Hale COLLAGE 2017 Lecture 23

Flare Impulsive Phase: Radio and HXR imaging spectroscopy II

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Outline

• Radiation from energetic particles
  • Bremsstrahlung → Lecture 20
  • Gyromagnetic radiation (”magnetobremsstrahlung”) → Lecture 21
  • Other radiative processes → Lecture 22
    • Inverse Compton, coherent radiation

• Diagnosing flare energetic particles using hard X-ray and radio spectroscopy and imaging
  • Where? → previous lecture
  • What? → this lecture

• Suggested reading: Ch. 13 of Aschwanden’s book for hard X-rays and Ch. 15 for radio
Diagnosing energetic electrons

- Each mechanism provides a method to probe the thermal plasma and/or energetic electrons

  ➔ Acceleration: Where? When? What?

- HXR:
  - Thermal bremsstrahlung ➔ $n_e, T_e$
  - Nonthermal thin-target and thick-target bremsstrahlung ➔ $f(E)$
  - Inverse Compton ➔ mostly corrections to $f(E)$

- Radio:
  - Thermal bremsstrahlung ➔ $n_e, T_e$
  - Gyrosynchrotron ➔ $f(E), n_e, T_e, B, \theta$
  - Coherent radiation ➔ $n_e$ (possibly $f(E), B, \theta$, model dependent)
A note on electron energies

• For an electron
  • Total energy $\varepsilon_{\text{total}} = \gamma m_e c^2$
  • kinetic energy $\varepsilon = (\gamma - 1) m_e c^2$, where $\gamma = 1/\sqrt{1 - \beta^2}$

• Thermal electron in the corona: $T \sim 1$ MK, $\beta \sim 0.018$, or $\varepsilon \approx 0.086$ keV → nonrelativistic

• Type-III-burst-emitting electron $\beta \approx 0.1$-0.3 or $\varepsilon \approx 5$-50 keV → 5~20 x thermal speed → bump-on-tail instability → nonrelativistic to mildly relativistic

• HXR-emitting electron $\varepsilon \approx 20$-200 keV → $\beta \approx 0.2$-0.5 → mildly relativistic

• Gyrosynchrotron-emitting electron $\gamma \approx 2 - 6$ → $\beta \approx 0.6$-0.9 or $\varepsilon \approx 0.5$-3 MeV → (upper-end of) mildly relativistic

Each emission probes a different part of the electron energy spectrum!
HXR spectral analysis

- Currently the most straightforward method to derive the distribution function of the accelerated electrons $f_{nt}(E)$. Also capable of obtaining $f_{nt}(E)$ of $\sim 20$ MK flare plasma.
- Number density ratio $n_{nt}/n_{th}$ (previous lecture).
- Energy density ratio $\varepsilon_{nt}/\varepsilon_{th}$.
- Details of $f_{nt}(E)$ and its spatiotemporal evolution provide diagnostics for acceleration and transport processes.
From HXR spectra to electron distribution

• Forward fitting with parameterized model(s): Thermal + power-law? Thermal + superhot? Thermal + kappa? Thin-target? Thick-target? ...

• Regularized inversion
Forward fitting HXR spectra

- People often use a two-component model electron energy spectrum to fit the HXR spectrum
  - Isothermal Mexwellian
  - Broken power-law with low-energy cutoff

\[
\overline{F}(E) = \begin{cases} 
0; & E \leq E_c \\
AE^{-\delta_1}; & E_c < E < E_b \\
AE_b^{-\delta_1} E^{-\delta_2}; & E_b < E 
\end{cases}
\]

Mean electron flux (electrons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\), different from \(f(E)\) -- c.f. Lecture 17)
Spot the difference...

What is the difference in the model? Which forward fit result is better?
Low-energy cutoff plays a key role

• Let’s assuming a single power-law with a low-energy cutoff: \( F(E) = AE^{-\delta} \) \( (E > E_c) \)

• Nonthermal electron flux (electrons cm\(^{-2}\) s\(^{-1}\)):
  \[
  \int_{E_c}^{\infty} AE^{-\delta} dE = \frac{A}{\delta-1} E_c^{-\delta+1} \quad (\text{if } \delta > 1)
  \]

• Nonthermal electron energy flux (erg cm\(^{-2}\) s\(^{-1}\)):
  \[
  \int_{E_c}^{\infty} AE^{-\delta+1} dE = \frac{A}{\delta-2} E_c^{-\delta+2} \quad (\text{if } \delta > 2)
  \]

• Both are very sensitive to \( E_c \)
  • e.g., for \( \delta = 4 \) (“typical” in a flare peak), a factor of 2 error in \( E_c \) means a factor of 4 error in energy flux!

