# Determining the Relative Roles of SMFR Acceleration Mechanisms on Particle Acceleration Behind Traveling Shocks Within 1 AU

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## Introduction

While particle energization in the inner heliosphere is traditionally viewed through the lens of diffusive shock acceleration (DSA), recent research suggests that acceleration processes related to magnetic reconnection behind traveling shocks occurring in the vicinity of interplanetary coronal mass ejections (ICMEs) can explain observed particle flux enhancements that contradict predictions by standard steady state DSA theory. A better way of interpreting flux enhancements downstream of traveling shocks might be to consider a combination of DSA and acceleration by a multitude of dynamic small-scale flux-ropes (SMFRs). Interactions of particles with many dynamic SMFRs can lead to energy gain which can model these flux enhancement profiles. We present a new event observed by Helios A near its perihelion at ~0.3 AU, where the flux enhancement behind a traveling shock can be explained in terms of SMFR acceleration and not standard steady-state DSA theory. We fit a new solution of our Parker-type transport for energetic particle SMFR acceleration to the flux enhancements of the event with a Metropolis-Hastings algorithm.

## SMFR Acceleration Event

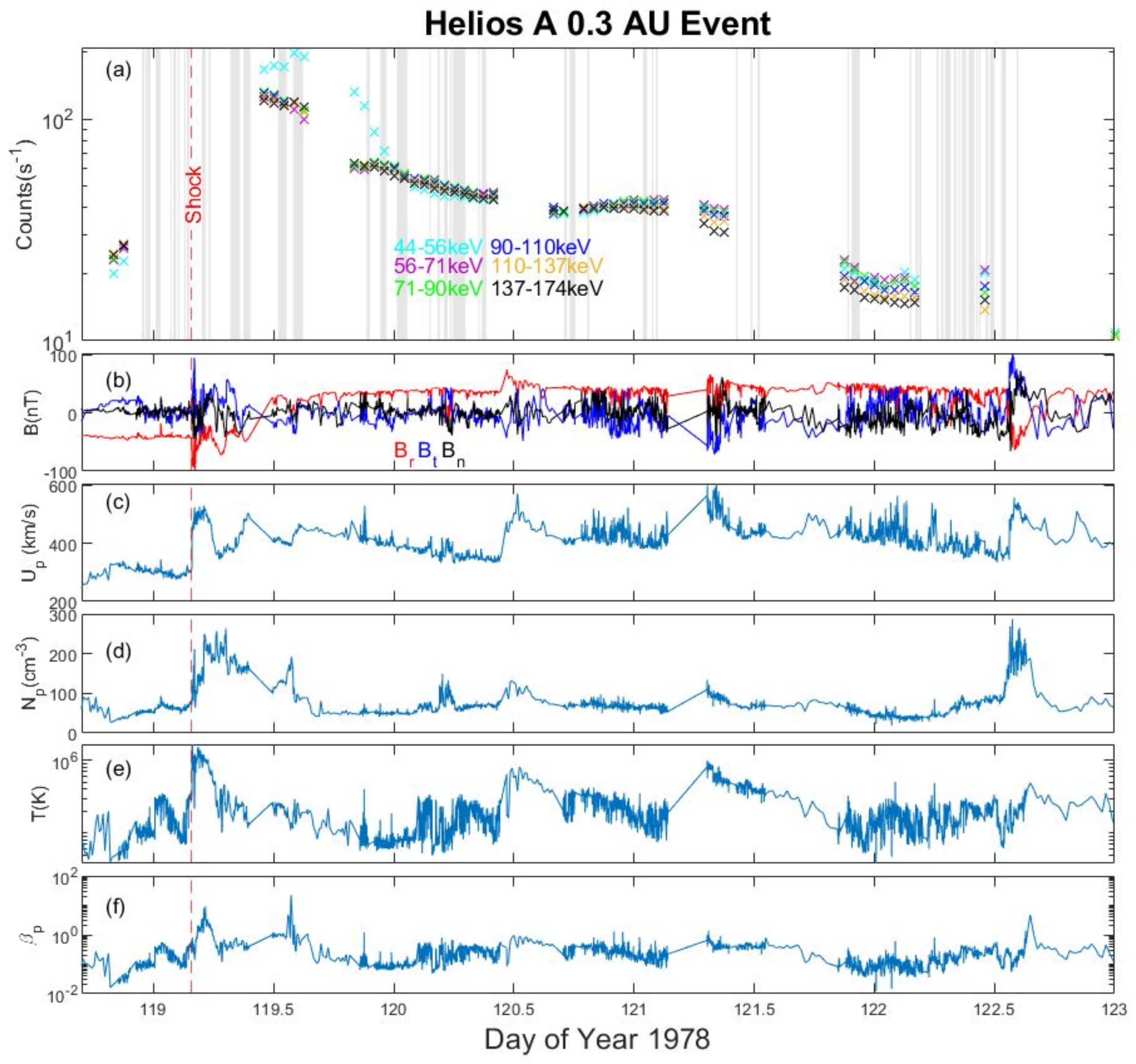

**Figure 1:** (a) Particle counts from the E8 detector on Helios A. The grey bars represent SMFRs identified by Chen & Hu (2020). (b) The magnetic field (E2) presented in the RTN coordinate system. (c) The proton flow speed as measured in the spacecraft frame (E1). (d) The proton number density (E1). (e) The proton temperature (E1). (f) The plasma beta (calculated)

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## Analytical Model

The Parker-type transport equation for energetic particle SMFR acceleration from le Roux et al. (2019) in heliocentric spherical coordinates, assuming a steady state distribution function and injection of particles at a single position and momentum, can be written as follows

