

The Significance of Magnetospheric Precipitation for the Coupling of Magnetosphere-Ionosphere-Thermosphere Systems: Sources and Properties

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Synopsis:

Magnetospheric precipitation plays an important role for the coupling of Magnetosphere, Ionosphere, and Thermosphere (M-I-T) systems. Particles from different origins could be energized through various physical mechanisms and in turn disturb the Ionosphere, the ionized region of the Earth's atmosphere that is important for telecommunication and spacecraft operations. Known to cause aurora, bright displays of light across the night sky, magnetospheric particle precipitation, modifies ionospheric conductance further affecting the plasma convection, field-aligned (FAC) and ionospheric currents, and ionospheric/thermospheric temperature and densities. Therefore, understanding the properties of different sources of magnetospheric precipitation and their relative roles on electrodynamic coupling of M-I across a broad range of spatiotemporal scales is crucial. In this paper, we detail some of the important open questions regarding the origins of magnetospheric particle precipitation and how precipitation affects ionospheric conductance. In a companion paper titled "The Significance of Magnetospheric Precipitation for the Coupling of Magnetosphere-Ionosphere-Thermosphere Systems: Effects on Ionospheric Conductance", we describe how particle precipitation affects the vertical structure of the ionospheric conductivity and provide recommendations to improve its modelling.

1. The complexity of the coupled M-I-T system electrodynamics

The geospace response to the solar wind-driven convection electric field in the magnetosphere strongly depends on ionospheric conductivity, which results from coupled complex processes in the Magnetosphere-Ionosphere-Thermosphere (M-I-T) system that are governed by the laws of electrodynamics. Determined mainly by the solar EUV and particle precipitation-induced ionization and plasma-neutral interactions, ionospheric conductivity affects the ionospheric convection and field-aligned current patterns, thereby modulating the magnetosphere's response to the solar wind. However, due to the difficulty in measuring the neutral and plasma parameters in the lower thermosphere-ionosphere, where conductivities peak, large uncertainties exist regarding their characterization under different driving conditions (Palmroth et al., 2021).

Understanding variations of ionospheric conductivity on global, meso, and small scales is a prerequisite for advancing the ability to quantify ionospheric and magnetospheric electric fields and the many physical processes throughout the M-I-T system that are influenced by these electric fields. Thus, a comprehensive understanding of ionospheric conductivity is needed for realistic geospace modeling and space weather prediction of the M-I-T system.

Magnetospheric particle precipitation is one controlling factor for the ionospheric conductance. There are various open questions associated with the characteristics of magnetospheric precipitation that determines the spatial, temporal and energy ranges of the precipitating particles, however lack of global, high-resolution, multi-dimensional, and coordinated measurements hinders our ability to make further progress on these topics. Collaborations among different domain scientists that are focused on particle precipitation are necessary to better understand ionospheric conductance and improve its modelling (Ozturk et al., 2020). Therefore, we advocate for advancements in the following science questions that will help our field achieve a global, self-consistent, and multi-scale understanding of the coupled M-I-T system.

1. What are the magnetospheric processes associated with various types of auroral particle precipitation? What are the characteristics of these magnetospheric processes?
2. How do precipitating energetic ions and electrons associated with different auroral forms contribute to the ionospheric conductance across multiple scales as a result of these magnetospheric processes?
3. How does varying ionospheric conductance affect the I-T system response?

Two companion white papers, one on the sources of magnetospheric precipitation (this white paper) and another on their effects on ionospheric conductance and its modelling, are presented for this purpose. This white paper will focus on the science questions needed to be addressed to characterize magnetospheric particle precipitation.

2. Open questions related to Magnetospheric Particle Precipitation

2.1. Origins and characteristics of magnetospheric particle precipitation

There are three main auroral electron precipitation mechanisms: wave scattering of plasma sheet electrons into the loss cone (diffuse), acceleration by interactions with Alfvén waves (broadband), and acceleration due to a quasi-static parallel electric field (monoenergetic). Based on statistical analysis of FAST data, Dombeck et al. (2018) reported that intense electron precipitation events are often caused by a combination of two or more of the main mechanisms noted above. Therefore, it is important to focus on studies that target the origins and characteristics of the three aurora types.

