Hale COLLAGE 2017 Lecture 22
Flare Impulsive Phase: Radio and HXR imaging spectroscopy I

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Outline

• Radiation from energetic particles
  • Bremsstrahlung → lecture 20
  • Gyromagnetic radiation ("magnetobremsstrahlung") → Previous lecture
  • Other radiative processes → This lecture (briefly)
    • Inverse Compton, coherent radiation
• Diagnosing flare energetic particles using hard X-ray and radio spectroscopy and imaging → This and next lecture
• Suggested reading: Ch. 13 of Aschwanden’s book for hard X-rays and Ch. 15 for radio
Inverse Compton Scattering

• Low-energy photon elastically scatter off low energy electrons → Thomson scattering
  • Responsible for white-light corona

• Low-energy photon scatter off a high energy electron and emit at higher energy → Inverse Compton
Inverse Compton and HXR spectrum

- HXR photons of 10-100 keV get Compton backscattered from the lower solar atmosphere
- It is therefore important to take into account these effects when interpreting HXR spectra

Kontar et al 2006
Inverse Compton and HXR spectrum

- EUV and SXR photons can be upscattered to HXR energies
- Significant esp. when electrons are directed toward the LOS

Chen & Bastian 2012
Coherent radiation

- All the previously discussed radiative processes - bremsstrahlung, gyromagnetic, inverse Compton - are incoherent, which means each electron radiates photons independently.

- But if electrons somehow “know” each other and excite waves in phase, the radiation becomes “coherent”
Nonlinear wave growth

• From Lecture 19, we obtained a bunch of wave modes $\omega(k)$ using the Fokker-Planck equation. The imaginary part is the key for wave growth:

$$E(x,t) = \hat{E}^{(1)} e^{ikx - i\omega t}$$

$\text{Im}(\omega) < 0$: damped
$\text{Im}(\omega) > 0$: unstable  $\rightarrow$ Wave Growth

• Plasma oscillation (Langmuir wave) is a natural wave mode of a plasma and can be excited by a variety of mechanisms.
Growth of Langmuir waves

• One can use the (collisionless) Vlasov Equations, with some approximations, to obtain the dispersion relation \( \omega(k) \) of Langmuir waves:

\[
\omega_L^2 = \omega_{pe}^2 + \frac{3k_B T_e}{m_e} k^2
\]

where \( \omega_{pe} \) and \( T_e \) are the electron plasma frequency and temperature. This is the real part of \( \omega(k) \).

• The imaginary part of \( \omega(k) \), often denoted \( \Gamma_k \), is the growth (or damping, if <0) rate:

\[
\Gamma_k \propto \frac{\omega_{pe}^2 \omega_L}{k^2} \frac{\partial f(v_z)}{n_e \partial v_z}
\]

where \( f(v_z) \) is the electron distribution function along the B field direction.
Growth of Langmuir waves

• Normally $\frac{\partial f(v_z)}{\partial v_z} < 0 \rightarrow$ negative $\gamma_k$ $\rightarrow$ damped waves (Landau damping)
• Sometimes $\frac{\partial f(v_z)}{\partial v_z} > 0 \rightarrow$ positive $\gamma_k$ $\rightarrow$ waves grow exponentially
• In the Sun’s corona, propagating electron beams, trapped electrons, and/or shocks can excite plasma waves, which may result in observable radio bursts
Bump-on-tail instability

- A fast electron beam has two velocity components at a given location: a thermal component and a beam component.

![Diagram showing velocity distribution](image)

Velocity distribution leading to the “bump-on-tail” instability of growing plasma waves.
ISEE-3 type III

1979 Feb 17

Lin et al. 1981
Lin et al. 1981

ISEE-3 type III

1979 Feb 17

IP Type III bursts (harmonic plasma radiation)

IP Langmuir waves

IP electrons

Lin et al. 1981
Velocity distribution

Bump-on-tail instability
Plasma radiation

• However, Langmuir waves are longitudinal plasma oscillations with very small group velocity, which have to convert to transverse waves in order to escape.

• How? Nonlinear wave-wave interactions. The resulting transverse waves have frequencies near the fundamental or harmonic of the local electron plasma frequency: i.e., $\nu_{pe}$ or $2\nu_{pe}$.

• Fundamental plasma radiation: Langmuir waves scatter off of thermal ions or, more likely, low-frequency waves (e.g., ion-acoustic waves)

\[
\omega_L + \omega_S = \omega_T \quad \text{and} \quad k_L + k_S = k_T \quad \text{coalescence}
\]

or

\[
\omega_L = \omega_S + \omega_T \quad \text{and} \quad k_L = k_S + k_T \quad \text{decay}
\]
Plasma radiation

Harmonic plasma radiation

• A process must occur that is unstable to the production of Langmuir waves

• A secondary spectrum of Langmuir waves must be generated

• Two Langmuir waves can then coalesce

\[ \omega_L^1 + \omega_L^2 = \omega_T \]

\[ \omega_T \approx 2\omega_L \]

\[ k_L^1 + k_L^2 = k_T \ll k_L \]

\[ k_L^1 \approx -k_L^2 \]
Plasma Radiation

- Type I, II, III, IV, V bursts discussed in Lecture 7
- Some of them show as fundamental-harmonic pairs
Loss-cone instability: resonance condition

• Resonance condition for strong wave-particle interaction:

\[ \omega - kv_z = \pm s \Omega_c \]

resonance: \( \omega - kv_z = \pm s \Omega_c \)
electrons (s=-1) resonate w/ RH wave

• S can be other integer numbers for different wave modes

• For energetic electrons, we need to apply relativistic correction to the gyrofrequency: \( \omega_B = \omega_{ce} / \gamma \) (\( \Omega_c \) in Dana’s notation)

