Suprathermal electrons in Earth’s magnetotail: What can they teach us about flare electron energization?

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How are suprathermal electrons produced?

Up to 50% of flare released energy goes to suprathermal electrons [e.g., Lin+, 2003; Holman+, 2003; Krucker+, 2010; Krucker & Battaglia, 2014]

[Shibata et al., 1995]
Magnetic configuration & beta in solar flares are similar to those in the magnetotail.
Volume-filling magnetic islands?

Motivated by [Drake et al., Nature, 2006]

Later work: [Dahlin et al., PP, 2014, 2015; Arnold et al., PRL, 2021]
Energetic electrons in magnetic islands: magnetotail

[Chen et al., Nature Phys., 2008]

Islands are di scale, grew out of the electron current layer
[Chen et al., PP, 2012]

Signatures =? if islands are volume-filling
Use all MMS magnetotail passes (127 orbits in 4 years) to test out

- Whether volume-filling islands are dominant accelerators
- If primary energization occurs at the X line or downstream
90 keV e’s tend to be detected in regions with $B_z > 0$ and $V_{ix} \sim 0$

Events: flux > threshold

![Image showing a diagram with $B_z$ and $V_{ix}$ axes plotting the number of events.](image)
Solar flare

Magnetotail

[Lin et al., 2011]

$\begin{align*}
\text{Flux (1/cm}^2\text{-sr-s-keV)} \\
\text{Energy (keV)} \\
\text{Energy (keV)}
\end{align*}$

$n = 0.32$
$T_{\text{core}} = 1.4\text{keV}$
$\gamma = 4.0$
$W_{\text{break}} = 7.05\text{keV}$
$m_iV_A^2 = 20.01\text{keV}$
Solar flare

[Lin et al., 2011]

Magnetotail

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\[ n = 0.12 \]
\[ T_{\text{core}} = 4.5 \text{keV} \]
\[ \gamma = 3.9 \]
\[ W_{\text{break}} = 21.34 \text{keV} \]
\[ m_1 V_A^2 = 16.49 \text{keV} \]
Magnetotail (in earthward jet)

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\[ n = 0.08 \]
\[ T_{\text{core}} = 5.4 \text{ keV} \]
\[ \gamma = 3.5 \]
\[ W_{\text{break}} = 38.36 \text{ keV} \]
\[ m_i V_A^2 = 45.66 \text{ keV} \]
**Magnetotail/Turbulence**

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[**Ergun et al., 2020**]

**Intense heating!**

\[
T_{\text{core}} = 8.0 \text{keV}
\]

**Magnetotail/flux pileup**

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\[
n = 0.12, \quad T_{\text{core}} = 4.5 \text{keV}, \quad \gamma = 3.9, \quad W_{\text{break}} = 21.34 \text{keV}, \quad m_{l}V_{A}^{2} = 16.49 \text{keV}
\]
In the diffusion region, acceleration by $E_{rec}$ can achieve: a few keV for e’s; a few tens of keV for ions.

[Torbert et al., Science, 2018; Bessho et al., GRL, 2018]

[Giles et al., GRL, 2021]
90 keV e’s only appear Earthward of the X-line: key acc. physics is in the closed field line region.

X-line (EDR) crossing in

[Torbert et al., Science, 2018]
90 keV e Flux more intense Earthward of the X-line: a higher density case for spectra analysis

X-line (3 EDRs) crossing in

[Chen et al., GRL, 2019]
thermal+double power laws

\begin{align*}
  n &= 1.24 \\
  T_{\text{core}} &= 0.3 \text{keV} \\
  \gamma &= 3.8 \\
  \gamma &= 2.1 \\
  W_{\text{break}} &= 1.78 \text{keV} \\
  m_i V_A^2 &= 6.06 \text{keV}
\end{align*}

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Energy (keV)
**PIC with flux rope kinks**

**Magnetotail reconnection outflow**

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\[
\frac{f(\varepsilon)}{\varepsilon/m_iV_A^2} = \begin{cases} 
10^3 & \text{for } \varepsilon/m_iV_A^2 < 10^{-3} \\
10^6 & \text{for } 10^{-3} < \varepsilon/m_iV_A^2 < 10 \cdot 10^{-3} \\
10^8 & \text{for } 10 \cdot 10^{-3} < \varepsilon/m_iV_A^2 < 10^0 \\
10^{10} & \text{for } 10^0 < \varepsilon/m_iV_A^2 < 10^1 \\
10^{12} & \text{for } 10^1 < \varepsilon/m_iV_A^2 < 10^3 \\
10^{15} & \text{for } 10^3 < \varepsilon/m_iV_A^2 < 10^6 \\
10^{18} & \text{for } 10^6 \leq \varepsilon/m_iV_A^2 \end{cases}
\]

- Indices: $L_x = 300d_i$, $L_x = 150d_i$
- $\varphi = 4.3$

**Flux (1/cm$^2$-sr-s-keV)**

- $n = 1.24$
- $T_{core} = 0.3$keV
- $\gamma = 3.8$, $\gamma = 2.1$
- $W_{break} = 1.78$keV
- $m_iV_A^2 = 6.06$keV
Summary

- Suprathermal e’s are primarily found in the earthward B pileup regions.
- Across the X line, earthward exhaust is favored.
- Statistical results do not support volume-filling islands as the dominant accelerators in the magnetotail.