

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

Thomas Do<sup>1</sup>, Federico Fraschetti<sup>2</sup>, and Manpreet Singh<sup>3</sup>

<sup>1</sup>University of Washington Seattle Campus

<sup>2</sup>Harvard-Smithsonian Center for Astrophysics

<sup>3</sup>University of Arizona

November 23, 2022

## Abstract

Charged particles accelerated by interplanetary shocks can escape from the shock without returning to it. However, the simplest version of the model of Diffusive Shock Acceleration (DSA) does not include an energy-dependent escape from the foreshock region. We present a model for interplanetary shock acceleration that includes such escape and expands upon DSA. Building off our past research, we analytically solve a one-dimensional transport equation that includes an escape-time dependent on both particle position and momentum. In addition to previous work, we consider the case where a shock encounters a population of preexisting charged particles with a power law energy distribution. We find that at lower energies our solution is concave, whereas at higher energies it asymptotically approaches a power law whose slope depends on the original energy spectrum's power law index and shock parameters. We fitted the solution obtained from this transport equation to ACE/EPAM shock data measured from multiple shock events. We also compared the best fit parameters to the predicted parameter values, with the latter being derived from measured shock properties. We find that for the shock events considered, our model's best fit parameters match very well with the predicted values. From this model, we can better understand the mechanism of interplanetary shock acceleration and how this phenomenon energizes charged particles near other objects such as blazars and supernova remnants. This work is supported by the NSF-REU solar physics program at SAO, grant number AGS-1850750. This work is also partially supported by the NSF under grant 1850774.

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**Thomas M. Do**

*Department of Astronomy, University of Washington – Seattle, Seattle, WA, 98178, USA.*

