Tens to Hundreds of keV Electron Precipitation Driven by Kinetic Alfvén Waves During an Electron Injection

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Abstract

Electron injections are critical processes associated with magnetospheric substorms, which deposit significant electron energy into the ionosphere. Although wave scattering of <10 keV electrons during injections has been well studied, the link between magnetotail electron injections and energetic (≥100 keV) electron precipitation remains elusive. Using conjugate observations between the Electron Loss and Fields Investigation (ELFIN) and Magnetospheric Multiscale (MMS) missions, we present evidence of tens to hundreds of keV electron precipitation to the ionosphere potentially driven by kinetic Alfvén waves (KAWs) associated with magnetotail electron injections and magnetic field gradients. Test particle simulations adapted to observations show that dipolarization-front magnetic field gradients and associated VB drifts allow Doppler-shifted Landau resonances between the injected electrons and KAWs, producing electron spatial scattering across the front which results in pitch-angle decreases and subsequent precipitation. Test particle results show that such KAW-driven precipitation can account for ELFIN observations below ~300 keV.

Plain Language Summary

Energetic electron precipitation from magnetospheric injections has a major impact on magnetosphere-ionosphere coupling. This energy deposition is largely in the form of electron precipitation driven by wave-particle interactions in the magnetotail. Although wave-driven precipitation with energies less than approximately ~10 keV has been studied extensively, the link between energetic electron precipitation (≥~100 keV) and electron injections remains elusive. Combining observations and simulations, this paper provides evidence of such precipitation driven by kinetic Alfvén waves, which have been previously observed to be ubiquitously associated with magnetospheric electron injections but have not been considered as an important driver for precipitation of such electrons.

1. Introduction

Magnetospheric plasma sheet electron earthward injections feature abrupt and intense flux increases of electrons with energies of tens to hundreds of keV on the nightside magnetotail-inner magnetosphere interface, which are an inherent phenomenon associated with magnetospheric substorms (Akasofu, 1964; Birn et al., 2014; Gabrielse et al., 2014; McIwain, 1974; Turner et al., 2016). These energetic electron injections provide a seed population for the radiation belts (Jaynes et al., 2015; Turner et al., 2015) and generate significant magnetospheric electron precipitation to the ionosphere (Cilverd et al., 2008; Ni et al., 2016).

Electron acceleration in injections often leads to precipitation via wave-particle interactions, so there is an upper limit of the trapped electron fluxes, that is, the Kennel-Petschek limit (Kennel & Petschek, 1966). Injected ion and electron distributions can be unstable to various plasma waves, such as whistler mode chorus waves, electron cyclotron harmonic (ECH) waves, electromagnetic ion cyclotron (EMIC) waves, and nonlinear time domain structures (TDSs), which produce diffuse auroras (Kasahara et al., 2012; Ni et al., 2016; Shen et al., 2021; Thorne et al., 2010; Vasko et al., 2017) and the loss/acceleration of radiation belt particles (Albert, 2003; Li & Hudson, 2019; Millan & Thorne, 2007; Shprits et al., 2008; Thorne et al., 2021). Statistical studies have revealed a high correlation between energetic (>~30 keV) electron injections and ground-based riometer absorption (cosmic radio noise), both at geosynchronous magnetic footprints (Arnoldy & Chan, 1969; Baker et al., 1981; Kellerman et al., 2015; Spanswick et al., 2007) and at the stretched-to-dipolar field transient region up to L.
Electron scattering by whistler mode chorus waves has been known as a driver of energetic precipitation from the inner magnetosphere (\(T \leq 7\); Horne & Thorne, 2003; Lam et al., 2010; Omura & Summers, 2006), but its efficiency of producing strong scattering of injection electrons in the plasma sheet has been questioned in a recent statistical study of 733 dispersionless injections (Ghaffari et al., 2021). Indeed, statistical whistler observations have shown that the occurrence rate and intensity of waves drop significantly beyond \(T \sim 8\) (Li et al., 2009; Meredith et al., 2021), and resonant field-aligned electron energies hardly reach \(\sim 100\) keV for parallel-propagating whistlers associated with plasma sheet injections (Li et al., 2011). For similar reasons, diffuse auroral precipitation \((<50\) keV\) from the outer magnetosphere has been mainly attributed to ECH waves instead of whistlers (Ni et al., 2016; Zhang et al., 2015). EMIC waves mainly scatter relativistic \((\sim \text{MeV})\) electrons from the dusk and dayside sectors and thus are less likely responsible for nightside plasma sheet electron precipitation (Albert, 2003; Allen et al., 2015; Thorne, 2010). Another precipitation mechanism concerns magnetic field line curvature (FLC) scattering, which produces efficient plasma sheet electron pitch-angle isotropization if the magnetic field configuration provides \(R_j/\rho_i \leq 8\), where \(R_j\) is the field line curvature radius and \(\rho_i\) is the energetic electron gyroradius (Buchner & Zelenyi, 1989; Sergeev et al., 1983). During dipolarizations associated with injections \(R_j\) is significantly increased, so curvature scattering will be reduced for injection electrons. The dip in \(B_j\) ahead of the dipolarization front can produce transient, localized, and isotropic precipitation (Eshetu et al., 2018), but such localized dips cannot be responsible for massive precipitation. MHD ULF waves associated with injections (Runov et al., 2014; Shiokawa et al., 1997) have a limited effect on modifying magnetic field gradient scale length \((\nabla B/B)^{-1} \sim R_j\) and seldom directly impact energetic electrons in pitch angle (Fullhammar, 1965; Ukhorskiy & Sitnov, 2013). Instead, ULF waves are more likely to contribute by coupling with other kinetic-scale waves (Zhang et al., 2019), including the generation of kinetic Alfven waves (KAWs) through mode-coupling (Hasegawa & Chen, 1975; Lin et al., 2012) or phase-mixing (Allan & Wright, 2000) at plasma boundaries, such as dipolarization fronts where injections are seen.

