

The Storage and Propagation Mechanisms of Solar Energetic Particles: Conceptual Evolution from "Reservoir" to "Flood" and Multi-Spatiotemporal Scale Observations

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Abstract. Solar Energetic Particle (SEP) events are among the most destructive space weather phenomena produced by solar eruptive activities, and their propagation and storage mechanisms are key to understanding and forecasting space weather. Traditional theory attributes the widespread spatial uniformity in the late decay phase of SEP events to an "inner heliosphere reservoir" formed by macroscopic magnetic structures driven by Coronal Mass Ejections (CMEs). However, this explanation based on deterministic structures has recently been challenged by the "flood" model based on stochastic processes. This paper systematically reviews the historical context of SEP research, from the early discovery of the two-phase decay characteristics, to the proposal and maturation of the "reservoir" model, and then to the refined observations of SEP spatial distribution in the multi-spacecraft era. On this basis, this paper focuses on integrating breakthrough observational results from recent missions such as Parker Solar Probe, Solar Orbiter, and Tianwen-1, and deeply analyzes the theoretical core of the "flood" model proposed. By comparing the physical mechanisms and explanatory power of the old and new perspectives, this paper demonstrates that the "flood" model possesses stronger logical self-consistency and a more solid physical foundation in uniformly explaining the widespread distribution phenomena of SEP events with different energies and types. Finally, this paper constructs a multi-level conceptual model integrating the "acceleration-diffusion-flood" process, providing a more universal theoretical framework for understanding the entire process of SEP events and improving space weather forecasting capabilities.

Keywords: solar energetic particles, reservoir, flood model, perpendicular diffusion, multi-spacecraft observations

1. Introduction

Solar Energetic Particle (SEP) events are important products of violent solar activities such as solar flares and Coronal Mass Ejections (CMEs). These particles, accelerated to extremely high energies (from tens of keV to tens of GeV), propagate through the heliosphere and can severely impact spacecraft electronic systems, astronaut health, and even the earth's magnetosphere, serving as a major driving source of space weather. Therefore, a deep understanding of the acceleration,

propagation, and storage mechanisms of SEPs is not only a core topic in heliospheric physics but also provides a crucial scientific basis for space weather warnings and the support of deep space exploration missions.

Early studies of SEPs primarily relied on local observations from single spacecraft, which limited the ability to distinguish between the temporal evolution and spatial distribution effects of particle flux. With the advent of the multi-spacecraft joint observation era, especially the recent implementation of missions such as Parker Solar Probe (PSP), Solar Orbiter (SolO), and China's Tianwen-1, humanity has been able to conduct panoramic observations of SEP events from multiple perspectives and radial distances, revealing their complex spatiotemporal evolution characteristics.

While this observational picture has become increasingly refined, theoretical explanations have also undergone profound changes. McKibben [1], based on early multi-spacecraft data, first discovered the "fast-slow" two-phase decay characteristics of low-energy proton flux, suggesting the coexistence of different propagation mechanisms. Two decades later, Roelof et al. [2] proposed the "inner heliosphere reservoir" concept, attributing the uniform distribution in the late decay phase to the trapping of particles by macroscopic magnetic structures (such as magnetic clouds and magnetic mirrors) driven by CMEs. This model was widely accepted over the next three decades to explain the long-duration decay of SEP events. Richardson et al. [3] systematically cataloged proton events using the STEREO three-spacecraft array, further revealing the Gaussian decay law of SEP intensity and delay time with longitude, enriching the observational evidence for the "reservoir" model.

However, entering the 2020s, new observations and theoretical simulations have fundamentally challenged the traditional view. On one hand, observational data from PSP, SolO, and Tianwen-1 [4-6] have provided new constraints for propagation models from multiple dimensions, including radial dependence and the evolution of shock connectivity. On the other hand, He [7], by solving the five-dimensional Fokker-Planck transport equation, numerically reproduced the globally uniform distribution phenomenon of SEP events for the first time and demonstrated that this phenomenon can naturally arise entirely from the stochastic diffusion process of particles in the interplanetary turbulent magnetic field (i.e., the "flood" mechanism), without assuming any macroscopic reflecting boundaries. This theoretical breakthrough marks a paradigm shift in understanding SEP propagation mechanisms from "deterministic structures" to "stochastic processes."

This paper aims to systematically integrate the aforementioned traditional research and recent advances, elucidating the theoretical evolution of SEP propagation mechanisms. The article will first review key historical observations and models, then focus on comparing the physical mechanisms and explanatory power of the "reservoir" and "flood" perspectives, and finally construct an updated conceptual model encompassing the "acceleration-diffusion-flood" process.

