

Red Line Diffuse-Like Aurora Driven by Time Domain Structures Associated with Braking Magnetotail Flow Bursts

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Key Points:

- Predominantly red-line auroras are linked to flow bursts, TDSs, and <1 keV electron precipitation
- For the first time, red-line diffuse-like auroras have been forward-modeled using TREx-ATM with TDS inputs
- A good correlation between forward-modeled and observed red-line emissions suggests that TDSs are a major driver

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21 Abstract

22 Magnetotail earthward-propagating fast plasma flows provide important pathways
 23 for magnetosphere-ionosphere coupling. This study reexamines a flow-related red-line
 24 diffuse-like aurora event previously reported by Liang et al. (2011), utilizing THEMIS
 25 and ground-based auroral observations from Poker Flat. We find that time domain struc-
 26 tures (TDSs) within the flow bursts efficiently drive electron precipitation below a few
 27 keV, aligning with predominantly red-line auroral intensifications in this non-substorm
 28 event. The diffuse-like auroras sometimes coexisted with or potentially evolved from dis-
 29 crete forms. We forward model red-line diffuse-like auroras due to TDS-driven precip-
 30 itation, employing the time-dependent TREx-ATM auroral transport code. The good
 31 correlation (~ 0.77) between our modeled and observed red line emissions underscores
 32 that TDSs are a primary driver of the red-line diffuse-like auroras, though whistler-mode
 33 wave contributions are needed to fully explain the most intense red-line emissions.

34 Plain Language Summary

35 Fast plasma flows in the magnetotail, traveling earthward at several hundred kilo-
 36 meters per second, transport energetic particles and magnetic flux into the inner mag-
 37 netosphere. Upon braking near Earth’s high magnetic flux regions, they trigger plasma
 38 instabilities and waves, leading to increased electric currents and particle precipitation
 39 in the polar regions. This precipitation, depending on its driver, results in either diffuse-
 40 like auroras from electron pitch-angle scattering, or discrete auroras from field-aligned
 41 electron acceleration and currents. Our case study highlights the important role of time-
 42 domain structures in diffuse-like aurora generation during flow braking. This reveals a
 43 new aspect of magnetosphere-ionosphere coupling: the generation of diffuse-like auro-
 44 ras through electron scattering by time-domain structures in braking flow bursts.

45 1 Introduction

46 Since their discovery in the 1970’s (Scarf et al., 1974; Gurnett et al., 1976), broad-
 47 band electrostatic noise in the frequency range of tens of Hz up to several kHz have been
 48 observed to be ubiquitous in various space plasmas (Ergun et al., 1998; Cattell et al.,
 49 2005; Williams et al., 2006). These fluctuations, when examined in the time domain (Matsumoto
 50 et al., 1994), manifest unique localized electrostatic solitary structures, comprising mostly
 51 electron phase-space holes and double layers, which are collectively termed as time-domain
 52 structures (TDSs) (Mozer et al., 2015).

53 Recently, there have been active discussions on the role of TDS-induced electron
 54 scattering in generating diffuse auroras (Mozer et al., 2018; Nishimura et al., 2018; Vasko
 55 et al., 2017, 2018; Shen et al., 2020, 2021). While Mozer et al. (2018) proposed that TDSs
 56 contribute to electron precipitation into pulsating auroras, Nishimura et al. (2018) ar-
 57 gued that TDSs were more likely linked to discrete auroras or non-pulsating diffuse au-
 58 roras. Furthermore, a few studies showed that TDSs can efficiently scatter less than a
 59 few keV electrons into the loss cone, thereby contributing to the diffuse auroral precip-
 60 itation (Vasko et al., 2017, 2018; Shen et al., 2020, 2021). Although individual conjunc-
 61 tion events have revealed moderate correlations between TDSs and diffuse auroras (see
 62 Supporting Information in Shen et al., 2020), and their similar statistical distributions
 63 in the nightside plasma sheet lend support (Newell et al., 2009; Malaspina et al., 2015),
 64 direct evidence remains elusive.

65 Prior statistical studies revealed that TDSs are abundant in the plasma sheet within
 66 most plasma injections and braking fast ion flows or bursty bulk flows (BBFs) (Gurnett
 67 & Frank, 1977; Angelopoulos et al., 1992; Ergun et al., 2015; Malaspina et al., 2015). These
 68 fast ion flows often manifest in the ionosphere as north–south auroral structures or “stream-

ers” (e.g., Lyons et al., 2012; Henderson, 2012; Nishimura et al., 2011). Auroral streamers are typically discrete in nature and are linked to upward field-aligned currents forming on the western edge of flow bursts (Nakamura et al., 2001; Nishimura et al., 2011). However, some streamers may coexist with or evolve into diffuse-like aurora enhancements as they move equatorward and reach the inner edge of the plasma sheet (Henderson et al., 1998). Within the braking flows, TDSs may contribute to electron precipitation into structured diffuse-like and non-accelerated auroras (Sergeev et al., 2004; Shen et al., 2020).

