X-ray and EUV observations as diagnostic of accelerated electrons and atmospheric response in solar flares

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Overview

1. Solar flares: open questions

2. The standard solar flare scenario

3. Emission mechanisms at X-ray and EUV wavelengths

4. Electron acceleration: Distribution and energies of accelerated electrons from simultaneous EUV and X-ray analysis

5. Chromospheric response: chromospheric evaporation seen in X-rays and EUV

1. Summary and Conclusions
1. Solar flares: open questions

- What is the energy contained in the flare?
- Where are electrons accelerated?
- How are electrons accelerated?
- Re-acceleration?
- Trapping?
- Chromospheric response?
1. Solar flares: open questions

- What is the energy contained in the flare?
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The standard solar flare scenario

Shibata et al. 1995

Hudson Flare Cartoon

Shibata et al. 1995
X-ray and EUV emission in the standard solar flare scenario

Using observations at X-ray and (E)UV wavelengths we can investigate many aspects of a flare:

• **Hard X-rays**: acceleration region, spectrum of accelerated electrons, and total non-thermal energy

• **SXR/EUV**: chromospheric, transition region, and coronal response, plasma heating

• **optical/UV**: photospheric, chromospheric, and transition region response, plasma flows
3. Emission mechanisms at X-ray and EUV wavelengths

Emission mechanism: bremsstrahlung

- Thermal bremsstrahlung $T \approx 25$ MK
- Non-thermal bremsstrahlung
- Accelerated electrons with energies typically $> 10$ keV
- Ion recombination lines

Idealized X-ray flare spectrum

Lin et al. 2002
Non-thermal bremsstrahlung from flare accelerated electrons
number of electrons, total non-thermal energy, acceleration region

Thermal bremsstrahlung: temperature and emission measure of heated plasma
EUV line emission

Emission from partially ionized ions in the solar atmosphere. Different lines are formed under different conditions (temperature, density). Doppler shifts indicate upflowing and downflowing plasma.

**Diagnostic of atmospheric response (from photosphere to corona) to flare energy input**
4. Electron acceleration: Distribution and energies of accelerated electrons from simultaneous EUV and X-ray analysis

The challenge: infer mean electron flux spectrum \(<nVF>\) over largest possible energy range

Mean electron flux spectrum from RHESSI observations
Can use AIA differential emission measure!

\[ \langle nV F \rangle = \frac{2^{3/2}E}{(\pi m_e)^{1/2}} \int_{0}^{\infty} \frac{\xi(T)}{(k_B T)^{3/2}} \exp\left(\frac{-E}{k_B T}\right) dT. \]

Combining AIA with RHESSI we can extend the energy range down to \( \sim 0.1 \) keV
Can use AIA differential emission measure!

DEM from regularized inversion (Hannah & Kontar 2012)

\[ \langle nV F \rangle \] is directly related to DEM:

\[ \langle nV F \rangle = \frac{2^{3/2}E}{(\pi m_e)^{1/2}} \int_0^\infty \frac{\xi(T)}{(k_B T)^{3/2}} \exp \left( -\frac{E}{k_B T} \right) dT. \]

Combining AIA with RHESSI we can extend the accessible energy range down to \( \sim 0.1 \) keV

Quite the patchwork. Can do better than that!
Simultaneous fitting of RHESSI and AIA data (Motorina & Kontar 2015)

Ingredients:

Fitfunction $I(RHESSI, AIA) \sim F(\text{electron distribution})$

Combined temperature response matrix

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Simultaneous fitting of RHESSI and AIA data (Motorina & Kontar 2015)

Ingredients:

Fitfunction
$I(RHESSI, AIA) \sim F(\text{electron distribution})$

Electron spectrum

Combined temperature response matrix
• Treat RHESSI and AIA data as one dataset

Detected X-ray or EUV signal is

\[ g_i = R_{ij} \xi_j dT_j \]

\[ \text{signal} = \text{temperature response} \times \text{DEM} \times \text{temperature bin width} \]

• Generate one temperature response matrix

• Forward-fit model DEM

• Find electron flux distribution from DEM

\[ \langle nVF \rangle = \frac{2^{3/2} E}{(\pi m_e)^{1/2}} \int_0^\infty \frac{\xi(T)}{(k_B T)^{3/2}} \exp \left( -\frac{E}{k_B T} \right) dT. \]
Fitfunction: kappa-distribution

Thermal + power-law

$F(E) \propto E \left(1 + \frac{E}{k_B T_K} (\kappa - 1.5)\right)^{-(\kappa+1)}$

Why kappa?

- Single analytic function to describe whole spectrum
- No cutoff needed
- Supported by stochastic acceleration models (e.g. Bian et al. 2014)
- Found in multiple RHESSI observations (e.g. Kasparova & Karlicky 2009, Oka et al. 2013/2015)

$\rightarrow T, EM, \gamma, \text{flux normalization}$, $E_{\text{cut}}$

$\rightarrow T_K, EM_K, \kappa$
AND: Can express kappa-distribution as differential emission measure!

