Effect of turbulence on transport SEPs in the Heliosphere

Valeriy Tenishev

Marshall Space Flight Center, Huntsville, AL

Abstract

Solar energetic particles (SEPs) are high-energy particles originating from the Sun and accelerated at the front of a CME-driven shock. They pose potential risks to space missions, especially those outside Earth's protective magnetosphere. Understanding their behavior in both the heliosphere and Earth's magnetosphere is vital for the safety and functionality of space exploration. The study focuses on how pitch angle scattering impacts the overall SEP population during various phases of SEP events.

Incorporating pitch angle scattering effects at these extended distances is essential for a comprehensive understanding of SEP event decay dynamics. This modeling of SEPs is further integrated with simulations of other critical space phenomena, including the solar wind, interplanetary magnetic field, and Alfvén wave turbulence. This presentation details the modeling techniques employed in this research and explores the impact of pitch angle scattering at various heliocentric distances on the SEP events' decay phase dynamics.

SEP Origin & Acceleration

Solar energetic particles (SEPs) originate primarily from two key mechanisms: solar flares and coronal mass ejection (CME)-driven shocks. These acceleration processes can lead to rapid and intense enhancements in SEP flux, often increasing by several orders of magnitude within minutes to hours. CME-driven shocks efficiently accelerate particles via the diffusive shock acceleration (DSA) mechanism, where charged particles undergo repeated interactions with upstream and downstream turbulence, gaining energy with each cycle. The efficiency of this acceleration depends on shock geometry, seed particle populations, and pre-existing turbulence in the interplanetary medium.

Transport & Scattering

Once accelerated, SEPs propagate through the heliosphere, experiencing complex transport effects governed by interactions with turbulent magnetic fields. Pitch-angle scattering, primarily caused by resonant interactions with magnetohydrodynamic (MHD) waves, modifies the particle distribution, leading to diffusion both along and across the interplanetary magnetic field. Cross-field diffusion can result in significant broadening of SEP events, allowing particles to reach distant longitudes from their original acceleration site. The interplay between these transport processes influences the intensity profile and decay phase of SEP events, impacting space weather forecasting and radiation hazard assessment for interplanetary missions.

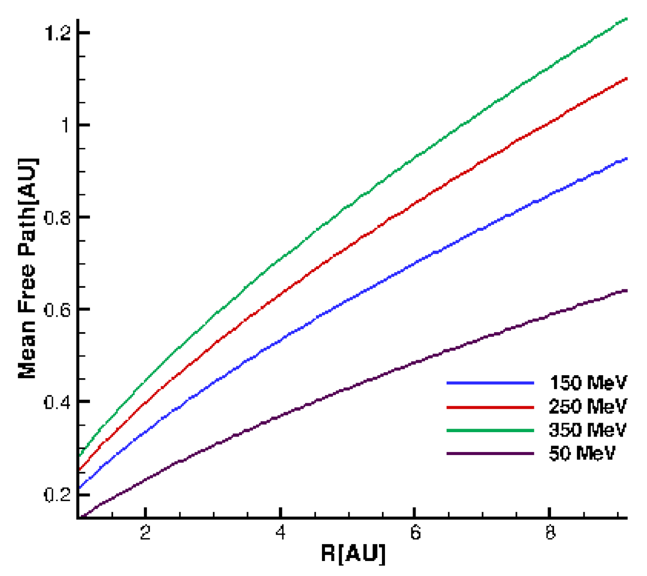
Modeling Transport and Acceleration of SEPs

Monte Carlo Method

SEP scattering on Alfven waves is described as a Monte Carlo process, capturing the stochastic nature of particle interactions. The test-particle Monte Carlo method models SEP transport, where individual particles represent the distribution function with statistical weights. This probabilistic approach provides a rigorous framework for studying SEP dynamics in turbulent magnetic fields.

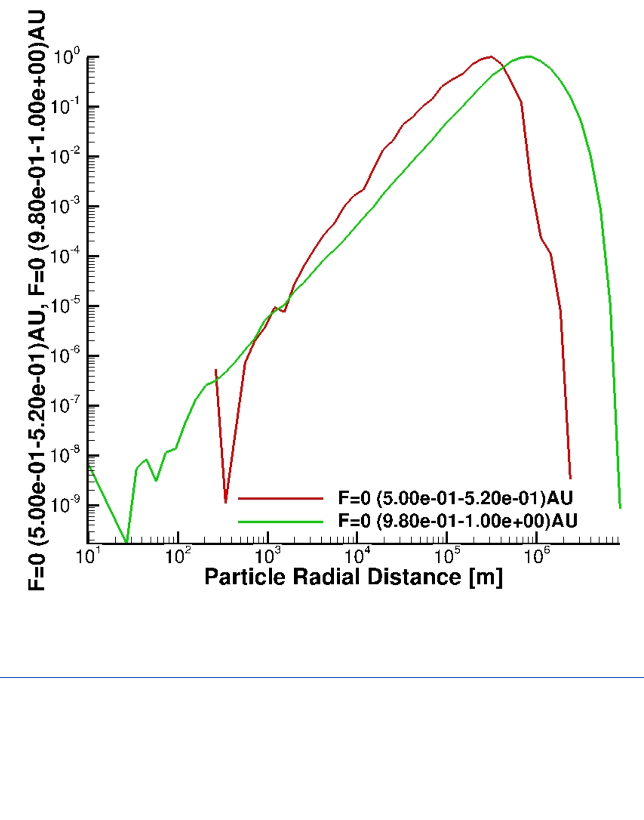
Transport and Scattering

Scattering is governed by a momentum and heliocentric-distance-dependent mean free path. Particles undergo isotropic pitch-angle scattering in discrete steps, modeling their stochastic interactions with magnetic turbulence. This method ensures an accurate representation of SEP transport, energy redistribution, and spatial diffusion.



