_e(E). The remote sensing problem of inferring f_e from its bremsstrahlung signature in turn requires accurate data of high resolution simultaneously in energy, space, and time only now becoming available from RHESSI. Here we discuss some RHESSI spectra and spectral imaging results in terms of their compatibility with the predictions of the collisional thick target model (Brown 1971, 1972, 1973) and of energy budget implications.

HXR SOURCE MODELS

The 3 main models are thick target (TT) – Brown (1971), trap plus precipitation (TPP) – Aschwanden et al. (1998) and refs. therein - and thermal (TH) – Chubb (1970), Brown (1974). In the TT situation electron beams are accelerated at a rate \( \delta_a(E_e) \) s \(^{-1}\) in the corona and injected directly toward cool loop footpoints, emitting bremsstrahlung HXRs and losing energy by collisions and wave generation. Since only \( 10^2 \) of energy lost is in HXR, the luminosity \( L_{\text{HXR}} \sim 10^{37} L_{\text{flare}} \) implies an electron beam power \( P_e \sim \frac{L_{\text{flare}}}{E_e} \) if the electron beam spectrum extends down to energies \( E_e = E_a < \sim 20 \) keV. The TPP model carries similar energy implications to the TT but the accelerated electrons reside in a trap region prior to entering the chromosphere and produce some coronal HXR emission (Aschwanden et al. 1998).

In the TH model a wide distribution of locally Maxwellian plasma temperatures \( T > 1 \text{ K} \) is invoked which yields a non-exponential spectrum like a ‘non-thermal’ power-law. For the same \( L_{\text{HXR}} \) this requires much less total electron energy than the TT since energy is not lost in interaction with a cold background. Mean free path limits on hot electron containment ensure that the TH model can only hold up to moderate energies but if these are even 40 keV then the increased \( E_e \) implies a non-thermal power \( P_e \sim L_{\text{flare}} \). Thus to test the hypothesis that \( P_e \sim L_{\text{flare}} \), we need to test the spectral energy distributions of \( f_e \), and then the spectral energy distribution we use X-ray spectral and other data to estimate the transition energy \( E_a \) between predominantly thermal and nonthermal emission. Aschwanden et al. (1996) have given convincing evidence of flight evidence from YohKoh in favour of the TT/TPP model. Here we concentrate on RHESSI TT tests in the space and spectral domains.

RHESSI HXR SOURCE HEIGHT STRUCTURE

Brown et al. (2002) and Aschwanden et al. (2002) have derived models for the energy dependent HXR height distribution for the basic TT model with only collisional energy losses and shown how one can derive the atmospheric density structure \( n(h) \) needed for the model to fit RHESSI spectral images. The essence of the idea is that photons of energy \( \epsilon \) are mainly emitted near a column depth \( N(h(\epsilon)) = \epsilon / (4 \pi e^2 \lambda) \) and then we get \( n(h(\epsilon)) = -dN(n(\epsilon)) / dh \) where \( h(\epsilon) \) is the peak emission height for photons of energy \( \epsilon \). Their results are shown in Fig.1 superposed on various models of atmospheric density and are found to be in close agreement with recent dynamical models of the atmosphere. This means that the collisional propagation characterising the


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TT/TPP models is well supported by these spatial data in the sense that the relative energy dependent height structure of HXR footpoints agrees with the model predictions within a factor of two or better for purely collisional energy losses. This is well within the uncertainty associated with the modelling approximations like neglect of pitch angle scattering and ionisation changes along the electron paths. These conclusions were found to be fairly insensitive to the exact form of $\delta(E_0)$. 

Using the equations of McArthur et al. (1998), Kontar et al. (2002) fitted the predicted $I(e)$ (a power-law times an incomplete Beta function deviation factor) to RHESSI spectra for 4 events and found a $\chi^2 = \chi^2_{\text{red}}$ fit which is much better than the value $\chi^2 = \chi^2_{\text{red}}$ when a pure power-law $I(e)$ is used – i.e. when the essential ionisation effect is ignored. Results are summarised in Table I while Fig. 2 shows one example of spectral fits and residuals between observed and predicted $I(e)$ for the two models. Residuals at high energy are noise dominated but at around 50 keV the model ignoring ionisation structure has residuals with the systematic $\varepsilon$ trend expected from this systematic model error. Thus for these events the TT model with collisional losses only fits $I(e)$ data very well for a power-law $\delta(E_0)$ with no characteristic energy in it only when target ionisation structure is included.

Table I : Global spectrum model fitting parameters for each event and ratio of $\chi^2$ fit values. $T=$ temperature of thermal component; $(\delta_\text{c}, \delta_\text{th})$ and $(\chi^2, \chi^2_{\text{red}})$ are the electron spectral indices and $\chi^2$ values of models without/with ionisation. $E_\text{c} = (4\pi e^4 A N^{-1})^{1/2}$ is the electron energy stopping collisionally at the transition zone.

