Model for the Energetic Particles Spectrum at Interplanetary Shocks resulting from Acceleration and Escape sourced by a Preexisting Population with Power Law Energy Spectrum

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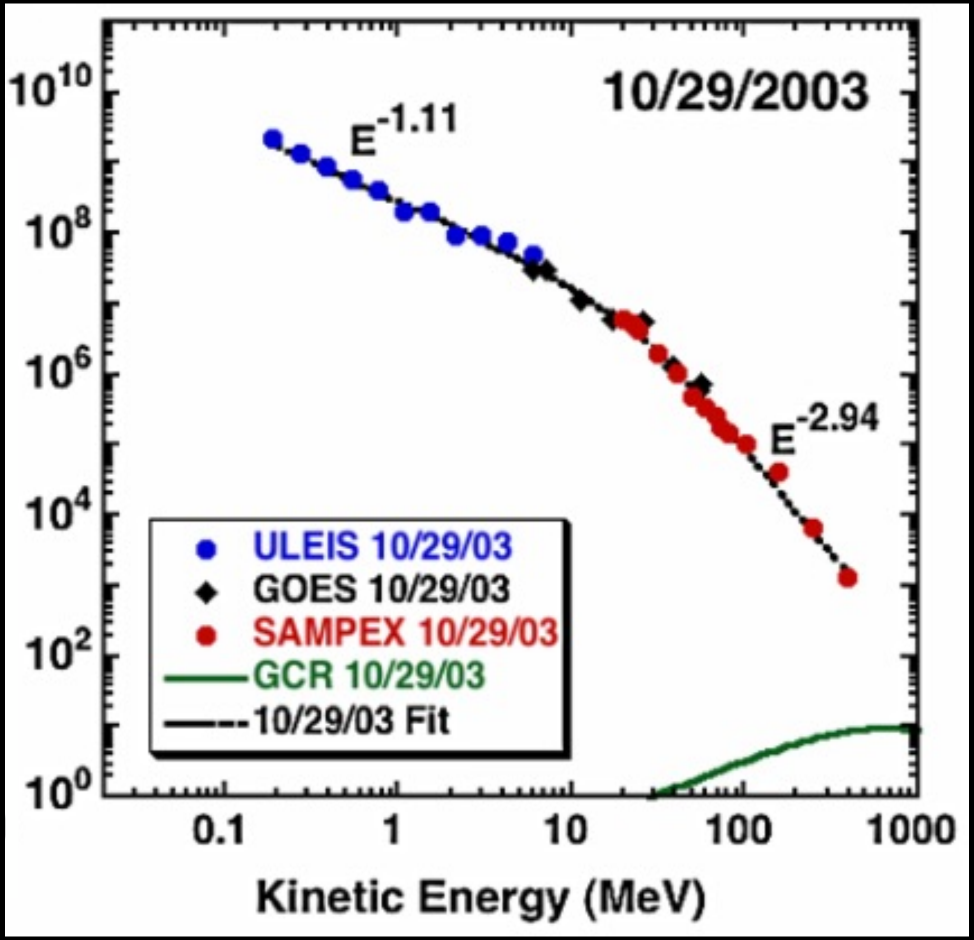
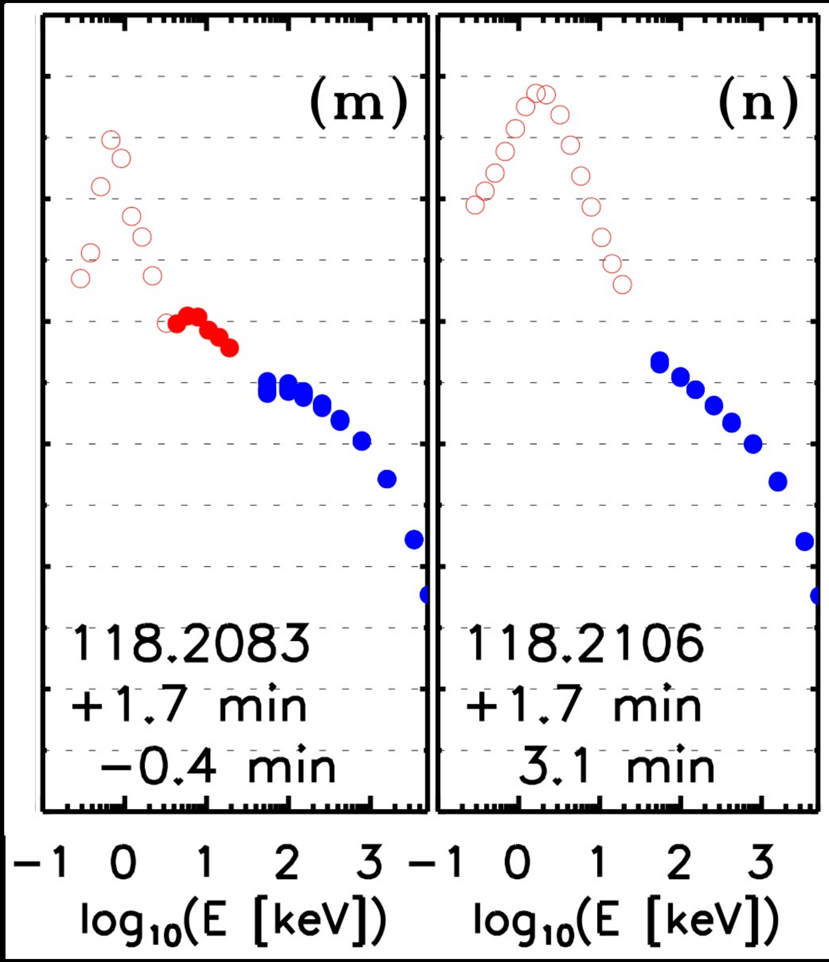
Key Points