KAWs carrying significant Poynting fluxes have been suggested to be an important pathway of energy transport associated with injections carried by bursty bulk flows (BBFs) in the flow-braking region (Angelopoulos et al., 2002; Chaston et al., 2012). Large-amplitude KAWs have been found to be pervasive within the braking BBFs and injection (dipolarization) fronts (Ergun et al., 2015). A high correlation between KAWs and injections has also been reported by (Malaspina et al., 2015) in the inner magnetosphere, which has further shown that KAW broadband emissions were colocated and comoving with the injection boundary. The movement of injection boundaries is reflected in riometer absorption on the ground, which usually rises and extends westward following the buildup of sustained injection and dipolarization (Gabrielse et al., 2019). Transient riometer rises are also associated with auroral streamers, which have been viewed as the signature of BBF channels in the plasma sheet (Henderson et al., 1998; Lyons et al., 2012). Recent global hybrid simulations have provided a comprehensive picture of BBF and KAW generation and propagation within the flow-braking region (Cheng et al., 2020). These studies have provided strong evidence that KAWs are correlated with injections, dipolarizations, and braking ion flows, and thus may play a role in energetic precipitation therefrom.

Conventionally, KAWs are not expected to resonate with injection energetic electrons directly. KAWs have perpendicular wavelengths comparable to the ion thermal gyroradius, and the finite Larmor radius effect produces charge separation and coupling to electrostatic (ion-acoustic) mode, so that a significant parallel-to-B electric field develops to maintain charge neutrality and counteracts the electron thermal pressure (Hasegawa, 1976; Lysak & Lotho, 1996). KAWs parallel electric fields allow electron Landau resonance but typically require the electron velocity to approach the Alfvén speed \(v_\parallel \approx \omega_0/k_\parallel \sim v_A\), limiting the resonant energies to below a few keV (Kletzing, 1994; Watt & Rankin, 2009, 2012) including resonance broadening effects (Artemyev et al., 2015; Damiano et al., 2015). One exception is nonlinear stationary inertial Alfven waves, which accelerate counter-propagating electrons greatly exceeding \(v_\parallel\) but only apply to the ionospheric low-B current sheets with normal plasma drifts (Knudsen, 1996; Liang et al., 2019). Although standing KAWs of field line resonances (FLRs) can pitch-angle scatter relativistic electrons above a few hundred keV through drift-bounce resonance...
(Chaston, Bonnell, Halford, et al., 2018), the time scales of such scattering (≈hours) do not allow this mechanism to operate within an injection time period (up to tens of minutes).

However, when observed by electrons drifting across the local magnetic field with velocity $v_{\text{drift}}$, KAW plasma frame $\omega$ can be significantly increased due to Doppler shift and the resonant energy can be shifted to a higher value $v_{\parallel} \sim (\alpha - k_\perp v_{\text{drift}})/k_\parallel$. This is possible because KAW perpendicular phase velocity $vk_\perp$ can be much less than $v_A$ with $k_\perp \gg k_\parallel$ (Chaston et al., 2012). Coupling between KAW electric fields and particle perpendicular magnetic drifts has been theoretically analyzed by Johnson and Cheng (1997) to explain plasma transport at the magnetopause. For electron injections in the tail, equatorial magnetic field gradients associated with dipolarizations (Liu et al., 2013) provide electron magnetic drifts (e.g., >100 km/s for >50 keV electrons) comparable to the KAW perpendicular phase speed, potentially moving energetic electrons into Landau resonance with KAWs. Will KAWs drive energetic electron precipitation associated with the plasma sheet injection via this Doppler-shifted Landau resonance?

In this paper, we present evidence of tens to hundreds of keV electron precipitation driven by KAWs during a magnetotail electron injection, based on observations from the Electron Loss and Fields Investigation (ELFIN; Angelopoulos et al., 2020) and Magnetospheric Multiscale (MMS; Burch et al., 2016) spacecraft. We show results from test particle simulations that demonstrate agreement of the proposed mechanism with such observations.

### 2. Data

We present conjugate observations of a magnetotail electron injection and electron precipitation based on data recorded by MMS and ELFIN on 29 September 2020. We will use the following data sets from MMS: (a) the Fast Plasma Instrument (FPI), which provides electron fluxes within energies of 10 eV–30 keV every ∼4.5 s in fast mode (Pollock et al., 2016); (b) the Fly’s Eye Energetic Electron Proton Spectrometer (FEEPS), which measures electron fluxes and pitch-angle distributions within energies of 25–650 keV every ∼20 s in the spin resolution (Blake et al., 2016); (c) the FIELDS instrument suite (Ergun et al., 2016; Le Contel et al., 2016; Lindqvist et al., 2016; Russell et al., 2016; Torbert et al., 2016), which in fast mode measures DC vector magnetic fields and electric fields at 16 samples per second (sps) and 32 sps, along with wave spectra in frequencies of up to 8 kHz every ∼2 s in low-frequency (LF) mode.

We use data from the ELFIN energetic particle detector for electrons (EPDEs) that measures electron fluxes and pitch-angle distributions in the energy range of 50 keV–5 MeV (Angelopoulos et al., 2020). The ELFIN twin CubeSat (ELFIN-A and ELFIN-B) were launched on 15 September 2018 into polar circular orbits at ∼450 km altitude. Mounted on a spinning spacecraft, EPDE has an angular resolution (FWHM) ∼22.5° and rotates across an angle of ∼24° in ∼0.18 s, nominally allowing full pitch angle resolution twice per spin (16 angular sectors in a ∼3 s spin period) when the B-field is within ±15° with respect to the spacecraft spin plane (as in our case). Given that the local loss cone is approximately 65° at ∼450 km altitude in our event, ELFIN can reliably resolve precipitating, backscattered, and trapped fluxes by averaging measurements from angular sectors within and outside the loss cone. Along-track separation of the identical ELFIN spacecraft has the advantage of resolving the spatio-temporal ambiguity of electron precipitation on time scales of seconds to minutes.

