Superposed Epoch Analysis of Dispersionless Particle Injections Inside Geosynchronous Orbit

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Abstract Dispersionless injections, involving sudden, simultaneous flux enhancements of energetic particles over some broad range of energy, are a characteristic signature of the particles that are experiencing a significant acceleration and/or rapid inward transport at the leading edge of injections. We have statistically analyzed data from Van Allen Probes (also known as Radiation Belt Storm Probes (RBSP)) to reveal where the proton (H+) and electron (e−) dispersionless injections occur preferentially inside geosynchronous orbit and how they develop depending on local magnetic field changes. By surveying measurements of RBSP during four tail seasons in 2012–2019, we have identified 171 dispersionless injection events. Most of the events, which are accompanied by local magnetic dipolarizations, occur in the dusk-to-midnight sector, regardless of particle species. Out of the selected 171 events, 75 events exhibit dispersionless injections of both H+ and e−, which occur within 2 min of each other. With only three exceptions, the both-species injection events are further divided into two main subgroups: One is the H+ preceding e− events with a time offset of tens of seconds between H+ and e−, and the other the concurrent H+ and e− events without any time offset. Our superposed epoch results raise the intriguing possibility that the presence or absence of a pronounced negative dip in the local magnetic field ahead of the concurrent sharp dipolarization determines which of the two subgroups will occur. The difference between the two subgroups may be explained in terms of the dawn-dusk asymmetry of localized diamagnetic perturbations ahead of a deeply penetrating dipolarization front.

1. Introduction

Energetic particle injections from Earth’s magnetotail—characterized as the sudden flux enhancements of tens to hundreds of keV electrons and/or ions—are one of fundamental signatures of substorm activity in the inner magnetosphere. Fractions of the injected electrons and ions play an important role in building-up Earth’s ring current during magnetic storms, providing the seed population for MeV electrons in the outer radiation belt, and introducing the source population responsible for the generation and growth of various plasma waves. How the particles of different species/energies can be transported and/or energized and what controls the penetration of injections inside geosynchronous orbit (GEO) where the magnetic field intensity becomes much stronger are a subject of ongoing debate. The dispersionless character of the flux enhancements—so-called dispersionless injection—is known as a manifestation of the particles that are undergoing either a local energization process or a rapid transport process, or both at/near the leading edge of injections (injection region). In other words, a spacecraft at/near the injection region itself should observe a dispersionless injection, and such in situ measurements would provide an opportunity to understand the underlying mechanisms responsible for the injection.

Dispersionless injections are categorized into three types: both-species injections (i.e., coincident injections of both ions (mainly protons, H+) and electrons (e−)), e−-only injections, and H+-only injections. Early energetic particle observations from a LANL spacecraft at GEO provided a statistical picture for the three types of dispersionless injections to occur with local time (or spatial) offsets with respect to midnight (Birn et al., 1997; Thomsen et al., 2001). That is, the e−-only (H+-only) injections are preferentially observed ∼2 h after (∼3 h before) local midnight, while the both-species injections occur around midnight. The spatially dependent pattern of the three types has been explained in terms of H+ and e− injection boundaries that have a dawn-dusk separation and move earthward quasi-stationarily.
Contrary to the statistical results at GEO, THEMIS observations outside GEO (up to 30 $R_E$) showed that all three-type dispersionless injections take place preferentially in the premidnight sector without significant local time offset (Gabrielse et al., 2014). The statistical results from THEMIS suggested that the dispersionless injections outside GEO undergo particle acceleration and transport processes due to earthward-moving dipolarization fronts (DFs) with an azimuthally localized structure which is of order of a few $R_E$. Gabrielse et al. (2014) also pointed out that the discrepancy between the occurrence patterns from LANL and THEMIS was attributed to different event selection criteria: the Birn et al. (1997)'s criterion permitted a dispersion of $\leq 2$ min, while the Gabrielse et al. (2014)'s criterion was much stricter ($\leq 1$ min). It is therefore possible that the broader local time distribution at GEO reflected azimuthal drift signatures of both H$^+$ and e$^-$ through magnetic gradient and curvature drifts. Thus, the injection region at and inside GEO needs to be investigated with a stricter timing criterion for further understanding of the tail-inner magnetosphere connections of the injection.

