Electron Acceleration at Slow-Mode Shocks in the Magnetic Reconnection Region in Solar Flares

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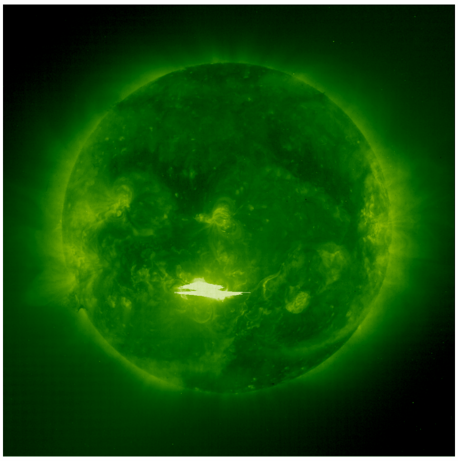
The Flare

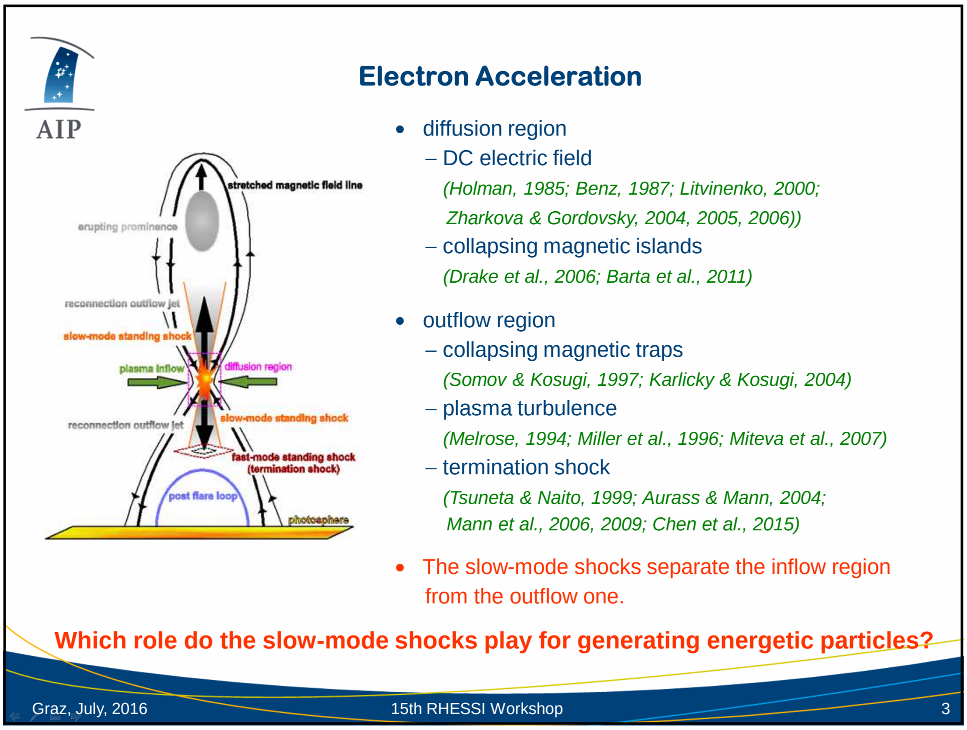


A flare is defined as a sudden enhancement of electromagnetic emission over a broad spectrum from the radio over the visible up to the γ-ray range.