In addition to spacecraft observations, we also use the horizontal magnetic perturbations, that is, the northward ($dB_n$) and eastward ($dB_e$) component from the ground-based magnetometer measurements at Rankin Inlet (lat ∼62.82°, lon ∼267.89°) in conjunction with ELFIN measurements. These data are obtained from SuperMAG in 1 sps (Gjerloev, 2012). Furthermore, we also use a well-developed and validated magnetometer data product of 2D ionospheric currents, applying the spherical elementary current system method (Amm & Viljanen, 1999; Weygand et al., 2011) to a dense network of North-American and Greenland ground-based magnetometer arrays (Engebretson et al., 1995; Mann et al., 2008; Russell et al., 2008). With a temporal resolution of 10 s and spatial resolution on the order of ∼350 km, dynamic maps of equivalent ionospheric currents (EICs, horizontal currents) and current amplitudes (spherical elementary current amplitudes [SECAs], a proxy for field-aligned currents) allow identification of large-scale substorm current wedges as well as small-scale transient currents associated with injection and dipolarization/BBFs (Panov et al., 2016). This identification can help us to pinpoint ELFIN precipitation locations relevant to the magnetospheric injection, which further helps to establish a better conjunction between ELFIN and MMS.
3. Observations

Figure 1 presents the plasma sheet electron injection and precipitation event observed from MMS-1, ELFIN-A (ELA), and ELFIN-B (ELB) on 29 September 2020. Figure 1a demonstrates MMS-1 observations of the background magnetic field, ion bulk flows, spectra of wave electric and magnetic fields, and spectra of electron energy fluxes at $L \sim 9R_E$ in the midnight magnetotail. MMS-1 was in the lobe before a sudden, strong electron injection with energies of 100 eV up to 500 keV engulfed the spacecraft near 06:35 UT, after which the injected electrons persisted over 40 min. Accompanying the injection front was a magnetic field $B_z$ increase, signifying the magnetic field dipolarization. More interestingly, enduring broadband waves from sub-Hz up to $\sim$1 kHz were associated with the injected electrons during the entire period. These broadband waves are electromagnetic below a few Hz and become increasingly electrostatic above a few Hz, which are potentially comprised of KAWs and nonlinear TDSs (Chaston et al., 2015; Mozer et al., 2015).

These KAWs can be identified from the fifth and sixth panels of Figure 1a, which display the DC-coupled perpendicular electric and magnetic field spectrograms of the LF broadband emission below approximately 10 Hz. We have transformed the measured fields from the Geocentric Solar Magnetospheric (GSM) coordinates into the field-aligned coordinates. The background magnetic field vector is determined by averaging DC-coupled
magnetic fields for 3 min. The $E_1$ and $B_3$ components denote field-aligned variations. The $E_1$ and $B_3$ components are perpendicular to $B_3$ and lie in a plane defined by $B_3$ and the geocentric radius vector (see, e.g., Rae et al., 2005). The $E_1$ and $B_2$ components complete the right-handed orthogonal set.

Before the injection took place, ELA crossed the ionospheric footprint of MMS in the Southern Hemisphere during 06:24–06:30 UT around magnetic midnight. Figure 1b presents ELA-measured trapped and precipitating electron energy fluxes in the outer radiation belt. The ratios of precipitating to trapped energy fluxes reach one at the sharp outer edge of the radiation belt in the bottom two panels, indicating broadband electron precipitation in the energy range of 50 keV up to 1 MeV. It is possible that the precipitation is a net result of many different scattering and acceleration mechanisms in the inner magnetosphere (Li & Hudson, 2019; Millan & Thorne, 2007; Sergeev et al., 1993). Of particular interest is the complete absence of precipitation in the high-latitude ($\lesssim70^\circ$) region beyond the radiation belt. In the second panel, the plasma sheet precipitation with energies less than 300 keV seems to be confined to just outside the radiation belt within a narrow latitudinal extent of less than half a degree. This is potentially due to stretching of magnetic field lines and current sheet thinning during the substorm growth phase and prior to the injection (Baker et al., 1996; Runov et al., 2021).

Figure 1c shows that ELB traversed the magnetically conjugate region to MMS in the Northern Hemisphere during the injection period of 06:56–07:02 UT, although behind the injection front. In addition to intense and $>500$ keV electron precipitation in the outer radiation belt, ELB observed significant broadband electron precipitation below 500 keV from the plasma sheet region. Because the ELFIN spacecraft travels at a speed of $\sim8$ km/s and traverses a wide range ($\sim15^\circ$) of magnetic latitudes in the auroral ionosphere within $\sim4$ min, the precipitation observed by ELB represents mostly spatial features. As the injection and waves had been observed since 06:30 UT, we expect the energetic precipitation also took place before 06:56 UT, when ELB was not at the right position to capture it. The plasma sheet precipitation is identified according to (a) the precipitation region is observed poleward of the outer radiation belt boundary (or the isotropic boundary) with magnetic latitudes $>\sim70^\circ$ and $L_{\text{IOR}} \geq \sim8$ Re; (b) the energies of plasma sheet electron precipitation are mostly $<500$ keV; and (c) a clear energy flux decrease can be identified outside the radiation belt (with energies $>500$ keV).

The identified intense plasma sheet precipitation during the injection by ELB is in sharp contrast to little precipitation observed by ELA before the injection occurred (Figure 1b). The upper energy limit of the high-latitude precipitation is roughly consistent with that of injected electrons as observed from MMS-1 (Figure 1a). Such precipitation may be explained by wave-particle interactions, or by FLC, or current sheet scattering from the equatorial magnetosphere (Sergeev et al., 2018, 1993). FLC scattering in principle produces relatively isotropic precipitation (Sergeev et al., 1993) and is more efficient for higher-energy electron precipitation than lower-energy electrons because of smaller ratios of curvature radius over electron gyroradius for higher-energy electrons. This ratio determines the efficiency of FLC scattering (Buchner & Zelenyi, 1989). Smaller curvature-radius-to-gyroradius ratios will produce larger precipitating-to-trapped flux ratios for higher-energy electrons.