Low-energy ($< \sim 1$ keV) electron precipitation more effectively excites red-line (630 nm) auroras, whereas higher-energy (> 1 keV) electrons predominantly induce green-line (557.7 nm) and blue-line (427.8 nm) auroras. Thus, TDSs are likely linked to red-line-dominated auroras, especially when the plasma sheet state is prime for such low-energy precipitation, like quiet times with low temperatures. In fact, to reliably identify TDS-driven diffuse auroras, non-substorm conditions are more suitable, as it is often challenging to disentangle aggregated effects from different, concurrent drivers during substorms that preclude direct linkage to flow bursts and TDSs (e.g., Sergeev et al., 2012; Shen et al., 2023).

One potential example has been reported by Liang et al. (2011), where conjugate THEMIS and ground-based optical and radar observations revealed flow-related auroral signatures, including high-latitude poleward boundary intensifications (PBIs), streamer-like discrete auroras, and red-line diffuse-like auroras that are associated with the discrete forms. In that study, THEMIS waveform data and potential TDS signatures have not been investigated, leaving the impact of TDS-induced electron scattering on red-line auroras unresolved. In this paper, we revisit this event, aiming to provide the first forward modeling and data-model comparison of red-line diffuse auroras driven by TDSs.

2 Instrumentation and Models

We use the following data from THEMIS (Angelopoulos, 2008): electron and ion fluxes and moments measured by the Electrostatic Analyzers (ESA) and the Solid State Telescope (SST) instruments in the energy range of several eV up to 900 keV (McFadden et al., 2008; Angelopoulos et al., 2008), DC vector magnetic fields at spin resolution (~ 3 s) measured by the Fluxgate Magnetometers (FGM) (Auster et al., 2008), electric and magnetic field wave power spectra within 1 Hz–4 kHz (FBK with 6 frequency bands and FFP with 64 bands), and waveform data at 8,192 samples per second (sps, DC-coupled), measured by the Electric Field Instrument (EFI), the search coil magnetometer (SCM), and the Digital Fields Board (DFB) (Le Contel et al., 2008; Bonnell et al., 2008; Cully et al., 2008).

The flow-related red-line auroral event occurred during 10:30–11:30 UT on March 3, 2009. Following Liang et al. (2011), we primarily use the ground-based Poker Flat meridian spectrograph (PFMSP) for auroral observations, recording every 15 seconds and capturing emissions in the red (630 nm), green (557.7 nm), blue (427.8 nm), and proton H_β (486.1 nm) lines along the meridian. Complementarily, the Poker Flat digital all-sky camera (DASC) provided 2D auroral data to elucidate the longitudinal or magnetic local time (*MLT*) extent of the red-line diffuse auroras. Note that the DASC does not provide absolute intensities of 630 nm emissions and it recorded images at 41-s cadence for this event. We also use auroral observations from the THEMIS whitelight all-sky imager (ASI) at Fort Yukon with 3-s cadence (Mende et al., 2008).

Although TDSs include different types of nonlinear electrostatic structures as noted by Mozer et al. (2015), electron phase space holes are the predominant type in the near-Earth plasma sheet (e.g., Ergun et al., 2015; Malaspina et al., 2018). Electron scattering by electron holes can be quantified using the quasi-linear approach initially devel-

119 oped for an ensemble of plane waves (Kennel & Engelmann, 1966; Lyons, 1974). We use
 120 the formulation of local pitch-angle diffusion coefficients $D_{\alpha\alpha}$ derived in Vasko et al. (2018)
 121 and refined by Shen et al. (2021). We bounce average the local diffusion rates using the
 122 standard procedure (Lyons et al., 1972; Glauert & Horne, 2005):

$$\langle D_{\alpha_{eq}\alpha_{eq}} \rangle = v^{-1} \tau_B^{-1} \int D_{\alpha\alpha} (\partial\alpha_{eq}/\partial\alpha)^2 (\partial s/\partial\lambda) d\lambda / \cos\alpha, \quad (1)$$

123 where the integration is over the period of bounce motion τ_B , and $s = s(\lambda)$ is the length
 124 of a field line. We use the relatively realistic T89 magnetic field model for bounce-averaging
 125 (Tsyganenko, 1989; Ma et al., 2012). The latitudinal profile of \mathbf{B} near the equator is ad-
 126 justed to reduce stretching so as to align with local THEMIS magnetic field observations
 127 (e.g., Ni et al., 2012). In addition, bounce-averaged pitch angle diffusion coefficients due
 128 to transient whistler-mode waves are also calculated using the Full Diffusion Code (Ni
 129 et al., 2008; Ma et al., 2020), including the Landau ($n=0$) and higher order (n up to ± 10)
 130 cyclotron harmonic resonances.

131 We use the full precipitating electron distributions calculated from quasilinear dif-
 132 fusion theory to forward model TDS-driven red-line auroras. Because the varying timescale
 133 of precipitation is typically shorter than the radiative timescale (~ 110 s) of 630 nm emis-
 134 sion, it is imperative to use a time-dependent auroral transport code, such as the TREx-
 135 ATM model (Liang et al., 2016). TREx-ATM is a time-dependent ionosphere aurora model,
 136 adopting the two-stream electron transport code embedded in the GLOW model (Solomon
 137 et al., 1988) and ambipolar diffusion to compute the electron transport in the atmosphere,
 138 with additional capabilities to compute the impact ionization, secondary electron pro-
 139 duction, and impact excitation of neutrals.