- Summary of models predicting energy spectrum steepening
- Steady state 1D solution
- Results and fit of 1 AU spacecraft data
- Summary
- Potential future research

DSA and deviations from it



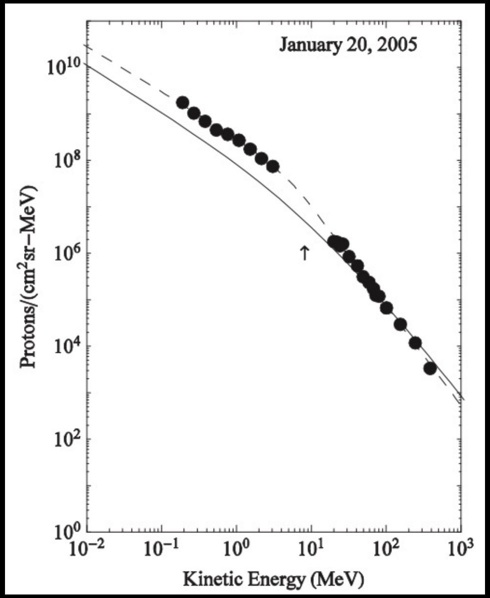
Credit: Mewaldt et al. 2012



Credit: Lario et al. 2019

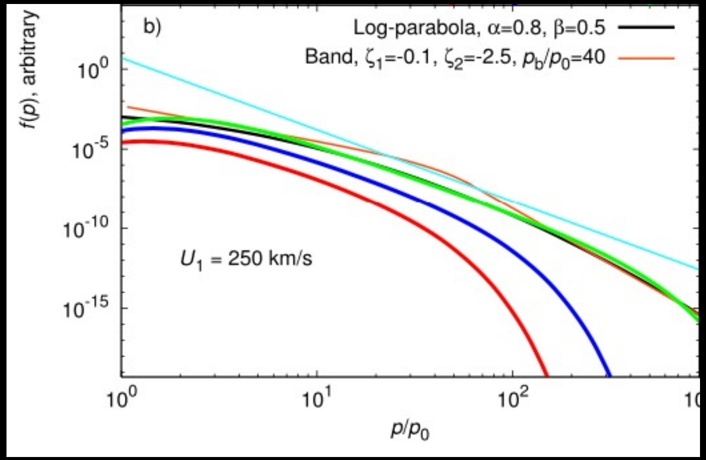
Transport vs. Acceleration/Escape

- Transport
  - Li & Lee 2015: A double power-law spectrum arises due to transport of the particles from the source to 1 AU
  - Zhao et al. 2017 and Strauss et al. 2020
- Acceleration/Escape
  - Ellison & Ramaty 1985: Power law and exponential cut-off
  - Schwadron et al. 2015: Escape from shock driving CMEs
  - Fraschetti 2021: A solution given by a power law times two exponentials due to particle escape