2.1.1. Diffuse aurora

The diffuse electron aurora, typically concentrated on the midnight to morning side over a broad latitudinal range, contributes about 60% of the energy into the auroral oval (Newell et al., 2009) and is therefore crucial to the magnetosphere-ionosphere energy budget. There are several components that can affect electron precipitation into the ionosphere that produces diffuse aurora: the plasma sheet source distributions (Lui et al., 1977), electron drift (Khazanov et al., 2015, 2019), electron pitch-angle scattering—which is the dominant loss process for inner magnetospheric electrons (Shprits, Elkington, et al., 2008; Shprits, Subbotin, et al., 2008; Thorne, 2010)—and magnetosphere-ionosphere energy coupling that includes backscatter, production of secondary electrons in the atmosphere, and multiple downward precipitation and upward backscatter of electrons in the loss cone between conjugate hemisphere (Khazanov et al., 2015, 2019; Khazanov & Chen, 2021). Although, it is the most dominant type of aurora observed, there are various open questions regarding the origin and modelling of particles leading to diffuse aurora.

Magnetospheric Waves:

At a geocentric radial distance $r \leq 8$ RE, the resonant scattering of plasma sheet electrons (~ 100 eV–20 keV) by whistler mode chorus has been shown to be the major contributor to diffuse aurora precipitation (Ni et al., 2016). In contrast, using THEMIS observations and numerical analysis of scattering rates, Ni et al. (2012) reported a case in which enhanced electron cyclotron harmonic (ECH) waves were the dominant cause of electron diffuse precipitation at $r \geq 8$ RE. The ability to globally and dynamically quantify storm-time electron losses due to pitch-angle scattering with waves is challenging because the rate of pitch-angle diffusion for a given electron energy depends on the wave amplitude, wave frequency and wave normal distributions, as well as the plasma density and background magnetic field. Since these quantities are not measured globally, researchers have had to rely on theoretical or empirical models even if wave measurements are available from a few satellites for a particular event. **An array of spatially separated satellites that cover multiple MLTs simultaneously could provide a global context of wave parameters observationally.** A potential alternative way is to use multiple simultaneous NOAA/POES satellites measurements of electron fluxes to infer global wave characteristics under certain assumptions (Ni et al. 2014). A real-time wave model is necessary in the determination of event-specific, global diffusion rates for modeling dynamic electron precipitation globally (Yu et al. 2022).

To account for diffuse aurora generated by magnetospheric waves, the numerical models have incorporated parameterized electron loss rates of whistler chorus waves and of hiss (e.g., Chen et al., 2015, 2019; Yu et al. 2016, 2018), but have been unable to incorporate electron loss rates from ECH waves due to the current lack of parameterization. **Parameterized electron loss rates of ECH waves in the magnetosphere are needed.** Furthermore, development of a more complex electron loss characterization that also includes self-consistent generation of waves globally is desirable to narrow the uncertainties in the wave scattering rates.

Lastly, questions remain about the origins of the **dayside diffuse aurora**. Han et al., (2017) reported the first observations of ECH waves associated with the diffuse aurora on the dayside in absence of chorus waves. However these observations showed that precipitation events can have significantly different particle populations, dispersion forms, and can map to different regions in the ionosphere. **Further coordinated studies using magnetospheric and ionospheric plasma measurements spanning a range of magnetic latitudes and MLTs are needed to understand the formation and evolution of the dayside diffuse aurora.**

Ion precipitation:

Ions of tens of keV can precipitate down to the upper atmosphere as, especially in the night-dusk sector, carrying considerable energy source (Tian et al. 2020). Precipitating ions of magnetospheric origin can be resonantly scattered by EMIC waves, or chaotically scattered when the ion's gyro-radius is comparable to a field line's curvature radius, that is, in regions with highly stretched magnetic field lines. Comparative studies of these two mechanisms suggested that EMIC wave-induced ion precipitation predominantly occurs in the dusk sector of inner magnetosphere, the statistically preferred source region of EMIC waves, whereas field line curvature scattering of ions is effective in the stretched nightside magnetosphere (Shreedevi et al. 2021; Zhu et al. 2021). It is further found that heavy ions tend to experience the field line curvature scattering and subsequent precipitation in wider L and MLT regions than light ions (Yu et al. 2020). **Investigating other direct/indirect mechanisms causing ion precipitation and quantifying their relative contributions are essential; for a comprehensive understanding of particle precipitation.**

