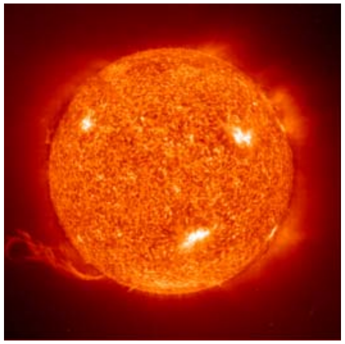

Electron Acceleration at the Reconnection Outflow Shock

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Ramaty High Energy Solar Spectroscopic Imager

Launch: February 5, 2002

prolongation at least until April, 2008

- In which way are electrons accelerated?
- What is the production rate of energized electrons?
- What is the energy content in the accelerated electrons?

Possible Mechanisms of Electron Acceleration

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basic question – electron acceleration in the solar corona

energetic electrons → non-thermal radio and X-ray radiation

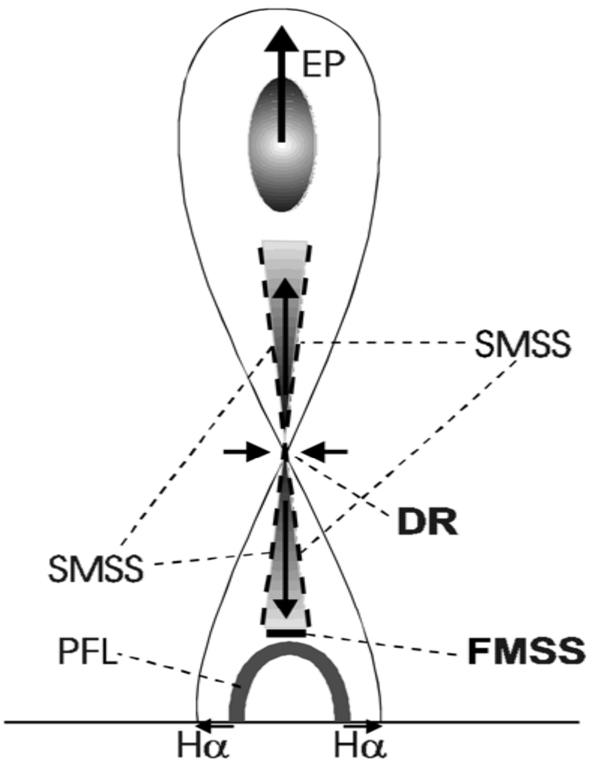
electron acceleration

- magnetic reconnection
  (*Holman, 1985; Benz, 1987; Litvinenko, 2000*)

- ***shock waves*** (*Holman & Pesses,1983; Schlickeiser, 1984; Mann & Claßen, 1995; Mann et al., 2001*)

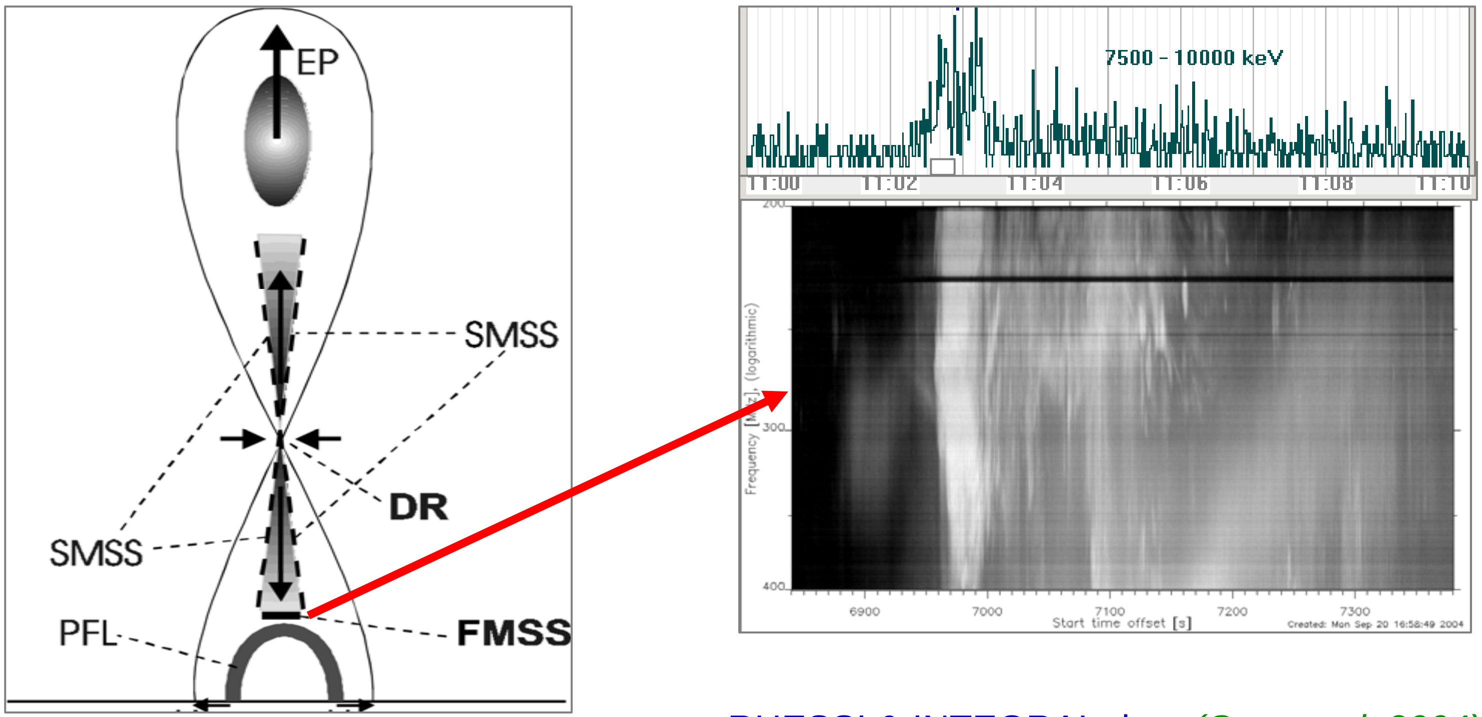
- stochastic acceleration via wave particle interaction
  (*Melrose, 1994; Miller et al., 1997*)