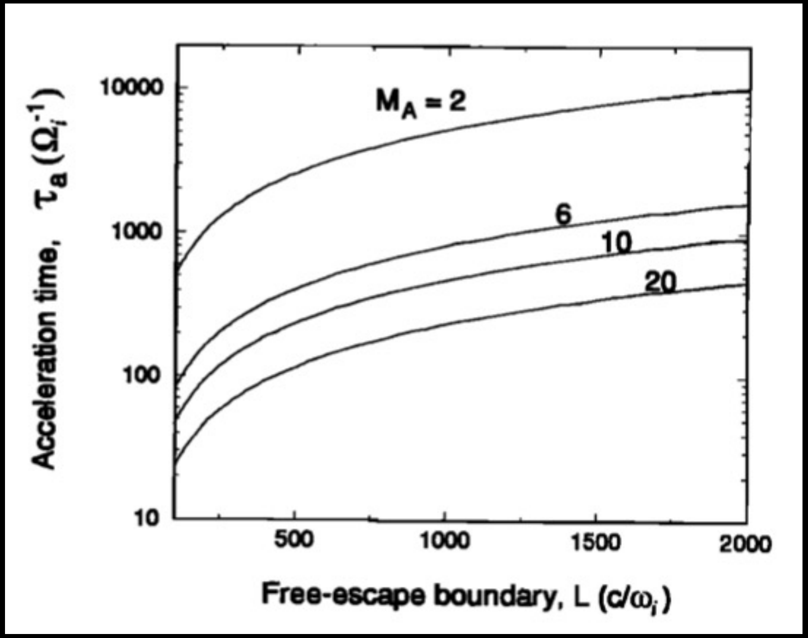
Credit: Li and Lee, 2015

Credit: Fraschetti, 2021



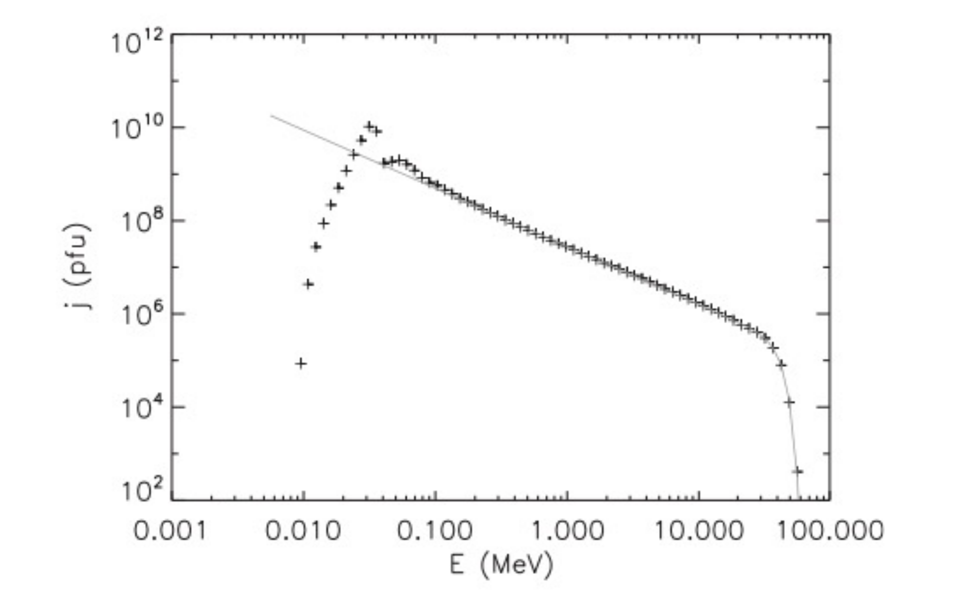
Models with FEB vs. Escape Time

- Free Escape Boundary (FEB)
  - Giacalone et al. 1997: Builds upon DSA by implementing a FEB to allow for particle escape
  - Vainio et al. 2014: Also uses a FEB, found a power law and exponential cut-off
- Escape Time
  - Fraschetti 2021: Adds to DSA by including acceleration and escape at all energies (not just the highest) and introduces an energy dependent escape time