**Federico Fraschetti**

*Center for Astrophysics, Harvard & Smithsonian, Cambridge, MA, 02138, USA.*

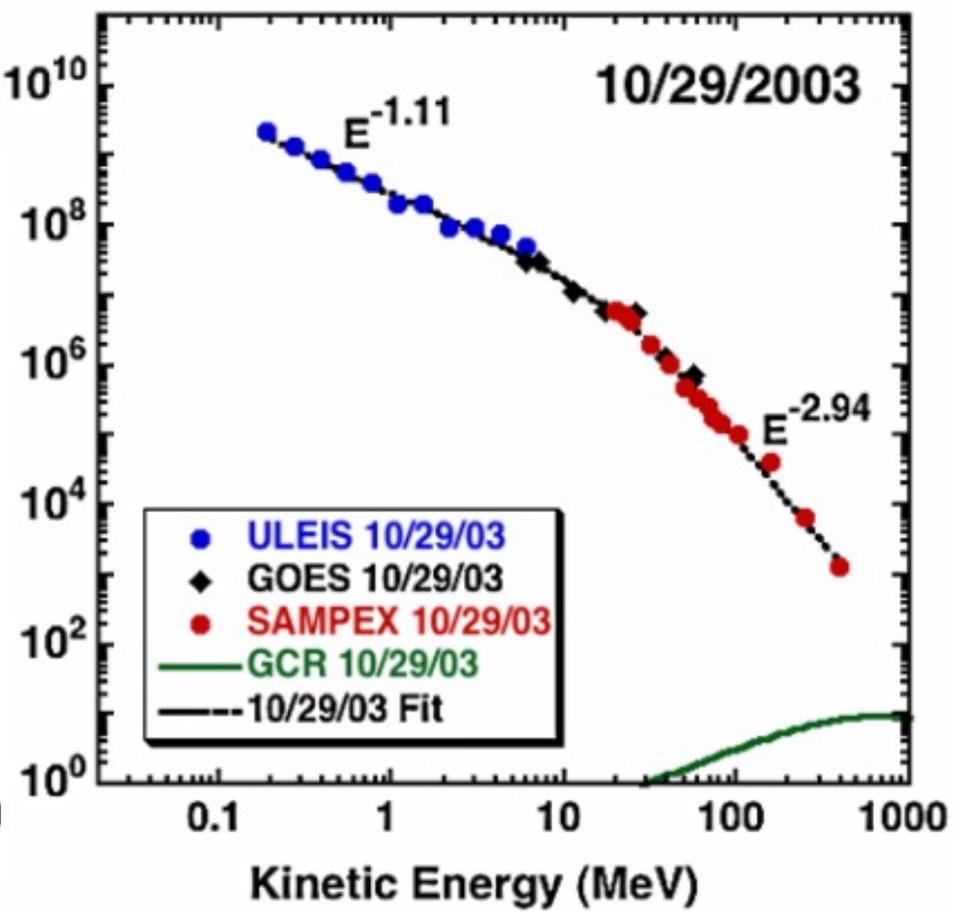
**Manpreet Singh**

*Department of Planetary Sciences – Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ,  
85721, USA.*