- outflow from the reconnection site
  (***termination shock***)
  (*Forbes, 1986; Somov & Kosugi, 1997; Tsuneta & Naito, 1998; Aurass, Vrsnak & Mann, 2002 Aurass & Mann, 2004*)



Outflow Shock Signatures During the Impulsive Phase

Solar Event of October 28, 2003:



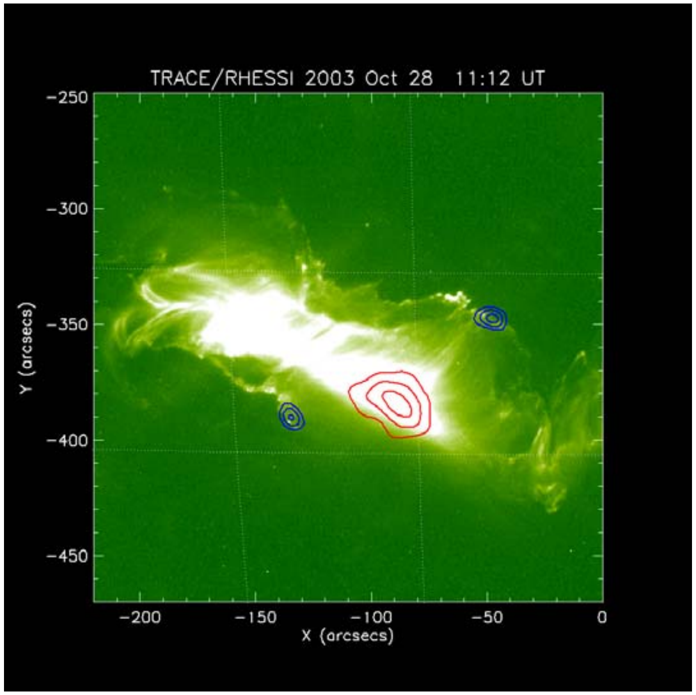
RHESSI & INTEGRAL data *(Gros et al. 2004)*

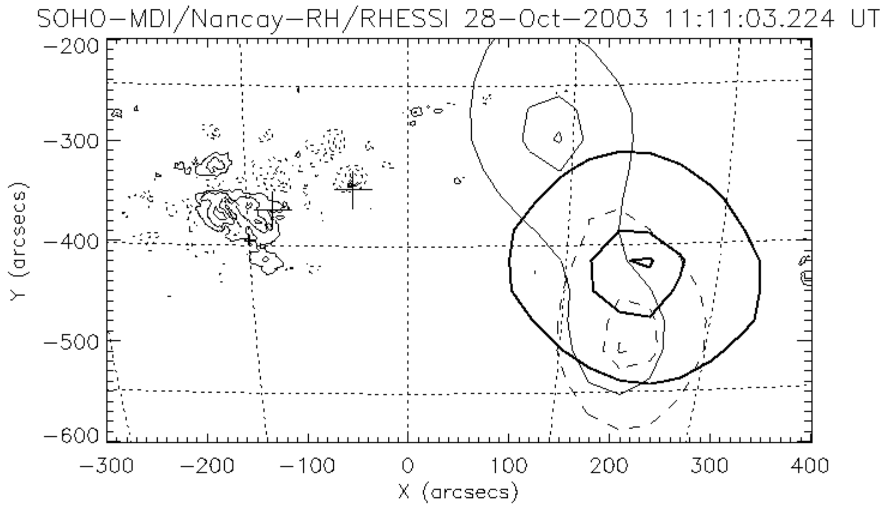
- outflow from the reconnection site ***(termination shock)*** (*Forbes, 1986; Tsuneta & Naito, 1998; Aurass, Vrsnak & Mann, 2002 Aurass & Mann, 2004*)
- termination shock radio signatures start at the time of impulsive HXR rise

The event produced electrons up to 10 MeV.