→ **generation of energetic electrons**

Basic question:

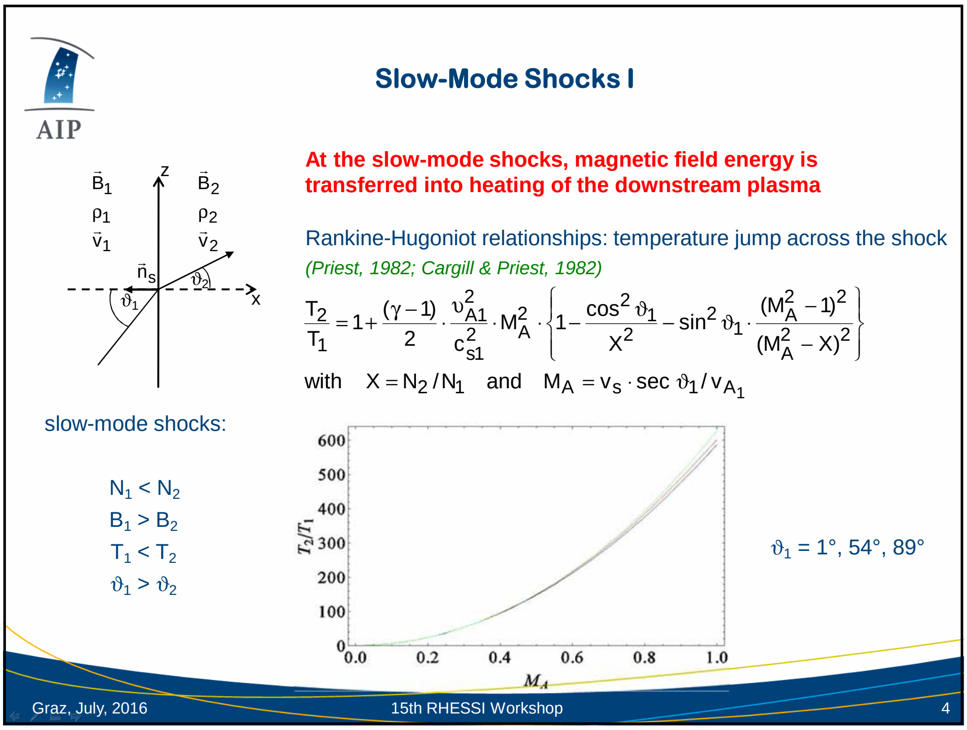
How are 10^{36} electrons accelerated up to high energies (> 30 keV) within a second?



Electron Acceleration

- diffusion region
  - – DC electric field
    (Holman, 1985; Benz, 1987; Litvinenko, 2000; Zharkova & Gordovsky, 2004, 2005, 2006))
  - – collapsing magnetic islands
    (Drake et al., 2006; Barta et al., 2011)
- outflow region
  - – collapsing magnetic traps
    (Somov & Kosugi, 1997; Karlicky & Kosugi, 2004)
  - – plasma turbulence
    (Melrose, 1994; Miller et al., 1996; Miteva et al., 2007)
  - – termination shock
    (Tsuneta & Naito, 1999; Aurass & Mann, 2004; Mann et al., 2006, 2009; Chen et al., 2015)
- The slow-mode shocks separate the inflow region from the outflow one.

Which role do the slow-mode shocks play for generating energetic particles?



Slow-Mode Shocks I

At the slow-mode shocks, magnetic field energy is transferred into heating of the downstream plasma

Rankine-Hugoniot relationships: temperature jump across the shock

(Priest, 1982; Cargill & Priest, 1982)

$$\frac{T_2}{T_1} = 1 + \frac{(\gamma-1)}{2} \cdot \frac{\upsilon_{A1}^2}{c_{s1}^2} \cdot M_A^2 \cdot \left\{ 1 - \frac{\cos^2\vartheta_1}{X^2} - \sin^2\vartheta_1 \cdot \frac{(M_A^2-1)^2}{(M_A^2-X)^2} \right\}$$

with $X = N_2/N_1$ and $M_A = v_S \cdot \sec\vartheta_1 / v_{A_1}$

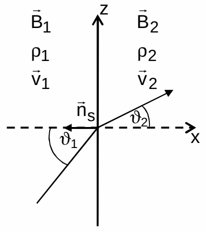
slow-mode shocks:

$N_1 < N_2$
$B_1 > B_2$
$T_1 < T_2$
$\vartheta_1 > \vartheta_2$

ϑ_1 = 1°, 54°, 89°

Slow-Mode Shocks II

switch-off shock ($\vartheta_2 = 0 \rightarrow M_A = 1$) → strongest heating



- $B_{x_2} = B_{x_1}$ and $B_{z_2} = 0$
- $\frac{T_2}{T_1} = 1 + \frac{(\gamma - 1)}{2}\left(1 - \frac{\cos^2\vartheta_1}{X^2}\right)\cdot\frac{v_{A_1}^2}{c_{s_1}^2}$
- $\frac{B_1^2 - B_2^2}{B_1^2} = \sin^2\vartheta_1$
- $M_A = 1 \rightarrow v_s = v_{A_1}\cdot\cos\vartheta_1$

The strongest heating occurs at the switch-off shock in regions with a large Alfvén speed

explanation: $v_{A_1}^2 \propto \frac{B_1{}^2}{N_1}$ → magnetic field energy available per particle

Slow-Mode Shocks III

$\sin^2\vartheta_1$ -th part of the inflowing magnetic energy is available for the energetization of the plasma

$$\sin^2\vartheta_1 \frac{B_1^2}{8\pi}\cdot v_s = \sin^2\vartheta_1 \frac{B_1^2}{8\pi} v_{A_1}\cdot M_A\cdot\cos\vartheta_1$$

→ max $(\sin^2\vartheta_1 \cos\vartheta_1) = 0.38$ at $\vartheta_1 = 54.7°$ → $N_2 / N_1 = 2.87$

In the case of the switch-off shock the annihilation of the magnetic field energy is most efficient if $\vartheta_1 = 54.7°$.

Motivation

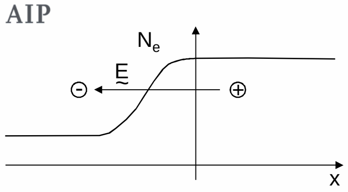
- At slow-mode shocks, magnetic field energy is efficiently annihilated.
- The plasma is strongly energized.
- The spatial extension (40 Mm · 10 Mm) of slow-mode shocks is much greater than of the diffusion region. *(Mann et al., 2011)*

(Cargill & Priest, 1982; Somov et al., 1982; Forbes & Malherbe, 1991)

Which consequences have the slow-mode shocks

for producing energetic electrons?

Cross Shock Potential



in the de Hoffmann-Teller frame:

stationary momentum equation of the electron fluid

$$\frac{dp_e}{d_x} = -eN_e E$$

with $p_e = p_{e,o}\left(\frac{N_e}{N_o}\right)^{\gamma}$ and $E = -\frac{d\varphi_{HT}}{dx}$

Due to proton inertia, a charge separation is established at the shock transition region leading to the cross shock potential

cross-shock potential

$$\Phi_{HT} = \frac{e\varphi_{HT}}{k_B T_1} = \frac{\gamma}{(\gamma-1)}\left[\frac{T_2}{T_1} - 1\right]$$

in the case of the slow-mode switch-off shock ($M_A \rightarrow 1$)

$$\Phi_{HT} = \frac{\gamma}{2} \cdot \frac{v_{A_1}^2}{c_{s_1}^2}\left[1 - \frac{\cos^2\vartheta_1}{X^2}\right]$$

for example: v_{A_1} = 3000 km/s;
c_{s_1} = 180 km/s (for T_1 = 1.4 MK)
$e\,\varphi_{HT} \approx 28$ keV

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Electron Kinematic at Slow-Mode Shocks

- Since the magnetic field is decreasing at the slow-mode shocks, all electrons are transmitted from the upstream region into the downstream one.
- Due to the mirror force, the electrons are focused during their transmission into the downstream region.
- Additionally, the electrons are accelerated by the cross-shock potential.

