New Insight into the Formation Mechanism of the Energetic Particle Reservoirs in the Heliosphere

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ABSTRACT
The concept of energetic particle reservoirs, essentially based on the assumption of the presence of outer reflecting boundaries/magnetic mirrors or diffusion barriers (deterministic) rather than on the effect of particle diffusive propagation (stochastic) in magnetic turbulence, has been used for decades to describe the space-extended decay phases of energetic particle events within the fields of space physics, solar physics, and plasma physics. Using five-dimensional time-dependent Fokker–Planck transport equation simulations, in this work we demonstrate that the so-called particle reservoirs are naturally explained and quantitatively reproduced by diffusion processes in turbulent magnetic fields, without invoking the hypothesis of reflecting boundaries. Our results strongly suggest that the so-called “reservoir” (based on deterministic structure) should be renamed “flood” (based on stochastic diffusion), which symbolizes an authentic shift in thinking and in pragmatic rationale for the studies of energetic particles and relevant plasma phenomena in heliophysics and in astrophysics.

Key words: Sun: particle emission – diffusion – scattering – turbulence – interplanetary medium – Sun: heliosphere

1 INTRODUCTION
Solar energetic particles (SEPs), emitted by powerful solar bursts, can serve as sample particles for cosmic ray studies by providing fundamental information regarding particle acceleration and propagation in the turbulent magnetic fields. Moreover, SEPs risk astronauts and damage satellites in space, and significantly influence the solar-terrestrial space environment, space weather, and space climate. Hence, the subject of energetic particles has become one of the most important foci in space physics, solar physics, plasma physics, and astrophysics. Basically, the propagation of energetic particles in the turbulent magnetic fields consists of a handful of fundamental mechanisms, such as field-aligned particle streaming, convection with the plasma medium, adiabatic focusing, adiabatic deceleration, pitch-angle diffusion, and perpendicular diffusion. The concept of particle diffusion process at microscale is essentially based on the philosophy and thought of stochasticism (probabilism) in a mathematically tractable style (e.g. Brown 1828; Kubo 1957; Parker 1965; Jokipii 1966). The energetic charged particles in the turbulent magnetic fields undergo significant diffusion processes due to the effects of stochastic magnetic fluctuations.

The parallel diffusion along the guide magnetic field has been intensely and extensively studied; however, the perpendicular diffusion across the guide magnetic field has remained a puzzle for quite a long time. Recently, the important effect of the perpendicular diffusion mechanism in the transport processes has been found (e.g. Zhang et al. 2003; Matthaeus et al. 2003; Shalchi et al. 2004; He 2015). The effects of nonlinear terms have been introduced and discussed so as to explain perpendicular diffusion and scattering of cosmic rays near 90° pitch-angle.

There is a well-known phenomenon or conception in the field of energetic particles, especially in the SEP community, i.e., the “reservoir” (e.g. Simnett 1995; Poletto & Sussa 2004; Klecker et al. 2006; Reames 2013; Desai & Giacalone 2016; Reames 2017; Simnett 2017; Reames 2018; Anastasiadis et al. 2019). The reservoir effect refers to the interesting phenomenon where the flux-time profiles of particles evolve similarly in time with almost the same declining rate in the decay stage of the particle events. This intriguing feature was first reported from the wide-heliolongitude (∼180°) concurrent observations of ∼20 MeV protons measured by the spacecraft Interplanetary Monitoring Platform (IMP) 4 and Pioneer 6 and 7 (McKibben 1972). Twenty years later, uniform intensities were observed spanning ≥2.5 AU in the radial direc-