Observations I

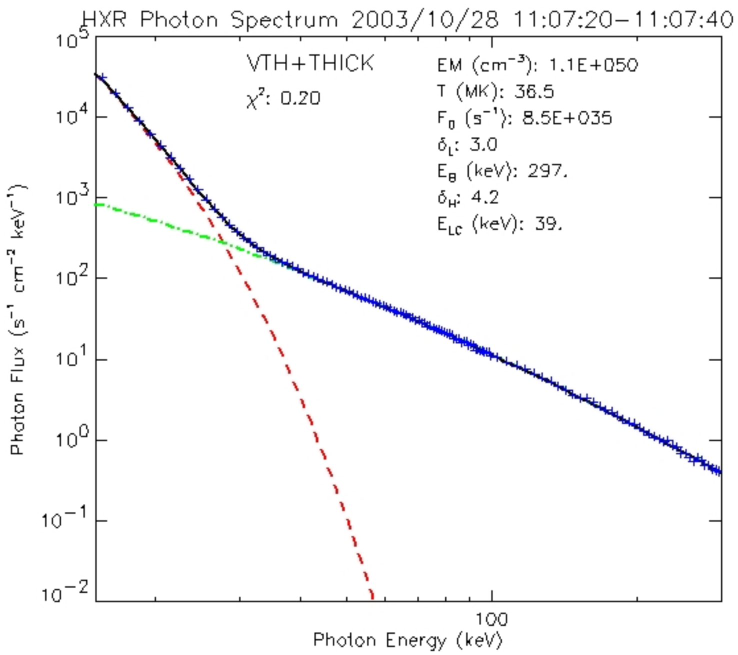
Solar Event of October 28, 2003:

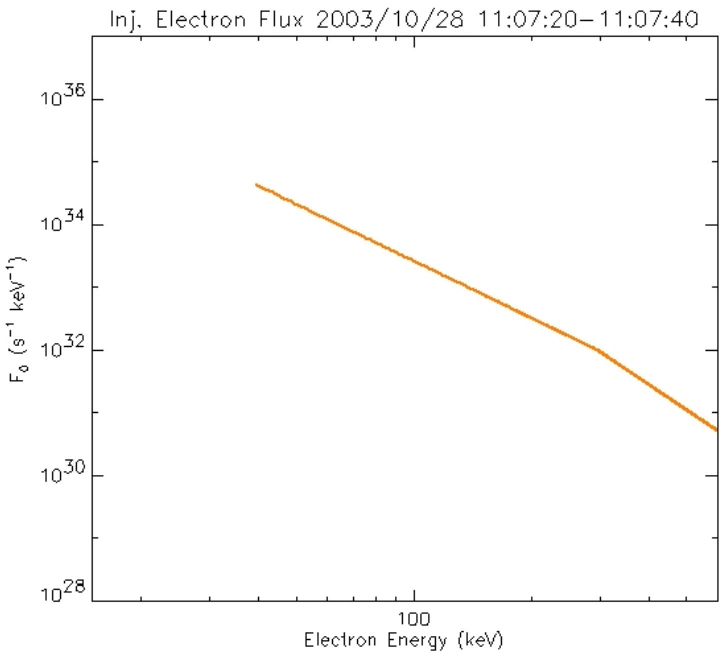




- distance hard X-ray foot point sources — 87 Mm
- distance from the hard X-ray sources to the TS — 350 Mm
- sources area of the TS — $3 \cdot 10^4$ (Mm)^2

Observation II





impulsive phase (extrapol.):

$F_e \approx 5 \cdot 10^{36}\ s^{-1}$

$P_e \approx 5 \cdot 10^{28}$ erg $\cdot\ s^{-1}$

late phase:

$F_e \approx 10^{36}\ s^{-1}$

$P_e \approx 10^{29}$ erg $\cdot\ s^{-1}$

Relativistic Shock Drift Acceleration I

fast magnetosonic shock $\rightarrow$ magnetic field compression

$\rightarrow$ moving magnetic mirror

$\rightarrow$ reflection and acceleration

reflection in the ***de Hoffmann-Teller frame*** *(see e.g. Ball & Melrose, 2003 (non-rel. appr.) and Mann et al., 2006 (rel. appr.))*