140 3 Results

141 The event featuring bursty bulk flows and red-line auroras was observed from 11:40
 142 to 11:20 UT on March 3, 2009. During this time, THEMIS-C spacecraft detected a se-
 143 ries of high-speed flow bursts (>400 km/s) in the Earth’s plasma sheet, as shown in Fig-
 144 ure 1. Figures 1a–1c illustrate the magnetic fields threading all five THEMIS spacecraft,
 145 modeled by T89, alongside the 2D ionospheric red-line auroras observed by Poker Flat
 146 DASC. The red-line auroras spanned nearly 45° in magnetic longitude or 3 hrs in *MLT*,
 147 primarily drifted eastward, occasionally moving equatorward, and exhibited both diffuse-
 148 like and discrete enhancements.

149 For this event complementary ground-based measurements, including THEMIS ASIs
 150 and Poker Flat incoherent scatter radar, provided synergistic auroral and ionospheric
 151 density observations as detailed by Liang et al. (2011). While not described again here,
 152 the key findings include: (1) flow-related auroras featured intermittent poleward bound-
 153 ary intensifications (PBIs) and streamer-like green line emissions, occasionally coincid-
 154 ing with or transitioning to predominantly red-line diffuse-like auroras at lower latitudes;
 155 (2) ionospheric density altitude profiles were consistent with the red-line emissions and
 156 soft (<1 keV) electron precipitation; (3) southward-moving density patches corresponded
 157 to earthward flow bursts and red-line auroral enhancements. It was noted that the ab-
 158 sence of substantial density enhancements above 200 km and the latitudinally-extended
 159 red-line diffuse-like emissions were inconsistent with typical small-scale Alfvénic auro-
 160 ras and broadband acceleration (Chaston et al., 2003; Liang et al., 2019). However, for
 161 some observed discrete auroras, such as the bright stripes around -100° magnetic lon-
 162 gitude and discrete structures near the poleward boundary (likely linked to PBIs) in Fig-
 163 ure 1c, Alfvénic acceleration cannot be ruled out (Damiano et al., 2015; Tian et al., 2021;
 164 Hull et al., 2022), though these aspects are not the main focus of this study. Auroral fea-
 165 tures will be further examined using multi-spectra PFMSMSP measurements.

166 Figures 1b–1c indicate that of the five THEMIS spacecraft, THB and THC were
 167 closest to midnight, with their footprints less than 1 hr *MLT* east of Poker Flat. THC

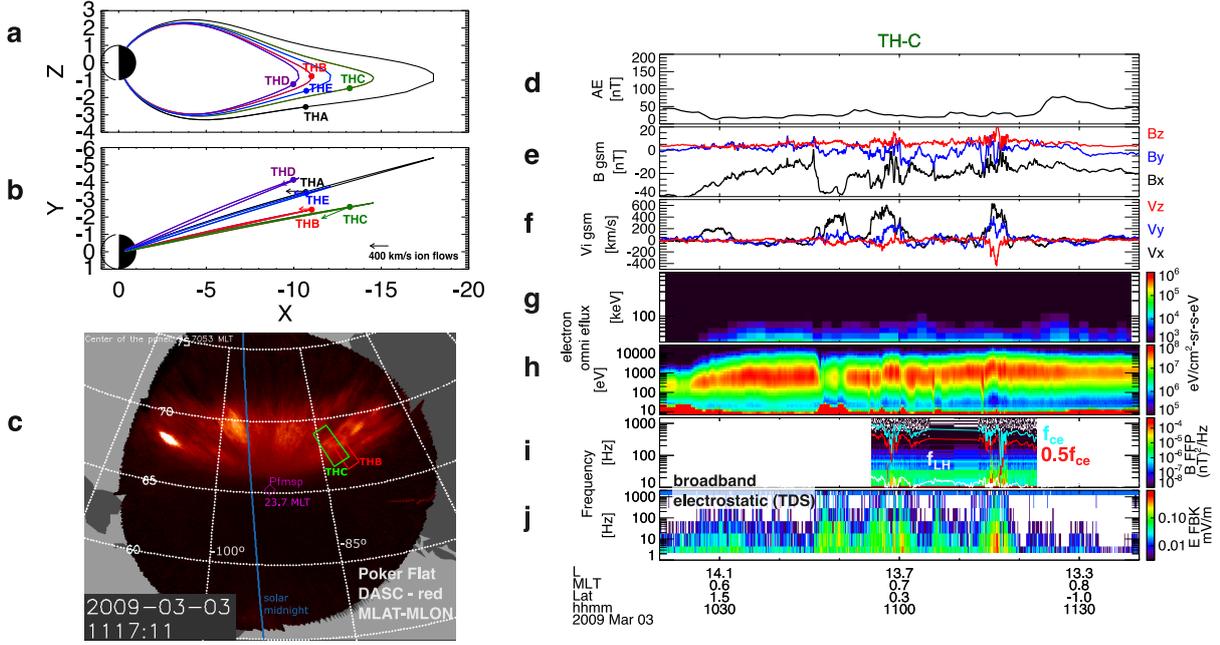


Figure 1. Overview of the flow-related red-line diffuse aurora event observed by THEMIS-C and Poker Flat all-sky camera (DASC). (a–b) Field line configuration threading the five THEMIS spacecraft in the GSM coordinates. Colored vectors represent ion flow velocities for each spacecraft. (c) Poker Flat DASC red-line auroras measured near 11:17 UT. The grids represent AACGM magnetic latitude and magnetic longitude, while the blue line marks the actual local midnight. The assumed emission height and approximate footprints of THEMIS-B (red box), THEMIS-C (green box), and Poker Flat have been mapped to ~ 200 km altitude using different Tsyganenko models of T89, T96, and T01. (d) THEMIS AE index. (e) Magnetic fields. (f) Ion flow velocities. (g–h) Electron energy spectrogram from 7 eV up to 900 keV. (i) Magnetic field FFP spectra in 10 Hz–2 kHz. (j) Electric field FBK spectra up to 2 kHz.