Several numerical modeling efforts suggest that deeply penetrating, meso-scale DFs act as a major agent in injecting energetic particles into the inner magnetosphere (e.g., Sorathia et al., 2018; Ukhorskiy et al., 2018; Yang et al., 2011). The DF-related impulsive, westward (dawn-to-dusk) electric field and sharp magnetic field gradients are potential factors for effectively energizing and/or transporting ions and electrons in and from the magnetotail. A recent global MHD simulation by Merkin et al. (2019) demonstrated that global-scale substorm dipolarization in the inner magnetosphere can result from the accumulation of meso-scale DFs, although the subject is still controversial (cf. Ohtani & Gjerloev, 2020). If a single, deeply penetrating DF (sharp dipolarization) directly drives a dispersionless injection at/inside GEO, the injection region will represent a localized signature in the azimuthal direction. Recently, longitudinally separated multipoint satellite measurements from GOES (Nagai et al., 2019) and Van Allen Probes (Motoba, Ohtani, Claudepierre, et al., 2020) spacecraft provided evidence for azimuthally localized injection regions at/inside GEO.

Sharp magnetic dipolarizations inside GEO have been investigated statistically by several recent studies using data from Van Allen Probes (Liu et al., 2016; Motoba et al., 2018; Motoba, Ohtani, Gkioulidou, et al., 2020). These statistical results consistently showed that: (a) the dipolarizations occur more frequently in the premidnight sector; and (b) typical field/plasma variations around the local dipolarizations inside GEO have many commonalities to those around DFs in the near-Earth tail. These experimental efforts have revealed important details of the actual roles of dipolarizations in energetic particles inside GEO. However, the local magnetic dipolarizations are found to be not always correlated with dispersionless injections inside GEO. Based on the 2012–2013 data, Liu et al. (2016) divided the sharp dipolarizations into two types—with and without dispersionless injections. One key factor that determines which of the two types will occur is whether the dipolarization is accompanied by a strong, impulsive electric field. Other factors that may determine the presence or absence of the concurrent injections could be the energy spectra of preexisting particles and radial flux gradients (Sergeev et al., 1998). In any case, these previous statistical studies—that first selected dipolarization events and then examined their related particle injections—did not perfectly extract the inherent nature of dispersionless injections inside GEO, because the primary focus for their event selections was placed on local dipolarizations, not on dispersionless injections. Thus, it still remains to be understood where dispersionless injections inside GEO occur on what spatial scale, and how the dispersionless injections relate to concurrent magnetic field changes.

We report in this study the typical particle and field behaviors in the injection region inside GEO in a statistical fashion. The study is based on 171 dispersionless injection events selected by surveying the Van Allen Probes energetic particle measurements during four tail seasons in 2012–2019.

The remainder of the paper is organized as follows. Section 2 presents the Van Allen Probes mission's data sets employed for this study and describe how events used for superposed epoch analysis are selected. The results of the analysis are presented in Section 3. Section 4 provides a discussion of the implications of the results and some speculation on how the results might fit into the underlying physics of injection processes.
2. Data and Event Selection

Data from the NASA’s Van Allen Probes Mission (formerly known as the Radiation Belt Storm Probes [RBSP]; Mauk et al., 2013) are used to characterize the statistical properties of dispersionless injections. The dual Probes are on highly elliptical orbits traversing the inner magnetosphere with a perigee of ∼600 km, an apogee of ∼5.8 RE, and an orbital period of ∼9 h. The analyses use the spin-time resolution (∼11 s) data of energetic electron (e⁻) and hydrogen ion (H⁺) fluxes measured by the Magnetic Electron Ion Spectrometer (MagEIS: Blake et al., 2013; Claudepierre et al., 2015) and Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE: Mitchell et al., 2013) instruments, respectively. Note that the data in local field-aligned pitch angle bins (α = 0.0–7.5° and α = 172.5–180.0° for RBSPICE, α = 0.0–16.4 and α = 163.6–180.0° for MagEIS) are excluded due to poor counting statistics near the loss cones. In addition to the particle data, we use 1-s averages of magnetic field measurements made by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS: Kletzing et al., 2013) instrument to characterize magnetic field changes associated with dispersionless injections inside GEO. To reduce the spacecraft spin-modulation effect on the magnetometer data, we subtract the bandpass-filtered component of 9–13 s from the original EMFISIS magnetometer data. The magnetic field data are also converted from the solar magnetospheric (SM) coordinates to the local dipole VDH coordinates: H (B₀), which is the same as B_z in SM) is parallel to the dipole axis and is positive northward, V (Bᵥ) points radially outward and is perpendicular to the magnetic dipole axis, and D (B₀) completes a right-hand orthogonal system and is positive eastward. The VDH coordinate system is widely used for identifying the transition of the magnetic field configuration from tail-like to dipole-like (or vice versa) at/near GEO.