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tion between spacecraft IMP 8 and Ulysses, and thus were named “reservoirs” to illustrate the uniformity of particle distribution (Roelof et al. 1992). The particle (protons, electrons, and heavy-ions) reservoirs are often seen by widely separated spacecraft at very different heliolongitudes, heliolatitudes, and radial distances (e.g. Reames et al. 1996; Maclellan et al. 2001; Dalla et al. 2003; Sanderson et al. 2003; Dainog et al. 2003; McKibben et al. 2003; Lario et al. 2010). Basically, the notion of reservoir is solely on the hypothetical presence of deterministic magnetic structures at macroscale, such as diffusion barriers, outer reflecting boundaries or magnetic mirrors produced by plasma disturbances in the solar wind. This idea invokes the presence of such diffusion barriers or reflecting boundaries to contain the particles long enough to gradually and uniformly redistribute them in heliographic azimuth and latitude. In this picture, the so-called reflecting boundaries or diffusion barriers are assumed to exist in the space to play the role of “reservoir dam” to impede, reflect, and redistribute energetic particles within the reservoirs. Ultimately, the concept of “reservoir” originates from conventional thought of scatter-free (deterministic) propagation, meanwhile ignoring the important effects of diffusive (stochastic) transport (e.g. Roelof 1975; Noote & Roelof 1975).

Recently, multi-spacecraft SEP observations, achieved with the spacecraft STEREO-A/B, ACE, SOHO and Wind, have shown that SEPs originating from a limited solar source can transport to very distant heliographic longitudes as wide as 136° – 360° both in the so-called gradual and impulsive (³He-rich) events (e.g. Dressing et al. 2012; Wiedenbeck et al. 2013; Richardson et al. 2014; Cohen et al. 2014; Gómez-Herrero et al. 2015). Essentially, these wide longitudinal spreads of SEP events are identical to the SEP “reservoir” phenomenon, since both of these two SEP effects indicate the same manifestation: the broad and gradually uniform particle distribution in the heliosphere. Therefore, the key physical mechanism for fundamentally understanding these novel observations still remains a debatable conventional issue regarding scatter-free propagation (determinism) and diffusive transport (randomness). To quantitatively explain and reproduce these intriguing particle phenomena in a compelling fashion eagerly requires a thorough and detailed investigation by means of physics-based numerical simulations and computationally tractable descriptions of particle transport in three-dimensional turbulent interplanetary magnetic fields (IMF).

2 FOKKER-PLANCK MODEL

We present the physics-based multi-dimensional Fokker-Planck transport model and relevant numerical calculations to shed new light on the formation mechanism of reservoirs of energetic particles in the heliosphere. The Fokker-Planck model is based upon dynamical stochastic diffusion motions of charged energetic particles in magnetic fields with turbulent effects, and can be formatted as (e.g. Schlickeiser 2002; Parker 1965; Zhang et al. 2009; He et al. 2011; Dröge et al. 2016)

\[
\frac{\partial f}{\partial t} + \mu \frac{\partial f}{\partial x} + V_{\text{sw}} \cdot \nabla f + \frac{dp}{dt} \frac{\partial f}{\partial p} + \frac{d\mu}{dt} \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} \left( D_{\mu} \frac{\partial f}{\partial \mu} \right) - \frac{\partial}{\partial x} \left( \kappa_{xx} \frac{\partial f}{\partial x} \right) - \frac{\partial}{\partial y} \left( \kappa_{yy} \frac{\partial f}{\partial y} \right) = Q(x, p, t),
\]

where \(f(x, \mu, p, t)\) denotes the gyrophase-averaged distribution function of particles, \(x\) is spatial position of particles, \(z\) is coordinate along magnetic field line, \(p\) is particle momentum, \(\mu\) is particle pitch-angle cosine, \(t\) is time, \(v\) is particle velocity, \(V_{\text{sw}}\) is solar wind velocity, \(\kappa_{xx}\) and \(\kappa_{yy}\) are perpendicular diffusion coefficients of particles, \(dp/dt\) represents adiabatic deceleration effect, \(d\mu/dt\) represents magnetic focusing effect and solar wind flow divergence, and \(Q(x, p, t)\) is source term of particles. We use the technique of time-backward Markov stochastic processes to solve the above five-dimensional Fokker-Planck model (Zhang et al. 2009; He et al. 2011). A constant solar wind speed of 400 km s\(^{-1}\), a Parker-type magnetic field with magnitude \(B = 5\) nT at 1 AU, and a particle source with limited longitudinal and latitudinal coverage centered at 0° heliolatitude (Equator) are typically used in the simulations. We simulate \(6 \times 10^7 - 1.2 \times 10^8\) particles on a supercomputer cluster. We analyze statistical data from numerical simulations and obtain intensity-time profiles of SEP events with different features. An arbitrary unit for particle flux is conveniently used in plotting figures. It is important to note that the simulation results and conclusions shown here essentially hold for varying values of the model parameters.