Pulsating Aurora:

One particular type of diffuse aurora, pulsating aurora, has been known to include a high-energy tail in the associated precipitation (Miyoshi et al., 2020). A building sequence of observational studies have confirmed the concept that modulated equatorial VLF chorus waves create the periodic pulsations observed (Nishimura et al., 2010, Jaynes et al., 2013, Kasahara et al., 2018). Additionally, pulsating aurora can be long-lasting and widespread (Jones et al., 2013) making this a significant source of energy transfer from the magnetosphere to the ITM system. Pulsating aurora can contain electron precipitation up to 1 MeV or higher (Miyoshi et al., 2021); although the relativistic energies do not contribute to the optical emission, the association of low and high energy precipitation illustrate the importance of pulsating aurora to the overall dynamics of both radiation belt variations and energy deposition into the D and E regions of the ionosphere and below. The canonical study of auroral energy flux into the topside ionosphere, Newell et al. (2009), found that the diffuse aurora (which included pulsating aurora) constitutes 84% of the energy flux into the ionosphere during low solar wind driving conditions and 71% during high solar wind driving conditions. Interestingly, this empirical model relied on DMSP spacecraft data, which did not extend upwards of 30 keV in electron flux measurements. Thus, **the entirety of the high-energy tail of pulsating/diffuse aurora is missing in this estimation, positioning these statistics as a lower boundary on the significance of auroral energy input.**

Relativistic Electrons:

Sub-relativistic (~ 100 -500 keV) and relativistic ($\sim >500$ keV) electron precipitation are not only present within pulsating auroral precipitation but also observed within non-pulsating but structured diffuse aurora. Field-aligned curvature or current sheet scattering (CSS) can lead to the pitch angle scattering of trapped relativistic electrons into the loss-cone at the outer radiation belt boundary (Pytte and West, 1978, Sergeev et al., 1983, Artemyev et al., 2013). Evidence of relativistic electron precipitation correlated with structured diffuse aurora was reported by Sivadas et al., 2019. These features, which are magnetically conjugate with the outer radiation belt boundary, appear to be associated with constant leakage of relativistic electrons from the outer boundary of the outer radiation belts. An important open question is **how long does precipitation from CSS last and whether the duration makes it a more prominent radiation belt loss mechanism** than more intermittent wave scattering. The precipitation is associated with faint auroral emissions, which are pronounced during the substorm growth phase when the field lines are stretched into a thin magnetotail. CSS occurs around midnight MLT and between L-shells ~ 6 -10 RE (in the dipolar transition region). However, EMIC waves are also observed in this region due to proton anisotropy in the dipolar transition region and can cause relativistic and sub-relativistic electron precipitation

(Capannolo et al., 2022, Capannolo et al., 2019, Sivadas et al., 2017). They are prominent in the dipolar transition region during substorm onset and expansion phases, and hence overlap with CSS. Furthermore, a large proportion of relativistic electron precipitation happens during active periods. Due to limitations in the global spatial and temporal coverage of relativistic electron precipitation, we are still **uncertain about the proportion of total energy brought into the ionosphere from relativistic electron precipitation.**

One might distinguish the likely source of relativistic precipitation by following the energy spectrum, spatial structure, and duration. However, it is unclear what is the contribution of high-latitude relativistic electron precipitation from different sources e.g. Chorus Waves, EMIC waves, Hiss, and CSS. In addition to the above, sub-relativistic precipitation can cause substantial D-region ionization. The contribution of sub-relativistic electron precipitation from CSS to total hall conductance during the growth phase is $\sim 25\%$ and $\sim 60\%$ during the expansion phase (Sivadas 2020). The sub-relativistic and relativistic electrons can also lead to ozone loss through NO_x production in the ionosphere that makes its way down to the stratosphere (Sinnhuber et al., 2012, Turunen et al., 2016, Maliniemi et al., 2022). These findings provide us with additional important open questions: **what is the contribution of sub-relativistic and relativistic electron precipitation to ozone depletion and total ionospheric conductance?** The former has the potential to impact climate, while the latter can affect space weather through magnetosphere-ionosphere coupling and needs to be better understood in the next decade.