We examined the 2012–2019 RBSPICE H⁺ and MagEIS e⁻ data sets independently from each other for H⁺ and e⁻ dispersionless injection events. In the first round of the event selection, the candidate events and their onsets are identified by semi-automatically scanning the entire RBSP tail passes with the following criteria: (1) the measuring spacecraft was located at radial distances (r) ≥ 3.5 RE in the 18–06 MLT sector; (2) both RBSPICE and MagEIS data were available; (3) H⁺/e⁻ flux enhancements at least in three consecutive energy channels were simultaneous within the spin-time resolution; (4) there were no such flux enhancements in the preceding 2 min; and (5) the magnetic elevation angle (θ = tan⁻¹(|B₀|/(Bᵥ² + B₀²)₁/²)) before the injection onset was larger than 30°. An example of injection events selected with the above criteria is shown in Figure S1. The fifth requirement is used to assure that the spacecraft was close to the magnetic equator (cf. section 5 of Motoba et al., 2018). After that, we carefully made a visual inspection of the individual candidate events to exclude non-injection flux change events that might result from a trapping boundary motion, an interplanetary shock, an unnatural flux change, etc. Eventually, 171 events in total were identified from both Probes.

Figure 1a illustrates the RBSP locations of the selected 171 dispersionless injection events. Like the LANL and THEMIS studies of dispersionless injections, the 171 events are categorized into three groups: (i) 75 both-species injections, (ii) 68 e⁻-only injections, and (iii) 28 H⁺-only injections. Group (i) means that H⁺ (e⁻) injections occur together with e⁻ (H⁺) injections within 2 min, while Groups (ii) and (iii) mean that a dispersionless injection is observed in only one species. The great majority of the 171 events occurred at r ≥ 5 RE. Appreciably more events occurred in the pre-midnight sector than in the post-midnight sector, regardless of group. The r-MLT distribution is similar to that of dipolarizations inside GEO (Motoba et al., 2018; Ohtani et al., 2018).

Figure 1b displays the occurrence probability of dispersionless injection events, calculated for each 1-h bin by dividing the number of events by the total interval of RBSP data points with ϑ ≥ 30° for that bin. The occurrence probability of Group (i) reaches a peak at 22–23 MLT (median = 22.4 MLT; lower/upper quartile = 21.4/23.7 MLT), at 21–22 MLT (22.2 MLT; 21.2/23.1 MLT) for (ii), and at 23–00 MLT (23.4 MLT; 22.6/24.0 MLT) for (iii). Interestingly, the occurrence probability of e⁻-only injections peaks at slightly earlier MLT than that of H⁺-only injections, unlike the previous LANL results (Birn et al., 1997; Thomsen et al., 2001). This may imply that the selected events were little affected by subsequent azimuthal magnetic drifts.
3. Results

3.1. Dispersionless Injections: Both-Species, e⁻-Only, and H⁺-Only

In order to examine the typical characteristics of H⁺ and e⁻ flux changes and their relationship with concurrent \( B_H \) changes for each group, we performed superposed epoch analysis of each group of (i), (ii), and (iii) dispersionless injection events. In this analysis the zero-epoch time \( t_0 \) is set as the onset time of H⁺ flux enhancements for (i) and (iii), while for (ii) \( t_0 \) is set as the onset time of e⁻ flux enhancements.