3 RESULTS

The reservoirs were first noted in the wide-heliolongitude observations of \(\sim 20\) MeV protons (McKibben 1972). Fig. 1 presents our numerical simulations of flux-time profiles of 20 MeV protons transporting in the interplanetary space. The diffusion coefficients of energetic particles are set as follows: the radial mean free path \(\lambda_r = 0.32\) AU (corresponding to the parallel mean free path \(\lambda_p = 0.64\) AU at 1 AU), and the perpendicular mean free paths \(\lambda_\perp = \lambda_p = 0.008\) AU. We note that the values of the mean free paths chosen for numerical simulations in this work are consistent with the observational and theoretical results within the SEP community (e.g. Bieber et al. 1994; Dröge 2000; Matthaeus et al. 2003; Bieber et al. 2004; He & Wan 2012a,b, 2013). The observers (spacecraft) are located at 1 AU Equator (0° heliolatitude). The different longitudinal separations between the particle source and the magnetic field line footpoints of different observers are: 0°, 30°, 60°, 90°, 120°, 150°, and 180°. In Fig. 1, the solid and dashed lines denote the flux-time observations made by spacecraft located at west and east, respectively, relative to magnetic field line connecting the center of the source. As one can see, in the beginning, the farther the magnetic footprint of the observer is away from the particle source, the smaller is the particle flux observed and also the later the onset and the peak flux of the event appear (He et al. 2011). In addition, with the same heliolongitude separation between particle source and magnetic footpoints
of observers, the particle fluxes observed by spacecraft located at western side of source are systematically larger than the fluxes observed by spacecraft located at eastern side, and also the SEP event (onset and peak) arrives at the western spacecraft earlier than at the eastern spacecraft (He et al. 2011; He & Wan 2017). Most interestingly, however, in the late phase of SEP events, the particle fluxes observed by these widely longitudinally separated spacecraft show nearly the equal intensities and decay at the same rate. Therefore, the typical features of a circumsolar particle reservoir which spans 360° in longitude is reproduced without invoking a hypothetical outer reflecting boundary.

The particle reservoirs are observed radially spreading out over several AU between IMP 8 near Earth and Ulysses in the outer heliosphere (e.g. Roelof et al. 1992; Lario 2010). Fig. 2 presents the numerical simulation results of radial distribution of 20 MeV protons in the inner and outer heliosphere. The diffusion coefficients of particles are the same as those used in Fig. 1. The observers here are located in the Sun’s equatorial plane and are magnetically connected with the center of the particle source through a nominal Parker spiral. The different heliocentric radial distances of different observers are: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 AU. As one can see, during the early phases of particle events, the farther the observer is radially away from the solar source, the smaller is the particle intensity detected and also the later the onset and the peak intensity of the event occur. However, during the late phases of particle events, all the intensity profiles present nearly the same intensities and decay rates within the range of statistical errors. Hence the radial particle reservoir has been reproduced in the Fokker-Planck equation simulations without invoking the artificial hypothesis of outer reflecting boundaries or diffusion barriers.