Credit: Giacalone et al. 1997

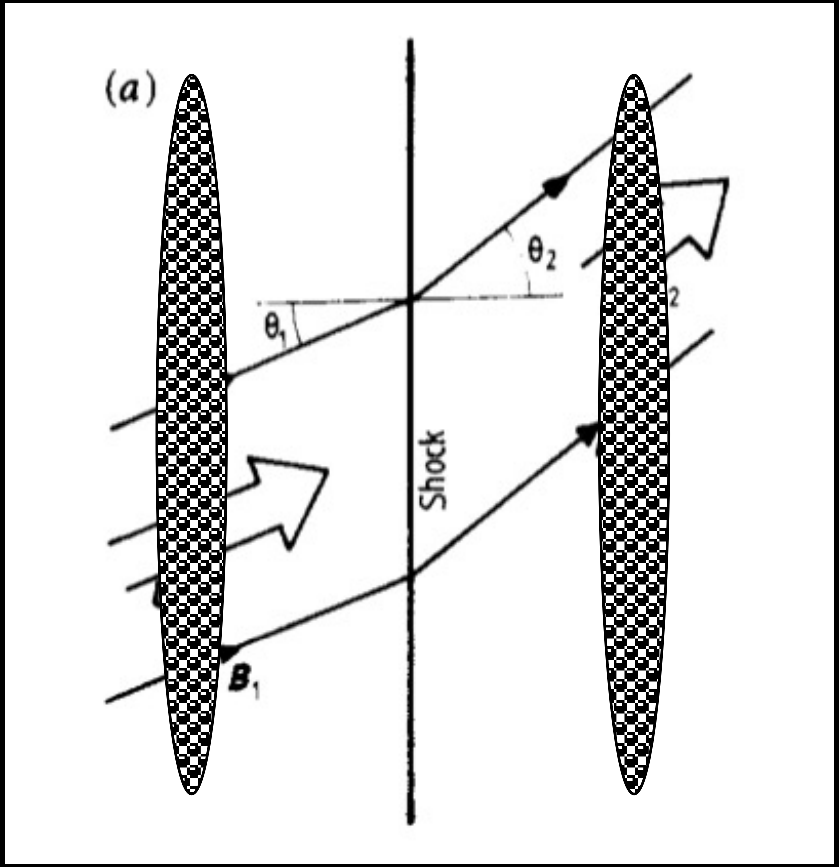
Credit: Vainio et al. 2014



Methods

- Analyzed the case where the source term is a power law:

$$S(x,p) = S_0\,\delta(x - x_0)\left(\frac{p}{p_0}\right)^{-\alpha}$$



Credit: Drury 1983

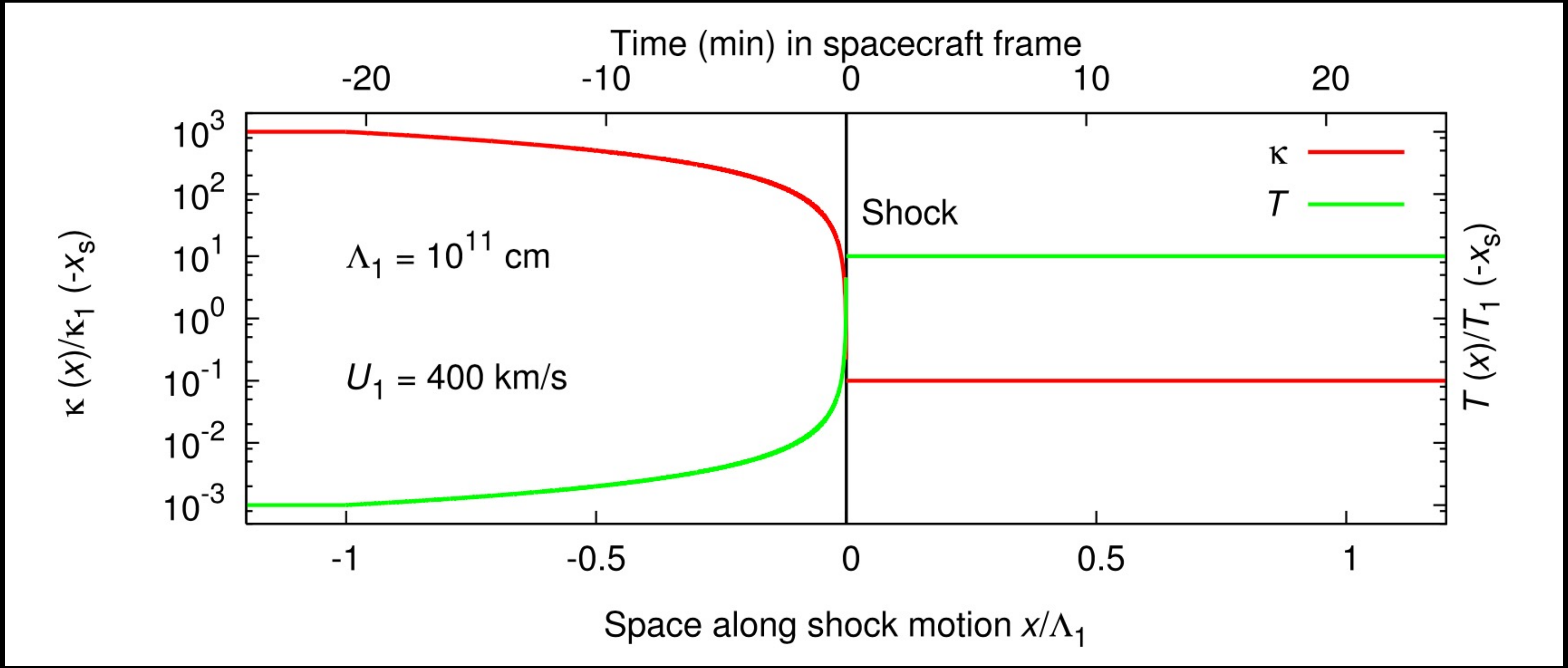
$$\underbrace{U\frac{\partial f(x,p)}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left[\kappa(x,p)\frac{\partial}{\partial x}f(x,p)\right]}_{\text{Diffusion of particles}} + \underbrace{\frac{1}{3}\left(\frac{dU}{dx}\right)p\frac{\partial f(x,p)}{\partial p}}_{\text{Change in particle energy}} + \underbrace{S(x,p)}_{\text{Source of Particles}} - \underbrace{\frac{f(x,p)}{T(x,p)}}_{\text{Escape of Particles}}$$

$$\kappa(x,p) = \begin{cases} \dfrac{\kappa_1(p)|x-\epsilon|}{|\Lambda_1|} \; for\ x < 0\ (upstream) \\ \kappa_1(p)\ for\ x \ll 0\ (far\ upstream) \\ \kappa_2(p)\ for\ x > 0\ (downstream) \end{cases}$$

$$T(x,p) = \begin{cases} \dfrac{T_1\ (p)|\Lambda_1|}{|x-\epsilon|} \; for\ x < 0\ (upstream) \\ T_1(p)\ for\ x \ll 0\ (far\ upstream) \\ T_2(p)\ for\ x > 0\ (downstream) \end{cases}$$