Figure 2 presents a closer view of the loss cone filling ratios and precipitating fluxes measured at 63, 138, and 183 keV, along with the identified wave-driven precipitation regions from ELB by comparing the loss cone filling ratios at three different precipitating energies. As shown by the example electron pitch-angle distributions at 63 and 183 keV, FLC-scattering is mostly associated with larger precipitation-to-trapped flux ratios at higher energies (Figure 2c), whereas potential wave-driven scattering is associated with larger precipitation-to-trapped flux ratios at lower energies (Figures 2d and 2e). At relatively higher-latitude region during 06:56:00–06:56:35 UT, the precipitation is likely mapped to distant magnetotail regions where the magnetic field strength is weak, and the FLC radius is small enough such that it is comparable to the energetic electron gyroradius. When the ratio of curvature-radius-over-gyroradius becomes smaller than $\sim8$ (Buchner & Zelenyi, 1989; Sergeev et al., 1983), effective electron precipitation driven by FLC scattering is more likely to take place. This precipitation was thus observed by ELFIN in the relatively higher-latitude region. During 06:56:30–06:57:15 UT, as the spacecraft flew into relatively lower-latitude ionospheric regions where the corresponding equatorial magnetic fields are stronger and more dipolarized (i.e., $B_z$ increases and $\partial B_y/\partial z$ decreases), the magnetic field curvature radius is increased (Lukin et al., 2021; Sergeev et al., 1983). Thus, we do not see precipitation driven by FLC scattering in this region. Two localized (less than $\sim10$ km) sub-spin ($<1.5$ s) precipitation bursts with the precipitating-over-trapped flux ratios significantly exceeding 1 were observed by ELB during 06:56:35–06:57:10 UT. The flux ratios for these sub-spin bursts cannot be used to infer realistic loss cone filling ratios due to spatial aliasing. Whether these precipitations can be attributed to wave-particle interactions or very localized curvature scattering remains unclear.
From the perspective of EICs and SECAs inferred from the ground, the transient tailward flows and broad-band waves encountered by MMS near 06:32 UT were associated with a sudden enhancement of the substorm current wedge (Kepko et al., 2014; McPherron et al., 1973; Shiokawa et al., 1997) in Figure 1d. The injection and dipolarization observed by MMS near 06:35 UT were correlated with a transient, equatorward moving small-scale SECAs and EICs that swept across the MMS and ELB footprints in the panel d2 in Figure 1d. This magnetospheric injection can be reasonably mapped to the ionosphere and was associated with ELB-observed precipitation region later near 06:56 UT shown as the thickened green line. We use the TS04 storm-time model (Tsyganenko & Sitnov, 2005) coupled with the IGRF model (Alken et al., 2021) to perform field line mapping of MMS and ELB. The model inputs are constrained by real-time observations of the Dst index (on average ∼−31 nT), IMF B_y (on average ∼1 nT) and B_z (on average ∼0 nT), and the solar wind density (on average ∼2 cm$^{-3}$) and speed (on average ∼650 km/s). The uncertainties associated with field line mapping of MMS to the ionosphere (∼100 km altitude) are estimated to be ∼2° in geographic latitude and ∼3° in geographic

Figure 2. (a) ELB-measured loss cone filling ratios for 63, 138, and 183 keV. Plasma sheet precipitation originated from field line curvature (FLC) scattering and potentially from waved-driven scattering is indicated outside the radiation belt (RB). The isotropic ratios within the radiation belt are affected by flux saturation during this event. Two intervals show ratios larger than 1 due to the presence of localized (less than ∼10 km) sub-spin (<1.5 s) precipitation bursts. (b) Precipitating electron fluxes for 63, 138, 183, and 520 keV. A sharp flux decrease is observed at the outer radiation belt boundary. There is little 520 keV electron flux beyond the identified radiation belt. (c) Three example electron pitch-angle distributions measured at 63 and 183 keV energy channels.
longitude by different Tsyganenko models. Although the magnetic footprint MMS is only approximate during the substorm, it can be reasonably associated with the downward current region during the injection. Because the magnetic field configuration did not change appreciably after the initial injection in Figure 1a and because large-scale currents near the MMS footprint are very similar in location during the ELB crossing, dynamic field line mapping in panel d2 near 06:34:40 UT is similar to mapping during the ELB passage in panel d3. Although there exists a near 20 min time separation between the injection front and the ELB crossing, which is comparable to the injection passage time, the injection is persistent and develops into pile-up or overshooting of injection/dipolarization fronts at the near-Earth region, such that the fronts rebound and oscillate at the equator (Birn et al., 2011; Panov et al., 2010; Schmid et al., 2011). This dynamic oscillatory behavior has been observed in the SECA and EIC current system in our case. The dynamic movie of the current maps has been provided in Supporting Information.

In addition to the current map, ground-based magnetometers conjugate to the ELFIN-precipitation region provide additional support that ELB-observed precipitation was likely associated with KAWs and the magnetospheric injection/dipolarization. Figure 3 displayed the AE indices during the event along with dynamic magnetic spectra measured from the fluxgate magnetometer at Rankine Inlet and from the induction coil magnetometer at Fort Churchill stations. The locations of these two stations are displayed in Figure 1d relative to the ELB orbital footprints and precipitation. Figure 3 demonstrates that enhanced broadband compressional waves below ~1 Hz (shown in the northward component), known as Pi1B magnetic pulsations, were correlated with both the substorm onset near 06:30 UT and with the injection/dipolarization observed by MMS near 06:40 UT. Previous studies have established that compressional ULF waves in the Pi1-2 range are inherent features associated with substorm dipolarizations and ion fast flows (Kepko et al., 2014; Shiokawa et al., 1997). Lessard et al. (2006, 2011) have reported a similar correspondence between broadband compressional waves, substorm onset/dipolarizations, low-altitude dispersive Alfvén waves, and Alfvénic electron acceleration. Our observations of conjugate compressional waves suggest that ELFIN precipitation was potentially associated with KAW activities in the magnetospheric plasma boundaries, such as injections fronts and plasma sheet boundary layers. In these regions, KAWs can be generated through mode conversion (Hasegawa & Chen, 1975; Lin et al., 2012) or phase mixing (Allan & Wright, 2000).