The SEP reservoirs are also found extending to quite high heliolatitudes, e.g., up to > 70°, both North and South (e.g. Dalla et al. 2003; Sanderson et al. 2003; McKibben et al. 2003; Lario et al. 2003). Fig. 3 displays the simulation results of latitudinal distribution of 20 MeV protons. The parallel and perpendicular diffusion coefficients of particles are the same as those used in Fig. 1. The observers are located at 1 AU. The heliolongitudes of magnetic footpoints of observers are the same as the heliolatitude of the center of particle source. The different heliolatitudes of different observers are: 0° (Equator), 30°, 60°, and 90° (Poles). The solid and dashed curves in Fig. 3 denote the flux-time profiles of SEP’s observed in the northern and southern hemispheres, respectively. We can see that during the beginning stage of SEP events, the farther the magnetic footpoint of observer is away from the particle source in latitude, the smaller is the SEP flux observed and also the later the onset and the peak intensity of particle events occur. However, during the late phases of particles events, all the intensity profiles present nearly the same intensities and decay rates within the range of statistical errors. The reason is that the geometry of the Parker IMF is North-South latitudinally symmetric. During the late stage of the particle events, all the particle fluxes observed by these very widely latitudinally separated spacecraft show nearly equal fluxes (to within a small factor of ~2 – 3) that decline sim-
Figure 3. Numerical simulations of 180°-latitude distribution and reservoir (flood) effect of 20 MeV protons. A typical latitudinal particle reservoir extending to the highest latitudes of 90° (magnetic poles), both North and South, is quantitatively reproduced without invoking the hypothetical outer reflecting boundaries.

Figure 4. Fundamental shift in thinking and paradigm for understanding energetic particles and magnetized plasmas in magnetic turbulence. Conventional paradigm of “reservoir” concept on the left: the hypothetical outer reflecting boundaries or diffusion barriers (i.e., deterministic structures at macroscale) play the role of “reservoir dam” to inhibit, reflect, and redistribute energetic particles to form the uniform distribution. Novel paradigm of “flood” concept on the right: the parallel and perpendicular diffusion processes (i.e., stochastic transport at microscale) caused by the ubiquitous magnetic turbulence effectively and uniformly distribute the energetic particles in radial direction and in longitude and latitude to form the wide-spread flood-like distribution in the heliosphere. The authentic shift from “reservoir” (left) to “flood” (right) offers new insights into energetic particles and space plasmas in the turbulent magnetic fields.

4 DISCUSSION AND SUMMARY

The notion of particle reservoirs and the relevant concepts (e.g., collimated convection) have been employed for several decades in the data analyses and interpretations within the observational community. Essentially, these notions stem from the extreme assumption of scatter-free transport of particles and invoke an intuitive hypothesis of deterministic plasma structures at macroscale, e.g., reflecting boundaries or diffusion barriers (e.g. Roelof 1975; Roelof & Nolte 1992). This reservoir paradigm can be illustrated on the left-hand side of Fig. 4. As shown, this popular perception invokes the existence of hypothetical outer reflecting boundaries or diffusion barriers in the heliosphere, so as to contain the particles long enough to uniformly distribute them in heliolongitude, heliolatitude, and radial distance. In this paradigm, the conceived outer reflecting boundaries or diffusion barriers play the central role of “reservoir dam” to inhibit, reflect, and redistribute energetic particles in the so-called reservoirs. Besides, the reservoir concept completely ignores the effects of stochastic diffusion and scattering processes, especially for the cross-field diffusion process. This reflecting and redistribution process must be quite efficient to quickly dissipate all the particle intensity gradients (longitudinal, latitudinal, and radial) in the reservoir. To our knowledge, however, so far no explicit evidence or quantitative mechanism of such reflecting boundaries or diffusion barriers has been provided within the community (He 2015).