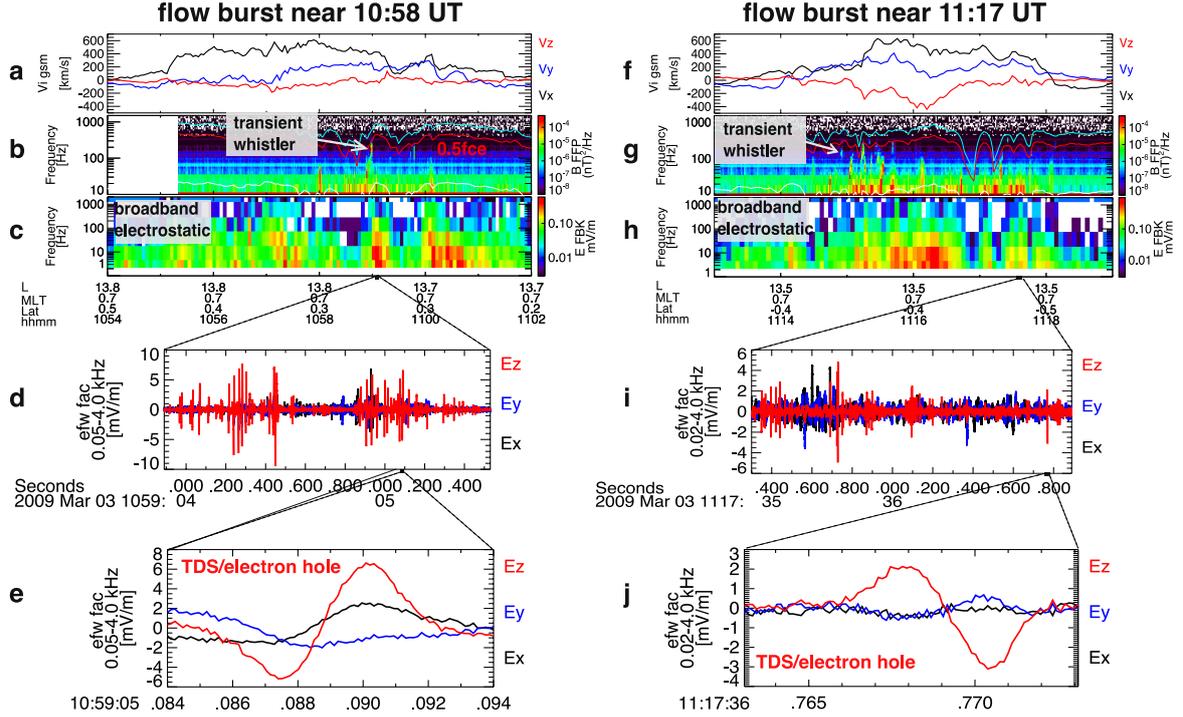


Figure 2. Zoomed-in view of the plasma waves within the two flow bursts near 10:58 UT (a–e) and 11:17 UT (f–j). Panels from top to bottom are: ion flow velocities, FFP magnetic field spectra, FBK electric field spectra, waveform measurements of high-frequency (>20 Hz and >50 Hz) electric fields in the field-aligned coordinates (\mathbf{B} is in the z direction), and expanded views of millisecond-scale electron phase-space holes, also known as time-domain structures (TDSs).

168 detected all flow bursts exceeding 400 km/s within BBFs, whereas THB, positioned further
 169 earthward, registered only a weaker flow burst (~ 200 km/s) that had waned during
 170 inward propagation. Figure 1d shows that the AE index remained below 80 nT throughout
 171 the event. Three strong flow bursts were recorded between 10:40 and 11:20 UT, each
 172 lasting ~ 5 minutes. The latter two, occurring closer to the equator, were accompanied
 173 by $|B_x|$ decreases, notable B_z dipolarizations (Figure 1e), and slightly energized electron
 174 spectra (Figure 1h). Despite heightened flow activity, the plasma sheet temperature remained
 175 below 1 keV (Liang et al., 2011). Figures 1i–1j show that the flow bursts corresponded
 176 to enhanced broadband electrostatic fluctuations (or TDSs) with frequencies ranging from
 177 tens of Hz to several kHz. Additionally, sporadic electromagnetic wave power enhancements,
 178 mostly below ~ 20 Hz, indicate the presence of kinetic Alfvén waves (KAWs) (e.g.,
 179 Chaston et al., 2012; Malaspina et al., 2018; Shen et al., 2023).