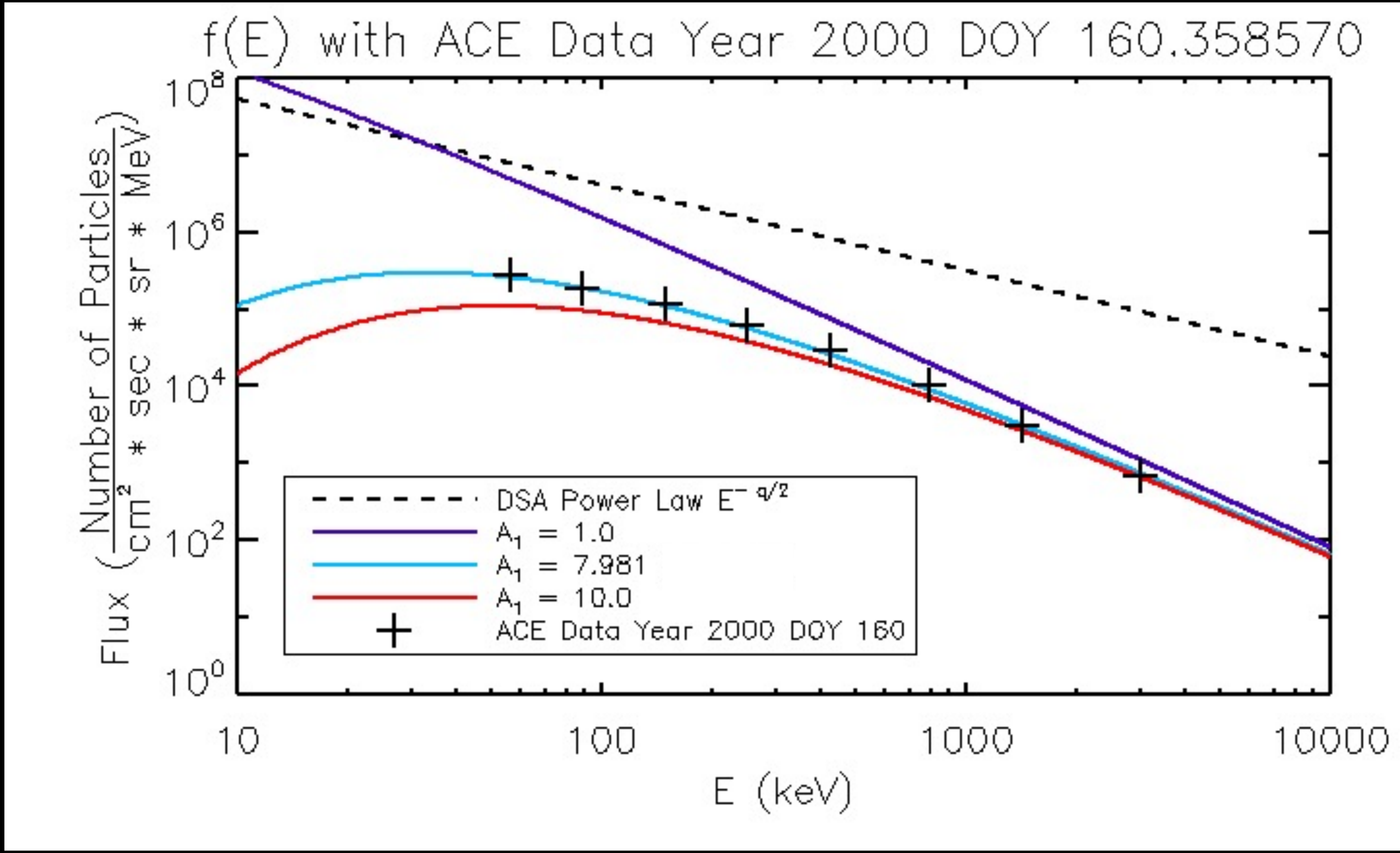
$$\kappa_i(p) = \bar{\kappa}_i \left(\frac{p}{p_0}\right)^{\delta_i}$$