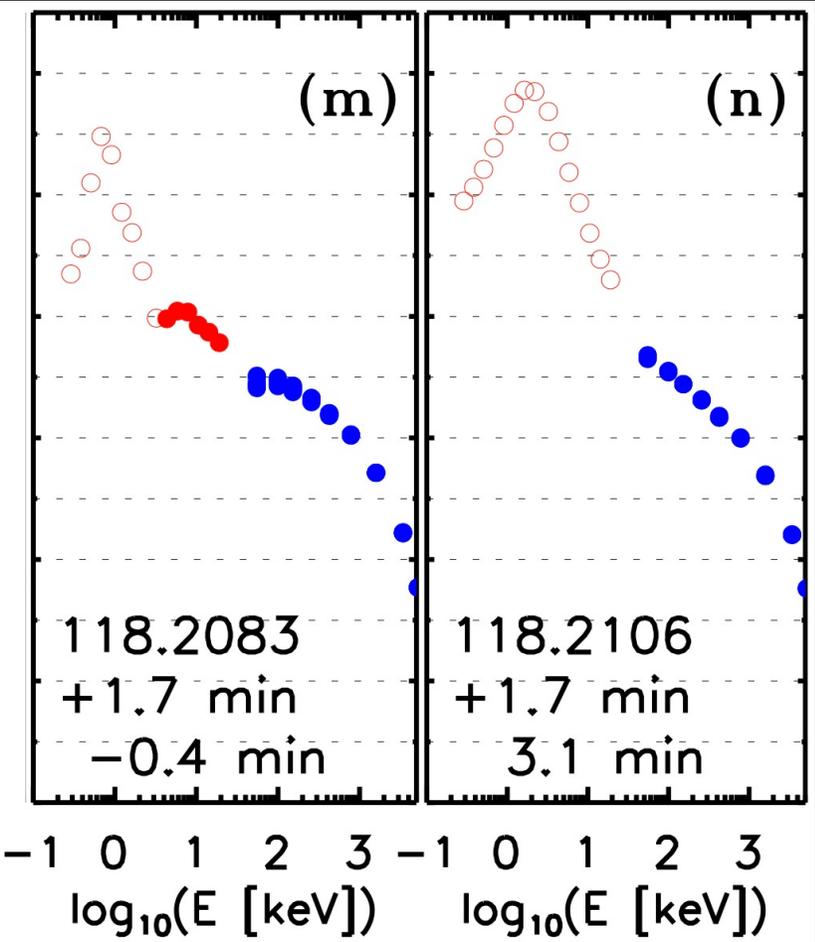
# Key Points

- 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

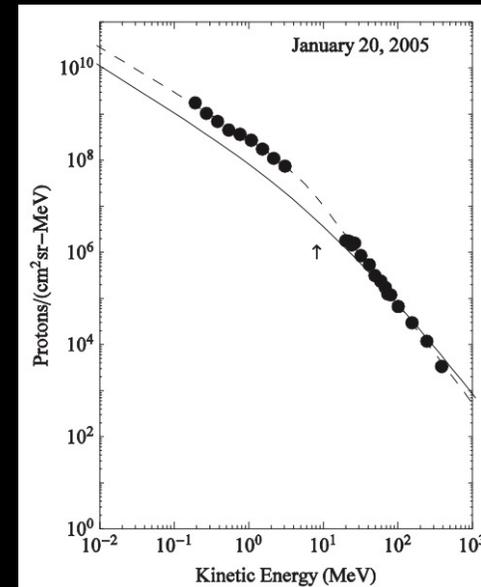
# Transport vs. Acceleration/Escape

- 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

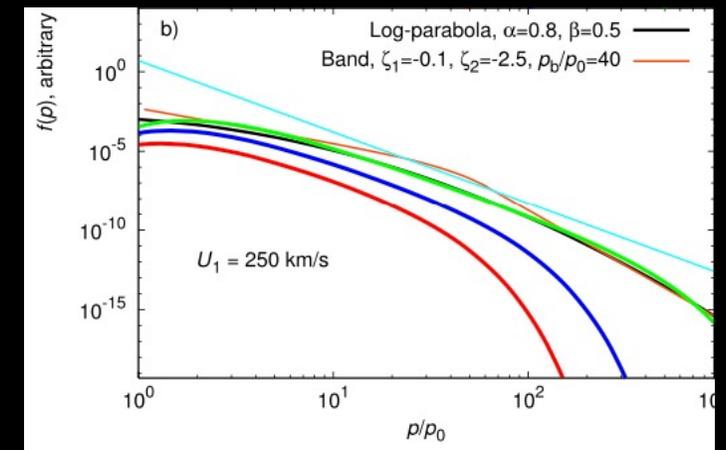
- Acceleration/Escape

- 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