Lorentz-transformations:

laboratory frame $\rightarrow$ shock rest frame $\rightarrow$ HT frame $\rightarrow$ back

- motional electric field has been removed
- conservation of kinetic energy: $\beta^2_{II,HT} + \beta^2_{\perp,HT} = \text{const}$

conservation of magnetic moment: $\frac{p^2_{\perp,HT}}{B_{HT}} = \text{const} \quad \rightarrow \quad \frac{\beta^2_{\perp,HT}}{B_{HT}} = \text{const}$

Relativistic Shock Drift Acceleration II

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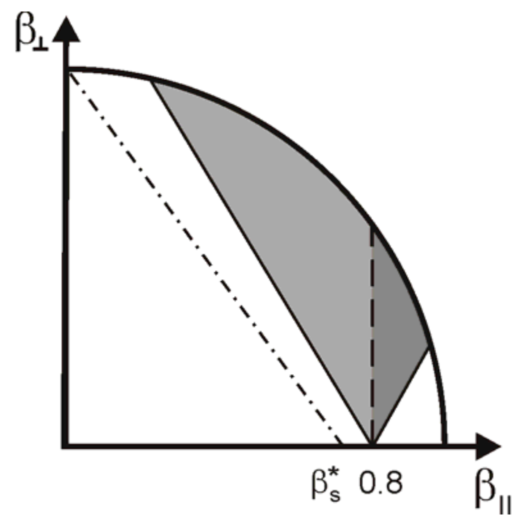
- transformation of the particle velocities $\{\beta_{i,II};\beta_{i,\perp}\} \rightarrow \{\beta_{r,II};\beta_{r,\perp}\}$

$$\beta_{r,II} = \frac{2\beta_s - \beta_{i,II}(1+\beta_s^2)}{1-2\beta_{i,II}\beta_s + \beta_s^2}$$

$$\beta_{r,\perp} = \frac{(1-\beta_s^2)}{1-2\beta_{i,II}\beta_s + \beta_s^2} \cdot \beta_{i,\perp}$$

$$\beta_s = v_s \cdot \sec\vartheta_{B,n} / c$$



- reflection conditions:

$$\beta_{i,II} \le \beta_s$$

$$\beta_{i,\perp} > \frac{\tan\alpha_{lc}}{\sqrt{1-\beta_s^2}} \quad (\beta_s - \beta_{i,II})$$

$$\text{loss-cone angle:} \quad \alpha_{lc} = \arcsin\left(\sqrt{B_{up}/B_{down}}\right)$$

(Mann et al., 2006)

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Relativistic Shock Drift Acceleration III

- magnetic field aligned flux of accelerated electrons

$$\Phi_{acc,II} = N_o\, c \cdot 2\pi \int_0^\infty d\beta_{II}\beta_{II} \int_0^\infty d\beta_\perp \beta_\perp \cdot f_{acc}(\beta_{II}, \beta_\perp)$$

- differential flux

$$j_{acc,II} = \frac{d\Phi_{acc,II}}{dE}$$

$$j_{acc,II} = \Theta(\varepsilon - \varepsilon_s) \cdot \frac{\varepsilon_{th}^{1/2}}{(2\pi)^{1/2}} \cdot \frac{(1-\beta_s^2)^2}{4\beta_s^2} \cdot \frac{e^{-\varepsilon/\varepsilon_{th}}}{(1+\varepsilon)^5}$$

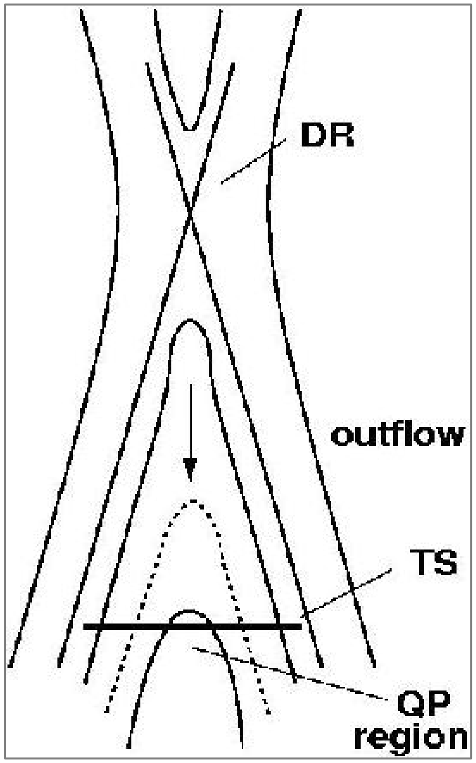
$$\mathrm{x} \left(e^{2\beta_s^2[Z(\varepsilon)-1]\cdot/\varepsilon_{th}} \left[\frac{2\beta_s^2}{(1-\beta_s^2)} Z(\varepsilon) \frac{(1+\varepsilon)}{\varepsilon_{th}} - 1 \right] + 1 - \frac{2\beta_s^2}{(1-\beta_s^2)} \frac{(1+\varepsilon)}{\varepsilon_{th}} \right)$$