According to the traditional pragmatic rationale of SEP event classification (gradual and impulsive events), the energetic particles in the so-called impulsive events can only form very narrow longitudinal and latitudinal distributions in the heliosphere. However, recent multi-spacecraft observations have revealed that SEPs released from a very small-sized source (e.g., solar flare) can also form the wide-range distribution phenomenon and the reservoir effect, even in the impulsive or 3He-rich SEP events (e.g. Dressing et al. 2012; Wiedenbeck et al. 2013; Richardson et al. 2014). Therefore, these new observations question the validity of the conventional classification paradigm of SEP events. Furthermore, the observations indicate that the plasma structures at macroscale must not be the dominant reason causing the formation of the reservoir effect. Actually, the up-to-date multi-spacecraft observations and numerical simulations of SEP three-dimensional transport have proven the violation of the notion of particle reservoirs in the heliosphere. Instead, we introduce a novel concept and paradigm, called “flood”, to much better describe the realistic transport processes of energetic particles. We point out that the notion of particle “flood” is based solidly on the physically meaning-
ful and mathematically tractable five-dimensional Fokker-Planck focused transport model and the relevant numerical simulations. The physical scenario of the particle “flood” is illustrated on the right-hand side of Fig. 4. As we can see, the energetic particles, after being released near the Sun, will diffusively transport in IMF with turbulence and fluctuations. Due to the effects of parallel diffusion along and perpendicular diffusion across the large-scale guide magnetic fluctuations. Due to the effects of parallel diffusion along and perpendicular diffusion, the particles can cross the IMF lines and transport to distant heliospheric locations, and consequently, the gradually space-filling phenomenon (“reservoir”) can be naturally formed. In the scenario of perpendicular diffusion, no artificial outer reflecting boundaries (diffusion barriers/magnetic mirrors) need to be invoked to play the role of “reservoir dam” to reflect/redistribute the particles to form the so-called “reservoir” phenomenon, especially for explaining the wide-spread particle distribution of $^3$He-rich SEP events often detected in recent multi-spacecraft observations. In this “flood” paradigm, the stochastic diffusion processes caused by ubiquitous magnetic turbulence enable the energetic particles to cross the IMF lines and gradually transport to distant heliospheric locations, analogous to that the surging dynamical river overflows its banks.

As discussed above, the wide-range flooding (space-filling) transport of SEPs in the heliosphere is an intrinsic property caused by stochastic diffusion at microscale rather than deterministic structure at macroscale. To accurately illustrate the realistic transport processes of energetic particles, we strongly suggest that the so-called “reservoir” should be renamed “flood”. Accordingly, the textbooks/books regarding space physics or solar physics that contain the term “reservoir” must be revised and updated. The traditional ideas of static structures (including “reservoirs”) and linear instabilities have been a cornerstone for many theoretical and observational investigations of space plasmas (e.g. Matthaeus & Velli 2011). Therefore, the renaming and redefinition (based on stochasticity and nonlinearity) of “reservoirs” signifies a fundamental shift in thinking and in paradigms for studying energetic particles and magnetized plasmas in turbulent magnetic circumstances. In light of this paradigm shift, the relevant theories and ideas based on determinism and linearity in space plasma physics need to be rethought and revised. The new paradigm of interpretation removes determinism from its central position in understanding the physical nature of the space plasma behaviors, phenomena, and effects. Instead, this central role should be given to stochasticism, especially at microscale in plasmas and in turbulence. More generally, the philosophical debate between determinism and stochasticism for understanding the essence of physics has remained a fundamental and long-standing topic in the literature. The results in this work, obtained in a quantitative fashion, favor the explanation of stochasticism (randomness), as the fascinating nature always reveals to us eventually.

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APPENDIX A: ADDITIONAL FIGURES OF SIMULATION RESULTS AND COMPARISONS WITH MULTISPACECRAFT OBSERVATIONS

The particle reservoir is a universal phenomenon independent of particle energy. We also investigate the reservoir effect formed by energetic particles with other energies. Fig. A1 presents the simulation results of longitudinal transport of 5 MeV protons. The diffusion coefficients of 5 MeV protons are set as follows: \( \lambda_x = 0.28 \) AU (corresponding to \( \lambda \parallel = 0.56 \) AU at 1 AU), and \( \lambda_y = 0.007 \) AU. Other physical parameters and conditions are the same as in Fig. 1. Similar to Fig. 1, the east-west longitudinal asymmetry of particle distribution is also obviously seen in Fig. A1. During the late phases of the energetic electron events, the particle intensities detected by the widely separated observers display equal intensities and evolve similarly in time with the same decay rate. Therefore, a typical particle reservoir spanning 360° in longitude has been reproduced in the large-scale simulations based on multidimensional Fokker-Planck transport equation including diffusion mechanism.