The slow-mode shock acts as a linear accelerator

Result: A nearly magnetic field aligned electron beam with a velocity $V_e = \sqrt{2e\varphi_{HT}/m_e}$ appear in the downstream region.
(for example: V_e = 100 000 km/s = c/3 for e $\varphi_{HT} \approx$ 28 keV)

Such an electron beam can excite whistler waves, which can resonantly interact with the ambient plasma. That leads to a dissipation of the beam energy and, finally, to a collisionless heating of the downstream plasma.

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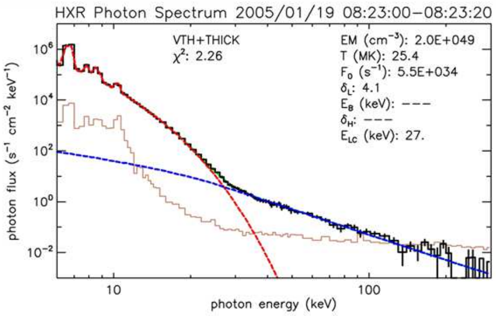
RHESSI Results I



The photon spectra are converted into electron flux spectra with the forward fitting method. *(Holman et al., 2003)*

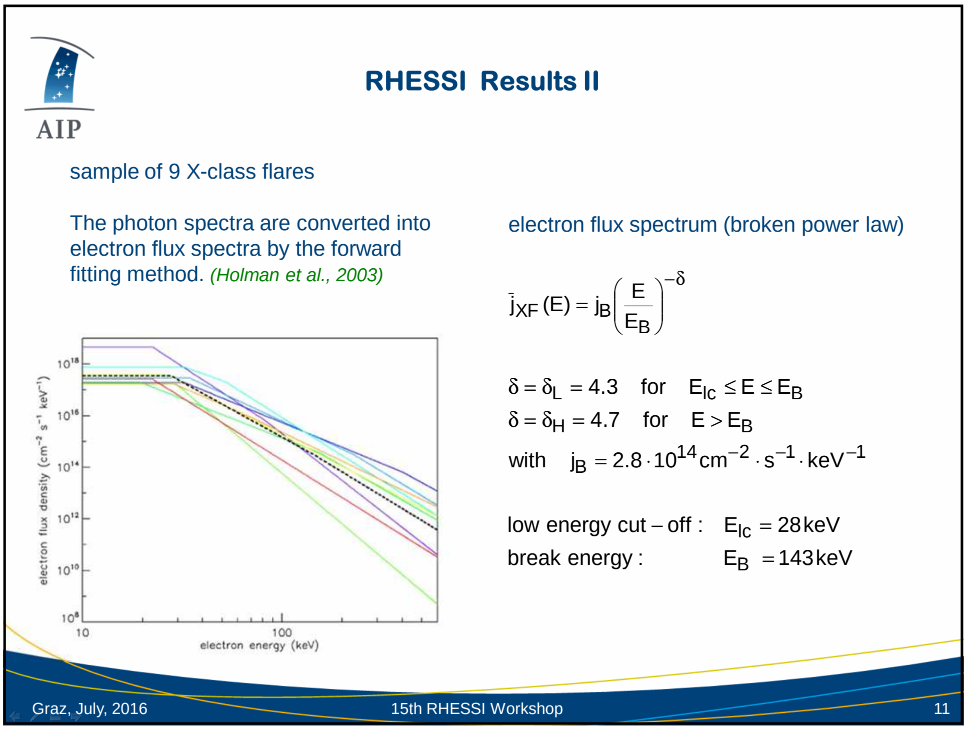
hard X-ray spectrum of a flare

- thermal component
- non-thermal component
- sample of 9 X-class flares
  - energetic electrons (> 28 keV)
  - particle flux

    $\overline{F}_{XF} = 3.1 \cdot 10^{18} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$
  - energy flux

    $\overline{P}_{XF} = 1.2 \cdot 10^{20} \mathrm{keV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$