Effect of perpendicular diffusion

Perpendicular diffusion is crucial in SEP transport, enabling cross-field motion and allowing SEPs to reach regions not magnetically connected to the source. This process occurs as SEPs "reattach" from one field line to another, decoupling from a single guiding line and spreading across the heliosphere. Its significance increases when the interplanetary magnetic field (IMF) becomes "twisted" and diverges due to solar wind shear, turbulence, or transient structures like CMEs. Under these conditions, perpendicular diffusion enhances radial and latitudinal transport, explaining SEP presence in regions far from their acceleration site.



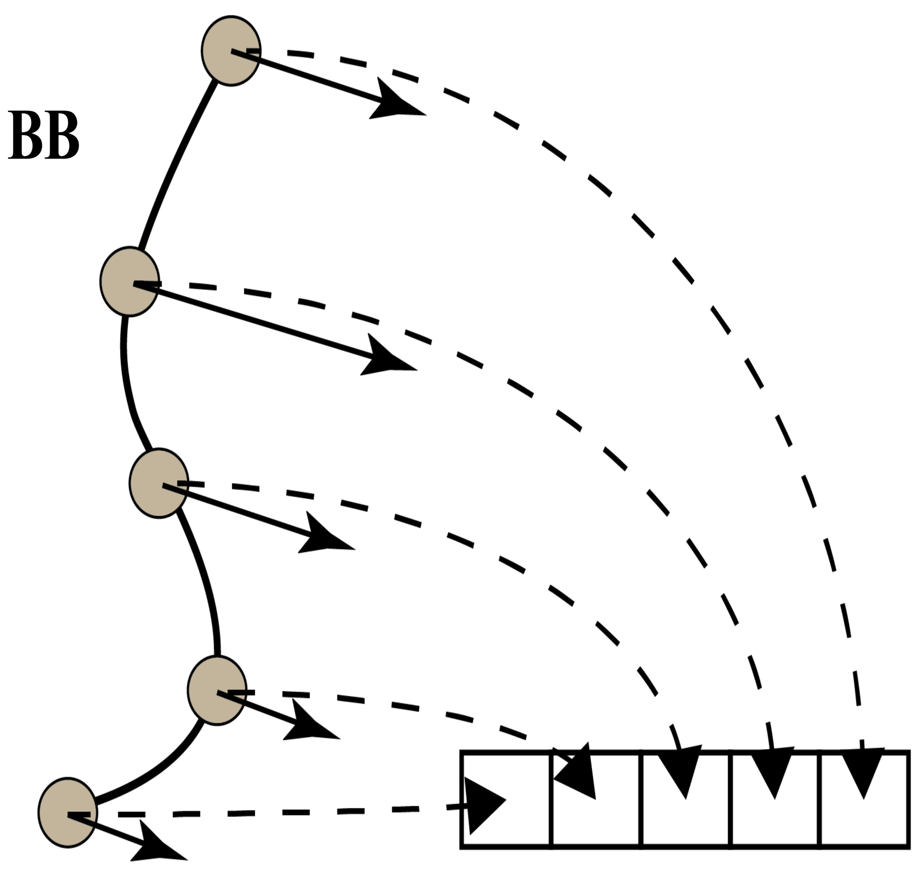
Physics Model

It considers SEPs as test particles that propagate along interplanetary magnetic field lines, and can handle multiple field lines and interpolate the flux and spectrum of particles in the region between them while accounting for isotropic scattering and mean free path. Parker equation or the focused transport equation may be expressed in the Lagrangian coordinates (Sokolov et al 2004, Kota et al 2005)

$$\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f - \frac{1}{3}(\nabla\cdot\mathbf{u})\frac{\partial f}{\partial \log p} = \nabla\cdot(k\cdot\nabla f), \quad k \propto \mathbf{BB}$$

Reduction to single spatial dimension transforms spatially 3-D problem to multitude of spatially 1-D problems

$$\frac{Df}{Dt} + \frac{1}{3}\frac{D\ln\rho}{Dt}\frac{\partial f}{\partial \ln p} = B\frac{\partial}{\partial s}\left(\frac{\varkappa}{B}\frac{\partial f}{\partial s}\right)$$