$$T_i(p) = \bar{T}_i \left(\frac{p}{p_0}\right)^{-\gamma_i}$$



Credit: Fraschetti, 2021

Derived Solution

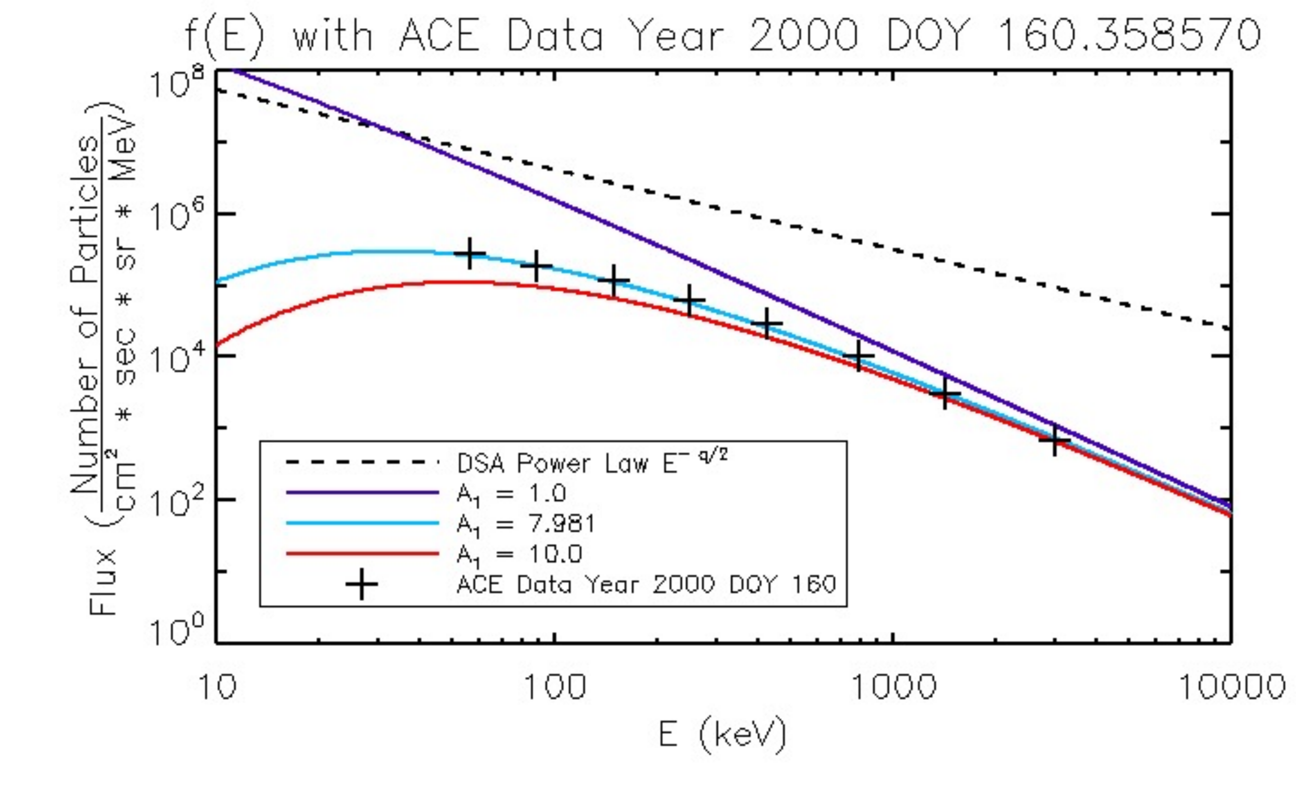


Applying our solution to shock data

- Particle flux data came from ACE/EPAM
- Considered Year 2000 DOY 160 (June 8)
- Shock parameters came from the ipShock database hosted by the University of Helsinki
- Found the predicted value of A_1 from given shock parameters

Credit: Wikipedia

ACE Data Fitting



$r = 3.44 \rightarrow q = 4.230, \quad \delta_1 = 1, \quad U_1 = 356\ km\ s^{-1},$

$|\Lambda_1| = 10^{11}\ cm, \quad \bar{\kappa}_1 = 10^{19}\ cm^2\ s^{-1}, \quad L_1(p_0) = 10^9 cm,$

$\epsilon = 10^7 cm, \qquad A_1 = 7.981$

Recap and Future Research

- Recap
  - We found a solution of the following form:

$$f(p) \propto \left(\frac{p}{p_0}\right)^{-\alpha-\delta_2-\gamma_2} \cdot \left(e^{-A_1\left(\frac{p}{p_0}\right)^{-\delta_1}}\right)$$

  - ACE/EPAM data appears to be fitted well by our model
- Future Research
  - Time dependence of our solution
  - Applicability of our model to different spacecraft
  - Applicability of our model to supernova remnant shocks

Acknowledgements

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Questions?

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