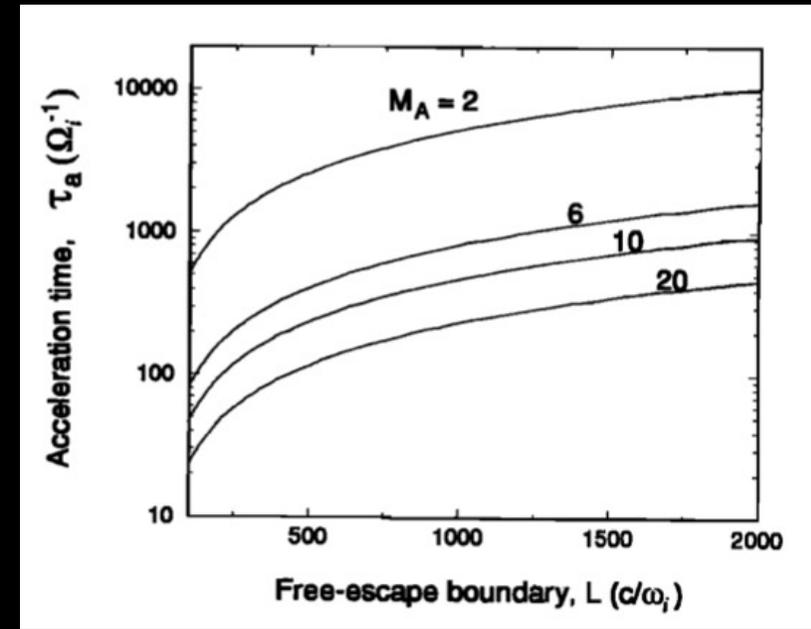
Credit: Li and Lee, 2015

Credit: Fraschetti, 2021



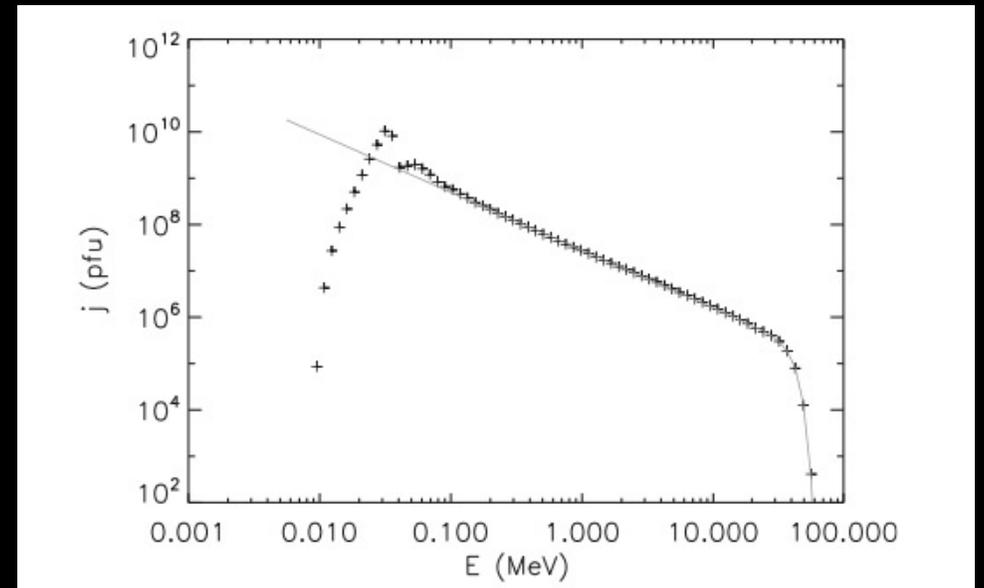
# Models with FEB vs. Escape Time

- 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

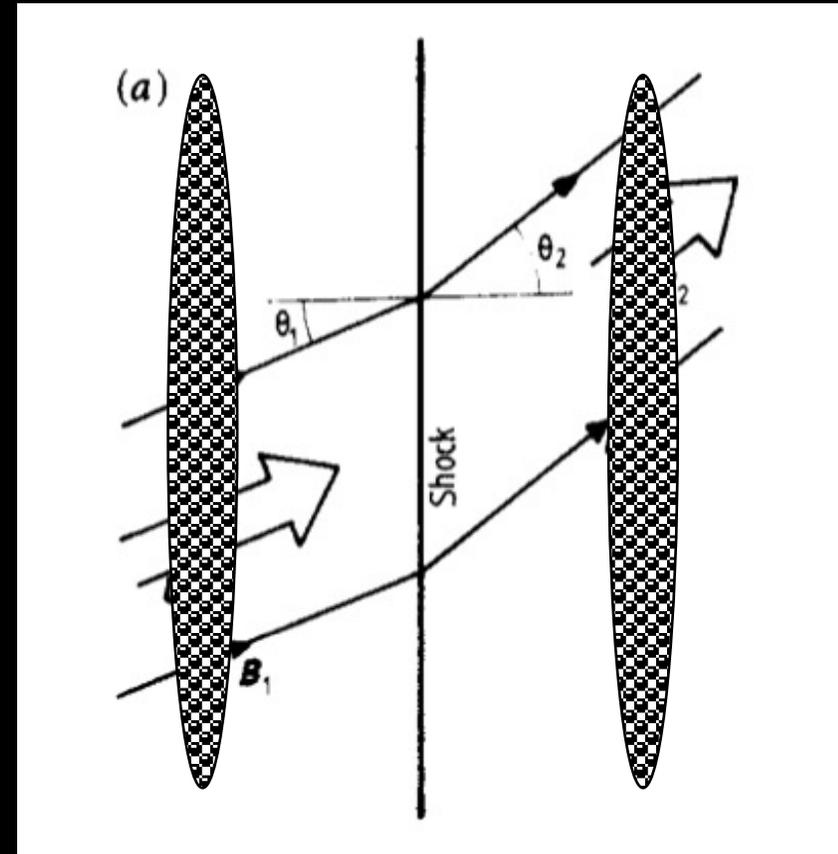
Credit: Vainio et al. 2014



# 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

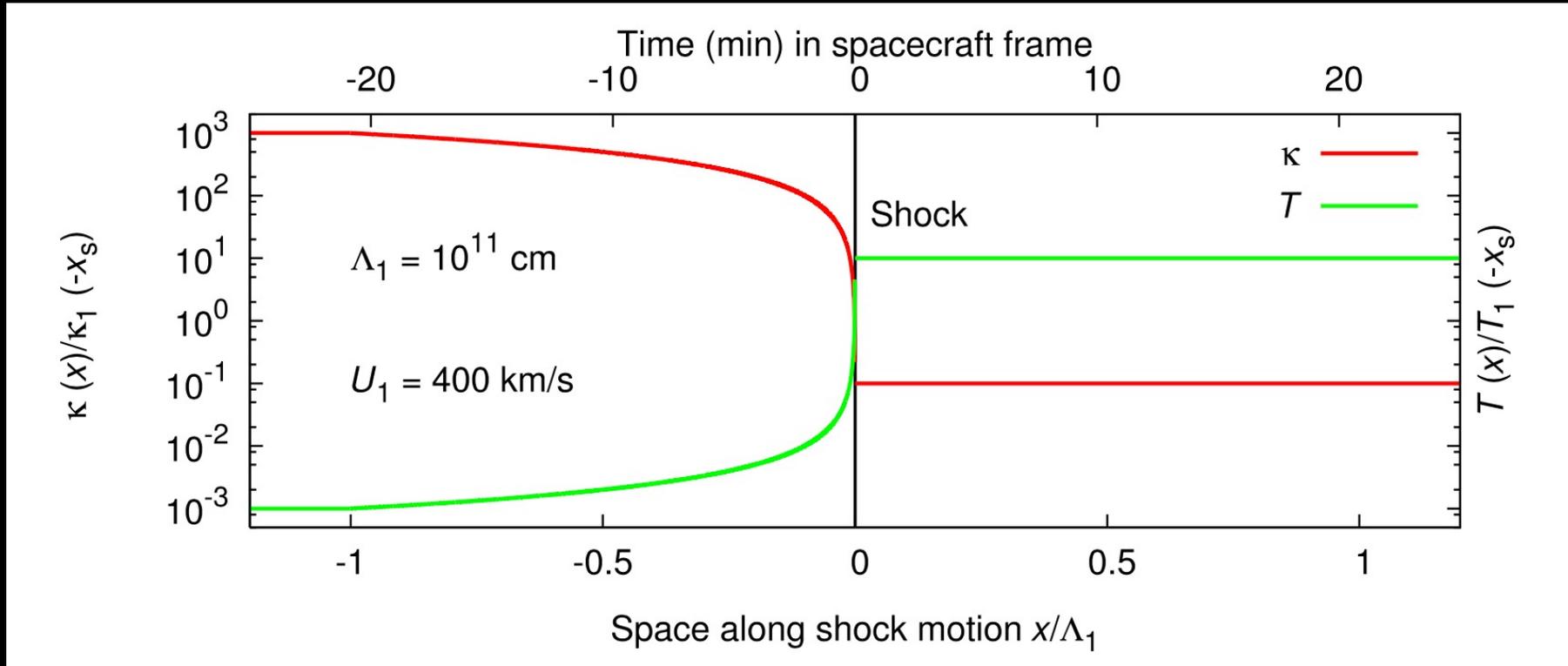
$$\underbrace{U \frac{\partial f(x, p)}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x} \left[ \kappa(x, p) \frac{\partial f(x, p)}{\partial x} \right]}_{\text{Diffusion of particles}} + \underbrace{\frac{1}{3} \left( \frac{dU}{dx} \right) p \frac{\partial f(x, p)}{\partial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