Figure 2 displays superposed epoch results for (i), (ii), and (iii) during the 15-min interval from 5 min before \( t_0 \) to 10 min after. Shown in the top and middle rows are the median normalized H⁺ and e⁻ fluxes (\( \delta_j^q \), where \( q \) is species) at local pitch angle \( \alpha \) of 90°. Here, \( \delta_j^q (=j^q_j/j^q_0) \) is normalized with the preonset-level value \( (j^q_0) \), obtained by averaging flux values from \( t_0–2 \) min to \( t_0–1 \) min. The bottom row shows \( \delta_B^H \) variations, where \( \delta_B^H = \Delta B_H - \Delta B_H(\text{preonset}) \) obtained by calculating the difference between the measured \( B_H \) and the quiet time \( (Kp = 0) \) T89 model field \( B_H(\text{T89}) \), \( \Delta B_H = B_H - B_H(\text{T89}) \), and then subtracting the preonset-level value (average value of \( \Delta B_H \) from \( t_0–2 \) min to \( t_0–1 \) min) from \( \Delta B_H \). The solid curve and shaded area denote the median value of \( \delta_B^H \) and its interquartile range, respectively.

For (i), \( \delta_j^{H(H+)} \) at \( \geq 81 \) keV starts to increase at \( t_0 \), while the \( \delta_j^{e(e-)} \) enhancement at \( \geq 32 \) keV starts a few tens of seconds after \( t_0 \). The \( \delta_j^{H(H+)} \) enhancement is most significant at 180 keV. The \( \delta_j^{H(H+)} \) enhancements at \( \geq 81 \) keV reach a peak within 1 min after \( t_0 \), and then quickly decay. In the 54 and 67 keV energy channels, on the other hand, \( \delta_j^{H(H+)} \) decreases or remains unchanged. The \( \delta_j^{e(e-)} \) enhancements at 32 and 54 keV are most noticeable. The intensity of the \( \delta_j^{e(e-)} \) enhancement decreases dramatically with increasing energy. Whereas the initial \( \delta_j^{H(H+)} \) enhancement is almost simultaneous in all energy channels, the subsequent peak appears to depend on energy. The both-species injection events are accompanied by local magnetic dipolarizations, characterized by a sharp, sustained enhancement in \( \delta_B^H \). On average, the dipolarization is preceded by a short, small negative dip.

For (ii), only \( \delta_j^{e(e-)} \) experiences a sharp, short-lifetime enhancement at 32–246 keV. The \( \delta_j^{e(e-)} \) enhancement reaches a maximum within 1 min after \( t_0 \). For (iii), on the other hand, only \( \delta_j^{H(H+)} \) undergoes a sharp enhancement at 54–268 keV. The \( \delta_j^{H(H+)} \) enhancement resembles that for (i), except for the lowest energy channel. Whereas both (ii) and (iii) are accompanied by the concurrent local dipolarizations, the dipolarization...
amplitude for (ii) is smaller than that for (iii). The risetime of the concurrent local dipolarization tends to be more gradual for (iii) than that for (i) and (ii).

3.2. Both-Species Injections: H+ Preceding e− Versus Concurrent H+ and e−

3.2.1. Event Study

When taking a close look at Group (i), it can further be divided into two subgroups. One is the “H+ preceding e−” dispersionless injection events for which the H+ onset precedes the e− onset by tens of seconds (up to 1 min). The other is the “concurrent H+ and e−” dispersionless injection events for which the H+ and e− onsets are simultaneous within the spin resolution of ∼11 s. Out of 75 both-species injection events (With only three exceptions that represent “e− preceding H+” events), 36 events are categorized as the H+ preceding e− injections, while the concurrent H+ and e− injections contain the remaining 36 events. In the following we focus on the two subgroups.

Figure 3 shows representative examples of H+ preceding e− and concurrent H+ and e− events. The H+ preceding e− event on October 15, 2016 and the concurrent H+ and e− event on October 24, 2016 (hereafter called “Event 1” and “Event 2”, respectively) fortuitously occurred at almost the same MLT, r, and magnetic latitude (0.5 MLT, 5.75 RE, and 0.45°), as evident from the spacecraft orbits (blue: Event 1, red: Event 2) at the XY and XZ planes shown in the bottom row. Shown in the first to third rows are H+ and e− fluxes, and BH component for a 15-min interval around the onset of the dispersionless injections.