    $\dfrac{\overline{P}_{XF}}{\overline{F}_{XF}} = 40\,\mathrm{keV}$



RHESSI Results II

sample of 9 X-class flares

The photon spectra are converted into electron flux spectra by the forward fitting method. *(Holman et al., 2003)*

electron flux spectrum (broken power law)

$$\bar{j}_{XF}(E) = j_B \left(\frac{E}{E_B}\right)^{-\delta}$$

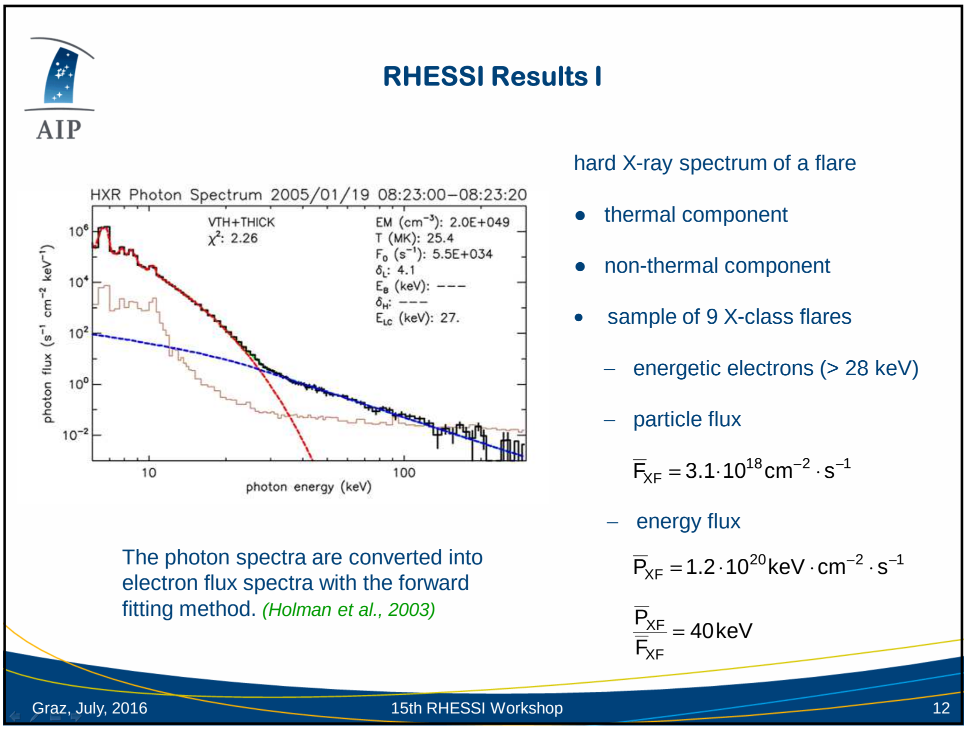
$\delta = \delta_L = 4.3$ for $E_{lc} \le E \le E_B$

$\delta = \delta_H = 4.7$ for $E > E_B$

with $j_B = 2.8 \cdot 10^{14} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{keV}^{-1}$

low energy cut – off : $E_{lc} = 28\,\mathrm{keV}$

break energy : $E_B = 143\,\mathrm{keV}$



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    $$\frac{\bar{P}_{XF}}{\bar{F}_{XF}} = 40\,\mathrm{keV}$$

Electron Flux

In the downstream (or outflow) region, the electrons are described by a hot Maxwellian distribution.

- electron flux along the magnetic field: $\Phi_{II} = N \int_0^\infty d\vec{p}\, V_{II} \cdot f$
- Maxwellian distribution:

$$f = C_0\, e^{-\varepsilon/\varepsilon_{th}} \quad \text{with} \quad \varepsilon_{th} = k_B T / m_e c^2$$