2.1.2. Discrete aurora

Monoenergetic precipitation:

“Monoenergetic” or inverted V precipitation spectra, often represented as sharply peaked Gaussian distributions with a mean energy of E_0 , are associated with parallel electric fields. The auroral acceleration region (AAR) is the portion of closed auroral field lines with field-aligned electric fields (McIlwain, 1960; Evans et al., 1967) that accelerate auroral electrons up to keV energies. It has been suggested from observations of accelerated electrons and ions in the aurora (Lundin & Eliasson, 1991; Reiff et al., 1988) and electric field measurements (Mozer & Hull, 2001) that the AAR occurs at altitudes of $2\text{--}3 R_E$. One mechanism supporting the formation of a potential drop along an auroral field line is the mirror force in a converging dc magnetic field (Alfvén, 1963). Knight (1973) described the current-voltage relation for a Maxwellian distribution and others (Chiu et al., 1981; Janhunen & Olsson, 1998; Khazanov et al., 1998; Lemaire & Scherer, 1974; Pierrard, 1996) refined the description for different representative electron distributions for space plasmas. Based on experimental work by Lyons et al. (1979) and theoretical analysis by Fridman & Lemaire (1980), it’s assumed that the monoenergetic electron fluxes with an energy peak at E_0 are produced by a distributed potential drop V where $E_0 = eV$. This relates the mean energy to the potential drop, so if the mean energy is known, the potential drop can be inferred. Because it is difficult to model the discrete precipitation self-consistently, the mean energy could be extracted from observations of discrete, precipitating energy flux but **observations with coverage on a continental scale for hours-long time durations are necessary to supply inputs for an entire event.**

The uncertainties of the location and mechanism of the field-aligned potential drops present obstacles for modeling discrete auroral electron precipitation in a self-consistent manner. Furthermore, many inner magnetospheric models use the Vasyliunas equation (1970) that relates the electrodynamics of ionospheric conductance, ionospheric electric field, FACs, perpendicular currents from particle drifts in the inner magnetosphere, and inner magnetospheric electric (E) and

magnetic (**B**) fields under an assumption of the electrostatic condition of $\mathbf{E} \cdot \mathbf{B} = 0$. While this condition is valid for diffuse auroral precipitation, it breaks down for discrete aurora precipitation. This makes it challenging to map ionospheric potentials to the magnetosphere for discrete aurora.

Broadband precipitation:

The broadband aurora (also known as the Alfvénic aurora) are defined by broadband electron spectra with energies extending from tens of eV to a keV in magnitude (e.g. Chaston et al. 2002) and are associated with the action of dispersive Alfvén waves (e.g. Lysak and Lotko, 1996; Staciewicz, 2000). These waves are Alfvén waves with perpendicular scales on the order of the electron inertial length, the ion acoustic scale length or the ion gyroradius. They are termed dispersive as they permit propagation of wave energy across magnetic field lines (Lysak and Lotko, 1996). Due to electron mass effects (for inertial Alfvén waves) and electron pressure effects (kinetic Alfvén waves) these waves can support parallel electric fields that lead to the energization of electrons that form the broadband aurora. Inertial Alfvén wave effects dominate at high latitudes (e.g. Kletzing, 1994; Watt et al., 2005, 2006) while the kinetic Alfvén wave regime is at higher altitudes along the field line. **There are still open questions regarding the details and relative contributions of these different wave limits to the electron energization that results in the broadband aurora.** Inertial Alfvén waves can lead to both resonant (Fermi) and non-resonant energization (Kletzing, 1994) of electrons and both test particle (Chaston et al., 2002) and self-consistent flux tube simulations (Watt et al., 2005; 2006) illustrate a very good correspondence with satellite observations. Electron trapping effects between the wave potential of the kinetic Alfvén and the magnetic mirror of the dipolar magnetic field are also thought to lead to substantial electron energization (Watt and Rankin, 2009; Artemyev et al., 2015; 2016). While the parallel electric field in KAWs is directly proportional to the electron temperature, it is inversely proportional to the ion temperature and so the high values of the latter can act to limit the electron energization (Chaston et al., 2003; Damiano et al. 2015; 2016). Thus stochastic ion heating by kinetic Alfvén waves (Johnson and Cheng, 2001) may act as a regulating mechanism of the broadband auroral emissions (Damiano et al., 2015).