Event 1 occurred during an isolated substorm (AL ∼ −400 nT, Sym-H ∼ −25 nT) under moderate solar wind conditions: solar wind speed (Vsw) was ∼500 km s−1; solar wind dynamic pressure (Psw) was ∼2.5 nPa; and the z component of the interplanetary magnetic field (IMF), Bz was about −5 nT. At ∼1700:30 UT (first vertical dashed line), the H+ fluxes at ≥147 keV started a steep rise, while the H+ fluxes at <100 keV started to decrease. About 30 s later (second vertical dashed line), the e− fluxes at <200 keV reached a maximum, while the e− fluxes at >200 keV reached a minimum. In contrast, the H+ fluxes experienced a negative (positive) excursion at <100 keV (>100 keV).
When comparing those flux changes with $B_H$ changes, it is obvious that the initial H$^+$ enhancements (injections) at 54–180 keV are well correlated with the onset of a preceding negative $B_H$ dip, while the initial e$^-$ injections are coincident with the onset of a subsequent prolonged $B_H$ enhancement (local dipolarization).

The peak-to-peak amplitude of the dipolarization is $\sim 30\%$–$40\%$ of the background field ($\sim 110$ nT).

On the other hand, Event 2 occurred in the middle of a moderate substorm activity interval ($AL \sim -400$ nT, $Sym-H \sim -25$ nT) under similar solar wind conditions to Event 1: $V_{sw} \sim 400$ km s$^{-1}$, $P_{sw} \sim 2.5$ nPa, and IMF $B_z \sim -2$ nT. For Event 2, both H$^+$ and e$^-$ dispersionless injections were simultaneously initiated at 1614:20 UT (first vertical dashed line) and characterized by a transient flux enhancement. The e$^-$ flux enhancement was evident in all the energy channels, while the H$^+$ flux enhancement was limited at <150 keV. Both H$^+$ and e$^-$ dispersionless injections were well correlated with a transient, small $B_H$ enhancement. The amplitude of the dipolarization is $\sim 20\%$ of the background field ($\sim 70$ nT).

Considering that the background $B_H$ for Event 2 was smaller than that for Event 1, one may suppose that the dipolarization/injections for Event 2 penetrated further earthward because the background field reduction affects the entropy radial profile (Dubyagin et al., 2010, 2011). What we emphasize here is that the dipolarization for Event 2 was not accompanied by any clear preceding $B_H$ depression, unlike Event 1.

### 3.2.2. Statistical Study

Comparison of the two examples presented above allows us to propose one hypothesis that the presence or absence of negative $B_H$ dip ahead of concurrent dipolarization determines which of the two subgroups will
occur. In order to test this hypothesis, we carried out superposed epoch analyses of the 36 H\(^+\) preceding e\(^–\) events and the 36 concurrent H\(^+\) and e\(^–\) events. In this analysis \(t_0\) is set as the onset time of H\(^+\) dispersionless injections. The median values of \(r\) and MLT where the two subgroups took place are 5.7 \(R_E\) and 22.3 MLT for the H\(^+\) preceding e\(^–\) events and 5.7 \(R_E\) and 22.6 MLT for the concurrent H\(^+\) and e\(^–\) events. This means that on average the two subgroups appeared almost in a common region at premidnight.

Figure 4 shows superposed epoch results for the 36 H\(^+\) preceding e\(^–\) events. The format of Figures 4a–4c is the same as Figure 2. Just after \(t_0\), \(\delta j_{H^+}\) starts to increase steeply at \(\geq 81\) keV and decrease gradually at 54 keV, while at 67 keV \(\delta j_{H^+}\) remains almost unchanged (Figure 4a). This means that 67 keV is the demarcation between the \(\delta j_{H^+}\) enhancement and depression. The \(\delta j_{H^+}\) enhancement at \(\geq 81\) keV reaches a maximum at \(t_0 + 55\) s, and then drops quickly. As presented in Figure 4d, the \(\delta j_{H^+}\) enhancement at \(t_0 + 55\) s reaches the most significant intensity peak of \(\sim 5.0\) at 147 keV. The \(\delta j_{H^+}\) enhancements at \(\geq 81\) keV are much stronger at \(\alpha = 90^\circ\) than at \(\alpha = 20^\circ\).