<table>
<thead>
<tr>
<th>EVENT</th>
<th>$02:20:02$</th>
<th>$03:17:02$</th>
<th>$05:31:02$</th>
<th>$06:01:02$</th>
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</thead>
<tbody>
<tr>
<td>$T(\text{keV})$</td>
<td>1.47</td>
<td>1.27</td>
<td>2.02</td>
<td>1.45</td>
</tr>
<tr>
<td>$\delta_\text{c}$</td>
<td>4.89</td>
<td>4.84</td>
<td>3.79</td>
<td>4.26</td>
</tr>
<tr>
<td>$\delta_\text{th}$</td>
<td>5.29</td>
<td>4.99</td>
<td>4.15</td>
<td>4.46</td>
</tr>
<tr>
<td>$E_\text{c}(\text{keV})$</td>
<td>37.4</td>
<td>34.4</td>
<td>6.2</td>
<td>21.0</td>
</tr>
<tr>
<td>$\chi^2/\chi^2_{\text{red}}$</td>
<td>31</td>
<td>21</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>

**TRANSITION ENERGY $E_\text{c}$ BETWEEN THERMAL AND NON-THERMAL CONTRIBUTIONS**

While the results summarised above are strongly supportive of the collisional TT model with a power-law $\delta(E_0)$ in the deka-keV range, whether or not this implies a $\theta_{\text{wind}} - L_{\text{flare}}$ depends crucially on the transition energy $E_\text{c}$ down to which the electron distribution remains non-
thermal since most of the beam power resides at the low energy end of the power-law – a fact known since Brown (1971). There is considerable circumstantial evidence for the idea that $\theta_e$ is sufficient to heat much of the impulsive phase flare plasma in the relationship of the HXR light curve to that at other wavelengths – e.g. the time integral Neupert Effect in Soft XR’s and close cross correlation at UV energies and the co-spatiality of simultaneous brightenings at HXR and other wavelengths – results which RHESSI data are testing further.

Though all these might only indicate a common source for accelerated electrons and atmospheric heating rather than a causal influence, it is not clear that any other heating mechanism than energetic electrons can synchronise spatially separated emissions as closely as observed. Arguments that energetic ions may be more important than electrons (e.g. Simnett 1995) require the ion power-law spectrum to extend down to 100 keV or less to yield $\theta_i \sim \theta_{\text{phot}}$, but such ions take $> 2$ sec to traverse a $10^5$ cm loop whereas $> 20$ keV electrons take $< 0.1$ sec. The former seems inconsistent with the observed degree of synchronisation between footpoints and between emission at various wavelengths while the electron time of flight agrees well with energy dependent HXR time delays (Aschwanden et al. 1996).

Nevertheless it would be highly desirable if a means could be found to infer $E_e$ directly from data in some way. The fact that RHESSI spectra can be well fit by the sum of an isothermal component, the contribution from which drops sharply above 10 keV or so, plus a roughly power-law ‘nonthermal’ component, does NOT mean that this is the only interpretation. A distributed non-isothermal thermal component may well fit at least the low energy end of the so-called non-thermal regime.

The only test so far proposed which might help rule out a thermal model for the bulk of the HXR spectrum is the ‘thermality criterion’ derived by Brown and Emslie (1987) based on the Kramers cross-section approximation. They showed that a necessary condition for any $I(\varepsilon)$ to be explicable by a physically possible distribution of plasma emission measure over temperature is that its $n$-th derivative $d^n(I(\varepsilon))/d\varepsilon^n$ should have sign $(-)^n$. Emslie et al (1989) applied this test with some success to pre-RHESSI Ge detector data and we are attempting the same with RHESSI spectra. The main problems are removal of systematic effects in the instrument, background subtraction, and Poisson noise which rapidly overwhelms higher order derivatives.

CONCLUSIONS

RHESSI spectral images of flares with bright footpoints have spatial properties in very good accord with predictions of the purely collisional thick target model (small losses to wave generation) and favour the idea that electron beams play a major role in flare energy budgets.

The TT model also fits global HXR spectral data very well for a pure power-law electron acceleration spectrum when atmospheric ionisation structure is properly considered. Such a power-law spectrum with no characteristic energy scale is certainly consistent with stochastic acceleration processes. However it is also compatible with particle acceleration in a complex large-scale reconnection region (Petkaki and MacKinnon 1997) in which a variety of initial conditions and the details of particle orbits contrive to produce a wide distribution of particle energies (certainly power-law in the case of the proton orbits studied by Heerikhuisen, Litvinenko and Craig, 2002). The present findings do, however, argue strongly against any simple picture where all electrons fall freely through a single fixed potential drop. (e.g. Holman 1985).

Spectral fitting also allows derivation of the transition zone depth $N_e = E_e^2/4\pi e^4/\Lambda$ and its evolution.

Ion energy budgets were not addressed here since RHESSI gamma data analysis is still very preliminary but we noted that ion flight times seem too long to be consistent with flare light curve data.
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