180 Figure 2 provides a detailed view of wave spectra and waveform measurements associated
 181 with two flow bursts near 10:58 UT and 11:17 UT. Throughout the flow intervals, there
 182 were continuous enhancements in broadband electrostatic fluctuations. Figures 2d, 2e,
 183 2i, and 2j clearly show that these broadband electrostatic fluctuations predominantly
 184 consisted of electron phase-space holes, identified by a deficit of the electron phase
 185 space density that exhibits bipolar parallel (in the z direction) and unipolar perpendicular
 186 (in the x and y direction) electric fields, on the timescales of millisecond or on the
 187 spatial scales of the local Debye length (Muschiatti et al., 1999; Hutchinson, 2017;
 188 Lotekar et al., 2020). In contrast, whistler-mode waves were more ephemeral, character-
 189 ized by sporadic, narrow-band magnetic power enhancements lasting less than one minute
 190 within the flow intervals (Figures 2b and 2g).

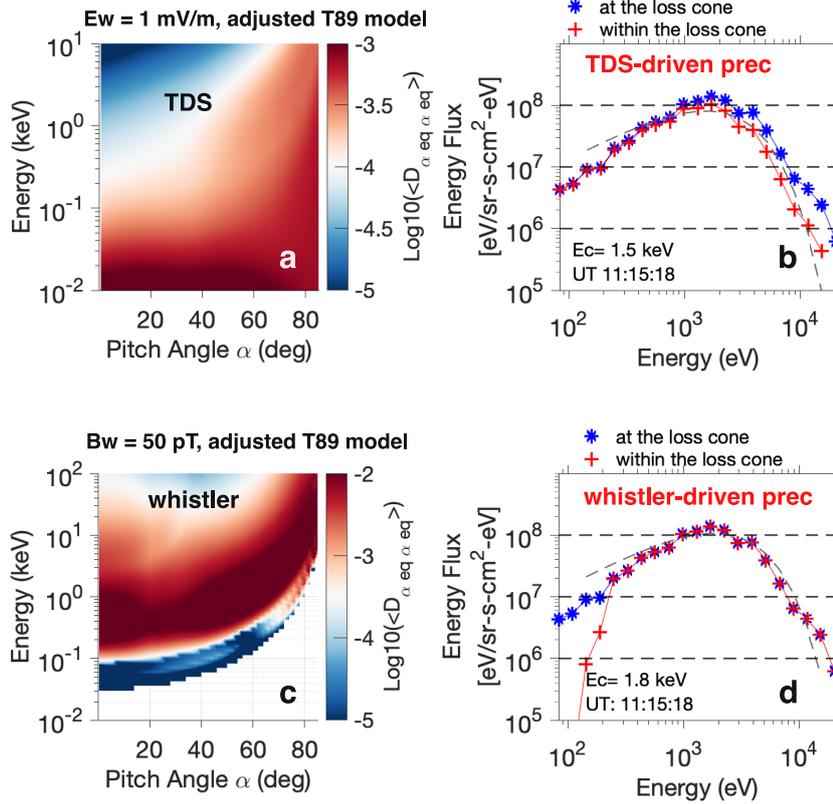


Figure 3. (a, c) TDS- and whistler-driven bounce-averaged electron pitch-angle diffusion rates ($\langle D_{\alpha_{eq}\alpha_{eq}} \rangle$) as a function of energy and pitch angle. We use adjusted T89 model for bounce averaging. (b, d) Example energy flux distributions extrapolated to the loss cone (blue) and calculated within the loss cone (red) based on $\langle D_{\alpha_{eq}\alpha_{eq}} \rangle$. The gray-dashed curves indicate Maxwellian fittings of the precipitating distributions due to TDSs and whistlers, indicating characteristic energies of 1.5 keV and 1.8 keV near 11:15:18 UT.

191 Based on the observed characteristics of TDSs and whistler-mode waves, we proceed
 192 to calculate bounce-averaged electron pitch-angle diffusion rates $\langle D_{\alpha_{eq}\alpha_{eq}} \rangle$ and resulting
 193 electron distributions precipitating into the ionosphere (Shen et al., 2021; Ma et
 194 al., 2012, 2020). TDSs can be generated locally at various latitudes and continuously along
 195 the propagation of flow bursts and injections toward Earth (Ergun et al., 1998; Franz
 196 et al., 2005; Mozer et al., 2015; Malaspina et al., 2015). We assume a latitudinal distri-
 197 bution of electron holes to be within $\pm 25^\circ$ near the equator; increasing the latitude extent
 198 to $\pm 45^\circ$ enhances the diffusion rate near the loss cone by $< 20\%$. For transient whistler-
 199 mode waves, we determine the average wave spectra near 11:15 UT (Figure 2g) as hav-
 200 ing a Gaussian with a lower limit $\omega_1 = 0.15\Omega_{ce}$, a mean frequency $\omega_2 = 0.3\Omega_{ce}$, an upper
 201 limit $\omega_m = 0.45\Omega_{ce}$, a semi-bandwidth $\delta\omega = 0.075\Omega_{ce}$, and a mean wave amplitude $B_w = 50$
 202 pT. No whistler-mode waves were measured by waveform data in our event, thus we do
 203 not have direct information on their wave normals. For the nightside equatorial plasma
 204 sheet (Li et al., 2011; Agapitov et al., 2013; Meredith et al., 2021), we can assume paral-
 205 lel whistlers confined within $\pm 15^\circ$ latitude near the equator, having Gaussian wave nor-
 206 mals with a width $\theta_w = 10^\circ$, a minimum $\theta_{min} = 0^\circ$, and a maximum $\theta_{max} = 30^\circ$. We set
 207 the background $n_e \sim 0.6$ cm⁻³, $f_{pe}/f_{ce} \sim 14.4$, and $L \sim 14.0$ based on THEMIS obser-
 208 vations. For bounce averaging, we use the T89 model with slight adjustments near the
 209 equator to align with THEMIS-C local B observations.