In contrast to such a prompt enhancement in \(\delta j_{H^+}\), \(\delta j_{e^–}\) stays almost at the pre-onset level for the first \(\sim 30–35\) s after \(t_0\) (Figure 4b). \(\delta j_{e^–}\) begins to increase at \(t_0 + \sim 1\) min when \(\delta j_{H^+}\) reaches a peak. The \(\delta j_{e^–}\) enhancement is most pronounced at 32 keV, and its intensity decreases dramatically with energy. The \(\delta j_{e^–}\) enhancement at 32 keV exhibits the first peak (the amplitude of \(\sim 10\)) at \(t_0 + 100\) s. As evident from Figure 4e, the 32-keV (54-keV) \(\delta j_{e^–}\) enhancements at \(t_0 + 100\) s have almost the same intensity at all pitch angles. On the other hand, the \(\delta j_{e^–}\) enhancements at \(>100\) keV are noticeable only at \(\alpha = 90^\circ\).

\(\delta B_{H}\) starts to drop immediately after \(t_0\), as shown in Figure 4c. Tens of seconds later, the negative \(\delta B_{H}\) dip is followed by a sustained dipolarization with the amplitude of \(\sim 20\) nT within 5 min after \(t_0\). The onset of the negative \(\delta B_{H}\) dip is well correlated with the initial \(\delta j_{H^+}\) enhancement over a wide energy range of \(\geq 81\) keV, while the subsequent \(\delta B_{H}\) enhancement nearly coincides with the initial \(\delta j_{e^–}\) enhancement.

Figure 5 presents superposed epoch results for the 36 concurrent H\(^+\) and e\(^–\) events. Compared to the H\(^+\) preceding e\(^–\) events, both \(\delta j_{H^+}\) and \(\delta j_{e^–}\) exhibit much sharper enhancements. Immediately after \(t_0\), \(\delta j_{H^+}\) at \(>81\) keV undergoes a sharp, transient positive excursion, while \(\delta j_{H^+}\) at 54 and 67 keV is characterized by a
transient negative excursion. The $\delta_\mathbf{j}_{\text{H}^+}$ enhancement (drop) reaches a maximum (minimum) at $t_0 + 35$ s. As evident from Figure 5d, $\delta_\mathbf{j}_{\text{H}^+}$ at $t_0 + 35$ s has the most significant peak at 220 keV (the amplitude of $\sim 6.5$), higher than that for the H$^+$ preceding e$^-$ events. This indicates that the H$^+$ spectrum becomes harder. Similar to the H$^+$ preceding e$^-$ events, the $\delta_\mathbf{j}_{\text{H}^+}$ enhancements at $>100$ keV become much stronger at $\alpha = 90^\circ$.

$\delta_\mathbf{j}_{\text{e}^-}$ also exhibits a rapid, sharp enhancement, which starts in concert with the $\delta_\mathbf{j}_{\text{H}^+}$ enhancement. $\delta_\mathbf{j}_{\text{e}^-}$ becomes a peak at the same time ($t_0 + 35$ s) as the $\delta_\mathbf{j}_{\text{H}^+}$ peak, and its intensity is greater than 2.0 in energy channels from 32 keV up to 246 keV, as seen in Figure 5e. When compared to the H$^+$ preceding e$^-$ events, the $\delta_\mathbf{j}_{\text{e}^-}$ intensity at 70–250 keV is relatively stronger, which means that the e$^-$ spectrum becomes harder. The $\delta_\mathbf{j}_{\text{e}^-}$ intensities at lower energies than 100 keV are nearly comparable at all local pitch angles, while above 100 keV they become predominant at $\alpha = 90^\circ$.