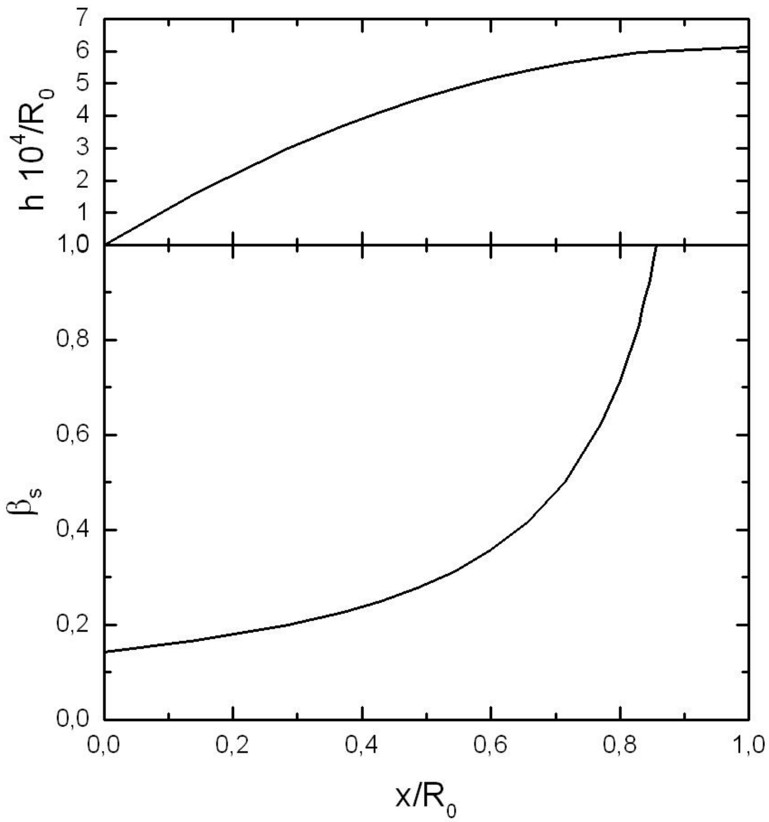
with $$Z(\varepsilon) = \frac{D^2}{(1+D^2)} + \left[\frac{\varepsilon(2+\varepsilon)}{(1+\varepsilon)^2} \cdot \frac{1}{\beta_s^2} \frac{1}{(1+D^2)} - \frac{D^2}{(1+D^2)} \right]^{1/2}$$

$$D = (1-\beta_s^2)^{1/2} \cdot \tan_{\alpha,c}$$

$$\varepsilon_s = (1-\beta_s^2)^{-1/2} - 1 \quad ; \quad \varepsilon = E/m_o c^2 \quad ; \quad \varepsilon_{th} = K_B T/m_o c^2$$