210 Figures 3a and 3c present the calculated $\langle D_{\alpha_{eq}\alpha_{eq}} \rangle$ as a function of energy and pitch
 211 angle, resulting from electron scattering by TDSs and whistler-mode waves, respectively.
 212 Near the loss cone ($\sim 1^\circ$), TDSs efficiently induce pitch-angle scattering at energies be-
 213 low a few keV, with $\langle D_{\alpha_{eq}\alpha_{eq}} \rangle$ on the order of 10^{-4} – 10^{-3} s $^{-1}$, assuming $E_w \sim 1$ mV/m.
 214 Due to large f_{pe}/f_{ce} for this event, whistler-mode waves can also drive efficient electron
 215 scattering at energies as low as 200 eV, but the scattering rates exhibit a broad peak near
 216 1 keV, extending up to 100 keV. This suggests that whistler-mode waves tend to pro-
 217 duce more energetic precipitation spectra compared with TDSs.

218 Example precipitating electron energy distributions are shown in Figures 3b and 3d.
 219 The differential energy flux (red pluses) within the loss cone can be estimated as $x(E)J(E, \alpha_{LC})$,
 220 where

$$x(E) = 2 \int_0^1 I_0(Z_0\tau)\tau d\tau / I_0(Z_0), \quad (2)$$

221 being the index of loss cone filling, $J(E, \alpha_{LC})$ is the electron differential energy flux near
 222 the loss cone (blue stars), I_0 is the modified Bessel function with an argument $Z_0 \simeq \alpha_{LC} / \sqrt{\langle D_{\alpha\alpha} \rangle_{LC} \cdot \tau_{loss}}$
 223 (Kennel & Petschek, 1966), and τ_{loss} is assumed to be half of the bounce period.

224 Time-varying precipitating electron full distributions are input into the time-dependent
 225 TREx-ATM code to forward model red-line auroras and compare their evolution with
 226 that of the measured red-line diffuse-like auroras by PFMS. We begin by examining PFMS
 227 auroral observations. Figures 4a–4d display approximately correlated ion flow bursts, TDS
 228 E_w , and enhanced auroral activities in the green line (577.7 nm), blue line (427.8 nm),
 229 and red line (630 nm). To obtain wave amplitudes of TDSs from FBK spectra (Figure 2),
 230 we integrate wave power in the frequency range of 20–900 Hz, as informed by TDS wavelet
 231 analyses (Shen et al., 2021). The flow bursts (>400 km/s) were associated with inter-
 232 mittent poleward boundary intensifications (PBIs) near 160° elevation angle (or $\sim 68^\circ$
 233 magnetic latitudes) in the green and blue line emissions, exhibiting distinct equatorward
 234 movement. These features align with auroral streamers associated with earthward flow
 235 channels in the plasma sheet (e.g., Lyons et al., 2012; Henderson, 2012; Nishimura et al.,
 236 2011).

237 However, the majority of the auroral enhancements were noted in the red line, pre-
 238 dominantly equatorward of the green-line enhancements. These enhanced red-line emis-
 239 sions, characterized by “patchiness” or short-lived activations, coincided with TDS am-
 240 plitude increases and exhibited discernible equatorward movement. As noted by Liang
 241 et al. (2011), this movement was also in accord with the equatorward shift of soft elec-
 242 tron precipitation and enhanced density patches at altitudes above 150 km. Figure 4f
 243 suggests that TDS-driven precipitation has characteristic energies mostly below 1 keV,
 244 consistent with the overwhelmingly red-line emissions and soft electron precipitation. In
 245 contrast, assuming the presence of whistler-mode waves throughout the flow bursts near
 246 10:58 UT and 11:17 UT, these would produce precipitation with characteristic energies
 247 exceeding 1 keV.

248 To compare with TREx-ATM model output, we need to identify PFMS red-linediffuse-
 249 like aurora intensifications that were approximately conjugate with THEMIS observa-
 250 tions. First, we focus on the time interval between 10:45 and 11:30 UT, during which
 251 the longitudinal separation between the PFMS meridian and projected THEMIS-C foot-
 252 prints was less than 15° , or equivalently $|\Delta MLT| < 1$ hr (Figure 4g). Second, we ad-
 253 just the PFMS red-line data counts by subtracting a uniform background attributed
 254 to ambient diffuse auroras, likely arising from non-TDS mechanisms like diffuse proton
 255 precipitation (e.g., Lyons et al., 2015) as indicated by PFMS H_β -line emissions. Third,
 256 after applying Van Rhijin correction to data counts for aspect angle effects, we identify
 257 an optimum range of elevation angles of 139° – 146° , which probably corresponded to THEMIS
 258 measurements. These optimal angles were determined by searching the maximum cor-