A high correlation of KAWs with injections, dipolarizations, and fast ion flows has also been reported by many previous studies (see, e.g., Chaston et al., 2012; Ergun et al., 2015; Malaspina et al., 2015).

It is worth emphasizing here that the conjugacy between MMS and ELB observations is established through the following procedures: (a) we first associate the MMS-observed injection and dipolarization with those ground-based observations of the currents of EICs and SECAs; and (b) assume the MMS-observed injection fluxes and waves have similar characteristics to those in equatorial source regions; (c) then, we use the TS04 model to perform field line mapping to locate the approximate footprints (~100 km) of MMS relative to the large-scale current systems during the injection and dipolarization. This relative position is valid within uncertainties of field line mapping; (d) ELB-observed precipitation region can be more reliably mapped to the ionosphere (~100 km) relative to the injection currents because ELB was at an altitude of ~500 km and the magnetic field configuration close to the Earth can be modeled with little uncertainty by the IGRF model; (e) the ground-based magnetometer observations of compressional and shear Alfvén waves support that ELB-observed precipitation observations are probably linked to KAWs in the magnetosphere where MMS were located nearby. Therefore, the linkage of ELB precipitation to MMS is established through the corresponding EICs and SECAs of the injection and the ground-based wave observations.

Because the MMS spacecraft were off the equator, we infer the equatorial magnitude of the dipolarization front associated with the injection based on ground-based ΔH measured by the mid-latitude stations, which are relatively unaffected by ionospheric currents and are known signatures of the field dipolarization during substorms.

**Figure 3.** (a) Magnetic AE index measured from THEMIS ground-based observatories. (b, c) Magnetic spectrograms obtained from the magnetometer stations at Rankin Inlet (RANK, at geographic latitude 62.82° and longitude 267.89°). Results are shown for RANK in the parallel (or northward, dBn) and perpendicular (or eastward, dBe) components.
The comparison is performed with data during 06:36:40–06:45:00 UT and 06:45:20–06:55:00 UT. The black dots represent the measured \(E_i/B_i\) spectra, each calculated using a window size of 16 s. The local Alfvén speed is shown as the red dashed line. (g, h) Least squares power law fitting of the mean KAW \(E_i\) spectra for the two time periods.

Figure 4. (a–f) Magnetospheric Multiscale (MMS)-measured magnetic field and electric field in the field-aligned coordinates (\(B_i\) is in the \(\mathbf{B}\) direction), spanning the period from 06:00 UT to 07:20 UT. (g, i) Mean \(E_i/B_i\) spectra (red) in comparison with the prediction by kinetic Alfvén wave dispersion relation using different observed values of ion flows (black lines). The comparison is performed with data during 06:36:40–06:45:00 UT and 06:45:20–06:55:00 UT. The black dots represent the measured \(E_i/B_i\) spectra, each calculated using a window size of 16 s. The local Alfvén speed is shown as the red dashed line. (h, j) Least squares power law fitting of the mean KAW \(E_i\) spectra for the two time periods.

(C.-S. Huang et al., 2004; Kokubun & McPherron, 1981). Three ground-based magnetic perturbation measurements at middle latitudes are provided in Supporting Information. The inferred magnitude of dipolarization has a very typical value of \(\Delta B_z \approx 25\) nT (Runov et al., 2011) and will be used to specify magnetospheric \(B_i\) gradients in the following test particle simulations.

Figure 4 presents the nature of KAWs associated with the injection observed by MMS-1 during the period of 06:00–07:20 UT. The electric field measurements demonstrate small-scale fluctuations and intermittent spikes. These small-scale fluctuations are quasi-electrostatic and relatively less evident in the magnetic field data. These features are consistent with the quasi-electrostatic property of KAWs with \(k_z \gg k_i\) (Hasegawa & Chen, 1975). We have transformed the measured fields into the field-aligned coordinates as mentioned above. We compare the measured \(E_i/B_i\) spectra with the theoretical prediction of KAW dispersion relation, assuming the measured spacecraft frame spectra are largely due to Doppler shifts of KAW perpendicular wave structures due to ion flows (Chaston et al., 2015; Stasiewicz et al., 2000):

\[
\left| \frac{E_i}{B_i} \right| = \nu_A \left( 1 + k_\perp^2 \rho_i^2 \right) \left[ 1 + k_\parallel^2 \left( \rho_i^2 + \rho_e^2 \right) \right]^{-1/2},
\]

where based on MMS observations of a background magnetic field \(B_0 \approx 75\) nT, an average (proton-dominated) ion number density \(n_i \approx 0.5\) cm\(^{-3}\), \(T_i \approx T_e \approx 4\) keV, the local Alfvén speed \(\nu_A = B_0/\sqrt{\mu_0 n_i} \approx 2,300\) km/s, \(k_i \approx 2\pi f_i/\nu_i\) is the KAW perpendicular wavenumber inferred from the spacecraft frame frequency \(f_i\) and perpendicular ion flows \(\nu_i\) (up to 80 km/s and on average \(\sim 25\) km/s near the injection front based on MMS FPI observations), and \(\rho_i, \rho_e\) are the corresponding ion thermal gyroradius and ion acoustic gyroradius. Following Chaston et al. (2012) and Malaspina et al. (2015), we can test the assumption of Doppler-shift effects by examining the invariance of magnetic field spectra with \(f_i/\nu_i\). Because \(f_i/\nu_i = f/|\nu_i| + \mathbf{k}/2\pi|\nu_i|\), only the Doppler shift term is invariant with \(\nu_i\). If the magnetic field spectrum as a function of \(f_i/\nu_i\) is also invariant with \(\nu_i\), then the assumption of \(f_i \approx k\nu_i/2\pi\) is reasonable. Such testing is provided in Supporting Information and shows that the Doppler-shift assumption is mostly justified with \(\nu_i\) larger than \(\sim 25\) km/s.