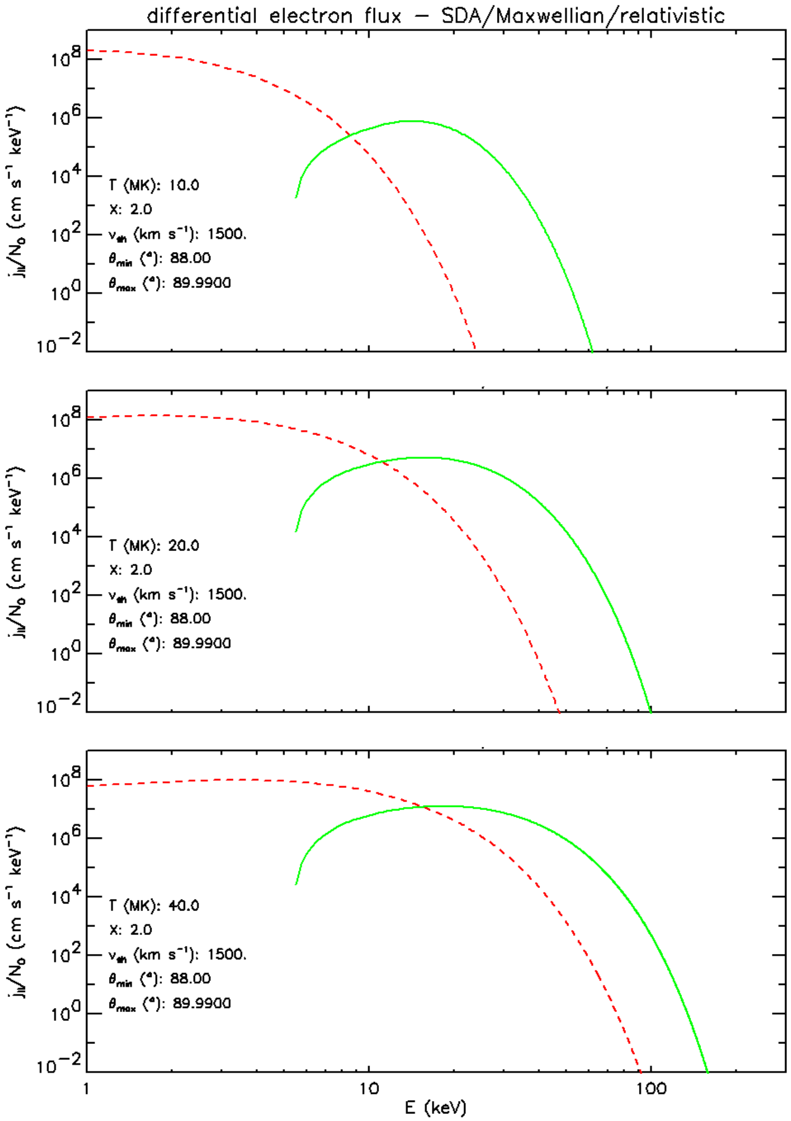
Discussion I





$\vartheta_{B,n}$ and, consequently, β_s change across the shock.

Discussion II



numerical illustration of the differential flux

$$F_e / N_0 \; A(> 20\,\text{keV}) = 1.51 \cdot 10^6\,\text{cm} \cdot \text{s}^{-1}$$

$$P_e / N_0 \; A(> 20\,\text{keV}) = 0.056\,\text{erg} \cdot \text{cm} \cdot \text{s}^{-1}$$

$$F_e / N_0 \; A(> 20\,\text{keV}) = 3.22 \cdot 10^7\,\text{cm} \cdot \text{s}^{-1}$$

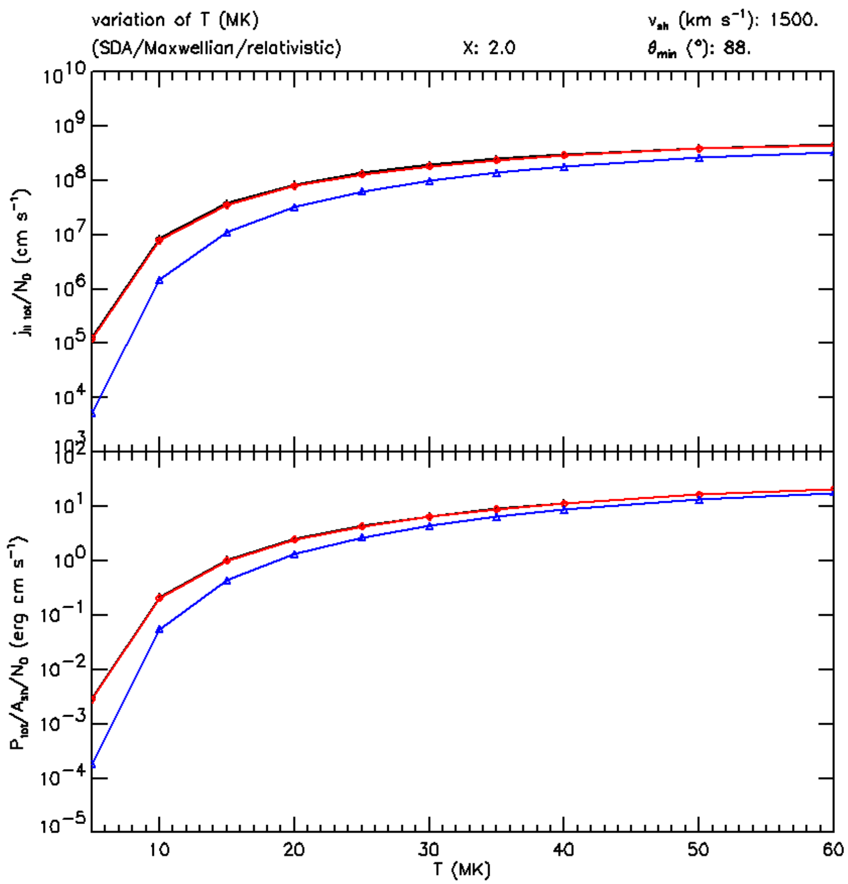
$$P_e / N_0 \; A(> 20\,\text{keV}) = 1.33\,\text{erg} \cdot \text{cm} \cdot \text{s}^{-1}$$

$$F_e / N_0 \; A(> 20\,\text{keV}) = 1.80 \cdot 10^8\,\text{cm} \cdot \text{s}^{-1}$$

$$P_e / N_0 \; A(> 20\,\text{keV}) = 8.74\,\text{erg} \cdot \text{cm} \cdot \text{s}^{-1}$$