2. Observational basis and model evolution of SEP propagation and storage

2.1. Early observations: the two-phase decay and the proposal of the diffusion model

McKibben [2] utilized joint observations from IMP-4, Pioneer-6, and Pioneer-7 to analyze 9 solar proton events during 1967-1968. The study first revealed the two-phase nature of low-energy (~ 10 -30 MeV) proton flux decay: a fast decay phase, with a time constant $\tau \approx 10$ -20 hours, where the flux exhibited a significant azimuthal gradient; and a slow decay phase, with $\tau > 40$ hours, where the flux tended toward uniformity in longitude. This study focused on the diffusion process of particles in the interplanetary magnetic field, estimating parallel and perpendicular diffusion coefficients, but did not discuss the potential trapping effects of CME magnetic structures on particles, laying the foundation for subsequent research.

2.2. The birth of the "reservoir" concept: the inner heliosphere as a particle reservoir

Roelof et al. [3], using joint observations from Ulysses (2.5 AU) and IMP-8 (1 AU) during the CME outburst period of February-April 1991, found that low-energy particles (<1 MeV) persisted for a long time after their initial enhancement, with a nearly zero flux gradient along the magnetic field lines. This study first directly linked the complex magnetic structures formed by multiple CMEs to the prolonged confinement of particles, explicitly proposing the concept of the "inner heliosphere reservoir." In this picture, magnetic mirrors, diffusion barriers, or closed magnetic structures driven by CMEs act as "dams," inhibiting the outward escape of particles and homogenizing them within the reservoir.

2.3. Systematic observations in the multi-spacecraft era: the Gaussian law of longitudinal propagation

Richardson et al. [4], based on joint observations from STEREO A/B and SOHO during 2006-2013, systematically analyzed 209 proton events with energies >25 MeV, finding that the peak intensity decays as a Gaussian function of the connection angle. The characteristic width $\sigma = 43^\circ \pm 13^\circ$ for protons (14-24 MeV) and $\sigma = 47^\circ \pm 14^\circ$ for electrons (0.7-4 MeV). This macroscopic statistical law quantitatively describes the longitudinal distribution of SEPs in the ecliptic plane and suggests that the lateral expansion of CME-driven shocks is an important mechanism for the widespread distribution of particles.

2.4. New constraints in the radial dimension: findings from PSP and SolO

Cao et al. [5] utilized joint observations from PSP, SolO, and SOHO to systematically quantify the radial dependence of 10.5-40 MeV protons for the first time: the radial index α for peak flux ranged from -3.7 to -2, and for fluence, α ranged from -2.7 to -1.4. This study extends SEP spatial distribution research from the traditional one-dimensional longitudinal view to a two-dimensional (longitude-radial) framework, confirming the significant contributions of radial diffusion and adiabatic cooling to flux decay.

2.5. Statistical validation and quantification of the reservoir phenomenon

Zhao, L. et al. [8], using four decades of multi-spacecraft data, identified 62 proton events exhibiting reservoir effects, conducting the first large-sample statistical validation of the "inner heliosphere reservoir" concept. The study found that reservoir events can be observed at nearly all longitudes in the 1 AU ecliptic plane and indicated that the superimposed structure of ICME sheath regions and magnetic cloud bodies is the optimal condition for reservoir formation. This study quantitatively correlated the perpendicular diffusion coefficient with storage efficiency, pointing out that when the ratio of the perpendicular diffusion coefficient to the parallel diffusion coefficient ($\kappa_{\perp}/\kappa_{\parallel}$) is approximately 0.01-0.05, longitudinal uniformity can be achieved on a 1 AU scale.

2.6. Extension to Mars orbit: validation by Tianwen-1

Li et al. [6], using China's Tianwen-1 Mars Energetic Particle Analyzer, first reported SEP event observations at 1.39 AU. The study showed that the flux ratio in the decay phase was close to 1, and the duration exceeded 3 days, confirming that the reservoir effect can extend to Mars' orbit. Simultaneously, the double power-law energy spectrum remained self-similar within 1.39 AU,

indicating that the spectral characteristics of the acceleration source are preserved during propagation.