The broadband aurora peak at substorm onset (e.g. Wing et al, 2013) and observations (Keiling et al., 2003) illustrate substantial Alfvénic Poynting flux on both the nightside and within the cusp. In the magnetotail, both observations (e.g. Chaston et al., 2012) and MHD (Zhang et al., 2012) and hybrid (Cheng et al., 2020) illustrate the presence and generation of kinetic Alfvén waves within reconnection driven fast flows where the energy then propagates along the magnetic field lines to the ionosphere. **The exact details of the transfer of wave energy to dispersive (kinetic) scales to facilitate the energization is not completely resolved.** The distribution of Alfvénic energy in the broadband aurora illustrates a power law distribution (Chaston et al. 2008) that is often associated with a turbulent cascade and similar power law distributions are also evident in hybrid model simulations (Cheng et al., 2020). Phase mixing effects (e.g. Lysak and Song, 2000; 2008; Mann et al. 1995; Damiano et al., 2003) and ionospheric feedback (e.g. Lysak, 1991; Streltsov and Lotko, 2005) are also thought to contribute to the cross-scale coupling of wave energy to dispersive scales. Observations also illustrate quasi-static systems of field aligned currents are able to form from Alfvénic regions (Hull et al., 2010) which suggests that these regions may be an early stage of development for quasi-static systems, but the details are not fully understood.

Auroral forms associated with discrete precipitation:

As mentioned above, discrete auroral forms result from upward field-aligned currents. The more intense the FAC is, the larger the field-aligned potential drop it leads to (Knight 1973), and thus

the more significant the discrete aurora is. Therefore, the major sources of discrete precipitation are intense FAC-carrying dynamic phenomena in the magnetosphere. On the dayside, these phenomena are flux transfer events generated by magnetopause reconnection, and their FACs lead to discrete poleward-moving auroral forms (Sandholt et al., 1992). On the nightside, the magnetotail reconnection drives the dynamic phenomena. When the reconnection ejecta first appears near the reconnection site, its intense FAC leads to a discrete auroral known as the poleward boundary intensification (Lyons et al., 1999). When the ejecta travel earthward as a flow channel, its discrete auroral form is a streamer (Nakamura et al., 2001). When the ejecta arrives at the inner edge of the plasma sheet, it will lead to enhanced FACs called embedded Region 1 and 2 currents, which cause bright, east-west aligned discrete auroral arcs (Liu et al., 2021).

A discrete arc is collocated with a narrow region of very high conductivity because of its electron precipitation. This conductivity will lead to intense polarization effect around the arc, and the resultant electric field and flows may significantly impact the M-I system. For example, the high conductivity arc caused by the embedded Region 2 current in the dawn sector leads to a dawnside auroral polarization stream, an eastward flow of several km/s, immediately poleward of the arc (Liu et al., 2020). This flow has a steep gradient at the edge of the arc and maps to the magnetotail transition region. The flow and its gradient, which directly result from ionospheric conductivity distribution, can lead to instabilities responsible for dramatic reconfigurations of the M-I system—auroral Omega bands and substorm onset (Liu et al., 2018; Lyons et al., 2021). **Therefore, it is important to understand how different auroral forms occur and propagate in relation to geomagnetic activity.**

2.2. Effects of magnetospheric particle precipitation on the ionospheric conductance

2.2.1. Role of diffuse aurora on ionospheric conductance

The diffuse precipitating electron flux can be used to infer auroral ionospheric conductance during quiet geomagnetic conditions. Figure 4 from Khazanov et al., 2019 shows an example of RCM-E simulations results of Hall conductance intensity at 850 km mapped to the equatorial plane with and without using modifications from the SuperThermal Electron Transport (STET) model that accounts for complex backscatter effects during the early main phase and late recovery phase of a large storm. The conductance was calculated using Robinson et al. (1987) equations. One can see the stark difference in conductance depending on whether the backscattering electrons are included (with STET) or not (without STET)—and therefore how important capturing the various inputs is to correctly modeling conductance.