• Both are very important observables to examine particle acceleration mechanisms
  → e.g., a smaller low-energy cutoff would require a much more efficient acceleration mechanism
Low energy cutoff plays a key role

\[ D_{\text{col}}(\nu) \]

To Maxwellian

\[ D_{\text{turb}}(\nu) \]

To power-law

\[ v^p \]

\( p > -3 \)

\[ E_c \]

Lecture 19 by Prof. Longcope
Low-energy cutoff: Can we determine it from HXR spectral analysis?

![Graph showing photon flux vs. photon energy for thermal and power-law components in a hard X-ray spectrum. The graph includes curves for a large flare with parameters T=30 MK, log(n)=11, log(EM)=49, d=1000 s, and a small flare with parameters T=10 MK, log(n)=10, log(EM)=46, d=100 s. The cutoff energy for the large flare is ε_c=19.5 keV, and for the small flare is ε_c=4.7 keV.]}
HXR spectra: low-energy cutoffs

Low energy cutoff *flattens* the HXR spectra at lower energies
Low-energy cutoff

• Results in a flattening of HXR spectrum below $E_c$
• But usually masked by the thermal component!
• For a typical flare with distinctive thermal + nonthermal component:
  o Well constrained at the high-energy side
  o Poorly constrained at the low-energy side
• Low-energy cutoff is usually really the “highest value of $E_c$ that still fits the data”, which gives a lower limit of the total nonthermal energy
Different forms of low-energy cutoff lead to subtle difference in the observed X-ray spectra → difficult to determine

• Luckily, the exact shape of low-energy cutoff is not dramatically important in terms of energetics
Low-energy cutoff: An example

Can you identify the possible location of $E_c$ and $E_b$?

Kontar et al. 2006
High energy cutoff leads to a *steepening* of the HXR spectra at high energies.
HXR Spectral breaks

- HXR spectral fit results usually show a spectral break at ~30-60 keV
- Flatter at lower energies, and steeper at higher energies

Philips 2004
Possible 1: less e$^{-}$ at higher energies

Stochastic acceleration (Miller et al. 1996, see also Lecture 19 by Prof. Longcope)

Acceleration by termination shock (Guo & Giacalone 2012)
Possibility 2: loss of low energy e⁻

- **Return current**: large number of electrons precipitating to the footpoint → “returning” ambient electrons to re-establish neutral charge → self-induced “return current”

- Return current generates an electric field (Ohm’s law) along the loop

- Lower energy electrons lose a larger *fraction* of energy than their higher energy counterparts → flattening of the HXR spectrum at lower energies
Spectral breaks at higher energy

- At higher energies, the HXR/γ-ray spectrum break “up” again
- Contribution from the e-e bremsstrahlung
- Acceleration mechanism?
Microwave gyrosynchrotron spectra

- HXR photons with energy $\varepsilon$ come from electrons with $\sim \varepsilon$ via bremsstrahlung $\rightarrow$ 10s to 100s keV
- Microwave gyrosynchrotron probes electrons with higher energies (>300 keV)
- Can one electron distribution fits all?

Large discrepancy usually found between HXR and microwave!
HXR and microwave discrepancy: What’s wrong?

- HXR emission is dominated by the precipitated electrons at the chromosphere

- Gyrosynchrotron emission is mainly from the trapped electrons in the flare loop
- Trapping may resulting in hardening
- Anisotropy of electron distribution also contributes to spectral hardening. How?

The HXR/microwave discrepancy is still largely unexplained
HXR/microwave spectra evolution

• Events showing **impulsive** HXR/microwave peaks usually have a **harder** spectral index during the peaks, and **softer** both in the rise and decay phase, known as a **soft-hard-soft (SHS)** spectral evolution.

• In some events, the spectra stay **hard** or even gets **harder**, known as a **soft-hard-harder (SHH)** spectral evolution.
SHS HXR spectral evolution

Dennis 1985
SHS feature at every HXR peak

**Flux and spectral index evolution**

**Photon flux at 35 keV ($I_{35}$)**

**Spectral index ($\gamma$)**

**Grigis & Benz 2004**

**Non-thermal flux at 35 keV ($I_{35}$)**

**Flux vs. spectral index**
SHS spectral evolution in microwave

Flux and spectral index evolution

2000–09–16 flare
γ = (34.2 ± 1.0)F_{35}^{(-0.49 ± 0.0098)}

1999–07–28 flare
γ = (8.4 ± 1.1)F_{35}^{(-0.30 ± 0.0014)}

Flux vs. spectral index

Ning & Ding 2007
SHH HXR spectral evolution

13 MAY 1981

POWER-LAW SPECTRAL INDEX $\gamma$

COUNTS $S^{-1}$

FLUX in PHOTONS $cm^{-2} S^{-1} keV^{-1}$

PHOTON ENERGY in keV

DECAY

RISE

Dennis 1985
SHH microwave spectral evolution

Fig. 7. Examples of type-II flares following the soft–hard–harder spectral behavior in the rise–peak–decay phases at 35 GHz (thick lines). The flare peak at 35 GHz and the softest index are indicated by the dashed and dotted lines, respectively, for the 2001 April 03 flare.