As shown in Figure 5c, the concurrent H$^+$ and e$^-$ events also tend to be accompanied by $\delta \mathbf{B}_{\text{H}^+}$ enhancements (local magnetic dipolarization). However, the magnetic dipolarization has two different properties from that for the H$^+$ preceding e$^-$ events. One is that a negative $\delta \mathbf{B}_{\text{H}^+}$ dip preceding the dipolarization is less (or not at all) pronounced. Another difference can be seen in the risetime of the dipolarization, which becomes much shorter (within 1 min), that is, sharper dipolarization. This is generally consistent with Motoba et al. (2018), who demonstrated a tendency for the spectrum of ion injections to become harder for sharper dipolarizations than that for gradual dipolarizations. Overall, the superposed epoch results prove our hypothesis derived from the event study in Section 3.2.1.

4. Summary and Discussion

In this study, we examined the fundamental properties of H$^+$ and e$^-$ dispersionless injections inside GEO and their relationship with concurrent magnetic field changes. This was done by performing a statistical study of 171 dispersionless injection events observed by RBSP during the 2012–2019 tail seasons. Some important aspects and implications from the dispersionless injection statistics inside GEO are discussed below.

Most of the 171 events occurred in the dusk-to-midnight sector with a high occurrence probability at 21–00 MLT and outside of $r = 5$ $R_E$, regardless of species. It is also found that there was no significant MLT offset in occurrence rate between H$^+$ and e$^-$. The occurrence probability of dispersionless injections inside GEO...
resembles the statistical results of Gabrielse et al. (2014), who studied H\(^+\) and e\(^–\) dispersionless injections outside (far beyond) GEO with THEMIS spacecraft measurements. The similarity between the statistical RBSP and THEMIS results implies a potential link of dispersionless injections in the magnetotail plasma sheet and inside GEO. Such a tail-inner magnetosphere connection of injections is also supportive of the picture drawn from recent numerical simulations (Sorathia et al., 2018; Ukhorskiy et al., 2018), demonstrating that mesoscale structure in DFs can play an efficient role in local energization of plasmasheet particles and their inward transport into the inner magnetosphere.

It is important to note that our results do not necessarily fit the statistical picture drawn from the LANL spacecraft measurements at GEO (Birn et al., 1997; Thomsen et al., 2001), indicating that both-species (H\(^+\) and e\(^–\)) events occur around local midnight, while H\(^+\)-only (e\(^–\)-only) events occur a few hours before (after) midnight. The LANL studies used decidedly different selection criterion, which permitted dispersion up to 2 min. As pointed out by Gabrielse et al. (2014), it is highly possible that the gradient and curvature drifts of H\(^+\) and e\(^–\) affected the LANL results. In contrast, we used a stricter selection criterion (≤11 s) in order to select “pure” injection regions as much as possible. We believe that our MLT distribution reflects a more precise site of locally accelerated/transported particles inside GEO.

The most interesting feature of our statistical results is that the both-species dispersionless injection events are divided into two distinctive subgroups: H\(^+\) preceding e\(^–\) and concurrent H\(^+\) and e\(^–\) events. Both occurrence distributions exhibit no apparent spatial offset in MLT-\(\tau\), which means that the difference cannot be explained in terms of large-scale injection boundaries. In addition to the presence and absence of temporal offset between H\(^+\) and e\(^–\), on the other hand, another marked difference is evident in the accompanying magnetic dipolarization signatures: that is, the H\(^+\) preceding e\(^–\) events have a pronounced negative dip ahead of dipolarization, while the negative dip is less clear for the concurrent H\(^+\) and e\(^–\) events.

The presence or absence of a negative depression ahead of an inner magnetospheric dipolarization can be interpreted in terms of the effect of double-current wedge systems, consisting of region-1-sense (R1-sense) FAC in the outer region and region-2-sense (R2-sense) FAC in the inner region (Ohtani et al., 2018; Sergeev et al., 2014). The double-current wedge systems (see Figure 3 of Sergeev et al., 2014) can produce a localized negative \(B_z\) disturbance just earthward of the R2-sense FAC loop in the equatorial region and a large \(B_z\) enhancement (local dipolarization) between the R1-sense and R2-sense loops. There is thus the possibility that the relative location of a satellite to the R2-sense loop (i.e., earthward or tailward) determines the presence or absence of a preceding negative dip. If that is the case, it is generally expected to see a tendency for the H\(^+\) preceding e\(^–\) events to occur further earthward than the concurrent H\(^+\) and e\(^–\) events. Contrary to expectation, no distinct radial difference is seen between the two occurrence distributions. Furthermore, the double-current wedge model cannot entirely explain the injection signatures together with the dipolarization-related magnetic signatures. Thus, the double-current wedge scenario seems unlikely to explain the presence or absence of a temporal offset between the H\(^+\) and e\(^–\) dispersionless injections shown here.