Diffuse electron precipitation has also been found to play an important role in the generation of mesoscale ionospheric structures. For example, using the MAGE model and controlled numerical experiments, Lin et al. (2021) reveal that properly characterizing the relative location of diffuse electron precipitation to the Region-2 field-aligned current is critical to resolving the mesoscale flow structures of subauroral polarization streams, which would require a treatment of kinetics based approaches that are underlying to the generation of diffuse electron precipitation.

Diffuse ion precipitation needs to be taken into account as it can augment the conductance on the dusk sector and alter electric potential patterns on a global scale (Zhu et al. 2021; Tian et al. 2022). The addition of ion precipitation-induced conductance would further cause feedback effects on magnetospheric dynamics and subsequently wave excitation. Figure 3 from Tian et al., 2023 shows an example of RAM-SCB-GLOW coupled simulation results of precipitating particle flux (both electrons and protons) and E/F region conductivity with and without adding the EMIC wave-

induced ion precipitation. The conductivity in the E/F region on the dusk sector is significantly enhanced.

2.2.2. Role of discrete aurora on ionospheric conductance

Low-Earth-Orbiting satellites (like DMSP) are able to observe the required energy flux and mean energy of the precipitating populations in order to calculate conductance. However, their orbits necessarily mean that they only observe the same area for a limited amount of time (minutes to 10s of minutes), meaning they cannot observe the storm or substorm evolution. Instead, previous studies have relied on statistics using solar wind parameters as input to estimate the location and intensity of the discrete aurora (e.g., the Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting (OVATION) models (e.g., Newell et al., 2009, 2010a, 2010b). **To avoid the dependence on statistics, 2D auroral imaging capable of resolving mesoscale aurora (10s to 100s km wide) is key.** Some work has begun in this direction, utilizing the THEMIS all-sky-imager mosaic across Canada and Alaska to monitor and resolve the aurora on mesoscales at 3 s cadence for hours at a time (e.g., Gabrielse et al., 2021; Nishimura et al., 2021). Such work is promising and is demonstrated in Figure 8 of Gabrielse et al. 2021, which compares the Hall conductance determined using ASI energy flux and mean energies as inputs to two models (the B3C auroral transport code and the Robinson formulae) with the Poker Flat incoherent scatter radar (PFISR)-observed Hall conductance. **The observational data are needed to extract spatial and spectral information about the monoenergetic precipitating spectra as input to auroral transport models to calculate ionospheric conductivity.**

2.2.3. Role of Field-aligned currents on ionospheric conductance

Ultimately, the aurora is an electrical phenomenon that is closely associated with magnetospheric and ionospheric currents linked by field-aligned currents. The correlation between FACs and auroral conductances was examined by Ridley et al. (2004) using the Assimilative Mapping of Ionospheric Electrodynamics model. This simple relationship between conductances and FACs was further refined by Mukhopadhyay et al. (2020). Robinson et al. (2020) derived relationships between field-aligned current and conductances using observations from AMPERE and the PFISR. The correlations were strongly dependent on magnetic local time. Wang and Zou (2022) performed a similar study based on PFISR and the SWARM satellites. Figure 11 from Wang and Zou (2021) compares the results from these different approaches. Although there are some differences, all show that **conductances can be estimated from the field-aligned current densities in both upward and downward current regions.** This provides a very powerful tool for modeling auroral electrodynamic parameters. By combining the FACs with the derived conductances, the electric potential and electric fields can be calculated. Robinson et al. (2021) showed that this technique can be used to replicate the SuperMAG magnetic indices. However, this approach is unable to capture the fine spatial and temporal scale structures in conductances associated with extreme and dynamic auroral events. **This drives the need for in situ measurements of precipitating particles and other electrodynamic parameters to complement the large-scale view made possible by global field-aligned current maps from AMPERE and its current operation on Iridium NEXT.**

3. Conclusion

In summary, there are various open questions about the origins of diffuse and discrete aurora and their role on the ionospheric conductance which require further attention in the next decade to further our understanding of the coupled Magnetosphere-Ionosphere-Thermosphere system and our capabilities of forecasting space weather.

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