$$\frac{\partial^2 f}{\partial r^2} - \left[\frac{u_0 - u_{Er} - 3K}{K}\right]\frac{1}{r}\frac{\partial f}{\partial r} - \left[\frac{\frac{2}{3}\left(-u_0 - u_{Er} + \overline{\langle \nu^I_{COM}\rangle}/2\right) - 3D_0}{K}\right]\frac{1}{r^2}\frac{\partial f}{\partial z} + \frac{D_0}{Kr^2}\frac{\partial^2 f}{\partial z^2} + \frac{2u_{Er}}{3Kr}\frac{\partial^2 f}{\partial r \partial z} - \frac{f v_{esc}}{Kr^2} = -\frac{dN/dt}{16\pi^2 K r_0^3 p_0^3}\delta(r - r_0)\delta(z)$$

- $f(r,p)$ -direction averaged distribution function
- $r$ - heliocentric radial distance
- $z = \ln(p/p_0)$ - log of momentum over injection momentum
- $u_0$ - solar wind speed
- $u_{Er}$- advection speed associated with the turbulent motional electric field parallel to the guide magnetic field
- $K$ - radial diffusion due to SMFR interaction
- $\langle \nu^I_{com} \rangle$ - 1st order Fermi acceleration due to mean compression rate
- $D_0$ - associated with 2nd order Fermi acceleration
- $v_{esc}$ - particle escape term
- $dN/dt$ - particle injection rate

$$f(r,p) = \frac{dN/dt}{32\pi^3 K r_0^2 p_0^3 \sqrt{A^*}}\left(\frac{r}{r_0}\right)^{\bar{a} - \frac{B}{2A}\tilde{a}}\left(\frac{p}{p_0}\right)^{-\frac{B}{2A}}\kappa_0\left[b\sqrt{\left(\ln(r/r_0)\right)^2 + \frac{1}{A^*}\left(\ln(p/p_0) + \tilde{a}\ln(r/r_0)\right)^2}\right]$$

$$b = \sqrt{\left(1 - \frac{(u_0 - u_{Er})}{2K}\right)^2 + \frac{v_{esc}}{K} + \frac{D_0}{4K}\frac{\left(3 - {}^1/_{3D_0}\left[\overline{\langle \nu^I_{COM}\rangle} - {}^{u_{Er}u_0}/_K + {}^{u_{Er}^2}/_K - 2u_0\right]\right)^2}{\left(1 - u_{Er}^2/9KD_0\right)}} \qquad A^* = \frac{D_0}{K}\left(1 - \frac{u_{Er}^2}{9KD_0}\right)$$

$$\frac{B}{2A} = \frac{1}{2}\frac{\left(3 - {}^1/_{3D_0}\left[\overline{\langle \nu^I_{COM}\rangle} - {}^{u_{Er}u_0}/_K + {}^{u_{Er}^2}/_K - 2u_0\right]\right)}{\left(1 - u_{Er}^2/9KD_0\right)} \qquad \bar{a} = -\left(1 - \frac{u_0 - u_{Er}}{2K}\right) \qquad \tilde{a} = -\frac{u_{Er}}{3K}$$