The polarization predicted from KAW dispersion in Equation 1 assumes plane waves in a uniform medium with purely H\(^+\) ions. The full dispersion relation from Lysak (2008) and Lysak and Lotko (1996) is expanded in the limit of \(m_i/m_e \ll \beta_i < 1\) and \(f \ll f_i\) for Equation 1, where \(\beta_i, f_i, \nu_i, \rho_i, \rho_e, E_i, B_i, T_i, T_e\) are the electron plasma beta and ion...
cyclootron frequency. Application of Equation 1 to plasma sheet observations of KAWs has been examined first by Wygant et al. (2002) using Polar observations and on a larger database by Chaston et al. (2012) using THEMIS observations.

Near the front before 06:45 UT, the measured wave fields are consistent with those predicted by the KAW model, when applying an average transverse ion flow velocity of 25 km/s measured by MMS (Figure 2g). The variations of $E_z/B_1$ spectra may be attributed to the variations of ion flow velocities during this interval, or due to nonlinear effects associated with small-scale Alfvén waves (e.g., Wygant et al., 2002). The calculated $E_z/B_1$ spectra (fast mode data) have frequencies up to 8 Hz, corresponding to $k_z\rho_i \sim 3$–270 in the kinetic branch (Lysak & Lotko, 1996). In addition to dispersion fitting, we have also performed coherence analyses of $E_z$ and $B_1$ measurements. The data are consistent with traveling Alfvén waves at frequencies below $\sim$5 Hz. This information has been provided in Supporting Information.

Figure 2h presents the fitted power law spectrum of the mean $E_z$ field as $E_z = E_0 f_\omega \nu^\nu$ (mV/m$\sqrt{Hz}$), where $E_0 = 2.5$ mV/m and $\nu = 0.7$, an observable to be used in the test particle simulations. Similarly, during the period of 06:45:20–06:55:00 UT, only 1 min before ELB traversed the MMS footprint in Figure 1d, the KAW spectra show consistency with the KAW dispersion relation in frequencies up to $\sim$2 Hz. The fitted power law spectrum of the mean $E_z$ field has $E_0 = 1.6$ mV/m and $\nu = 0.5$. Because MMS observations were not at the equator within the center of the fast ion flow channel, larger KAW amplitudes may be associated with wave-particle interaction processes responsible for ELB-observed precipitation. We will mainly use the observed injection-front KAW intensities but also apply different wave amplitudes for the test particle simulations to explore potential variations in scattering rate.

4. Resonant Interaction Between KAW and Injected Electrons

We consider a scenario in which injected electrons interact with KAWs in the magnetic field $B_i$ gradients along the $x$ direction (e.g., in GSM coordinates) near equator. Including energetic electron perpendicular magnetic drifts (i.e., VB drifts) associated with $B_i$ field gradients, the wave-electron resonant condition is given as (Summers et al., 1998):

$$\omega - k_\perp v_{dri} - k_\parallel v_1 = n\Omega_c/\gamma,$$

which is simplified as $v_1 \approx -k_\perp v_{dri}/k_\|$, where the KAW frequency $\omega$ is negligibly small, $n = 0$, corresponding to Landau resonance. As shown in Supporting Information, KAW real frequency $\omega \ll k_\perp v_1$ where $v_1$ is on the order of 50 km/s. With an equatorial magnetic field dipolarization of 25 nT and a typical gradient scale of 400 km on the order of the local ion gyroradius in the magnetotail (Runov et al., 2011), $v_{dri}$ is generally larger than 100 km/s for 50 keV electrons at above 10° pitch angle. Therefore, the KAW real frequency will typically be negligibly smaller than the Doppler-shift term. However, when electron pitch angles decrease to near the loss cone, the real frequency term cannot be neglected. We consider resonant electrons move in the direction opposite to the KAW parallel wave vector $k_\parallel$ direction, whereas the VB drift of resonant electrons is aligned with the perpendicular wave vector $k_\perp$ direction. The resonant energy and efficiency of electron scattering are collectively determined by KAW intensities, wave normal angles, and electron perpendicular magnetic drifts.

5. Test Particle Simulations and Precipitating Flux Comparison

We use a test particle simulation code to estimate electron pitch angle scattering by broadband electric fields of KAWs associated with injections and magnetic field $B_i$ gradients. We solve full relativistic Lorentz equations of electrons and obtain the electron position ($\vec{r}$) and momentum ($\vec{p}$) using the classic fourth order Runge-Kutta integrator (see tests in Shen & Knudsen, 2020). The relativistic electron equation of motion is:

$$\frac{d\vec{p}}{dt} = q_e \left[ \vec{E} + \frac{\vec{p}}{m_e\gamma} \times \vec{B} \right]$$
where \( \vec{p} = \gamma m_e \vec{v} \) is the electron momentum, \( \gamma = \left(1 + p^2/\left(m_e c^2\right)^2\right)^{1/2} \), and the magnetic field is specified as \( \vec{B} = B_{0}(x) \hat{z} = B_{0} \left[1.1 + 0.9 \tanh (x/L_{ci})\right] / 2 \hat{z} \), where \( B_{0} \sim 25 \text{ nT} \) and \( L_{ci} \sim 400 \text{ km} \) based on current and previous observations as aforementioned (Runov et al., 2011).