DEM: \[ \xi(T) \propto T^{-(\kappa+0.5)} \exp \left( -\frac{T\kappa}{T}(\kappa - 1.5) \right) \]

via:
\[ \langle nVF(E) \rangle = \frac{2^{3/2}E}{(\pi m_e)^{1/2}} \int_0^\infty \frac{\xi(T)}{(k_B T)^{3/2}} \exp \left( -\frac{E}{k_B T} \right) dT \]

gives:
\[ \langle nVF(E) \rangle = n^2 V \frac{2^{3/2}}{(\pi m_e)^{1/2}(k_B T_\kappa)^{1/2}} \frac{\Gamma(\kappa + 1)}{(\kappa - 1.5)^{1.5}\Gamma(\kappa - 1/2)} \frac{E/k_B T_\kappa}{(1 + E/k_B T_\kappa(\kappa - 1.5)^{\kappa+1})}. \]

= kappa-distribution!
Application on single loop flare

Comparison of mean electron flux spectrum from different fit methods

$\xi_\kappa(T)$ on RHESSI data, only
$\xi_\kappa(T)$ on RHESSI and AIA data combined (low and high T component)
AIA DEM from regularized inversion
...... RHESSI thin kappa
Comparison of total energy

Total energy density $U_\kappa = \frac{3}{2} k_B n T_\kappa$

Total energy: $U_\kappa V$ where $V \approx 1.5 \times 10^{27}$ cm$^3$

Without low-energy constraint, total energies derived from RHESSI data could be over-estimated by factor $\sim 5$
Electron energization in the pre-impulsive phase of SOL2012-07-19T05:58
(see also Liu et al. 2013, Sun et al. 2014, Oka et al. 2015, Huang et al. 2016, Krucker & Battaglia 2014)

Figure 1. RHESSI count-rate lightcurves (corrected for instrumental effects) at 6-12 keV (black), 12-25 keV (red), and 25-50 keV (blue). The green line is the GOES lightcurve. The red arrow indicates the time-range on which this study focuses.

Representative images of the flare morphology during three distinct phases are given (see Figure 2 for larger images).

Time
This study

reconnection
region

Figure 2. AIA 131˚A images at three times (two from before the impulsive phase, one from the impulsive phase). The image on the lefthand side shows a snapshot from the time interval that was analysed in the present study. 40%, 70%, 90% contours from a RHESSI CLEAN image are given in four energy bands: 7-8 keV (red), 13-14 keV (blue), 16-20 keV (yellow), 38-44 keV (green). Two sources, one above the reconnection region (labelled A) and one below (labelled B) were observed during the early pre-impulsive phase until source A disappeared at \( \sim 04:51 \) UT. We interpret these sources as lying below the reconnection region (henceforth referred to as source B) and above the reconnection region (henceforth referred to as source A), respectively. In the second image, source A is not visible anymore. The third image shows the flare morphology at the onset of the impulsive flare phase during which a HXR footpoint was observed in addition to source B. In the following we focus on the pre-impulsive phase.

In the next section, we present observations of electron energization over a \( \sim 20 \) minute interval of pre-impulsive activity, starting 50 minutes before the HXR peak of the event.

2.1. RHESSI and SDO/AIA data processing
Using the RHESSI data analysis software we generated CLEAN images over three minutes integration time between 04:34 UT and 04:51 UT, with the last image only having an integration time of 2 minutes due to an attenuator state change. The event evolved rather gradually during this phase, therefore the long integration time improves count
Two sources during the pre-impulsive phase:
One **Below** the reconnection region, one **Above**

Use simultaneous EUV and X-ray fitting to investigate time evolution of electron spectrum from to 0.1 keV to 30 keV

Continuous hardening in Source A vs overall rise in spectrum in Source B
Energies

Electron acceleration in source A vs density increase due to evaporation in source B
Energy loss by free streaming electrons dominates in both sources → efficient acceleration even in this early flare phase → importance of pre-impulsive phase in overall flare energetics
5. Chromospheric response: chromospheric evaporation seen in X-rays and EUV

Energy deposition in the chromosphere leads to overpressure and heating causing plasma to expand upward = “chromospheric evaporation” → EUV / soft X-ray loops
Milligan et al. 2009: Velocities of evaporating plasma observed with Hinode/EIS

Temporal and spatial correlation of HXR emission with upflows and downflows → explosive evaporation driven by non-thermal electron beam
Battaglia et al. 2015: spatial and temporal evolution of chromospheric evaporation with IRIS and RHESSI

GOES X1 flare from 29 March 2014

Two moving flare ribbons
HXR emission during 2 min coinciding with location of ribbons

![Image](image-url)
Slit position relative to location of HXR source

- Upflows along the flare ribbon
- Maximum speed ~ 200 km/s
- Sustained several minutes after HXR

**Interpretation**
Electron beam driven chromospheric evaporation dominates early in the flare. Evaporation is sustained in later phase due to conductive energy input from hot loop.

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Summary and conclusion

Signatures of flare accelerated electrons and chromospheric response are readily observed at X-ray and EUV wavelengths.

Combining observations at these wavelengths with new data analysis methods is key to understanding particle acceleration and transport in solar flares.