## Metropolis-Hastings Best Fit Values

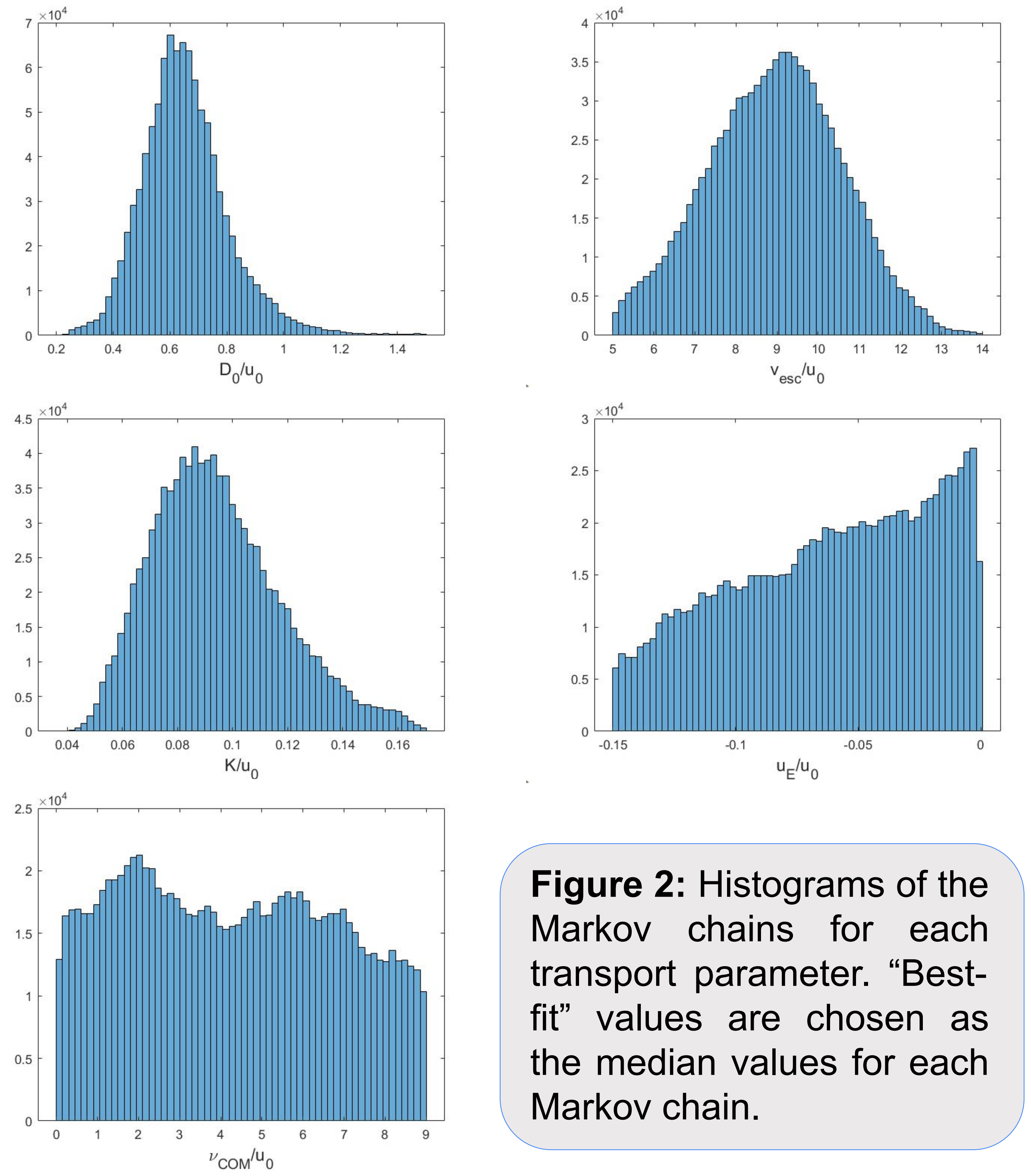

**Figure 2:** Histograms of the Markov chains for each transport parameter. "Best-fit" values are chosen as the median values for each Markov chain.

