Nonthermal Hard X-Ray Radiation from Solar Flares: Observations and Models

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What do we mean by “hard X-rays and “nonthermal radiation”? 

- **Hard X-rays**: 10 keV – 300 keV, between soft X-rays and gamma-rays

- **Nonthermal radiation**: radiation from an electron distribution that is *not locally* Maxwellian
First X-ray Observations

• X-rays first observed from the Sun by Friedman (Naval Research Lab.) with Geiger counters on a V-2 rocket in 1949

• First detection of a solar flare in hard X-rays/γ-rays: 1958 by Peterson & Winckler (Univ. of Minnesota) during a balloon flight from Cuba (1958 Physical Review Letters)
First Image of Hard X-ray Footpoints?

**Solar Maximum Mission (SMM)**
Hard X-ray Imaging Spectrometer (HXIS)

Spectra from the Solar Maximum Mission
Hard X-Ray Burst Spectrometer

Dennis, Solar Physics, 1985
Flare Spectra Obtained with Cooled Germanium Detectors - 1980 Balloon Flight

34 MK “superhot” plasma

Double power-law spectra

![Graph showing flare spectra with photon flux and photon energy axes]
SMM HXRBS Spectra Indicating a Thermal Component at Low Energies

From Fast Electrons to Bremsstrahlung Photons

\[ N_{ph} = nN_v \sigma \]

- \( N_v \) electrons cm\(^{-2}\) s\(^{-1}\)
- \( \sigma \) (cm\(^2\))
- Bremsstrahlung
- photons s\(^{-1}\) cm\(^{-3}\)
From an Electron Distribution Function to a Bremsstrahlung Spectrum

\[ N_{ph}(\varepsilon, E) = nN(E)v\sigma(\varepsilon, E) \]

\( \varepsilon = \) photon energy

\( E = \) electron energy

**Differential cross section**

\[ \sigma(\varepsilon, E) = \frac{d\sigma(\varepsilon, E)}{d\varepsilon} \]

**Electron Flux Distribution Function**

\[ F(E) = N(E)v \quad \text{electrons cm}^{-2} \text{s}^{-1} \text{keV}^{-1} \]

\[ N_{ph}(\varepsilon) = n \int_{\varepsilon}^{\infty} F(E)\sigma(\varepsilon, E) \, dE \]

\( \text{photons s}^{-1} \text{cm}^{-3} \text{keV}^{-1} \)
Photon Flux at Detector & Mean Electron Flux

\[
I(\varepsilon) = (1/4\pi R^2) \int_{V} n(r) \int_{\varepsilon}^{\infty} F(E, r) \sigma(\varepsilon, E) \, dE \, dV
\]
photons s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\)

\[
R = 1 \text{ AU}
\]

\[
I(\varepsilon) = (1/4\pi R^2) \int_{\varepsilon}^{\infty} \left[ \int_{V} n(r) F(E, r) \, dV \right] \sigma(\varepsilon, E) \, dE
\]

\[
I(\varepsilon) = (1/4\pi R^2) \langle n \rangle V \int_{\varepsilon}^{\infty} \langle F(E) \rangle \sigma(\varepsilon, E) \, dE
\]
photons s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\)

Mean Electron Flux: \( \langle F(E) \rangle = (1/\langle n \rangle V) \int_{V} n(r) F(E, r) \, dV \)
Thick-Target Bremsstrahlung I

\[ I(\varepsilon) = \frac{1}{4\pi R^2} \int_{V} \int_{\varepsilon}^{\infty} n(r) F(E, r) \sigma(\varepsilon, E) \, dE \, dV \]

\[ I(\varepsilon) = \frac{1}{4\pi R^2} \int_{x} \int_{\varepsilon}^{\infty} n(x) F(E, x) \sigma(\varepsilon, E) \, dE \, dx \]

For a steady state and \( E = E(x) \), electron flux conservation gives

\[ F(E, x) \, dE = F(E_0) \, dE_0 \]

\[ F(E, x) \, (dE/dx) \, dx = F(E_0) \, dE_0 \]

\[ F(E, x) \, dx = F(E_0) \, dE_0 / (dE/dx) \]

\[ I(\varepsilon) = \frac{1}{4\pi R^2} \cdot \int_{\varepsilon}^{\infty} F(E_0) \int_{E_0}^{\varepsilon} \left[ n(x) \sigma(\varepsilon, E) / (dE/dx) \right] \, dE \, dE_0 \]
Thick-Target Bremsstrahlung II

\[ I(\varepsilon) = \frac{1}{4\pi R^2} \int_\varepsilon^\infty F(E_0) \int_{E_0}^\varepsilon \left[ n(x) \sigma(\varepsilon, E) / (dE/dx) \right] dE dE_0 \]

For collisional energy losses in a fully ionized plasma,

\[ dE/dx = -K n / E \]

\[ I(\varepsilon) = \frac{1}{K4\pi R^2} \int_\varepsilon^\infty F(E_0) \left[ \int_\varepsilon^{E_0} \sigma(\varepsilon, E) E dE \right] dE_0 \]

Independent of plasma density, \( n(x) \)!