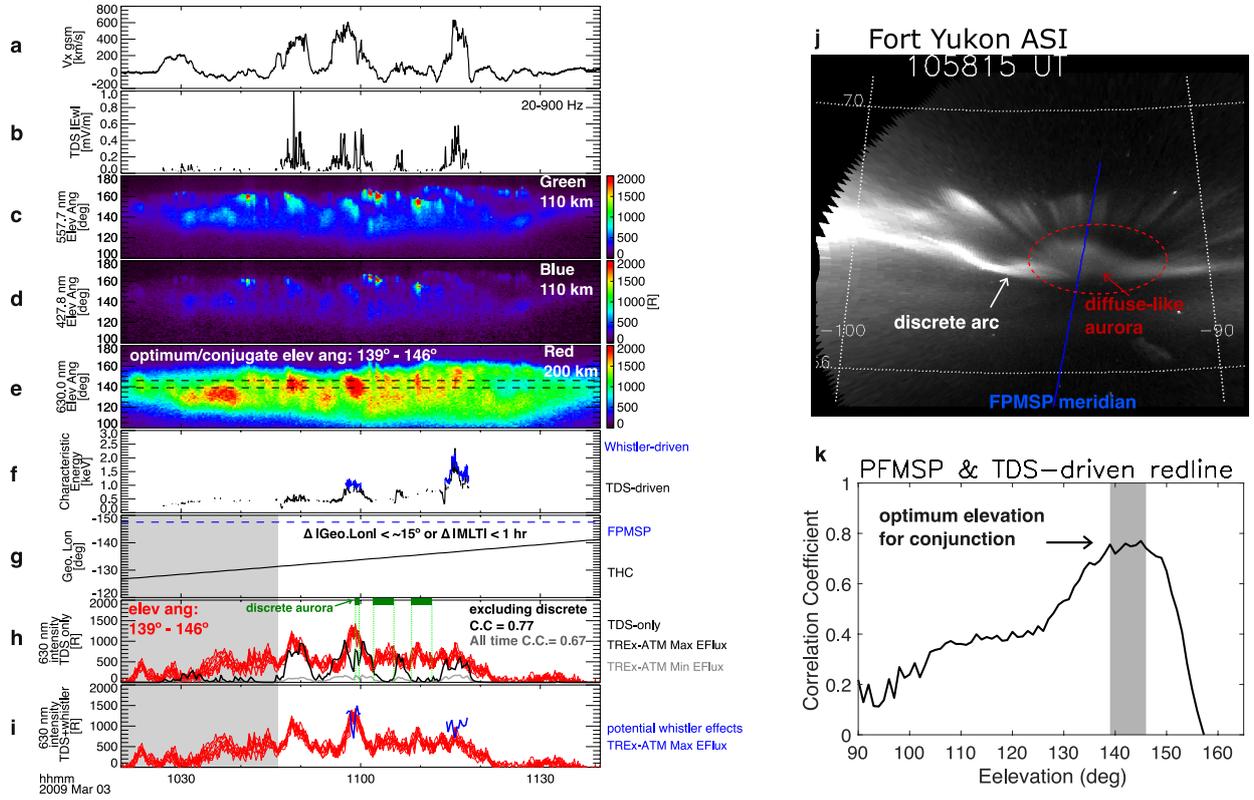


Figure 4. Auroral features and TREx-ATM model results. (a) Ion flow velocity V_x . (b) Root-mean-square TDS electric field amplitudes $|E_w|$ (20-900 Hz). (c-e) PFMSP 557.7-nm green-line, 427.8-nm blue-line, and 630-nm red-line intensity; dashed lines mark optimal elevation angle range for THEMIS conjunction. (f) Characteristic energies of electrons precipitated by TDS (black) and whistler-mode waves (blue). (g) Geographic longitudes of PFMSP and THEMIS-C footprints. (h) 630-nm intensity: PFMSP data (red) vs TDS-driven TREx-ATM model results (black, gray) based on THEMIS maximum and minimum fluxes around the equator (see Supporting Information). (i) TREx-ATM results with additional inputs from assumed, persistent whistler-mode waves; only maximum electron fluxes used. (j) Example ASI whitelight image showing diffuse-like auroras near PFMSP that likely evolved from discrete auroras. (k) Correlation coefficients for PFMSP and TREx-ATM modeled TDS-driven red-line auroras at various elevation angles.

259 relation coefficients between the modeled and observed red-line emissions across all el-
 260 evation angles (Figure 4k).

261 The event exhibited coexisting auroral types due to various mechanisms. TDS-induced
 262 soft electron precipitation leads to a broader altitude distribution of both 630 nm and
 263 557.7 nm emissions, unlike the narrow altitude range associated with monoenergetic elec-
 264 tron acceleration in discrete arcs. In oblique optical observations, like those from PFMSP
 265 and THEMIS ASI, this broader distribution may appear as more “diffusive” auroral forms
 266 (see Figure 4j around the PFMSP meridian). Additional ASI auroral images are provided
 267 in Supporting Information. The 630-nm emission, particularly sensitive to soft electron
 268 precipitation, aligns closely with TDS effects, which we mainly focus on in the study. We
 269 have carefully examined the observations from the Fort Yukon ASI (see Supplementary
 270 Movie in Liang et al. (2011)) and excluded three periods when discrete arcs predomi-
 271 nately contribute to PFMSP red-line emissions.