## Modeling Results

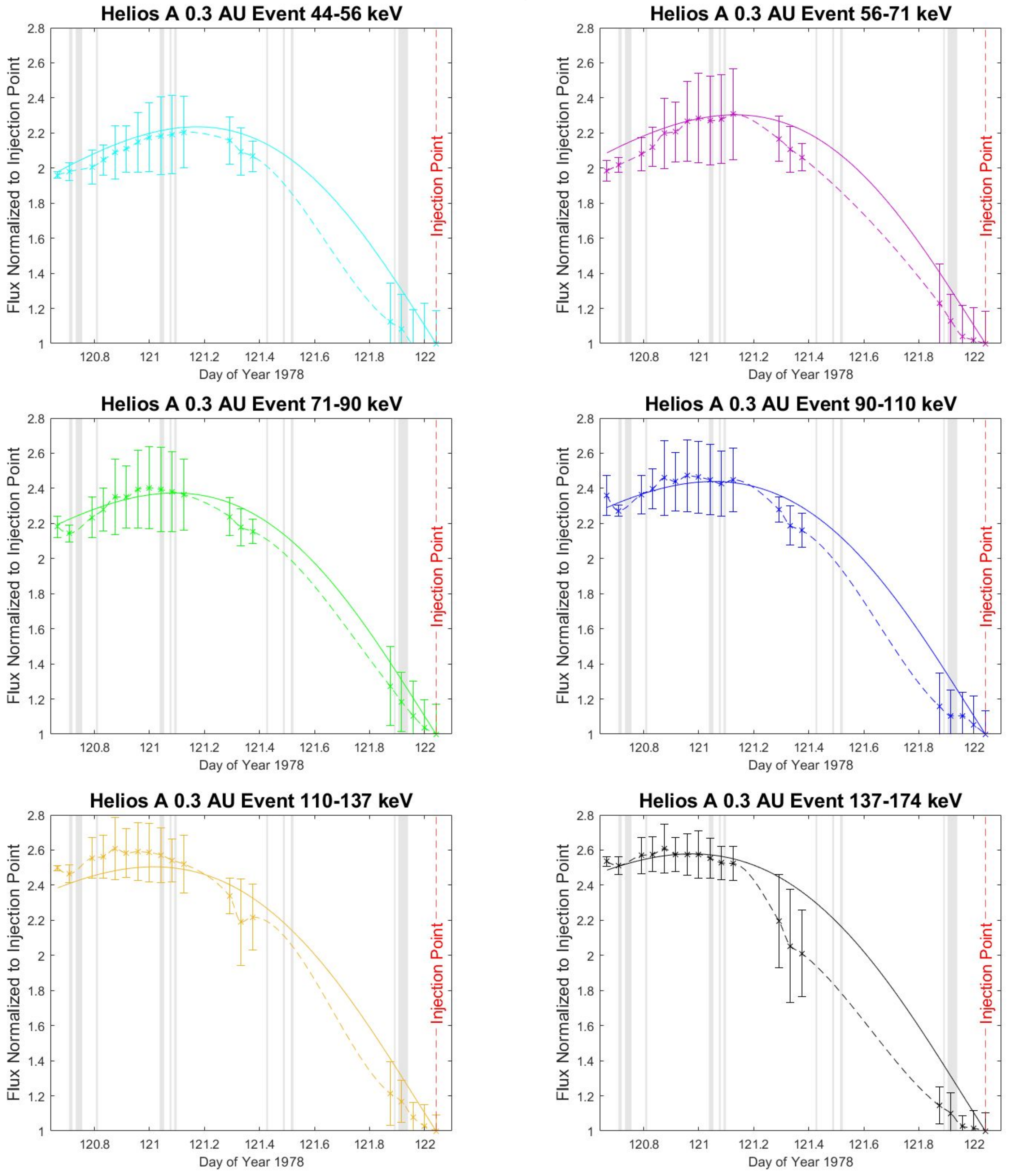

**Figure 3:** Cubic interpolation (dashed lines) of and model fit (solid lines) to the energetic proton flux enhancement data ("x") from of the SMFR acceleration event observed at 0.3 AU with Helios A.

| $D_0/u_0$ | $D_0^{ICOM}/u_0$ | $D_0^{IACC}/u_0$ | $D_0^{ISH}/u_0$ | $D_0^{IE}/u_0$ |
|---|---|---|---|---|
| 6.41<br>±2.35E-1 | 6.62E-4 | 7.80E-8 | 6.47E-3 | 1.88 |

**Table:** $D_0$ data fitting value compared to theoretical $D_0$ values calculated for different candidate 2nd Fermi SMFR acceleration mechanisms using observed SMFR quantities.

## Conclusions

- 2nd order Fermi SMFR acceleration is dominant, mixed derivative acceleration by the mean SMFR turbulent motional electric field along the guide field is the 2nd strongest, while 1st order Fermi by the mean SMFR compression rate is the least efficient SMFR mechanism for energizing suprathermal particles.
- 2nd order Fermi SMFR acceleration is dominated by the variance in the turbulent motional electric field along the guide field.
- Strong particle escape from the SMFR field is needed to reproduce the observed peaks in the energetic particle fluxes (and observed spectral slopes, see Van Eck et al. 2022).
- Radial diffusion through the SMFR field is inefficient. The large escape term might also partly indicate the need for more efficient interaction with multiple SMFRs.

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