Note that we have assumed no magnetic field variations in the \( z \) direction and have neglected the full bounce motion along the field line and focused on local equatorial wave-particle interactions. Thus, the interaction near the equator is artificially prolonged and exaggerated and the interaction along the field line is weakened due to lack of bounce motion. However, because interactions between KAWs and electrons mostly occur near the equator where perpendicular magnetic drifts are the most significant, the limitation of neglecting bounce motion does not negate our key results shown in the following, that is, energetic injection electrons below \( \sim 500 \text{ keV} \) can be driven into the loss cone by KAWs through Doppler-shifted Landau resonance. We also only consider the electric field spectra of KAW and neglect the small magnetic perturbations in the parallel direction (Hollweg, 1999). These magnetic perturbation effects and electron bounce motion will be examined in a future study.

The electric fields of KAWs are specified as \( \vec{E} = E_{\perp} \hat{y} - E_{||} \hat{z} \), in which we have (Stasiewicz et al., 2000):

\[
E_{\perp} = \sum_{k_{\perp} \rho_i=2^{-128}} E_k \cos (k_{\parallel} z - k_{\perp} y - \omega t + \phi_{\text{rand}}),
\]

(4)

\[
E_{\parallel} = \frac{k_{\parallel} \rho_i^2}{1 + k_{\perp}^2 \rho_i^2} \simeq \frac{k_{\parallel}}{4k_{\perp}},
\]

(5)

where \( \omega \) is set to a small number \( 2\pi \times 0.05 \), \( E_{\perp} \) and \( E_{||} \) are the perpendicular and parallel components of the KAW broadband \((k_{\perp} \rho_i = 2^{-128})\) electric fields. In order to single out wave effects, no background DC electric fields are included. The perpendicular magnetic field perturbations are implicitly included through the parallel electric fields based on Faraday’s law.

In simulations, the broadband KAW electric fields have 2,450 wavenumbers with (a) a representative spectrum \( E_{\nu} = E_{\nu}(k_{\perp} \nu_i/2\pi)^{-\nu} \), where \( \nu = -0.7 \) based on the measured spectrum in Figure 4b, and \( E_{\nu} = 0.4 \text{ mV/m} \) as reduced to conserve total wave power for increased \( k \)-modes in the frequency range of 0.1–6.3 Hz, and (b) a stepsize of 0.05 for \( k_{\perp} \rho_i \sim 2^{-128} \) to ensure stochastic interaction between electrons and KAWs, and the absence of artificial nonlinear Landau resonance trapping for individual \( k \)-modes introduced by sampling of the spectrum (Karimabadi et al., 1990; Karney, 1978). When converting the \( k \) spectrum to the frequency spectrum, we have specified a typical ion flow velocity \( \nu_i = 50 \text{ km/s} \), two times the average value used for fitting in Figure 4g. This allows including a larger portion of the measured spectrum while keeping the number of \( k \) numerically manageable and the stepsize small enough to avoid artificial nonlinear effects due to sampling, albeit at the expense of reducing the measured electric field amplitudes by a factor of \( 1 - 2^{-0.7} = 0.4 \). The variation in amplitude will be accounted for by testing different KAW \( E_{\nu} \).

Figures 5a and 5b present the evolution of the trajectories (in \( x \) direction) and magnetic moments of three test particles with an initial pitch angle of \( 5^\circ \) and an energy of 100 keV. The three electrons are initiated from the center \((x = 0)\) of the gradient magnetic field with both random gyrophases and random locations in the \( y \) position \((by, y) \leq \rho_i \). The electron orbits are integrated for a period of \( \sim 11 \text{ s} \) with a stepsize \( \Delta t = 1/400 \nu_i \). Figure 5a shows that as electron drifts toward a weaker \( B \)-field region, its pitch angle decreases; as electron drift toward a stronger field region, the pitch angle increases. These variations of pitch angle are due to adiabatic transport across the \( B \) field gradients on the large time scale, as shown by the steady baseline of Figure 5b. This transport is a result of small but accumulative \( E \times B \) pushes in the \( x \) direction. In this case, no \( E \)-field induced acceleration/deceleration occurs in the electron guiding-center frame.

Figure 5b shows that intermittent pitch angle and momentum alterations also take place, especially when electrons move toward the edge of the weaker field region. These sudden and intense variations of pitch angle and momentum lead to sporadic loss of electrons \((\Delta \leq 2^\circ)\), which can be attributed to two processes: (a) KAW \( E_{\perp} \) fields contain spatially small-scale, intense fluctuations, so that acute changes of \( E \times B \) drifts take place, which transforms into sudden electron acceleration or deceleration; (b) electron \( vB \) drift velocities vary significantly as electrons approach the edge of the weaker field region, so their perpendicular momenta change appreciably. The above two factors work together and produce electron pitch angle variations on a much shorter time scale than those driven by adiabatic transport. This is evidently shown as the momentum spikes in Figure 5b. As a result,
electrons can be driven into the loss cone by the combination of the large-scale adiabatic transport and small-scale momentum kicks due to varying $E \times B$ and $\nabla B$ drifts.

At the injection front, MMS observed counter-streaming electrons with a plateau pitch angle distribution within ±45°. The average electron pitch-angle distribution measured by MMS is provided in Supporting Information. Through test runs for electrons in the energy range of 10–500 keV, we find that only electrons with pitch angles less than 20° can be driven into the loss cone for the given KAW spectrum and gradient magnetic field. To calculate the loss rate applicable to observations, we specify a uniform pitch angle distributions below 20°, comprising discrete pitch angle elements (δ functions) of 5°, 10°, 15°, and 20°, each with 100 test electrons. Electrons are counted as being lost if their pitch angles decrease to be smaller than 2° during the integration period of ∼11 s. The loss rate is obtained as $r_{loss} = N_{loss}/400$. This procedure is repeated for different electron energies. Test particle simulation examples of electron pitch-angle and energy variations as well as loss rate calculations for different energies are provided in Supporting Information.