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

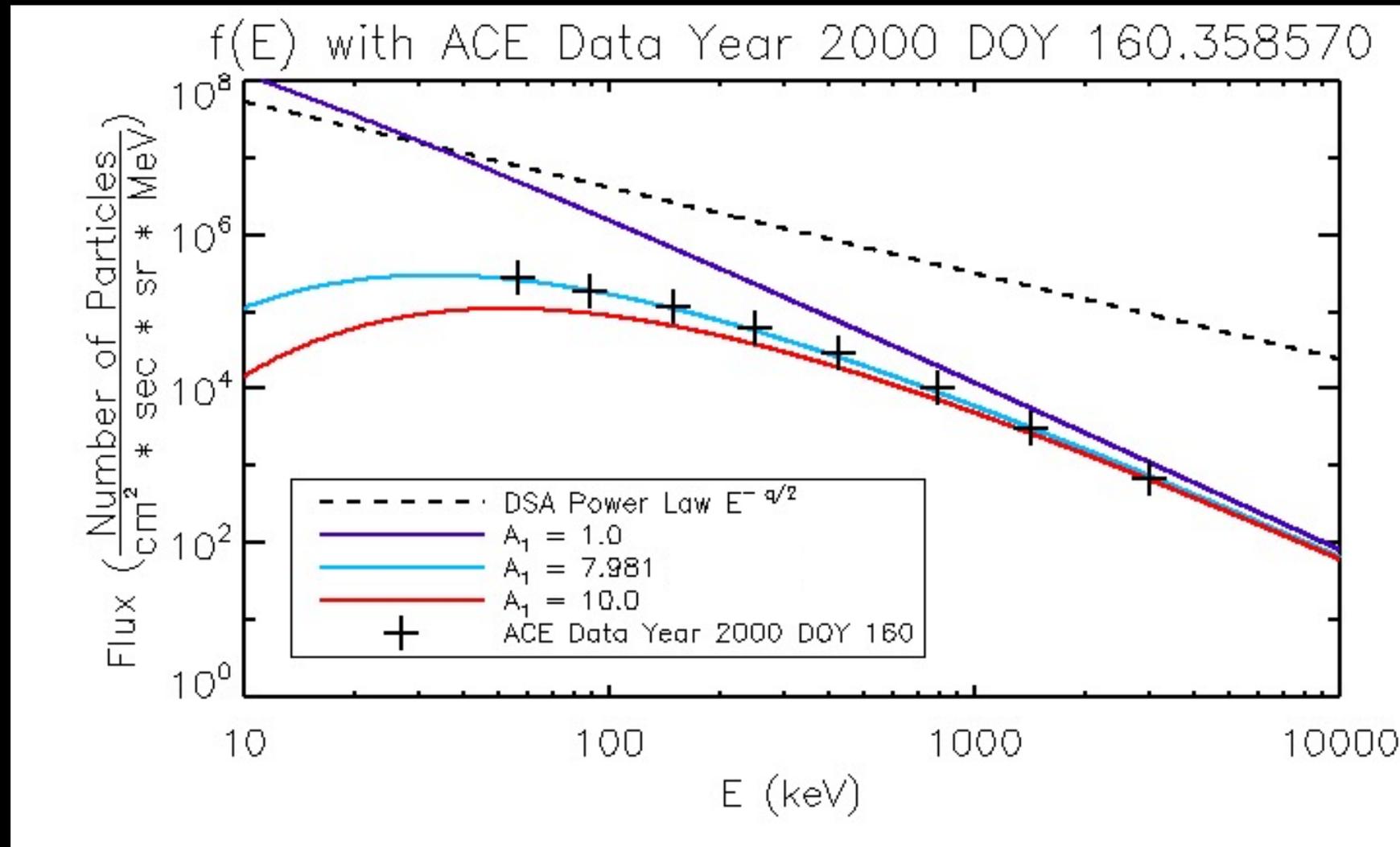
$$\kappa_i(p) = \bar{\kappa}_i \left( \frac{p}{p_0} \right)^{\delta_i}$$