272 Figure 4h shows a correlation coefficient of 0.77 between PFMSP observed and TReX-
 273 ATM forward-modeled red-line emissions, using inputs solely from TDS-driven precip-
 274 itation. The TReX-ATM model results, indicated by the black and gray lines, are based
 275 on maximum and minimum flux levels measured by THEMIS near the equator during
 276 10:40–11:20 UT. These in-situ measured fluxes were largely controlled by the spacecraft’s
 277 proximity to the true equator, where $|B_x|$ is minimum (see Supporting Information). Fig-
 278 ure 4h reveals that the majority of the observed red-line diffuse-like auroral enhancements
 279 during flow bursts can be explained by TDS-driven model results, albeit slightly under-
 280 estimated for the most intense emissions. Green bars highlight the time intervals of dis-
 281 crete emission peaks, unrelated to TDSs, near 11:00, 11:05, and 11:10 UT. Including these
 282 intervals in our analysis lowers the correlation to 0.67. Figure 4i suggests that includ-
 283 ing potential whistler-mode wave effects along with TDSs in the model offers a better
 284 explanation for the two bright red spots near 10:58 UT and 11:17 UT. This implies that
 285 whistler-mode waves might also contribute to the most intense red-line diffuse emissions
 286 during flow bursts. The compound effects of whistler-mode waves and field-aligned ac-
 287 celeration on energetic electron precipitation obscure TDS’s role in 557.7-nm emissions.
 288 Nonetheless, we have analyzed TDS-driven TReX-ATM 557.7-nm outputs and observed
 289 a weaker correlation with PFMSP’s green line (~ 0.6).

290 4 Discussion

291 Plasma sheet flow bursts are typically linked to ionospheric auroral PBIs and equatorward-
 292 moving auroral streamers, as evidenced by white-light all-sky imager (ASI) observations,
 293 often around substorm times (Donovan et al., 2008; Nishimura et al., 2011; Forsyth et
 294 al., 2020; Yadav et al., 2022). In our non-substorm event, while green-line PBIs and forms
 295 resembling equatorward-moving auroral streamers were noted, the most prominent fea-
 296 ture was the red-line auroras. These auroras extended towards lower latitudes and of-
 297 ten appeared more diffuse than discrete near PFMSP, likely due to wave scattering. Liang
 298 et al. (2011) suggests that the predominance of red-line emissions was probably due to
 299 a cooler inner plasma sheet ($T_e < \sim 1$ keV). Despite strong flows and potential associ-
 300 ation with hot electrons in the tail leading to streamer-inducing energetic precipitation
 301 (Angelopoulos et al., 1992; Nishimura et al., 2020), there was an absence of significant
 302 energetic injections intruding the inner plasma sheet around midnight (Figure 1g). This
 303 could be attributed to differences in adiabatic motion or Alfvén layers between soft and
 304 energetic electrons as they undergo convective, curvature and gradient drifts during in-
 305 ward propagation (e.g., Gabrielse et al., 2017).

306 While red-line emissions naturally accompany green-line emissions due to the $O(^1S)$
 307 to $O(^1D)$ transition linked with 557.7 nm photo emission (Solomon et al., 1988), the dom-
 308 inance of red-line auroral emissions indicates a major low-energy precipitation popula-
 309 tion, distinct from the energetic precipitation responsible for green line excitation. This

low-energy precipitation was confirmed by ionospheric density altitude profiles measured by PFISR (Liang et al., 2011). During the event period of our interest, ECH waves were not observed, ruling them out as a cause for the auroral precipitation (Ni et al., 2012; Zhang et al., 2015). Our investigations, encompassing wave spectra and waveform analyses, quasilinear calculations, and aurora forward modeling, point to electron scattering by TDSs as the primary driver of the observed low-energy precipitation and red-line diffuse-like auroras during this non-substorm event. Furthermore, during more active times like substorms, TDS wave amplitudes tend to intensify (Ergun et al., 2015; Shen et al., 2021; Khazanov et al., 2021). It remains to be determined how much TDSs contribute to the generation of red-line and green-line diffuse-like auroras during those active times.

5 Conclusion

This letter revisits a flow-related red-line aurora event initially reported by Liang et al. (2011). Analyzing THEMIS spectra and waveform measurements, we have revealed an abundance of time-domain structures (TDSs) associated with magnetotail flow bursts. Applying quasilinear calculations, we have estimated TDS-driven electron distributions precipitating into the ionosphere. Employing the time-dependent TREx-ATM auroral transport code, we have forward-modeled red-line auroras due to TDS-driven precipitation. The good correlation of ~ 0.77 between modeled and observed red-line emissions suggests that TDSs likely cause the observed red-line diffuse-like auroras, which sometimes coexisted with or likely evolved from discrete forms. However, to fully explain the most intense red-line emissions, contributions from whistler-mode waves are also necessary. Our study suggests that wave-driven red-line diffuse-like auroras, associated with braking flow bursts, offer a distinct yet complementary pathway of MI-coupling compared with well-established flow-driven discrete auroral streamers, typically seen in the green line and caused by field-aligned potential acceleration.

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Open Research

THEMIS data is available at <http://themis.ssl.berkeley.edu/data/themis/>. Poker Flat DASC and MSP can be accessed at <http://optics.gi.alaska.edu/optics/?q=archive>. Data access and processing was done using SPEDAS V4.1, see Angelopoulos et al. (2019).

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