The heliospheric energetic particle reservoirs are also observed in electron and heavy-ion data. We also numerically investigate the reservoirs formed by these particle species. Fig. A2 shows the numerical calculation results of azimuthal propagation of 100 keV electrons with diffusion coefficients as follows: \( \lambda_\parallel = 0.3 \) AU (corresponding to \( \lambda_\parallel = 0.6 \) AU at 1 AU), and \( \lambda_y = 0.006 \) AU. Other physical parameters and conditions are the same as those in Fig. 1. As we can see in Fig. A2, the distribution of energetic electrons clearly presents the feature of east-west azimuthal asymmetry. During the decay phase of the energetic electron events, the electron fluxes observed by the very widely azimuthally separated spacecraft present equal fluxes and decrease similarly in time within the range of statistical errors. Hence, a typical energetic electron reservoir spanning 360° in heliolongitude has been reproduced in the large-scale simulations based on Fokker-Planck transport equation incorporating particle diffusion processes.

The longitudinal flood/reservoir effect has been widely investigated with multispacecraft measurements (e.g., SOHO, STEREO-A, STEREO-B, ACE, Wind, etc.) in the observational community. Undoubtedly, the multispacecraft observations have provided important information on the transport and distribution of SEPs in the heliosphere. Fig. A3 displays the multispacecraft detections of the flood/reservoir phenomenon observed by SOHO and the twin spacecraft STEREO-A and STEREO-B during the 2013 October 11 (DOY 284) SEP event (adapted from Anastasiadis et al. 2019). At the onset of this SEP event, the longitudes of spacecraft SOHO, STEREO-A, and STEREO-B in the Heliographic Inertial (HGI) Coordinate System are 302°, 89°, and 162°, respectively. The solar eruptive activity associated with this SEP event occurred at E104 in longitude as seen from Earth. In Fig. A3, the black,
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Figure A3. Multispacecraft observations (SOHO, black; STEREO-A, red; STEREO-B, blue) of flood/reservoir effect (denoted by the gray shaded area) in the 2013 October 11 (DOY 284) SEP event. Red and blue curves denote the time-flux profiles of 25-53 MeV protons in this SEP event measured by SOHO, STEREO-A, and STEREO-B, respectively. As we can see, the time-flux profiles observed at the three widely separated spacecraft display quite different shapes during the onset and early phases of the SEP event. However, after 2013 October 15 (DOY 288), all the SEP fluxes detected at the three locations present approximately the same intensities and gradually decline to lower levels with nearly the same decay rate, which is the typical feature of the SEP flood/reservoir effect. The flood/reservoir phenomenon in this SEP event lasted for nearly 8 days (denoted by the gray shaded area). Through qualitative comparisons between observation results in Fig. A3 and simulation results in Figs. A1 and A2 and in Fig. 1 in the main text, we can readily see that all the essential features of flood/reservoir effect in SEP events have been numerically reproduced in the three-dimensional transport simulations without invoking the hypothesis of outer reflecting boundaries or diffusion barriers. Therefore, the conventional hypothesis of reflecting boundaries or diffusion barriers needs not to be necessarily invoked in the numerical reproduction of SEP flood/reservoir effect. In addition, note that the numerical reproduction results of SEP floods/reservoirs will remain qualitatively unaffected by the varying values of the model parameters in the three-dimensional transport simulations. We can further conclude that the stochastic diffusion processes (both parallel and perpendicular) at microscale in magnetic turbulence play a crucial role in the formation of particle floods/reservoirs and other relevant phenomena in space and astrophysical plasmas.

APPENDIX B: REMARKS

The gap of understanding between the observational and theoretical communities persists in space science for quite a long time. For simplicity in analyzing and interpreting data, the authors in the observational community usually employ some specific assumptions, such as “collimated convection” or scatter-free propagation (deterministic). Undoubtedly, these simplified scenarios can be tackled more easily. However, the analysis results obtained may significantly deviate from the realistic physical mechanisms behind the observations and the phenomena. The solar wind and the particles, fields, waves, and structures immersed in it naturally constitute a highly turbulent complex system. In principle, statistical descriptions based on nonlinearity and stochasticity are essential for the studies of space plasma physics. Therefore, it is quite pressing to bridge the wide gap between the theoretical and observational communities, within which there exist somewhat different terminologies (some misnomers) for the same phenomena or effects. In this work, we have demonstrated this important issue with a typical example, i.e., the so-called particle reservoir (flood) effect or phenomenon. In the future, we shall pay attention to and investigate other space plasma behaviors, phenomena, and effects.