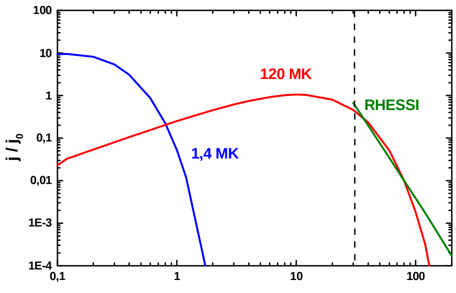
$$\frac{1}{C_0} = 4\pi (m_e c)^3 \int_0^\infty d\varepsilon\, \sqrt{\varepsilon(2+\varepsilon)} \cdot (1+\varepsilon)\, e^{-\varepsilon/\varepsilon_{th}}$$

- differential flux:

$$j_{II}(E) = \frac{d\Phi_{II}}{dE} = j^* \varepsilon (2+\varepsilon) e^{-\varepsilon/\varepsilon_{th}}$$

$$\text{with} \quad j^* = j_0 \cdot \pi \cdot (m_e c)^3 \cdot C_0$$

$$j_0 = \frac{Nc}{m_e c^2}$$



Comparison with RHESSI Observations

total electron flux: $F_e = j^* \int_{\varepsilon_{lc}}^\infty d\varepsilon\, \varepsilon(2+\varepsilon) e^{-\varepsilon/\varepsilon_{th}}$

$$\text{with} \quad \varepsilon_{lc} = E_{lc} / m_e c^2 = 0.0547$$

total energy flux: $P_e = j^* (m_e c^2) \int_{\varepsilon_{lc}}^\infty d\varepsilon\, \varepsilon^2 (2+\varepsilon) e^{-\varepsilon/\varepsilon_{th}}$

comparison with observations:

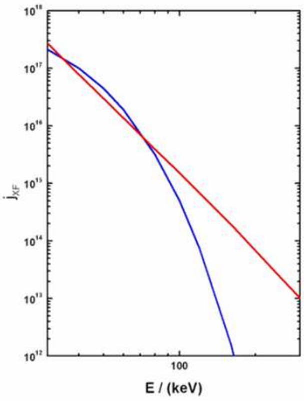
$$F_e = \overline{F}_{XF} \quad \text{and} \quad P_e = \overline{P}_{XF} \quad \rightarrow \quad \varepsilon_{th} = 0.0187 \; (\hat{=}\, 9.56\ \text{keV})$$

$$\rightarrow \quad N_2 = 8.877 \cdot 10^9 \text{cm}^{-3}, \; N_1 = 3.093 \cdot 10^9 \text{cm}^{-3}$$

$$v_{A_1} = 2807\ \text{km/s} \quad \rightarrow \quad B_1 = 27\ \text{G}$$

- 15 % of the inflowing electrons are accelerated up to energies > 30 keV. They carry 32 % of the flare released energy.

  (see e.g. Oka et al., 2014; Krucker & Battaglia, 2014)



spectrum of energetic electrons
red: RHESSI measurements
blue: model
(j_{XF} in $cm^{-2} \cdot s^{-1} \cdot keV^{-1}$)

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Problem

Problem: power law spectra are observed for energetic electrons !!!

What is the electron distribution function in the inflow region?

- Maxwellian distribution as discussed here
  (1 free parameter – temperature)
- kappa distributions are observed in the quiet solar wind *(Lin et al., 1996)*
  (2 free parameters – mean energy and kappa)

If a kappa distribution is taken as the initial one, then a power law spectra results for the accelerated electrons as observed. *(see also Oka et al., 2013)*

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Conclusions

- **The slow mode shocks can strongly energized the plasma in regions of large Alfvén-speeds (or in a very low β-plasma).**
- **The most efficient energetization of the outflow plasma occurs at the switch-off shock ($M_A = 1$) and $\vartheta_1 = 54°$.**
- **The energetization at the slow-mode shocks provides enough energetic electrons as required by RHESSI observations.**
- **15 % of the inflowing electrons are accelerated up to energies > 30 keV They carry 32 % of the flare released energy.**
  (see e.g. Oka et al., 2014; Krucker & Battaglia, 2014)

(see also invited contribution: G. Mann, J. Plasma Phys. 81 (2015) 475 810 601)

Thank you for your attention!