2.7. Theoretical breakthrough: paradigm shift from "reservoir" to "flood"

The work of He [1] is a profound theoretical response to all the above observational studies. By solving the five-dimensional time-dependent Fokker-Planck focused transport equation, He numerically reproduced the uniform decay phenomenon of SEP events in longitude, latitude, and radial space for the first time, completely without introducing any reflecting boundary or diffusion barrier assumptions. Simulation results show that with suitable parallel and perpendicular diffusion coefficients, the particle flux naturally tends toward uniformity during the decay period. Based on this, He [1] proposed that the "flood" concept should replace the traditional "reservoir" concept: the widespread distribution of particles is not due to passive trapping by macroscopic magnetic structures but because stochastic diffusion processes caused by micro-turbulence (especially perpendicular diffusion) allow particles to actively "flood" across magnetic field lines, naturally filling the entire heliospheric space. This shift marks a paradigm revolution from "deterministic structures" to "stochastic processes."

3. Physical mechanisms of SEP propagation and storage: perspective shift from "reservoir" to "flood"

3.1. Traditional "reservoir" model: an explanation based on deterministic structures

The traditional view [3, 8] holds that the SEP reservoir phenomenon depends on macroscopic magnetic structures driven by CMEs. Its core mechanisms include: (1) Energy dependence: Low-energy particles (<1 MeV) have small gyroradii and are easily trapped by small-scale magnetic structures (such as regions within ICMEs with a magnetic mirror ratio >2); (2) CME superposition structure: Compound magnetic clouds formed by multiple CMEs can create "magnetic cages," inhibiting particle escape; (3) Magnetic mirror effect: Regions of enhanced magnetic field can reflect particles, prolonging confinement time; (4) Perpendicular diffusion: Considered an auxiliary mechanism, helping to homogenize particles within the reservoir.

3.2. "Flood" model: an explanation based on stochastic processes

He's [1] "flood" model provides a brand-new physical picture: (1) Core driving force: Turbulence in the interplanetary magnetic field causes parallel and perpendicular diffusion of particles, where perpendicular diffusion enables particles to propagate across the mean magnetic field lines, being the key to achieving spatial uniformity; (2) No need for macroscopic structures: There is no need to assume any observationally unverified reflecting boundaries or magnetic mirrors; on sufficiently long timescales, the stochastic diffusion process itself can dissipate all spatial gradients; (3) Universality: This mechanism does not depend on the presence of a CME, thus naturally explaining why widespread particle distributions can also be observed in ^3He -rich events without large CMEs; (4) First-principles basis: Based on the five-dimensional Fokker-Planck equation, it provides quantitatively verifiable predictive capability.

3.3. Comparison of the two mechanisms

A comparison of the two mechanisms is summarized in Table 1.

Table 1. Comparison between traditional "reservoir" model and "flood" model

Comparison Dimension	Traditional "Reservoir" Model	"Flood" Model
Physical Picture	Particles are passively trapped by macroscopic magnetic structures	Particles diffuse actively in the turbulent magnetic field
Key Assumption	The existence of unconfirmed reflecting boundaries, magnetic mirrors or diffusion barriers	Only relies on observationally supported turbulence and diffusion processes
Explanation for He-rich Events	Difficult because of the lack of large-scale CME structures	Natural because diffusion is independent of CMEs
Explanation for Flux Homogenization	Requires perpendicular diffusion as an auxiliary mechanism	Perpendicular diffusion acts as the dominant mechanism itself
Logical Consistency	Explains the "overflow" by the hypothetical "dam"	Starts directly from the "flood" concept with more concise logic

In summary, the "flood" model is not only more fundamental in its physical mechanism but also superior in the scope and precision of the observed phenomena it explains. It is noteworthy that the $\kappa_{\perp}/\kappa_{\parallel} \approx 0.01-0.05$ found statistically by Zhao et al. [8] precisely provides crucial quantitative parameter support for the realization of the "flood" model.

4. Unified conceptual model: a multi-level framework integrating "Acceleration-Diffusion-Flood"

Based on the above analysis, this paper summarizes and proposes an "Acceleration-Diffusion-Flood" multi-level SEP propagation model integrating He's [1] "flood" concept. This model divides the entire process of an SEP event into four interrelated levels:

Level 1: Shock Acceleration and Injection

The CME-driven shock expands laterally along the solar surface (speed $\sim 500-2000$ km/s), injecting particles into interplanetary space via the Diffusive Shock Acceleration mechanism. The time-dependent nature of the acceleration process [9] determines the spectra and intensity of particles injected into open magnetic field lines or the turbulent heliosphere.