Discussion III

total flux and power of the energetic electrons (>20 keV)



observed values: $F_e \approx 10^{36}\ s^{-1}$

$P_e \approx 10^{29}\ erg \bullet s^{-1}$

i) 10 MK

$N_0A = 1.2 \bullet 10^{30} cm^{-1}$

$\rightarrow$ $A = 1.2 \bullet 10^{21} cm^2$ (d = 390 Mm)

ii) 40 MK

$N_0A = 8.3 \bullet 10^{27} cm^{-1}$

$\rightarrow$ $A = 8.3 \bullet 10^{18} cm^2$ (d = 16 Mm)

(at $N_0 = 10^9 cm^{-3}$ [300 MHz])

Discussion IV

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Solar event on October 2003

basic coronal parameters at 150 MHz

$N_e = 2.8 \cdot 10^8 \,\mathrm{cm}^{-3}$ (→ 160 Mm for 2 x *Newkirk (1961)*)

$B_o = 4.7\,\mathrm{G}$ (*Dulk & McLean, 1978*)

$T = 40\,\mathrm{MK}$ (flare plasma)

$\rightarrow \quad v_{th,e} = 12.300\,\mathrm{km/s}$

$v_A = 610\,\mathrm{km/s}$

shock parameter

$$N_{down}/N_{up} \approx B_{down}/B_{up} = 2 \quad \rightarrow \quad M_A = 2.32 \quad \rightarrow \quad v_s \approx 1500\,\mathrm{km/s}$$

comparison: theory ↔ observations

$F_e = 1.5 \cdot 10^{37}\,\mathrm{s}^{-1}$ $(\rightarrow 5 \cdot 10^{36}\,\mathrm{s}^{-1}$ observed by RHESSI)

$P_e = 7.3 \cdot 10^{29}\,\mathrm{erg\,s}^{-1}$ $(\rightarrow 5 \cdot 10^{29}\,\mathrm{erg \cdot s}^{-1}$ observed by RHESSI)

Conclusions

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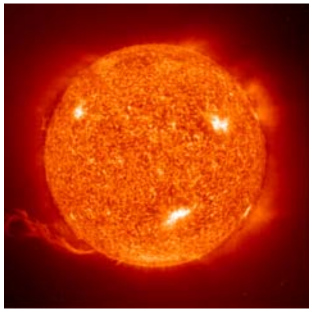
- The *termination shock* is able to efficiently generate energetic electrons.

  → *quantitative confirmations of Tsuneta & Naito's (1998) suggestion*

  → *quantitative agreement with RHESSI observations concerning the flux and power of energetic electrons (> 20keV)*

- Electrons accelerated at the termination shock could be the source of nonthermal hard X- and γ-ray radiation in *chromospheric footpoints* as well as in *coronal loop top sources.*

- The same mechanism also allows to produce *energetic protons* (< 16 GeV).



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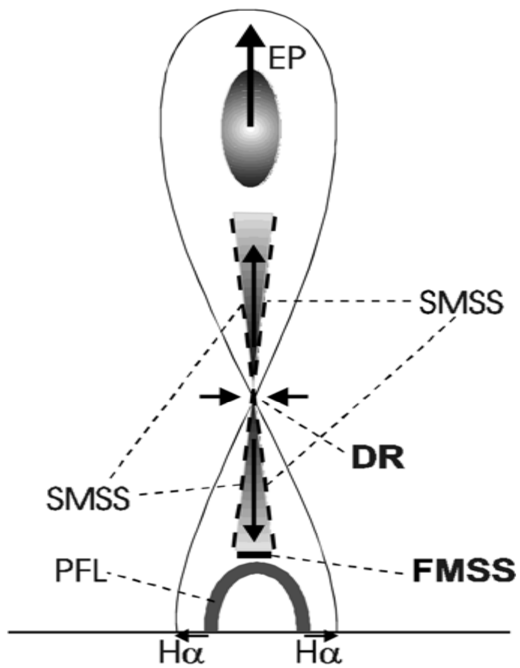
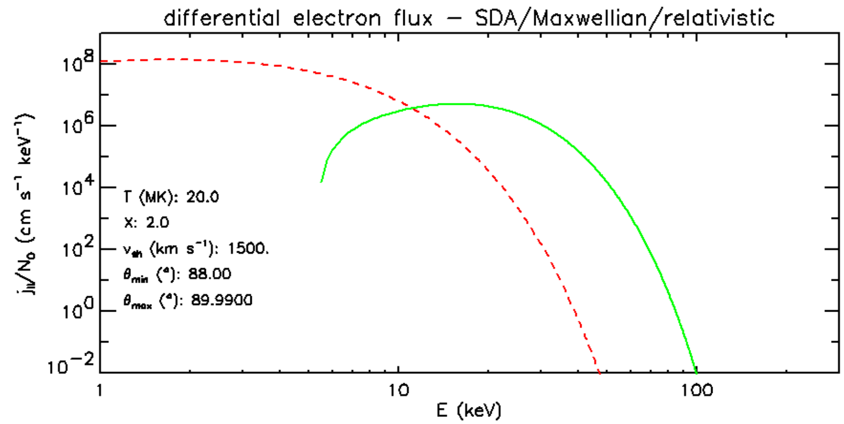
energetic electron production by relativistic shock drift acceleration at the termination shock