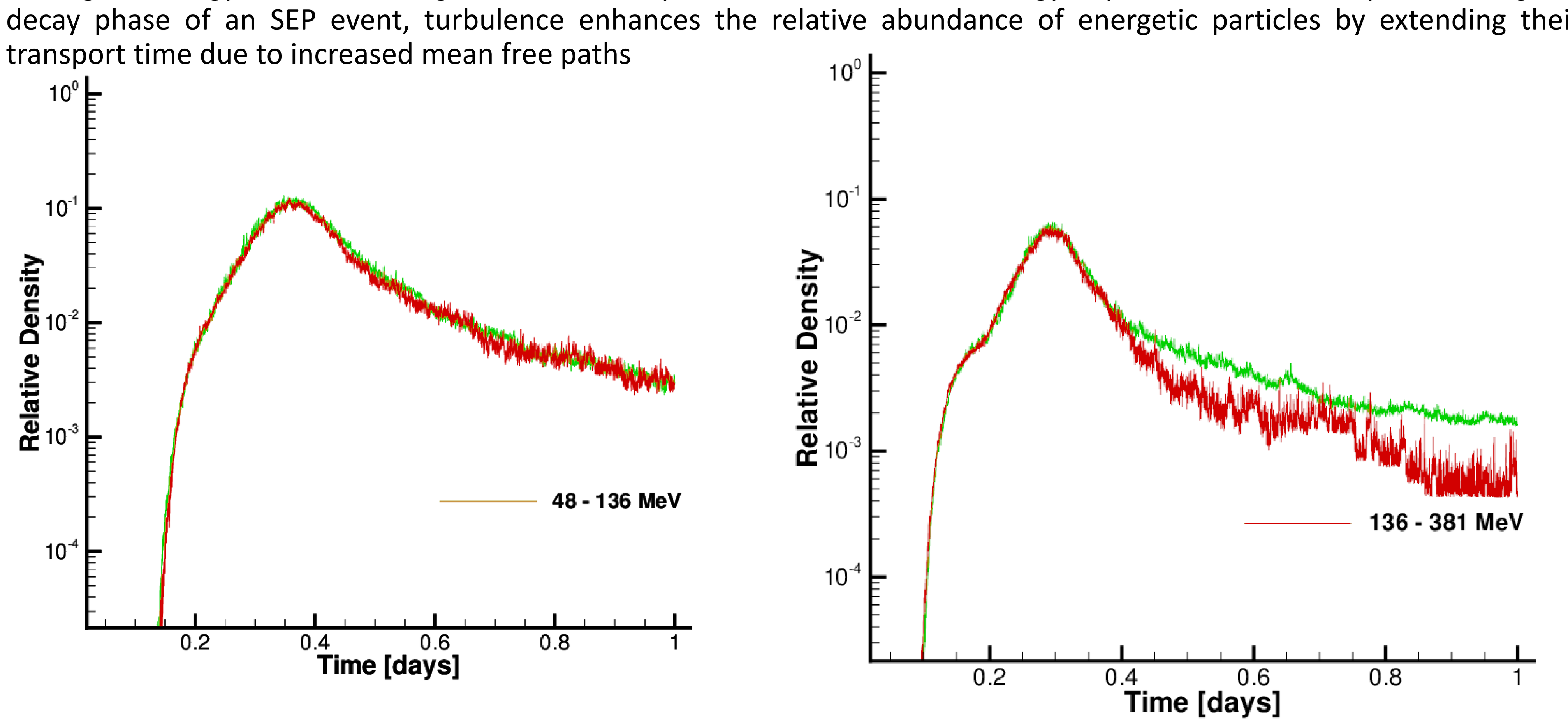
Mean Free Path and Diffusion in the Monte Carlo Method

In the Monte Carlo method, the mean free path (λ) defines the average distance a particle travels between scatterings, directly influencing transport dynamics. It relates to the diffusion coefficient (D) as: D=1/3vλ, where v is particle velocity. This relationship links microscopic scattering to macroscopic diffusion.

Mean free path model used here: $\lambda_{\parallel} = \lambda_0 \left(\frac{pc}{1\mathrm{GeV}}\right)^{\alpha}\left(\frac{r}{1\mathrm{AU}}\right)^{\beta}$ $\alpha = 1/3$ $\lambda_0 = 0.4\mathrm{AU}$ $\beta = 2/3$

Effect of scattering at different energies

For higher-energy SEPs, scattering becomes more pronounced due to the energy-dependent mean free path. During the decay phase of an SEP event, turbulence enhances the relative abundance of energetic particles by extending their transport time due to increased mean free paths



The effect of turbulence on the decay phase of an SEP event depends on particle energy. Higher-energy particles experience a more pronounced impact. This leads to a relative increase in the abundance of more energetic particles during the decay phase compared to less energetic ones.

Conclusions

The impact of turbulence on SEP transport is critical for accurately modeling their propagation in the heliosphere. **To fully capture the behavior of returning particles, transport simulations must extend beyond 1 AU, reaching at least 4–5 AU**. High-energy SEPs exhibit longer mean free paths and enhanced perpendicular diffusion, making turbulence effects more pronounced at these energies. Additionally, scattering processes vary with energy, influencing the spatial distribution and anisotropy of SEPs. Understanding these effects is essential for refining transport models and improving predictions of SEP behavior in space weather applications.

Fraction of particles that returns to 1 AU