Figure 5c presents the calculated electron loss rates for the observed energy range of the injection and precipitation. The loss rates reach more than 50% for 10 keV electrons but drop to near 0% for >500 keV electrons. The extent of pitch angle variations and the chance of loss largely depend on the amount of induced perpendicular
momentum variations, which are limited by the model $E$ fields and magnetic field gradients. Therefore, for a given scale of momentum variations, lower-energy electrons will experience proportionally larger pitch angle decreases. To account for the uncertainty in KAW amplitudes associated with precipitation in our observations, Figure 5c also presents variations in loss rate when we multiply the observed amplitudes of KAWs electric fields by a factor of 2 ($2E_0$) and 0.5 ($0.5E_0$). When the electric field amplitudes become weaker, scattering may become relatively more effective for higher-energy electrons in a certain energy range. This is because the resonant energy at the same pitch angle increases with smaller $k_z$ (or smaller wave normal angles [Chaston et al., 2009]) for a given field model, if we recognize the energy dependence of $\nu_{\text{res}}$ in Equation 3. This may produce flattened loss rates, because when the effects of electric field amplitudes become weaker, the falling shape of the wave spectrum determines the relative scattering efficiency. Furthermore, although electron bounce motion has been ignored in our simulations, we expect that inclusion of bounce motion will increase the parallel electric field effects associated with KAWs, therefore the extent of pitch angle decreases near the equator will likely be strengthened, albeit with reduced overall scattering efficiency due to shorter dwelling time near the equator. Also, electron curvature drift effects have not been incorporated due to absence of magnetic field gradient in $z$ direction in our idealized field model. Inclusion of this curvature drift will likely enhance the total perpendicular magnetic drift, thus shifting the resonance to a smaller $k$ or larger electric fields regime for the same resonant energy.

We apply the loss rates in Figure 5c to estimating precipitating electron energy fluxes from MMS in the magnetosphere in Figure 5d. We obtained the average electron parallel energy fluxes within 20° pitch angles from three MMS spacecraft (excluding MMS-4) when they were within the injection front, where magnetic field gradients were prominent (06:38–06:44 UT). The precipitating fluxes are calculated as the product of the observed parallel energy flux and the loss rate at the corresponding energy. Figure 5d compares the inferred precipitating energy fluxes from MMS with those measured by the ELFIN-B spacecraft, which captured wave-driven plasma sheet electron precipitation during the period of 06:56:34–06:57:10 UT (Figure 2). We have removed the contribution of backscattered electrons to the precipitating energy fluxes measured by ELFIN-B. In addition, the ELFIN-B flux data have been denoised using an uncertainty threshold of 50% based on counting statistics. The resultant average precipitating energy fluxes measured by ELFIN-B (black line) and MMS (red line) are consistent at energies below ~300 keV within spectral variations. The results in Figure 5 suggest that the precipitating electrons below ~300 keV observed by ELFIN-B in the plasma sheet region are probably driven by resonant wave-particle interaction between magnetospheric injection electrons and KAWs in the dipolarization front magnetic field gradients.

6. Discussion and Conclusions

Previous studies have shown that KAWs are important for accelerating electrons mainly in the thermal energy range (several eV up to a few keV) when electrons have parallel velocities close to the local Alfvén speed (Watt & Rankin, 2009, 2012; Wygant et al., 2002) and sometimes nonlinear resonance broadening occurs (Artemyev et al., 2015; Damiano et al., 2015). In more recent studies, standing waves of kinetic FLRs have been suggested to drive pitch-angle scattering and radial diffusion of radiation belt electrons with energies above a few hundred keV via drift-bounce resonance (Chaston, Bonnell, Halford, et al., 2018; Chaston, Bonnell, Wygant, et al., 2018). But the time scales of such scattering are ~hours compared with an injection time period of up to tens of minutes.

In this study, we consider KAWs with $k_{\|} > 1$ interacting with plasma sheet injection electrons via Doppler-shifted Landau resonances in the energy range of 10–500 keV, which is the main population of injected electrons from the magnetotail (Gabrielse et al., 2014; Turner et al., 2016). This range of resonant energies with KAWs has so far not been explored but can be significant if we include $VB$ drifts in the magnetic field gradients associated with injections and dipolarizations, where KAWs have been found to be pervasive (Chaston et al., 2012, 2015; Cheng et al., 2020; S. Y. Huang et al., 2012). Using conjugate ELFIN and MMS spacecraft observations and interpreting these observations through test particle simulations, we have the following results:

1. We have reported direct observations of tens to hundreds of keV electron precipitation most likely driven by resonant interaction with KAWs in the magnetic field gradients associated with a magnetotail injection.
2. The magnetic field gradients and the associated $VB$ drifts allow Doppler-shifted Landau resonant interaction between injected electrons and KAWs, producing scattering and precipitation of injection electrons. Electron
losses are attributed to a combining effect of large-scale adiabatic transport across the gradient magnetic field and small-scale perpendicular momentum kicks due to rapidly varying \(E \times B\) and \(VB\) drifts.

3. Taking into account the estimated electron loss rates from simulations, the calculated precipitating electron energy fluxes from MMS are roughly consistent with plasma sheet energetic (50–300 eV) precipitation observed by ELFIN-B.

Clilverd et al. (2008) and Gabrielse et al. (2019) have suggested that large-scale injections and dipolarizations during substorms are closely associated with energetic (≥30 keV) electron precipitation as observed by ground-based riometers. Wave-particle interactions are thought to be necessary in that process. The mechanism of KAW-driven precipitation proposed in our paper may be a significant contributor to such electron precipitation.

Data Availability Statement

ELFIN data can be accessed through http://data.elfin.ucla.edu/. MMS data can be obtained through https://lasp.colorado.edu/mms/sdc/public/about/browse-wrapper/. Matlab plotting code for simulation results is available through https://doi.org/10.5281/zenodo.5728276. The authors gratefully acknowledge the use of ground-based magnetometer data from SuperMAG (https://supermag.jhuapl.edu/mag/). EICs and SECA data sets can be accessed from https://doi.org/10.21978/P8D62B and https://doi.org/10.21978/P8PP8X. Data analysis was done using SPEDAS V4.1, see Angelopoulos et al. (2019).

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