$$F_e / N_0 \; A\,(> 20\,keV) = 3.22 \cdot 10^7\, cm \cdot s^{-1}$$

$$P_e / N_0 \; A\,(> 20\,keV) = 1.33\, erg \cdot cm \cdot s^{-1}$$

- quantitative confirmation of Tsuneta & Naito's (1998) suggestion
- agreement with RHESSI observations concerning the flux and power of e^- (> 20 keV)

Interpretation of Solar Radio Spectra?

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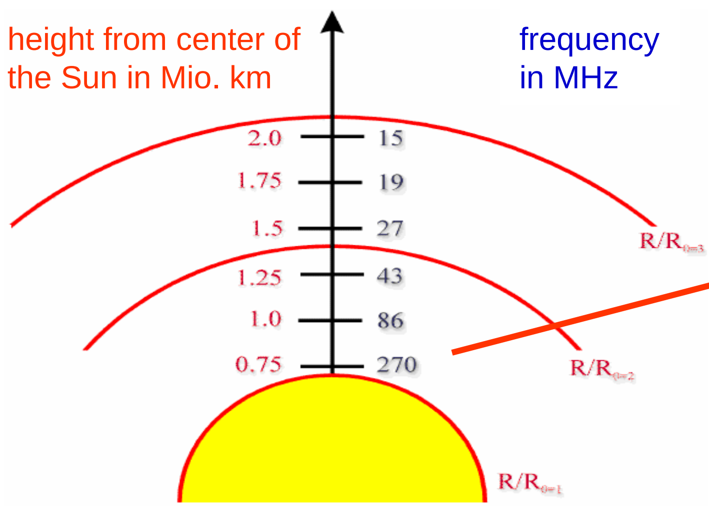
Radio wave emission → plasma emission

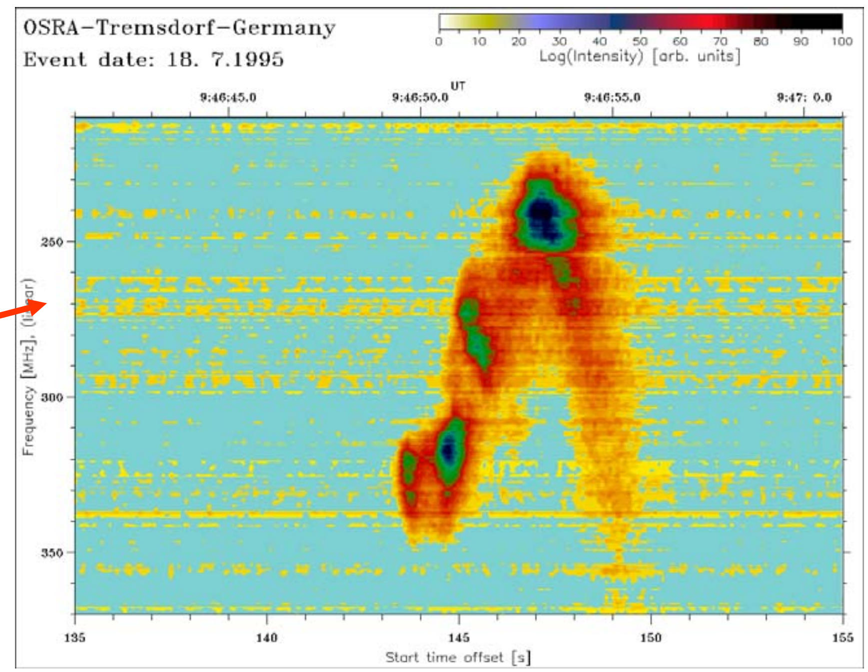
$f \approx \sqrt{e^2 N_e / \pi m_e}$ → drift rate: $D_f = \frac{df}{dt} = \frac{f}{2}\frac{1}{N}\frac{dN}{dr} V_{source}$

heliospheric density model (*Mann et al., A&A, 1999*)



height ≙ frequency

velocity ≙ drift rate



dynamic radio spectrogram ↔ height-time diagram

Observation III