Considering the similarities in the initial temporal variations of \(B_{Ri}\) and \(j_{Ri}\), on the other hand, one may try to explain at least the H\(^+\) preceding e\(^–\) events (Figure 4) in terms of the explosive growth phase, characterized by a sharp negative \(B_{Ri}\) dip at tens of seconds prior to the onset of local dipolarization (Ohtani et al., 1992). The preceding \(B_{Ri}\) depression is considered as a diamagnetic effect of the pressure enhancement, due to flux enhancement of energetic ions coming from tailward. However, it still remains incomplete when attempting to explain the concurrent H\(^+\) and e\(^–\) events, because the dipolarization onset is not preceded by any H\(^+\) signatures (Figure 5).

We propose here a rather speculative but possible scenario to explain both of our two subgroups, at least phenomenologically. The scenario relies on a localized dawn-dusk asymmetric structure of diamagnetic perturbations around a DF which can penetrate inside GEO. Some DFs—which originate in the magnetotail plasma sheet, have an azimuthal scale of ~2–3 \(R_E\) and propagate earthward—can reach GEO, even inside GEO (Merkin et al., 2019; Motoba, Ohtani, Claudepierre, et al., 2020). The deeply penetrating DF (sharp dipolarization) is usually accompanied not only by transient enhancements of the magnetic and electric fields, but also by dispersionless flux enhancements of energetic particles accelerated and/or transported by the fields (Liu et al., 2016; Motoba et al., 2018). DF is often preceded by a transient, negative \(B_z\) drop (\(B_z\) dip) and pressure enhancement, which can be interpreted in terms of a diamagnetic effect. The
transient diamagnetic perturbations result from ambient ions encountering the approaching DF and being reflected earthward. These DF-reflected ions, which appear as a new population with enhanced flux (plasma pressure), can carry a diamagnetic current responsible for the preceding negative $B_t$-dip. Due to the finite gyroradius effect of these DF-reflected ions, the diamagnetic perturbations ahead of the DF can be asymmetric in the dawn-dusk direction: that is, the local pressure peak (also its corresponding negative $B_t$ field) is skewed toward dusk from the DF central meridian (Zhou et al., 2014). The resulting diamagnetic perturbations are radially broader on the duskside head of the DF than on the dayside one (see Figure 4 of Zhou et al., 2014).

Such a localized dawn-dusk asymmetric structure can potentially determine which of our two subgroups will occur inside GEO. If a spacecraft is located duskward from the central meridian of deeply penetrating DF, it is possible that the spacecraft will first measure a longer-lived negative $B_t$ depression accompanying $H^+$ flux enhancements, and then $e^-$ flux enhancements in the DF region. The resultant injection could be a $H^+$ preceding $e^-$ event. If dawnward, on the other hand, since the spacecraft first passes through a thinner pre-DF region, a more transient negative $B_t$ depression will be observed. Such transient $B_t$ depressions may be smoothed out via the superposed technique. Shortly thereafter, the spacecraft, which encounters the approaching DF, will observe simultaneous $H^+$ and $e^-$ flux enhancements together with a strong $B_t$ enhancement. In that case, the resulting injection could represent a concurrent $H^+$ and $e^-$ event.

This statistical study brings insights on the spatial occurrence distribution and temporal evolution of dispersionless injections inside GEO. In order to further test the above scenario, however, detailed case studies with multiple-satellite observations inside GEO and detailed numerical simulation studies are needed.

Data Availability Statement

Data from Van Allen Probes used in this study are publicly available at the individual instrument websites (EMFISIS data, https://emfisis.physics.uiowa.edu/data/index; RBSPICE data, http://rbspice.ftecsc.com/; and MagEIS data, https://www.rbsp-ect.lanl.gov/science/DataDirectories.php), as well as CDAWeb (https://omniweb.gsfc.nasa.gov).

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