• The condition defines a surface in the velocity space

From Lecture 16 by Prof. Longcope
Loss-cone instability: wave growth

Relevant in e.g., some special types of solar radio bursts, Jupiter’s decametric radiation, aurora kilometric radiation, radio pulsars, etc.

\[ \omega - k_z v_z = \frac{s \omega_{ce}}{\gamma} \]

Also known as “cyclotron maser radiation”
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)
Overview of HXR sources in flares

- HXR halo/albedo sources
- HXR footpoint sources
- HXR thermal looptop source
- HXR above-the-loop-top source (Masuda-type source)
- HXR above-X-point source

Backscattering

Corona
Transition region
Chromosphere
Photosphere

From Aschwanden’s book
HXR footpoint sources

- HXR emission in flares is usually dominated by intense footpoint sources
- Nonthermal thick-target bremsstrahlung from precipitating electrons

From Kleint et al. 2016
HXR footpoint sources

- Higher-energy electrons reach deeper in the chromosphere

\[ N(s) = \int n_e(s') ds' \quad [\text{cm}^{-2}] \]

Stopping column: \( N \sigma_e = 1 \)

\[ N_c = \frac{E_c^2}{6\pi e^4 \Lambda} = 1.4 \times 10^{17} \text{ cm}^{-2} E_{c,keV}^2 \]

Stop cut-off

From Lecture 10 by Prof. Longcope
HXR footprint sources

HXR energy vs. height $\rightarrow$ chromospheric density vs. height

Kontar et al. 2008, 2009
Dominating footpoint HXR emission
→ Are particles accelerated near the footpoints?

There are debates, but probably not the primary site
Above-the-loop-top HXR source

• The celebrated “Masuda” flare (Masuda et al. 1994): A HXR source is located above the soft X-ray flare loop.
Nonthermal electrons are present above the looptop. Are they accelerated there?  
- If so, which acceleration mechanism(s)?  
- If not, transport effects?

Nevertheless, the “Masuda-type” flares made a significant contribution to the suggestion of the current “standard” flare scenario
Well, let’s back off a little... Are we sure that the ALT HXR source is nonthermal?

Thermal + Superhot   Thermal + Superhot + Power-law

Fitting choices of the observed HXR spectrum is not unique!
“Superhot” coronal HXR source

- First discovered by Lin et al. 1981 from balloon-borne observations
- Too hot for chromospheric evaporation (require extreme conditions)
- Appear in the pre-impulsive phase → evaporation has not begun
- Direct heating in the corona (collapsing trap? shock?), or, collisional relaxation from the nonthermal tail?
Above-the-X-point HXR sources

Higher energy sources “converge” to, perhaps, the reconnection site

Sui & Holman 2003

Liu et al. 2013
HXR spectra: Time of flight delays

- If acceleration site is in the corona, lower-energy electrons need more time to reach the chromosphere

\[ l_{TOF} = cT_{ij} \left( \frac{1}{\beta_i} - \frac{1}{\beta_j} \right)^{-1} \]

Aschwanden et al. 1996
Back to the Masuda flare

Time of flight analysis seems to place the acceleration site *above* the ALT HXR source (Aschwanden et al. 1996)

ALT HXR source due to transport mechanisms (e.g., trapping?)
Alternative view: ALT HXR source is the primary acceleration site

Krucker & Battaglia 2014:

RHESSI imaging spectroscopy to infer density of accelerated electrons: \( n_{nt} \approx 10^9 \text{ cm}^{-3} \)

SDO/AIA DEM analysis to determine ambient thermal density \( n_0 \)

\( \rightarrow \) ratio \( n_{nt}/n_0 \) is close to 1

\( \rightarrow \) bulk acceleration takes place within the ALT HXR source?

Similar findings were reported for partially occulted flares (Krucker et al. 2010)
Coherent radio radiation is another excellent probe

- Unlike HXR, **no need** for sufficient ambient density
- Coherent radiation $\rightarrow$ very efficient emission

Chen et al. 2015
Coherent Radio Emission at a Termination Shock

Termination Shock

Accelerated Electrons

Density Fluctuations

Radio emission at different frequencies

Reconnection outflow

Density Fluctuations

TS

e-

n1

n2

f ~ n^{1/2}

f1

f2

Flux

frequency
Coherent radiation allows diagnostics of highly dynamic phenomena

- This termination shock contributes to the acceleration of 10s of keV electrons

Chen et al. 2015
Decimetric type III bursts: electron beams near the flaring site

From Aschwanden’s book
A possible detection with imaging data

SDO/AIA 131

VLA Radio Burst Centroids

AIA 131

0.15 s later

upward beam

acc site?

downward beam

Chen et al in prep
Gyrosynchrotron radio emission

- Accelerated electrons also produce (incoherent) gyrosynchrotron emission
- At microwave frequencies (few to x10 GHz), GS emission is mainly from the flare loops (c.f., Lecture 21)
- Sometimes GS emission is seen above the flare loops
• More radiative processes: Inverse Compton and coherent radiation

• **Where?** ➔ Particles are probably accelerated in the *corona*, but exact location unknown
  • ALT HXR sources, type III bursts, GS sources
  • But, ALT HXR sources are rare – only a handful of events observed in >15 years of RHESSI + Yohkoh/HXT ➔ Direct focusing optics and more sensitive X-ray observations would help
  • Radio dynamic spectroscopic imaging is another powerful tool
  • *(Very)* active field of research

• What do the observed spatial, spectral, and temporal properties of the HXR and radio sources imply for the acceleration and/or transport mechanisms?
  ➔ Open question. Topic of next lecture

**Summary**