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

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

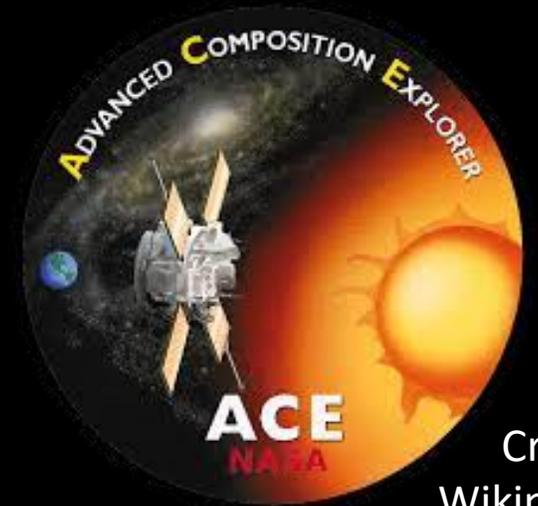


# Derived Solution



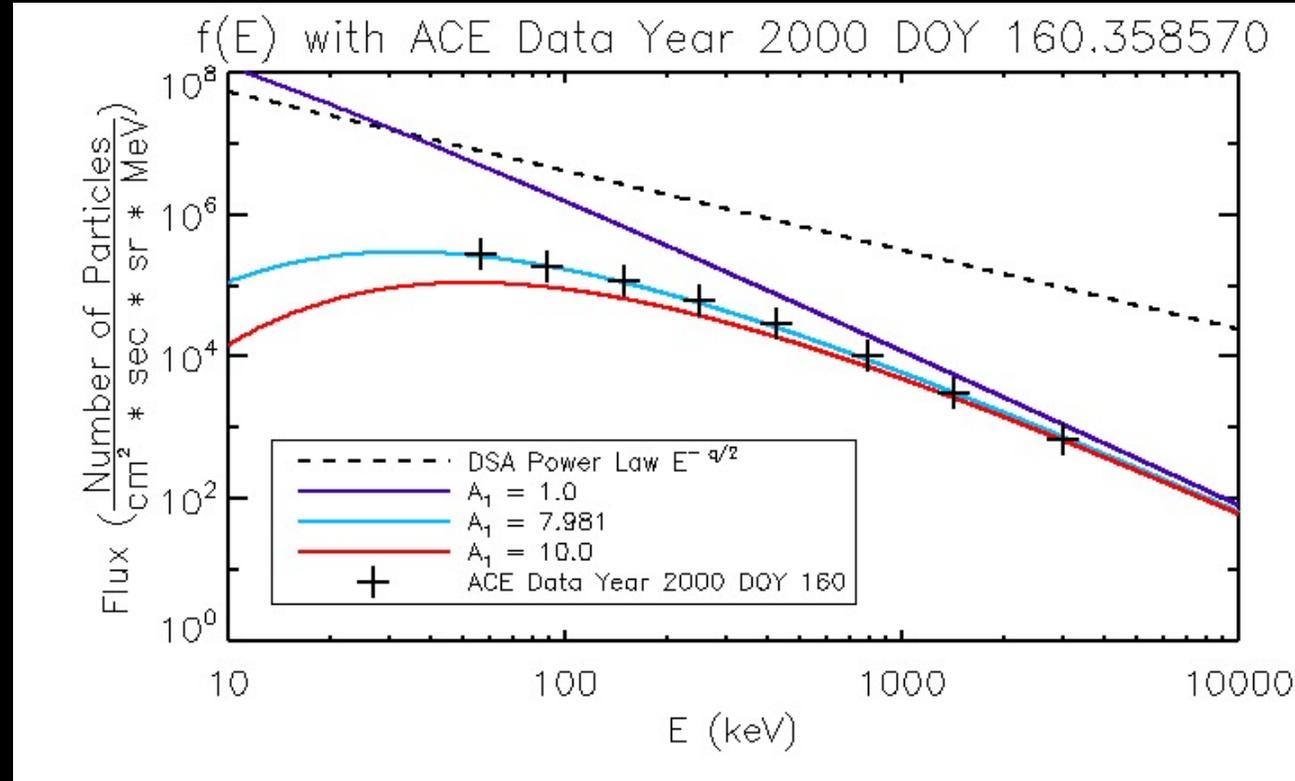
# Applying our solution to shock data

- 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



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

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

$$\epsilon = 10^7 \text{ cm}, \quad A_1 = 7.981$$

# 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

- This work is supported by the NSF-REU solar physics program at SAO, grant number AGS-1850750. This work is also partially supported by the NSF under grant 1850774, by NASA under Grant 80NSSC18K1213 and by Chandra Theory grant GO8-19015X.
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Questions?

Contact me at [tmd37@uw.edu](mailto:tmd37@uw.edu)