Level 2: Initial Propagation and Diffusion

In the early stage of the event, particle propagation is dominated by the magnetic field structure. High-energy particles (>10 MeV) mainly undergo parallel diffusion ($\kappa_{\parallel} \approx 10^{21}$ cm²/s); low- to medium-energy particles (1-10 MeV) are affected by both convection and diffusion; for GeV heavy ions, drift effects begin to manifest [10].

Level 3: "Flood"-Dominated Global Homogenization

This is the core innovative layer of the model. As time progresses, particles enter a propagation stage dominated by micro-turbulence. Perpendicular diffusion ($\kappa_{\perp}/\kappa_{\parallel} \approx 0.01-0.05$) becomes the key mechanism, enabling particles to propagate across magnetic field lines and naturally fill the longitudinal, latitudinal, and radial space like a "flood." In this stage, the homogenization of flux during the decay phase is an inevitable result of the diffusion process, rather than being "stored" by

macroscopic structures. This mechanism is equally applicable to ^3He -rich events without CMEs, reflecting the model's universality.

Level 4: Global Distribution and Multi-Scale Decay

The macroscopic statistical results of the "flood" process manifest as:

Longitudinal distribution: Obeys a Gaussian decay ($\sigma \approx 45^\circ$), resulting from the convolution of the source distribution and the diffusion process [4].

Radial distribution: Obeys a power-law decay (peak $\sim R^{-2.8}$, fluence $\sim R^{-2.0}$), reflecting the combined effects of diffusion and adiabatic cooling [5].

Spectral evolution: The double power-law spectrum remains self-similar within 0.1-1.4 AU, supporting the conclusion that the diffusion process does not alter the basic shape of the source spectrum [6].

The advantages of this model are:

1. Energy stratification: It clearly describes the differences in dominant mechanisms for particle propagation at different energies.
2. Spatiotemporal coupling: It unifies two timescales—fast propagation (shock, parallel diffusion) and slow homogenization (perpendicular diffusion)—explaining the two-phase decay phenomenon.
3. Physical unity: It attributes the core mechanism of SEP propagation to the well-established theory of turbulent diffusion, abandoning reliance on unverified macroscopic structures.

5. Conclusion

This paper reveals the paradigm shift in the study of SEP propagation and storage mechanisms and draws the following conclusions:

1. The two-phase decay characteristic of SEPs is a manifestation of the superposition of different physical processes: the fast decay corresponds to the cessation of shock acceleration and parallel diffusion dominance, while the slow decay is the macroscopic expression of the "flood" homogenization phase.

2. The traditional "reservoir" concept faces a fundamental challenge. He's [1] five-dimensional Fokker-Planck simulation proves that the so-called reservoir phenomenon can naturally arise entirely from the perpendicular diffusion process caused by micro-turbulence, without the need to assume macroscopic reflecting boundaries or magnetic mirror structures.

3. The "flood" model possesses stronger explanatory power and logical self-consistency. It not only unifies the explanation of widespread distribution phenomena in both gradual and impulsive (including ^3He -rich) events but also attributes the ultimate determinant of particle distribution to the ubiquitous turbulent diffusion process in the heliosphere, resting on a more solid physical foundation.

4. The latest observational data support the "flood" model. The $\kappa_{\perp}/\kappa_{\parallel} \approx 0.01-0.05$ found statistically by Zhao et al. [8] is precisely the key parameter for achieving "flood" homogenization; the spectral shape preservation observed by Tianwen-1 at 1.39 AU is also consistent with a diffusion-dominated picture. The longitudinal Gaussian decay and radial power-law decay laws of SEPs can both be viewed as macroscopic statistical manifestations of microscopic diffusion processes.

5. The "Acceleration-Diffusion-Flood" multi-level conceptual model constructed in this paper integrates particle acceleration, initial propagation, and the "flood" homogenization process within a unified framework. This model emphasizes the core role of perpendicular diffusion, reveals the differences in propagation mechanisms for particles of different energies, and provides a clear physical picture for understanding the spatiotemporal evolution of SEP events.

In the future, with the continued in-depth exploration by Solar Orbiter and Parker Solar Probe, and the implementation of deep space missions like Tianwen-2, research on SEP propagation mechanisms will progress from phenomenological statistics to first-principles prediction. The paradigm shift from "reservoir" to "flood" advocated by He [1] is not only a correction of a term but a profound transformation in the understanding of heliospheric particle physics, which will provide a more accurate and reliable theoretical foundation for crewed deep space exploration and space weather forecasting.

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