Can deduce the injected electron flux distribution, \( F(E_0) \) electrons s\(^{-1}\) keV\(^{-1}\)
Accelerated Electron Number Flux & Energy Flux

\[
d\frac{N_{\text{el}}}{dt} = \int F(E_0) \, dE_0 \quad \text{electrons s}^{-1}
\]

\[
d\frac{W_{\text{el}}}{dt} = \int E \, F(E_0) \, dE_0 \quad \text{erg s}^{-1}
\]
The Bremsstrahlung Cross Section

• Nonrelativistic approximations
  – Kramers: \( \sigma(\varepsilon, E) = \sigma_0 / \varepsilon E \)
  – Bethe-Heitler:
    \[
    \sigma(\varepsilon, E) = \left( \sigma_0 / \varepsilon E \right) \ln \left[ \left( E/\varepsilon \right)^{1/2} + \left( E/\varepsilon - 1 \right)^{1/2} \right]
    \]


- Assume $I(E) \propto E^{-\delta}$ (photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$)
- Thin target: $F(E) \propto E^{-(\delta - 1)}$
  (electrons cm$^{-2}$ s$^{-1}$ keV$^{-1}$)
- Thin target: $N(E) \propto E^{-(\delta - \frac{1}{2})}$
  (electrons cm$^{-3}$ keV$^{-1}$)
- Thick target: $F(E_0) \propto E_0^{-(\delta + 1)}$
  (electrons s$^{-1}$ keV$^{-1}$)
Spectra from Electron Distributions with a Low-Energy Cutoff

\[ N(E) = KE^{-3} \text{ el. cm}^{-3} \text{ keV}^{-1} \]

\[ N(E) = KE^{-5} \text{ el. cm}^{-3} \text{ keV}^{-1} \]

Spectra from Electron Distributions with a High-Energy Cutoff

N(E) = KE^{-3} el. cm^{-3} keV^{-1}

N(E) = KE^{-5} el. cm^{-3} keV^{-1}

Forward Fit to a RHESSI Flare Spectrum

23 July 2002
00:30:00 – 00:30:20 UT

\[
\frac{( \text{Observed Flux} - \text{Model Flux} )}{\sigma}
\]

Best-Fit Model Mean Electron Flux Electron Distribution

Spectral Fits to the 15 April 2002 Flare

Regularized Inversion of the July 23 Spectrum Compared with the Forward Fit Result

Photon Spectra from Theoretical Electron Distributions with “Interesting Features”

Three Inversions and a Forward Fit to the Theoretical Photon Spectra
Alternative Emission Mechanisms

• Inverse Compton Radiation
• Synchrotron Radiation
• Inverse (proton-electron) bremsstrahlung

• Electron-electron bremsstrahlung – becomes significant at energies above ~100 keV
Anisotropic Electron Distribution

Compton Backscattered Photons (Albedo)

Kasparova et al., *Solar Physics*, 2005
Partially Ionized Thick Target

\[ \log_{10} I(\varepsilon) \left( \text{photons/cm}^2\text{s/KeV} \right) \]

\[ \varepsilon \text{(KeV)} \]

Brown, Solar Physics, 1973
Time Delays & Electron Propagation

Fig. 7.—Distribution of measured time delays $\tau = t(25 \text{ keV}) - t(50 \text{ keV})$

Hard X-Ray Polarimetry
X4.8 Flare of 23-July-2002

20 - 40 keV Polarization

FLR2072301
20-40 keV

$\mu_p = 0.10 \pm 0.04$
$\Pi = 18\%$
$\Phi = 79^\circ \pm 3^\circ$

Mark McConnell, UNH
Model Flare Loop with Cusp
Model Loop in Hard X-Rays
Change with Plasma Density in Loop

Plasma Density
2 x 10^{10} \text{ cm}^{-3}

Plasma Density
2 x 10^{11} \text{ cm}^{-3}

Plasma Density
2 x 10^{12} \text{ cm}^{-3}
Computed Spectra

**X-Ray Spectra**

- **Photon energy** vs. **Photon flux**
- **Spectra** include:
  - nonthermal (green)
  - left footpoint (blue)
  - right footpoint (black)
  - conh thermal (T=20 MK) (magenta)
  - visip: total (red)

**Plasma Density:** $2 \times 10^{11}$ cm$^{-3}$

**Electron Distribution Function**

- **Electron energy** vs. **Accelerated electrons/cm$^2$ keV$^{-1}$**
- **Spectra** include:
  - left footpoint (red)
  - right footpoint (black)
  - normal (dotted)
  - sum (green)

**Plasma Density:** $2 \times 10^{11}$ cm$^{-3}$
Energy Deposition

Electron Energy Flux and Energy Deposition
Plasma Density: $2 \times 10^{13} \text{ cm}^{-3}$

Energy Flux Deposition (erg/arcsec) vs Distance (arcsec)

Energy Flux (erg/sec) vs Distance (arcsec)
Presentations at the SPD Meeting

• Oral
  – 27.05, Wednesday June 28, 10:50 AM – 12:25 PM: Wei Lu
    *X-ray Emission from Flaring Loops: Comparison Between RHESSI Observations and Hydrodynamic Simulations*
  – 28.05, Wednesday June 28, 1:30 – 3:00 PM: Linhui Sui
    *Motion of 3-6 keV Nonthermal Sources Along a Flare Loop*

• Poster
  – 13.15: Gordon Holman
    *Understanding X-Ray Source Motions in a Solar Flare Loop*