Fig. 8. Scatter plots of the time delay between the flare peak and \( \mathrm{CR}_{\text{max}} \) versus the flare peak flux, duration at 35 GHz, and the \( \mathrm{CR}_{\text{max}} \) value for type-II flares.

4. Conclusions and Discussions

We statistically analyzed the microwave spectral evolution of 103 solar flares observed by NoRP between 1998 and 2005. The spectral index was derived from the formula:

\[
\frac{\gamma}{\gamma_{\text{opt}}/2} = \frac{\gamma}{\gamma_{1.1}} + \frac{\gamma}{\gamma_{1.2}}
\]

where \( \gamma \) was obtained by fitting the spectra, assuming \( S_{\text{ETB}}(\nu) = F_0 \nu^{\gamma} \) in the optically thin part. We found two typical types of solar flares with different microwave spectral behavior. Type-I flares display a soft–hard–soft spectral evolution pattern, while type-II flares follow a soft–hard–harder behavior in the rise–peak–decay phases at 35 GHz. Our results are consistent with a previous study (e.g., Benz 1984).

We discovered 12 type-I and 91 type-II flares in the sample, respectively. Figure 10 plots their distributions against the flare durations at 35 GHz. There is no significant difference between the distributions of the two types of flares. The most important result obtained from our analysis is that the soft–hard–harder pattern is dominant in the microwave flares. Melnikov and Magun (1998) studied 23 microwave flares, and found that nearly all events indicate hardening of electron spectra. The soft–hard–harder pattern implies that highly energetic electrons have a longer lifetime, or a second acceleration contribution to them (e.g., Melnikov & Magun 1998). On the other hand, the type-I flares are very small compared with the type-II flares. On the contrary, most of the hard X-ray flares appear to have the soft–hard–soft characteristic, as noted earlier (Kosugi et al. 1988). Such differences give an observational constraint for electron acceleration and transport theories in flare models. It would be an interesting work to compare in detail the microwave and hard X-ray spectral behavior of solar flares in the future.

Microwave emission from solar flares includes a thermal component. Microwave spectral evolution is affected by this component, especially in the decay phase. Since the nonthermal component decreases rather rapidly and the thermal component increases gradually with time in the decay phase, the microwave spectrum would continuously harden with time in the decay phase. The hardening due to the thermal component in the decay phase would be significant, especially in the case of flares with small flux densities at higher frequencies. For example, the thermal component may make a significant contribution in the decay phase of two events in figure 4. The microwave flux densities at 35 GHz after
HXR spectral evolution: Why?

- Variation of thermal and non-thermal contribution in the X-ray energy range where spectral index is obtained

- Transport: Longer transport time → more loss in low-energy electrons → harder spectrum

- Particle acceleration mechanism itself
SHS also in coronal HXR sources

- Coronal HXR sources are at least closer to the acceleration site → probably from the acceleration mechanism?
What causes HXR spectral hardening?

- Stochastic acceleration model by turbulent fast-mode waves (c.f. Lecture 19 by Prof. Longcope)

\[ f(v) \propto |v|^{-\xi} \]

\[ \xi = \frac{e^2 n \Lambda \bar{k}}{\pi \epsilon_{turb}} \]

- Stronger turbulence \( \rightarrow \) harder spectrum
- Longer trapping time \( \tau \) \( \rightarrow \) harder spectrum

Grigis & Benz 2006
Modeling HXR flux vs. spectral index

Grigis & Benz 2004

Grigis & Benz 2006

Flux vs. spectral index
So what causes the SHS behavior?

- Stochastic acceleration example: variation of the level of turbulence during the particle acceleration process
  - Energy release $\rightarrow$ strong turbulence
  - Efficient particle acceleration $\rightarrow$ harder spectrum
  - Turbulence exhausted
  - Less efficient particle acceleration $\rightarrow$ softer spectrum
- Shock? DC electric field?
- How about SHH?

Bykov & Fleishman 2009
Summary

• HXR and microwave observations provide critical diagnostics for particle acceleration mechanisms
  • Low-energy cutoff → number, energetics
  • Spectral breaks
  • Spectral evolution

• Some success in interpreting the observed phenomena
• But more are unexplained
• What can be improved?
  • More advanced instrumentation: HXR/microwave imaging spectroscopy with high spatial, spectral, and temporal resolution
  • Data-driven, self-consistent particle acceleration modeling